Knowledge gaps about forest damage in Sweden

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Executive Summary

This report describes gaps in our knowledge regarding forest damage in Sweden. Such gaps limit our ability to predict the ecological, economic and social impact of damaging agents and factors, especially in a changing climate. Over the coming decades, the conditions for Swedish forestry are expected to change. This includes the structure and diversity of the forest, leading to uncertainty regarding risk from both biotic damaging agents and abiotic factors. This means that forest-related decisions will demand scientific knowledge beyond what is currently available and the development of new and better tools for forest planning.

Climate change has direct effects, through abiotic damage factors such as wind, drought and fire, and indirect effects, by altering conditions for browsing animals, insects and pathogens. We have identified the following knowledge gaps regarding the effects of climate change on individual damaging agents and factors in Sweden:

- Limited understanding of how longer growing seasons, elevated CO_2 levels, and more frequent extreme weather events affect tree physiology, growth and defence mechanisms. The combined effect of these factors on wildlife as well as insect and pathogen life cycles, the severity of infestations and infections, and dispersal dynamics is also unknown.

- Insufficient knowledge of how climate change will affect abiotic damage factors, such as droughts, fires and storms. Poor understanding of how water moves in the forest ecosystem, how drought occurs, and how fire spreads, due to limited historical experience.

- Lack of quantitative and qualitative comprehension regarding changes in host-insect-pathogen interactions in a warming climate, and of threshold levels at which climate-induced stressors compromise tree resistance and trigger disease/pest outbreaks.

- Poor knowledge of how climate change will affect the risk of disturbances by invasive species, either through northward range expansion or through human-induced introductions.

- Lack of quantitative understanding of how browsing by ungulates limits forestry yield through loss of quality and biomass, and of how browsing by ungulates, voles and hares affects future stand composition.

These knowledge gaps limit our ability to assess how climate change and management choices will affect damage risk.

Climate change also affects interactions between these disturbances and their management. Forest disturbances interact in complex and uncertain ways, and large-scale forest damage is usually the result of a confluence of more than one agent or abiotic factor. Our ability to understand, analyse, and predict the effect of multiple inter-related disturbances is currently lacking. Furthermore, managed forests are socio-ecological systems, meaning that ecological knowledge gaps translate into socio-economic ones, and vice versa. The gaps in knowledge identified here pertain not only to the actual frequency and magnitude of damage and interactions between damaging agents and factors, but also to how management strategies may affect the pattern of disturbances.

In this context, it is currently not possible to:

- Use the forest decision support system Heureka, to simulate effects of different damaging events on forests in a changing climate. This prohibits modeling the relationship between management strategy and the risk of damage, and determining optimal management strategies for different, possibly inter-related, damaging agents and abiotic factors.
- Model damage risk at different scales, for example comparing stand to landscape level. Forest owners have different attitudes to risk and its mitigation, but knowledge about both aspects is lacking. Fragmented ownership hampers landscape-wide risk management and effective use of forest insurance.
- Quantify economic impacts of large-scale forest damage on various forest product markets and evaluate how such events affect different stakeholders in the sector. A standardised national or regional Swedish forest sector model linked to these markets is needed.

In conclusion, conditions for Swedish forestry are likely to change over the next 30-40 years. Quantitative data are needed to predict and understand the ensuing forest disturbances and their effects. This report focuses mostly on the ecological-economic aspects of forest damage in Sweden. The understanding that forests in general are important for carbon sequestration and biodiversity conservation has put forests and their management high on the agenda at the Swedish and European level. This additional level of complexity is not addressed in this report. Neither are changes in forest ownership structure and demography, although they can have consequences for the wider management and diversity of forests in Sweden.

The identified gaps can be addressed through the following measures:

- Develop new models describing the consequences of different kinds of damage, and also models for alternative forest management to update the Heureka DSS
- Develop quantitative economic models to: understand optimal response to multiple damage risks; integrate the forestry industry and the forest sector to better understand how large-scale damage events affect them; assess the economic effects of long-term insect-borne and fungal disease outbreaks
- Develop risk and disease detection models for invasive species and emerging pathogens
- Improve biological control methods, and implement ecosystem-based approaches to reduce the spread of forest diseases.
- Quantify the effect of long-term trends in relevant insect populations
- Quantify the decrease in yield from browsing in young stands and the effects of browsing on future stand composition
- Assess trade-offs and synergies between different drought and fire mitigation methods and their relation to other forest management goals and other damaging agents and abiotic factors

Addressing the gaps in knowledge identified in this report will assist the development of improved tools for forest decision-making.

Innehåll

Person in forest. Photo: Theres Svensson

Introduction

This report aims to identify knowledge gaps concerning forest damage in a changing climate, and to discuss their implications for Swedish forestry. The report regards forest damage in Sweden, including interactions among damage-causing agents and abiotic factors. It also highlights insufficient use of existing tools and approaches.

Part I focuses on biotic damage-causing agents and abiotic factors. The biotic agents include insects, pathogens, and their interactions, as well as browsing damage. The abiotic factors are drought and forest fires. One overarching theme is whether the risks from these agents and factors will increase under a changing climate, and which management options may counter them.

Part II focuses on quantification and modelling of the interactions between damage, damaging agents and factors, and forest management. Different types of quantification frameworks are considered, with a focus on identifying what is missing in order to better understand the ecological drivers and possible damage-mitigation measures.

To illustrate the relationship between damaging agents and factors and different forest management practices under a changing climate, a quantification exercise is undertaken for wind damage under different future climate scenarios. The aim is, first, to illustrate how relevant knowledge of the future informs any quantification exercise; and second, to demonstrate how model limitations determine what can and cannot be learned from them. This may be of great importance for stakeholders in the sector.

Climate Change in Sweden

Since the late 1800s, the average temperature in Sweden has increased by 1.9 °C. The effect is most notable in the winter (2.3 °C) and spring (2.6 °C). Extremely warm months are more common, and cold months rarer. The growing season has been prolonged by an average of three weeks (five weeks in Götland, two weeks in Norrland). Average precipitation has increased from 600 to 700 mm per year, with an even greater increase in the winter. Years with abundant precipitation have become more common and dry years more unusual. The number of days with snow cover has decreased, although not the average snow depth.

Yearly solar radiation has increased by 10 % since the 1980s, mostly due to reduced cloud cover and particle presence in the atmosphere. Both mean and maximum wind speeds appear to have decreased, although there is some uncertainty regarding their extent and causes (Minola et al, 2016; 2021; SMHI, 2024). Climate projections for 2050-2100 indicate rising temperatures (up to 3 °C warmer in Norrland compared to 1961-1990), altered precipitation patterns with a particularly significant increase in Norrland, longer growing seasons, and more frequent extreme precipitation and flood events (Source: SMHI, 2024).

This pattern of change in temperature is displayed in Figure 1 for the RCP 4.5 scenario (Data for figures: SMHI) for four seasons. Figure 2 shows an increase in the number of dry days for both the summer and autumn, particularly in the southern and western parts of Sweden. The forecasted changes (Sjökvist et al, 2025; Eklund et al, 2015) have many implications for both biotic damaging agents and abiotic factors. Swedish forests and ecosystem services may become more sensitive to fires and drought, forest insect communities and pathogens in Fennoscandia may alter in abundance, distribution, and composition, and less cold-tolerant species may be allowed to spread. This may prolong local outbreaks and infections and increase their severity.

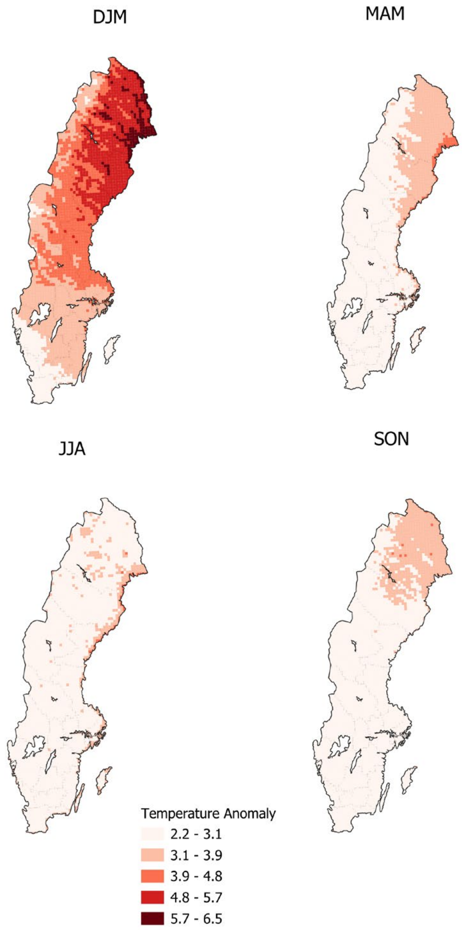
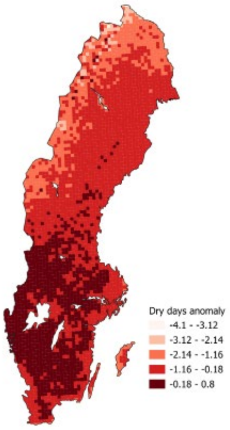


Figure 1: Computed seasonal change in average temperature for the period 2071-2100 compared to 1971-2000. Based on averages over multiple climate models in the RCP 4.5 climate scenario.

While the increasing temperature is predicted to increase biomass production in Swedish forests, it is also expected to increase the intensity and frequency of extreme weather events such as storms. Another predicted effect is an increase in extreme short-term precipitation, which may affect soil erosion and impact forests in other, uncertain ways. Increased winter precipitation and shorter time periods of frozen soil may also increase storm susceptibility during the winter.



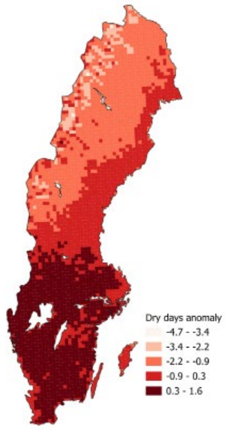


Figure 2a *Figure 2b*

Figure 2: Computed change in the number of dry days between 2071-2100 and 1971-2000 for the June-August (panel a) and September-November (panel b). Based on averages over multiple climate models for the RCP 4.5 climate scenario.

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[1]Full link for data: https://www.smhi.se/klimat/framtidens-klimat/klimatscenariotjansten/klimatscenariotjansten/met/sverige/medeltemperatur/rcp45/2071-2100/winter/anom (accessed last on June 16, 2025). The variables for which data was downloaded are: temperature (anomalies) for the respective seasons, and for the RCP 4.5 scenario for figure 1 and drydays (under Precipitation) for figure 2.

[2]IPCC's climate change scenarios to project future greenhouse gas concentrations, since the fifth assessment report (AR5) in 2014, have been reported in terms of RCPs (Representative Concentration Pathways). The most common RCPs used are the RCP 4.5 and 8.5, with the numbers referring to the expected increases in radiative forcing values from the years 1750 to 2100. RCP 4.5 and 8.5 are often used as short-hand for scenarios which significantly limit future emissions and a more conservative "business as usual" scenario respectively. These are the scenarios evaluated extensively in for instance SMHIs Report on Sveriges framtida klimat (updated regularly, see https://www.smhi.se/publikationer-fran-smhi/sok-publikationer/2025-02-10-klimatunderlag-for-klimat--och-sarbarhetsanalyser).

Part I: Damage-causing agents and factors

1. Damage caused by pathogens

The conditions of forest pathology are being reshaped. Rising temperatures, prolonged droughts, and shifting precipitation patterns are accelerating the emergence and northward spread of pathogens previously limited by climate. At the same time, intensified global trade, particularly importation of live plant materials, increases the risk of introducing new invasive pathogens.

These shifts create significant uncertainty about how forest diseases will evolve and interact with trees in the coming decades. Changing environmental conditions expose key knowledge gaps, including interactions between stress and resistance, vector dynamics, co-infections, long-term forest resilience, and the economic impact of emerging and invasive diseases.

This part of the report highlights the most significant knowledge gaps across key areas related to pathogens, including climate change challenges, changes in host-pathogen interactions, changes in pathogen-insect interactions, emerging diseases, invasive pathogens and globalization, and management strategies.

1.1 Climate change challenges

Rising temperatures, altered precipitation patterns, and longer growing seasons influence both pathogen survival and dispersal (Dale et al, 2001), though the effect on long-term dynamics remains uncertain. For example, the rapid spread of *Phytophthora spp.* highlights the need for improved risk assessments and monitoring.

Despite growing risks of outbreaks, Sweden currently lacks predictive models that incorporate climate, ecology, and forest management practices. Across Europe, climate change is driving the expansion of native pathogen ranges while creating favorable conditions for invasive species. Northward spread of fungi such as *Dothistroma septosporum* and *Diplodia sapinea* has been documented (Brodde et al, 2019), yet a comprehensive framework connecting climate variables with pathogen distribution is still missing. Extreme weather events such as storms and droughts are expected to further accelerate the proliferation of fungal pathogens.

The impact of climate change on host susceptibility needs to be better understood. While longer growing seasons may benefit tree growth, they also extend the active period for many pathogens (Desprez-Loustau et al, 2006). *Heterobasidion* spp., serious root rot pathogens in conifers, are expected to spread more under warming conditions (Thor et al, 2005). Moreover, climate-induced stressors such as drought can reduce tree resistance to infection, though data specific to Sweden remain limited (Knutzen et al, 2025). A major challenge to understanding change in pathogen behavior is early detection.

Current monitoring efforts often miss latent infections, allowing pathogens to spread undetected. Expanding the use of molecular diagnostics and remote sensing could improve real-time monitoring and facilitate faster response to emerging threats.

1.2 Changes in host-pathogen interactions

Climate change disrupts long-standing balances between trees and pathogens. It also increases the risk that pathogens introduced by global trade will cause outbreaks in regions that were previously inhospitable to them (Stenlid & Oliva, 2016). Shifts in seasonal timing further complicate this dynamic. If climate change causes trees and their pathogens to develop at different times, the risk of infection can rise — especially if trees lose their ability to adjust to these combined climate and disease pressures. A phenological change in response to a new climate could inadvertently lead to increased susceptibility to a pathogen.

The outbreak of *Gremmeniella abietina* in Sweden in 2001 illustrates how environmental mismatch increases susceptibility (Stenlid & Oliva, 2016): frost-prone southern-provenance trees were more vulnerable in northern climates.

Host susceptibility is shaped by a combination of genetic and environmental adaptation. Stressors such as nutrient imbalances, extreme weather, and phenological shifts raise vulnerability to pathogens. Understanding how plasticity interacts with evolving pathogen pressure is essential to understand long-term forest resilience (Trumbore et al, 2015). Tree breeding programs often focus on known pathogens, but the long generation times of forest trees make them vulnerable to newly emerging pathogens. Without continuous monitoring, resistance traits may quickly become outdated. Moreover, a climate change–related increase in temperature and atmospheric CO_2 may enhance growth while at the same time eroding trees' defensive capacity. Increased droughts in Sweden are weakening *Picea abies* defenses by reducing resin production (Jönsson & Lagergren, 2018), though thresholds linking stress to outbreaks remain unclear.

Changes in tree species compositions (i.e. mixed vs. pure stands) also affect disease dynamics. Tree species diversity generally lowers disease incidence, because outcomes depend heavily on species identity, and susceptible species benefit when mixed with resistant ones. Latent pathogens, currently causing minimal damage, may emerge as serious threats as climate shifts raise stress levels and alter pathogen behavior. Identifying and monitoring these emerging risks remains a major challenge for sustainable forest management.

1.3 Changes in pathogen-insect interactions

Many forest pathogens are transmitted by insects. Rising temperatures are altering insect behavior, lifecycles, and distribution, which increase spread of disease (Roos et al, 2010). Some relationships are well known, such as that between bark beetles (*Scolytus* spp.) and Dutch elm disease (caused by *Ophiostoma novo-ulmi*), but many remain poorly understood. This poses a risk to forest health and timber production.

A key example is the bark beetle (*Ips typographus*) whose northward spread and increasingly frequent outbreaks are driven by longer breeding seasons and milder winters. This beetle spreads blue stain fungi (*Ophiostoma, Grosmannia* spp.), which block water transport (Netherer et al, 2021). Warmer conditions may also enhance fungal development within insects, potentially increasing transmission efficiency. Milder winters also allow other vectors such as wood-boring and sap-feeding insects to expand their ranges. This includes invasive oak lace bug (*Corythucha arcuata*), linked to oak decline, and aphids and scale insects, which can transmit viruses and open pathways for secondary infections. Climate change may also drive the emergence of novel pathogen-insect interactions and increase the occurrence of co-infections.

While insects' natural enemies, such as predators and parasitoids, might help to reduce pathogen spread, their role in Nordic forest ecosystems remains poorly studied. Insect microbiomes also affect disease transmission. Bark beetles can carry multiple fungal associates, and interactions between these fungi may exacerbate disease outcomes, though such dynamics remain understudied (Davis et al, 2010). Some insect-associated viruses may suppress beetle populations, but others might enhance pathogen spread. Some bacteria in insect vectors may suppress or enhance pathogen virulence, and climate-driven microbiome shifts could thus alter infection dynamics.

Forest composition is also an important factor. Monocultures are especially susceptible to insect-vectored diseases, while mixed-species forests may disrupt transmission and provide greater resilience. Drought and extreme weather events can also intensify insect and pathogen damage by stressing trees and creating entry points for infection.

1.4 Forest diseases of increasing importance

Many forest diseases are expanding in range, severity, and host diversity, threatening both native and non-native plant species (Anderson et al, 2004). Their emergence is driven by global trade, land-use changes, and climate change. Host availability and susceptibility are affected, as well as pathogen virulence. Monoculture forestry and host-pathogen co-evolution (or lack thereof) further shape vulnerability (Gougherty, 2023).

In Sweden, conifer-dominated forests account for 83% of forest cover, with P. sylvestris and P. abies being particularly susceptible to root rot and rust fungi. Some of the most destructive root-rot pathogens are *Heterobasidion* spp. They spread via stump infections and root grafts and are increasing in prevalence (Woodward et al, 1998). *Armillaria* root rot is also on the rise, particularly in southern Sweden, but remains underdiagnosed due to subtle early-stage symptoms (Heinzelmann et al, 2018).

Recent outbreaks of *Cronartium pini* on pine in northern Sweden have raised concern. It causes significant growth loss, and the fungus' complex life cycle makes it difficult to counteract. The long-term effects of these outbreaks remain unknown (Samils & Stenlid, 2022). More research is needed on disease progression, spore dispersal, and host resistance mechanisms.

Gremmeniella abietina continues to be a major disease in Norrland, affecting multiple conifer species. Its outbreaks are associated with stressed stands and recurring cool, wet summers. Diagnosis and management are complicated by the fungus' multiple races (Stenlid & Oliva, 2016). Other pathogens, such as *Diplodia sapinea* and *Sydowia polyspora*, are increasingly detected in *Pinus contorta* in central Sweden, often following drought or other stress events. *D. sapinea* has expanded its range northward due to climate warming and is associated with reduced tree growth and sudden outbreaks (Brodde et al, 2019). *S. polyspora*, a widespread endophyte, becomes pathogenic under stress and co-infection scenarios (Busby et al, 2016).

Needle cast caused by *Lophodermium* spp. is re-emerging, especially in nurseries and young pine plantations. Interestingly, the presence of non-pathogenic species *L. pinastri* may suppress the more aggressive *L. seditiosum,* and might have potential as a biological control agent. However, genetic diversity within the *Lophodermium* complex requires further study (Patejuk et al, 2021).

Many emerging pathogens are often overlooked until triggered by environmental stress. Nurseries, in particular, act as hotspots for pathogen-host interactions and constitute a risk regarding the emergence of new diseases. This risk can be reduced by improved monitoring, training, and use of locally adapted genotypes. There is a need for long-term studies, genetic resistance screening, and strengthened cross-agency collaboration in order to manage future threats to forest health.

Symptom of gremminiella, Photo: Iryna Matsiakh

1.5 Invasive pathogens and globalization

Invasive forest pathogens are a growing threat across Europe, particularly in Fennoscandia (Santini et al, 2013). They disrupt ecosystems, threaten biodiversity, and reduce economic values of forests (Stenlid & Oliva, 2016). Sweden imports ca. 4,025 tons of plants annually, often originating outside Europe, creating indirect pathways for non-native pathogens. While quarantine regulations and phytosanitary inspections play a key role in limiting introductions, they cannot fully prevent them (Liebhold et al, 2012). Since 1800, 30–40 invasive forest pathogens have been recorded in Sweden (Santini et al, 2013). Native species may be especially vulnerable due to a lack of co-evolutionary defenses (Brasier, 2008), which is a particular concern regarding economically keystone species such as *P. sylvestris* and *P. abies.*

Effective management of invasive pathogens requires an approach that integrates early detection, resistance breeding, and scenario-based studies. Such studies can assess key tree species' susceptibility under changing climate conditions (Naidoo et al, 2019). Advances in molecular diagnostic tools, such as qPCR, LAMP, and remote sensing may allow for early detection, though they differ in terms of precision, cost, and scalability.

Forest management strategies must adapt to reflect these new threats. Mixed-species forests tend to be more resilient to pathogen invasion than monocultures (Gómez-Aparicio & Ruiz-Benito, 2022). Strategic diversification of tree species, improved monitoring, and rotating tree species can reduce the likelihood and severity of future outbreaks.

There is also a need for predictive tools and collaborative research frameworks. Developing risk maps, conducting economic assessments, and establishing a collaborative Scandinavian-scale research network would allow for a better understanding of pathogen dynamics and for the sharing of prevention strategies across the region. Coordinated shared pathogen-host databases would support forecasting and long-term resilience planning (Guégan et al, 2023).

Since forestry accounts for ca. 10% of Sweden's annual export value (Swedish Forest Agency, 2020), the rising threat level from pathogens is a national concern. Strengthening biosecurity protocols, improving field diagnostics, and investing in long-term ecological research are important steps to safeguard forest health and economic stability in the decades to come.

1.6 Management strategies

Forest management actions such as species selection, thinning, and stump treatment play a key role in shaping disease dynamics. Swedish forestry is dominated by monocultures, but increasing tree diversity improves resilience (Roberts et al, 2020). For example, spruce stands with a high proportion of pine trees suffer less damage from root rot. To decrease rot frequency, thinning operations should be conducted early, during winter or in combination with stump treatment. Rotstop® (*Phlebiopsis gigantea*) is widely applied to stumps in Sweden to prevent *Heterobasidion* spread, but improper application often reduces its effectiveness (Blomquist et al, 2023). On former agricultural land, young conifer plantations are particularly vulnerable to pathogens such as *Heterobasidion* (Delatour et al, 1998).

Further research is needed to understand how practices such as clear-cutting or group harvesting influence pathogen dynamics and tree resilience. Planting alternative species such as *Pseudotsuga menziesii* and *P. contorta* may help maintain forest productivity, but these species can be vulnerable to novel pathogen interactions. *P. contorta* is susceptible to *Dothistroma septosporum* and *D. sapinea* under Nordic conditions (Millberg et al, 2015).

Effective monitoring programs, e.g. spore trapping or the use of sentinel trees, are essential for early detection and outbreak control (Castaño et al, 2017). However, currently Sweden lacks standardized, long-term pathogen surveillance and a national database. Strengthened coordination across the Nordic-Baltic countries and investment in early warning systems are needed (Hopkins & Boberg, 2012).

Biological control remains underutilized in Sweden. *P. gigantea* is the primary biocontrol agent for root rot, but promising alternatives also include *Trichoderma*, *Gliocladium* and *Bacillus* spp. Fungal endophytes such as *Phaeotheca dimorphospora* have shown potential in suppressing *G. abietina* growth in laboratory and small-scale trials (Romeralo et al, 2015). Large-scale field validation is required to confirm these effects. Microbiomes may also enhance resistance, but they might be susceptible to disruption under climate change. Mycoviruses represent a novel frontier in pathogen control and could be explored as biological tools for virocontrol (Galli et al, 2025).

The economic impact of forest pathogens is significant. In the 1990s, *Heterobasidion* root rot alone was estimated to cost European forestry up to €580 million annually, and the disease is even more prevalent today (Woodward et al, 1998). The latest major *G. abietina* outbreak, in 2001, affected over 450,000 ha in Sweden. The eradication attempts against Dutch elm disease are costing Gotland more than 6 million SEK per year (Hopkins & Boberg, 2012). Indirect costs including biodiversity loss and reduced ecosystem services are more difficult to quantify. Moreover, socioeconomic impacts on rural communities and recreational forest users remain poorly studied (McKinney et al, 2011). Investments in early detection, monitoring, and prevention are relatively low compared to the higher costs associated with disease management, losses and outbreak control (Leung et al, 2002).

1.7 Priority areas for future research

Given these identified gaps in forest pathogen knowledge, the following research areas may be considered the most pressing to explore:

1. Enhanced Monitoring and Risk Assessment: Strengthen monitoring systems in forests and urban areas using systematic data collection, integration of climate and ecosystem dynamics, and the development of risk and disease detection models for invasive species and emerging pathogens.

2. Economic and Ecological Impact Analysis: Develop quantitative models to assess long-term impacts of insect-borne and fungal diseases on forest ecosystems, ecosystem services, and forest economics.

3. Sustainable Disease Management Strategies: Improve biological control methods, identify naturally resistant trees through forest breeding programs, and implement ecosystem-based approaches to reduce the spread of forest diseases.

Spruce. Photo: Theres Svensson

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Seedlings. Photo: Theres Svensson

2. Damage caused by insects

2.1 Introduction

Being ectothermic and small-bodied, insects are vulnerable to increased temperatures and changes in precipitation (Harvey et al. 2023). Climate change thus has a direct effect on insect development and reproduction. They are also impacted indirectly, through induced stress and adaptive responses in their host plants and natural enemies. This will shape future population dynamics and hence future threat levels in forest ecosystems (Klapwijk et al. 2012). However, changing weather patterns will affect different damage-causing species in different ways (Klapwijk et al. 2013). Furthermore, the combined effects of climate change and increased pressure from invasive pests are expected to intensify the challenges facing forest ecosystems (Ramsfield et al. 2016). This chapter focuses on the knowledge gaps in this field of research that could inhibit decision-making in forestry. A wealth of knowledge is already available, but uncertainty remains about how it is best applied in practice in order to optimize biomass production and reduce forest susceptibility.

2.2 Using new tree species

Over the past decades biomass production has been dominated by Norway Spruce and Scots pine. Currently, however, a wider use of other tree species is being considered, such as larch (*Larix* spp) and birch (*Betula* spp). Non-native species, like North American Douglas fir and lodgepole pine, are also discussed, mostly because of their climate tolerance. There is limited knowledge as to what level of insect threat such novel tree species would be subject to.

In mixed forests, the pine weevil *Hylobius abietis* will not only feed on spruce and pine but can also feed on larch seedlings (Wallertz, Nordenhem & Nordlander 2014). In addition, increasing the amount of planted larch could lead to a non-linear increase in damage caused by two non-native but established wood-boring species, *Ips cembrae*, and *Tetropium gabrieli* (Cocos et al. 2024), and also by *Coleophora laricella*; a needle-feeding moth considered a pest in other parts of its range (Polyakova, Pashenova & Senashova 2020).

Birch is more widespread in the Swedish landscape, accounting for 13% of the total growing stock (Nilsson et al. 2022). Birch may potentially be used in mixed forest stands together with spruce to reduce damage from the European Spruce bark beetle (*Ips typographus*). A too small volume of birch in spruce stands (up to 25m3/ha) has been shown to increase the risk of beetle attacks (Kärvemo, Rogell & Schroeder 2014), but higher volumes are believed to lead to reduced losses (Kärvemo et al. 2014; Müller et al. 2022).

However, it is unclear how this would affect the threat of attacks on birch. Very little research is available on insect damage on birch, except for the Winter moth (*Operophtera brumata*) (Tenow et al. 2013). Birch can also be a host for the invasive bronze birch borer (*Agrilus anxius*). Two native birch species, silver birch (*Betula pendula*, Roth) and downy birch (*Betula pubescens*, Ehrh.), have been found to lack resistance to this beetle, with 100% mortality (Nielsen, Muilenburg & Herms 2011).

2.3 Tree breeding and propagation

A longstanding hypothesis in ecology states that faster growing plants suffer from more herbivore damage than slower growing plants: the growth – defence trade-off (He, Webster & He 2022). This appears to be true for Norway spruce (Huang et al. 2019), which raises the question whether selecting trees for their stronger growth properties simultaneously selects them for their weaker defence. Propagation methods have been found to affect susceptibility, as spruce seedlings produced using somatic embryogenesis have an increased rate of survival against insect attacks (Puentes et al. 2018).

New techniques are under development to improve the genetic material of spruce and to control insect damage (Singh et al. 2024). Breeding for resistance against insect pests is a relatively new area of research that, together with genetic engineering, offers opportunities for the future (Naidoo et al. 2019; Pike, Koch & Nelson 2020).

2.4 Emerging pests

Changes in land-use and climate have together intensified disturbance regimes in European forests (Seidl, Schelhaas & Lexer 2011; Tudoran, Marquer & Jönsson 2016). Recently, Sweden experienced its largest outbreak of Spruce bark beetle to date, killing 34 million m^3 of trees in four years (Schroeder & Kärvemo 2022). Although much is known about this species (Seidl et al. 2016; Huang et al. 2020; Netherer & Hammerbacher 2022), controlling the population during outbreaks has proven difficult. Rectifying this will demand new methods and techniques developed with a holistic approach (Hlásny et al. 2021; Singh et al. 2024).

In Finland, the nun moth (*Lymantria monacha*) has been observed to increase in density and expand its range. The range for this native species has historically been confined to central Europe (Melin et al. 2020). Many other local species are predicted to expand their range northwards in a warmer climate (Robinet & Roques 2010). This will lead to changes in inter- and intra-specific competition over food resources, affecting the relative abundance of species in the affected communities (Bulleri, Bruno & Benedetti-Cecchi 2008).

2.5 Non-native insect species

The increasing global trade in wood commodities and the widespread use of wood packaging have facilitated the movement of species across countries and continents. While predicting which species will arrive and when remains difficult, preparedness based on ecological knowledge is crucial, though currently lacking. Risk assessment of quarantine species has identified at least 12 non-native insect species linked to the trade of ornamental plants and plant parts that could pose significant risks to coniferous forests (Marinova-Todorova et al. 2020).

Already established non-native insect species affecting forest trees in Sweden today include the small spruce bark beetle (*Ips amitinus*), the larch bark beetle (*Ips cembrae*), and the larch longhorn beetle (*Tetropium gabrieli*) (Cocos et al, 2023; Cocos et al, 2024). In its native range in Central Europe, *I. amitinus* coexists with *I. typographus*, and has been observed attacking the same tree species (Grodzki 2009; Holuša et al. 2012). The potential effects of both species overlapping in Sweden are difficult to predict, but a modeling study suggests that *I. amitinus* could exacerbate the severity of *I. typographus* outbreaks (Økland & Skarpaas 2008).

Importing deciduous wood chips from North America to northern Europe presents a risk of introducing invasive bark- and wood-boring insects (Flø, Krokene & Økland 2014), such as the bronze birch borer (*Agrilus anxius*), the emerald ash borer (*Agrilus planipennis, Fairmaire*), and the dark elm beetle (*Hylurgopinus rufipes*, Eichhoff). Although wood chipping is a good control method against certain insect species, the bronze birch borer has been known to survive chipping and detection is very difficult (Økland, Haack & Wilhelmsen 2012).

2.6 Community composition & Complex ecological interactions

Climate change is expected to have a profound impact on forest insect communities, influencing their diversity, distribution, and composition (Walther 2010). Rising temperatures are expected to expand the range for many species northward (Pureswaran, Roques & Battisti 2018; Johnson & Haynes 2023). Species such as the winter moth (*Operophtera brumata*, L.) and the autumn moth (*Epirrita autumnata*, Borkhausen) have already shown signs of such expansion, which could potentially extend the duration of their local outbreaks (Jepsen et al. 2008).

Defoliating insect species that overwinter as eggs are particularly likely to benefit from warmer winters, as these conditions may prevent egg mortality, leading to an increase in the frequency of outbreaks (Neuvonen & Viiri 2016). Shifts in insect communities may have far-reaching consequences for forest ecosystem health and management (Jaworski & Hilszczanski 2013). Changing forest management methods from even-aged monocultures to either mixed or uneven-aged stands will alter the composition and diversity of insect communities, with consequences for many ecological interactions. Our understanding of what the long-term effects would be remains limited.

2.7 Trade-offs, synergies and decision-making processes

One way to mitigate these changes in community structure is to alter forest management, and actively strive for diversity at local and landscape levels. However, we lack qualitative and quantitative understanding of trade-offs and synergies between different forest management systems in terms of economic returns and reduced susceptibility. In order to understand future threats, we need to understand tree response to both climate change and altered forest management, as well as how interactions with insects and between insect species will be affected. A more holistic approach is needed with a focus on ecosystem functioning instead of the individual agents and factors. One concept that provides a basis for such a holistic approach is forest health.

One definition of forest health that combines the ecosystem and utilitarian perspectives is: 'forest health describes a condition of forest ecosystems that sustains their complexity while providing for human needs" (O'Laughlin et al. 1994). Mixed-species forest stands are beneficial for many ecosystem services including forest growth (Huuskonen et al. 2020), and clear-cut free forestry has been found to enhance biodiversity of certain forest-associated taxa (Ekholm et al. 2023). In order for management decisions to increase forest health, synergies and trade-offs need to be identified that balance different threats with goals for biomass production and biodiversity.

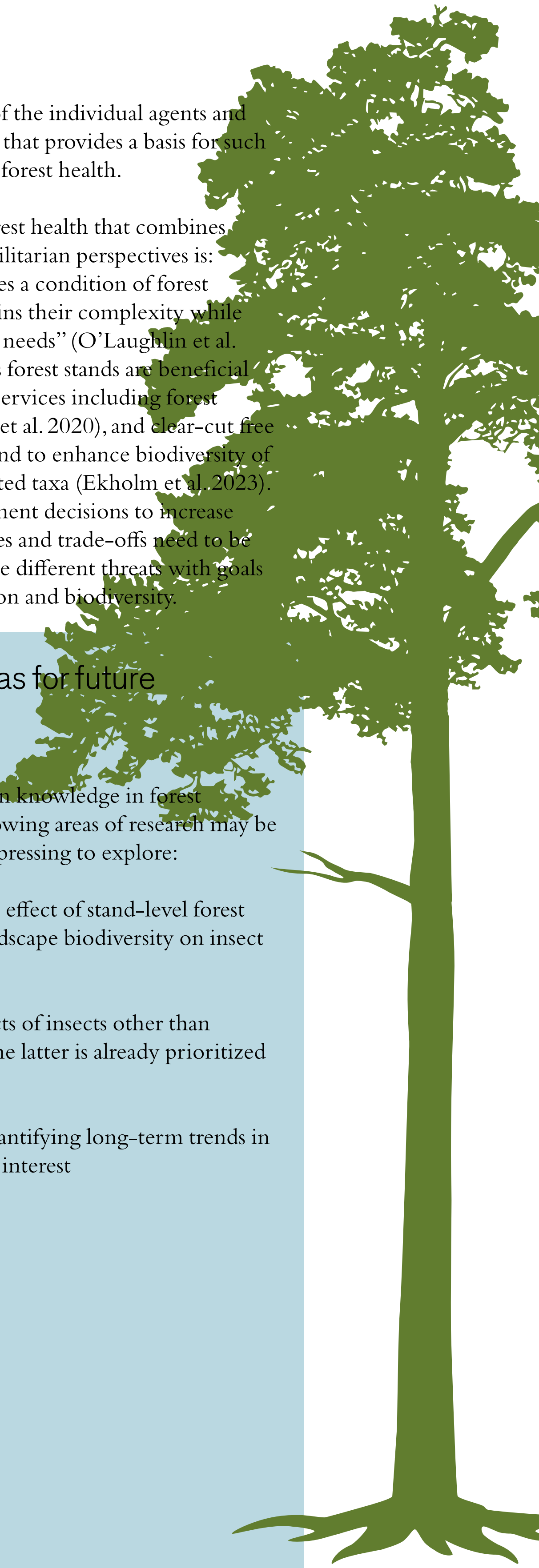
2.8 Priority areas for future research

Based on these gaps in knowledge in forest entomology, the following areas of research may be considered the most pressing to explore:

1. Understanding the effect of stand-level forest management and landscape biodiversity on insect outbreak risk

2. Quantifying impacts of insects other than spruce bark beetle (the latter is already prioritized enough)

3. Identifying and quantifying long-term trends in insect populations of interest



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3. Damage caused by drought and forest fires

3.1 Introduction

After almost a century-long increase, the growth of Swedish forests has abruptly decreased during the last decade, and climate-related drought has been pointed out as the most likely cause (Laudon et al. 2024). During the long drought in 2018, Fennoscandia experienced its largest forest fires in modern history (SNS 2021). Future climate projections indicate rising temperatures and an increase in the frequency of extreme weather events in Fennoscandia, which will likely make fires and drought more common in Sweden. On the other hand, forest fires are a natural disturbance in the boreal region and are important for ecosystem functioning and biodiversity. Since forest fires and drought have historically not been seen as a large problem in Fennoscandia, we lack scientific and practical knowledge of their functioning, impact, and potential mitigation in forest management. This summary identifies the key knowledge gaps regarding our understanding of droughts and forest fires, in Sweden specifically and in Fennoscandia more generally. The extended summary can be found in the Appendix.

3.2 Drought in forest ecosystems

Drought is here defined as a lack of available water in forest ecosystems. It may occur when groundwater and water storage are not refilled sufficiently, and is worsened by low summer precipitation and air humidity (Van Loon 2015). The southeastern part of Sweden is most susceptible to drought, but in the past decade, southern Götaland and Svealand have also suffered from decreased water flow. It is likely that other regions will also experience similar problems in the future (SMHI 2024). *More detailed analyses of drought risk across and within regions are needed, as well as improved models of how different future climate prognoses affect this risk.* Drought reduces plant growth and reproduction, and increases vulnerability to pests and diseases. It also leads to mortality, thereby affecting the provision of ecosystem services (e.g. McDowell et al. 2008). A shortage of water has been suspected to be the cause of decreased tree growth in Sweden during the last decade, but the cause of the drought is not clear. *Even though we have a good theoretical understanding of how drought occurs, we lack fundamental quantitative knowledge of how water moves in forest ecosystems, e.g. how winter climate, snowmelt, outflow, storage in soil, and uptake by trees are related to each other and to the occurrence and severity of drought.*

Some regions and soils are more sensitive to drought, typically those with low groundwater levels and soils with high water permeability, like sandy soils (Evaristo et al. 2017). Plants in shallow soils and in soils with a thin organic layer, like bedrock, suffer more often from drought. Pine and birch have been shown to tolerate drought better than shallow-rooted spruce trees (Lagergren and Lindroth 2002). On the other hand, deciduous trees have higher evapotranspiration than conifers. *Still, more quantitative knowledge is needed to understand how tree species, forest structure (e.g. variation in density, height, and canopy coverage), soil type, and local weather (short- and long-term), as well as their interactions, affect water availability and drought risk.*

3.3 Forest fires, fire spread and biodiversity

Forest fires play an important role in ecosystem function, regeneration, and biodiversity. However, Sweden's effective fire suppression minimizes the annual area affected by fire, which is why prescribed burning for nature conservation has been introduced (SNS 2021). On a regional level, high risk of fire correlates with high risk of drought, but local fire risk is more complex and depends on a combination of weather, available fuel, and human activity.

Prognoses indicate a significant increase in high-risk periods, especially in southern Sweden and along the Norrland coast (Berg et al. 2024). Extended periods of low relative humidity combined with high wind speeds create favourable conditions for fire. *More detailed risk analysis is needed, spatially and temporally, between and within regions, and for a variety of future climate scenarios. The risk of "mega-fires", already occurring in southern Europe, also needs to be analysed*. Surface fuels (mosses, lichens, shrubs, grass, litter) are the most important factor for fire ignition and spread. The risk of highly intense crown fires depends on tree species composition, stand development stage, and forest structure (ladder fuels). On the landscape level, heterogeneity in tree species compositions, age structures, and moisture conditions creates variation in fire spread and intensity (Bohlin 2024).

Although we have a qualitative (and partly quantitative) understanding of the factors affecting fire risk in Fennoscandia, we lack deeper quantitative knowledge of how fire ignition and spread are affected by forest characteristics and landscape structure, as well as by temporal variations in fuel/weather conditions. This is crucial for risk modelling and for creating recommendations for fire mitigation. Wildfires affect landscape heterogeneity and forest succession, and support fire-adapted species and habitats. This makes them critical for biodiversity (Kelly et al. 2020). Many species are also dependent on fire to create viable soil conditions, shape plant species compositions, and provide deadwood in sufficient amounts and quality.

The plant species succession after fire in boreal forest ecosystems is fairly well understood, *but the effect on other species needs to be investigated. We also lack knowledge on how the spatial and temporal variation in forest fires affects biodiversity.* Due to the lack of wildfires, nature conservation burning has been introduced to support biodiversity, *but more research is needed to find the most beneficial and optimal restoration methods*.

3.4 Mitigating drought and forest fires through forest management

Drought can be mitigated by silvicultural measures (Skogsstyrelsen 2019). For example, spruce and birch should be planted only on fertile soils and avoided on dry soils, bedrock, and slopes. Pine is the most suitable species for dry conditions. Mixed stands can also decrease the impact of drought. During stand regeneration, risk can be reduced by good soil preparation and correct planting location, and in already established stands, by thinning operations (Aldea et al. 2024). *We have some understanding of how management methods can be adopted to handle the risk of drought, but we need more quantitative knowledge on how species mixtures, different thinning intensities, ditches, and silvicultural systems (e.g. continuous cover forestry) affect the risk*. Drought-induced damage can also be mitigated by using more drought-tolerant plant material, but *we are still lacking fundamental knowledge and tools to assess these traits in trees, and the trade-off between breeding for growth and drought tolerance.*

Forest management can be used actively to mitigate forest fires (Bohlin 2024), usually by modifying fuel conditions. Short-term methods may include cleaning forest roads or removing harvesting residuals, and long-term methods favouring deciduous trees, maintaining forest road networks, re-wetting and protecting natural wetlands, and creating varied forest landscapes. Even though we have quite a good theoretical understanding of the methods that can be used to mitigate forest fires in Sweden, *we lack quantified measures of the effects of these methods, such as how large a proportion of deciduous trees is needed in conifer stands to decrease the risk of ignition or fire spread.* .

3.5 Modelling and mapping impact and risk of drought and fire

Models and tools are needed to support decision-making in forest management and policy drafting. Many of the currently available models support systems like Heureka (Lämås et al. 2023) that are based on the historical development of forests. They are unsuitable for describing forest development in a future climate or under new management goals. *In Sweden, we are lacking tools to predict and simulate the risk and impact of drought and fire, taking into account temporal and spatial variation, under different climate and management scenarios, as well as other damaging agents and factors.* Remote sensing technology has made it possible to estimate various forest variables, forest damage, and risks cost-effectively over large areas (Lindberg et al. 2022), *but we lack models and applications that take drought and fire into account. We need more knowledge on how remote sensing data can be combined to assess drought damage and detect the most vulnerable areas for drought and forest fires in forest landscapes.*

3.6 Trade-offs, synergies and decision-making processes

Sustainable forest management should account for different forest management goals, such as timber production, biodiversity, recreation, and carbon sequestration, while considering forest health and risk of forest damage in a changing climate. Damage mitigation methods can be applied separately or combined, and simultaneously support management goals.

For instance, favouring deciduous trees can benefit both biodiversity and fire mitigation (Felton et al. 2024). *We lack understanding of the trade-offs and synergies between different drought and fire mitigation methods, and of their relation to specific management goals and scenarios, including damaging insects and pathogens.* For example, more intense thinning may reduce damage from drought, but it will also reduce yield, or increase occurrence of root rot. When is it worthwhile to thin harder, and when is it not?

Or, how do we balance the positive (biodiversity) and negative (loss of biomass) effects of wildfires? Furthermore, *little is known about how risk of fire and drought, and other disturbances influence the forest owners' decision-making under different climate and management scenarios.* Addressing these gaps will require more interdisciplinary projects that examine trade-offs explicitly, link risk mitigation to broader management goals, and study how knowledge can be effectively exchanged and put into practice.

3.7 Priority areas for future research

Based on the gaps in knowledge identified above, the following areas of research may be the most pressing to address:

1. Assess how forest characteristics, management methods, and weather conditions affect drought and fire dynamics in Sweden.

2. Develop models and methods to evaluate risk of drought and fire in ways that can be integrated into forest decision support systems, like Heureka, and used for mapping such risk at a local, regional, and national level.

3. Analyse trade-offs and synergies between different drought and fire mitigation methods and their relation to other forest management goals and other damaging agents and factors.

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Forest fire. Photo: Unsplash

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4. The impact of ungulates

- on forest ecosystems, forest health, and forestry

4.1 Background

Moose (*Alces alces*) browsing on Scots pine is often cited as one of the most important limiting factors for forestry in Scandinavia. The estimated costs of browsing damage to Swedish forestry amount to several billion SEK(Skogsstyrelsen, 2019), annually, though the numbers vary by almost an order of magnitude. At the same time, large ungulate populations provide important ecosystem services, such as game meat and recreational opportunities for hunters and other nature enthusiasts. Hunters themselves estimate the ecosystem services from hunting at more than SEK 6 billion annually, with about 40% of that value attributed to moose (Widemo et al, 2019). Other cultural ecosystem services of benefit to the wider public, such as tourism, are more difficult to quantify.

Ungulate communities in Sweden are undergoing change, partly as a result of climate change. Present and future management therefore require both multi-species management of deer populations and integrated management of deer and forests, supported by new governance and monitoring systems (Cromsigt et al, 2023). Despite hundreds of published studies from Scandinavia (mostly on moose browsing on pine), we still lack the quantitative understanding needed to make well-informed management decisions. Even though Sweden may have the most formalized moose management system in the world, we are still far from achieving its stated goals.

4.2 Overview of limitations

Browsing affects forestry in several ways, developed in more detail below:

1. Growth and timber quality. Damage in young stands reduces future growth and timber quality.
2. Stand composition. Browsing on pine and other palatable species may favour spruce or less preferred tree species.
3. Monitoring and decision support. The long rotation time means that effects appear late and are difficult to quantify, creating uncertainty in management.
4. Silvicultural methods. The risk of browsing damage influences forest owners' choices of regeneration strategies.
5. Biodiversity and carbon storage. Browsing pressure can support biodiversity but also affect climate-regulating functions such as carbon sequestration.

4.3 Growth and timber quality

Moose browsing on pine accounts for the largest share of ungulate damage to forests, but bark stripping on spruce by red deer (*Cervus elaphus*) has increased as the species has expanded northwards (Månsson and Jarnemo, 2013). All deer species also compete for the same field-layer forage (e.g. Ericaceous shrubs such as bilberry), and if this is depleted the browsing pressure on regenerating trees increases (Spitzer et al, 2021). For this reason, most wildlife damage to forests occurs during the juvenile stand phase (Pfeffer et al, 2020).

However, under the Swedish forest management system, only damage affecting timber quality is currently recorded. Growth effects are not monitored. Our knowledge of how browsing impacts growth is based only on individual research studies lacking continuity and national coverage. Actual costs also appear only several decades later, making them difficult to calculate.

We lack quantitative values for how browsing pressure limits timber quality, growth, and yield (Persson et al, 2007) in future stands. Moreover, browsing pressure will change in line with changes in ungulate population density and forest management methods.

4.4 Stand composition

Physical damage to individual production stems is not the only consequence of high browsing pressure. The same process also alters future stand composition. Tree species such as rowan (*Sorbus aucuparia*), aspen (*Populus tremula*), goat willow (*Salix caprea*) and oak (*Quercus robur*) (Skogsstyrelsen, 2022) are important for biodiversity but are disfavoured because they are highly palatable to ungulates. Birch is attracting increasing interest as a production species, but how browsing may limit its growth has not received sufficient attention.

When planted pine is browsed, the forest may instead become dominated by spruce (Felton et al, 2020). This can lead to stands with acceptable future yield despite high browsing pressure, but the forest owner receives no return on their pine planting investment. If the resulting spruce stands occur on sites unsuitable for spruce, the risk increases for poor growth, as well as for drought, pests, windthrow or fire.

Cumulative changes in stand composition must therefore be studied in parallel with cumulative browsing damage in order to understand and predict the long-term effects of browsing pressure.

4.5 Monitoring damage

Forest management requires a long-term perspective, since earlier investments only provide returns at the end of the rotation period. In the same way, browsing damage materializes only decades later, in the form of reduced yield. For Scots pine, the rotation period is 80–100 years in southern Sweden, meaning that stands regenerated during the moose-dense early 1980s are still in the thinning phase. Recently, more complex ungulate communities with moose, roe deer (*Capreolus capreolus*), red deer and fallow deer (*Dama dama*) in competition with each other have emerged. Stands exposed to this complex browsing pressure are still young, and all estimates of how such ungulate communities constrain forestry are therefore based on projections far into the future. Such models rely on background data from ungulate communities composed only of moose and roe deer, from 40 years ago.
Predictions of the effects of browsing pressure on future yield are therefore uncertain. If we ignore these effects until they manifest, however, the consequences may last for decades.

Moose browsing damage on pine is measured with the standardized Moose Browsing Inventory (ÄBIN) at heights of 1–4 metres (Skogsstyrelsen, ÄBIN). One of the guiding goals in moose management is that the proportion of annual damage on pine should not exceed 5 % in areas with medium or high site productivity, or 2 % in areas of low site productivity. However, this management goal is set without regard to stand compositions. To understand and evaluate browsing effects, relative damage levels must be related to the proportion of production stems. For example, an annual average of 20 % damaged pine stems in an area where stands consist of 90 % spruce and 10 % pine means that only 2 % of all stems are damaged. If the same number of pines instead occurred as 10 % pure pine stands, the local effect would be 20 % damaged trees. Furthermore, a high percentage of damage to pine will not give a representative view of the limitations to forestry in landscapes dominated by other tree species. Finally, ÄBIN measurements have shown large random variation between years, raising questions about the validity of basing moose population management solely on these results (Widemo et al, 2022, 2025).

It is difficult to determine the proportion or number of stems damaged by wildlife once stands have grown out of the browsing window, since it is often impossible to identify the cause of damage that occurred more than a decade earlier. Therefore, stems and stands must be followed annually as they pass through the browsing window to determine correctly the proportion of accumulated ungulate damage. This is too resource-demanding to be done routinely within management. It is, however, partly carried out within the National Forest Inventory, and now with greater spatial detail along a latitudinal gradient within the monitoring program *Balanced Ungulate Populations*, funded by the SLU Forest Damage Centre.

4.6 Effects on silvicultural methods

At regeneration, the choice of tree species should be determined by site productivity and the preferences of the forest owner, if no other limiting factors are present. Currently, focus is shifting toward alternative silvicultural methods such as mixed-species regeneration and continuous cover forestry, but how browsing pressure is affected by such changes has not been studied. This raises the question: what is the optimal choice for forest owners, and to what extent does it differ depending on individual preferences and the type of landscape in which forestry is carried out? Choosing between different management strategies requires knowledge, time, and resources.

Conversely, the perceived risk of browsing damage may also influence the forest owner's choice of methods, including the tree species used for regeneration (Felton et al, 2020). Addressing these issues requires knowledge both from ecological studies and from research on forest owners' attitudes and behaviours, in order to assess the costs of altered management strategies (Fishbein och Ajzen, 2005). Such knowledge is essential for making informed decisions and for providing silvicultural advice.

4.7 Biodiversity and carbon sequestration

Browsing pressure is a form of disturbance that limits fibre production, but it can also have positive effects on biodiversity (Faison et al, 2016;Hegland et al 2013). This requires trade-offs within wildlife–forest co-management. Browsing pressure may also affect carbon storage both above and below ground, as well as albedo, i.e. how much of the sun's energy is reflected from the ground (Petersen et al, 2023). Major knowledge gaps remain regarding the overall impact of browsing pressure on biodiversity and climate-regulating functions in boreal forest ecosystems. This includes the trade-offs involved, and the questions of who should be responsible for making them.

4.8 Priority areas for future research

Based on the gaps in knowledge described here, the following areas of research are considered the most pressing to address:

1. Quantify how browsing pressure influences composition in the future stand.

2. Quantify how different levels of browsing damage in young forests limit yield later in the rotation period.

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Part 2: Quantitative Models for assessing forest damage

This part discusses two different approaches to modeling forestry activities. The first regards forest planning and models for decision support systems. The second focuses on models of forest owners' decision-making and behaviour, as well as their integration with the forestry industry.

5. Risk and consequence analysis with Heureka

5.1 Background

Swedish forests are currently facing many serious challenges. Climate change will affect temperature, precipitation, nutrient cycling, and species composition, which will alter conditions for future forest ecosystems. Natural disturbances are part of forest development and not inherently negative (Johnstone et al, 2016), but climate change increases the pressure from multiple disturbance agents (Thom and Seidl, 2016). Sweden's forests are dominated by a single tree species, which makes them more vulnerable to change (Felton et al, 2024).

Climate change must be properly addressed, but forests and forestry are simultaneously expected to meet multiple objectives from both society at large and forest owners themselves. For example, forests must supply timber and other wood products, safeguard biodiversity, sequester carbon, support reindeer husbandry, and provide opportunities for recreation. Balancing these diverse goals is already complex, and will become even more so in a future that is increasingly difficult to predict.
This is why decision-support tools are so important: they can help forest owners and other stakeholders test how different management strategies influence forest growth, health, and resilience in the long term. By using scientifically developed models and data from multiple sources (remote sensing, the National Forest Inventory, other surveys, etc.), decision-support tools can contribute to well-founded decisions in an uncertain future.

5.2 Gaps

There are many uncertainties concerning the consequences of climate change. We do not know how different tree species will grow under altered conditions, which species will be most suitable for regeneration, or how species composition will shift. The trees planted today are unlikely to be those best adapted to the same site in the future (Wessely et al, 2024). Because no models currently account for these uncertainties, the Heureka decision support system cannot yet fully incorporate the impacts of climate change.

We also lack robust, quantifiable knowledge of how forests will develop when managed with new silvicultural strategies in a changed climate. As these effects are difficult to predict, they are not fully reflected in today's models.
Another challenge is understanding and quantifying how disturbances such as storms, pests, or drought affect forests. There are models that estimate mortality and growth reduction after a disturbance event, but they could be substantially improved.

Finally, we do not yet fully understand how one type of disturbance can affect the risk of another. Storm damage increases the risk of fungal infections (and vice versa), and drought stress makes trees more susceptible to bark beetle attacks, but we do not know to what extent, or which other factors influence these cascading effects.

Given these uncertainties, it is reasonable to plan forestry with resilience and diversity in mind, i.e. by spreading risks. Such strategies also benefit biodiversity and multiple ecosystem services, including recreation and carbon storage.
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5.3 Heureka

Forest planning means deciding where and when specific silvicultural measures should be carried out in order to achieve the forest owner's objectives, and ensuring coordination between the measures. To plan for the future, we need models that simulate forest development over time, and allow us to study different future scenarios and the consequences of applying different management strategies. This process can be assisted by a decision support system.

Heureka is Sweden's most widely used decision support system and currently has the capacity to simulate forest growth and development (Lämås et al, 2023). The system is built on models describing stand establishment, diameter and height growth, ingrowth, and mortality (Fahlvik et al, 2014; Fridman & Ståhl, 2001; Wikberg, 2004).

However, Heureka's models are calibrated to the climate conditions of the 1980s and 1990s, and to traditional clear-cutting regimes. To adjust to the climate and silvicultural methods of the future, Heureka needs new process-based models based on functions that describe the mechanisms driving development, rather than historical data. An alternative is a fusion of empirical forest growth models and process-based climate models (so-called hybrid models). At present, results from the process-based vegetation model BIOMASS (McMurtrie et al, 1990) can be used to adjust Heureka's empirical growth functions according to the climate scenarios ECHAM5_A1B, MPI 4.5, and MPI 8.5 (Freeman, 2009). Work is also underway to develop new hybrid models, for example combining Heureka with 3PG (Subramanian et al, 2019) and ForSafe (Wallman et al, 2005).

Another problem is that Heureka does not account for the increased risk of damage in a new climate. When simulating forest growth over time, the system applies functions that assume a certain mortality, but does not specify exact causes of death. Large-scale disturbances, such as storms, fires, or insect outbreaks, are not directly included. These effects need to be integrated into the analyses. At present, storm is the only large-scale disturbance whose consequences can be modelled directly.

By analysing how storms have affected forests in the past, projections can be made about the future. However, this relies on the uncertain assumption that they will keep occurring with the same frequency and intensity. Modelling damage caused by insects and fungi is even more complicated, as biotic disturbances are influenced by complex ecological interactions. However, there are models that estimate the risk of root rot, as well as a risk index for bark beetle outbreaks. In addition, Heureka can also account for factors that indirectly influence damage, such as browsing, frost, snow break, or other stressors.

Several European models can estimate the probability of different types of forest damage, but far fewer can estimate their actual effects (Machado Nunes Romeiro et al, 2022). The Heureka system therefore needs new models that simulate the direct impacts of various damaging agents and abiotic factors on tree growth and survival under Swedish conditions. This would make it possible to account for the risk of future damage and adapt management to minimise the likelihood of large outbreaks or their consequences.

5.4 Areas of priority for future research

Based on the gaps in knowledge regarding decision support systems identified here, the following areas of research may be the most pressing to address:

1. Develop models to assess alternative forest management and the associated risk of damage.

2. Develop risk indices within Heureka for different damaging agents and abiotic factors, and for forest resilience against multiple agents and factors combined.

3. Improve Heureka's wind damage modelling by including wind direction, slope and other orographic features, and enable stochastic optimisation to be able to handle random events such as storms.

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6. Economic Aspects of Forest Damage

6.1 Background

Climate change affects the forest economy directly through productivity and indirectly through natural disturbance risks. These impacts occur at multiple levels: stands, landscapes, and nationally. They vary in scale, involving stakeholders from individual forest owners to forest companies and forest product users, and in scope, involving uncertainty at both the owner and societal levels. Understanding the economic implications of the future disturbances projected in Part I is the objective of this Chapter. The economic uncertainties stem both from damaging agents and abiotic factors themselves and from the forest owners adapting to the projected changes by altering their management choices. These shifts will also affect forest product markets. Part I concluded that there is uncertainty about how climate change will affect the damaging agents and abiotic factors and their effects on forests. Because of these uncertainties, both forest owners and society face difficulties in making decisions about the future of forestry. This Chapter briefly discusses the challenges involved in assessing the economic consequences of these knowledge gaps. The focus is on identifying gaps that economic models or frameworks can help bridge. The Appendix provides a further elaboration of some of these issues.

6.2 Economic aspects of forest risk management by small forest owners

Forest owners may take various management actions to adapt to climate change (Yousefpour et al, 2012; Guo and Costello, 2013), including continuous smaller-scale adaptations (the so-called intensive margin of adaptation) and more discrete, significant changes (the extensive margin) that have a larger effect on economic outcomes.

Forest owners' willingness to adapt appears to be affected by attributes such as risk preferences (Brunette et al, 2020; Thomas et al, 2022) and demographics (Thomas et al, 2022). However, the literature on this is limited.

Cautious forest owners are expected to be more positive toward insurance-based tools and to avoid riskier, though potentially more rewarding, alternatives. One way to assess risk attitudes is the risk-aversion coefficient, which is discussed in the Appendix. In a Swedish survey, Andersson and Gong (2012) found that about 40% of forest owners preferred financially riskier alternatives, although the framing makes it difficult to compare with studies using more controlled measures of risk preference. Another study, Eriksson (2014), examined forest owners' stated risk perceptions, though not their broader risk attitudes. Overall, little is known about Swedish forest owners' risk preferences measured through rigorous economic experiments, which are considered the gold standard.

We currently lack ways to estimate the risk of forest damage. In economics, such uncertainty is called *ambiguity*. Under ambiguity, standard approaches to risk management—for example, spreading risk by diversification—may not hold (Brunette et al, 2020). Very little is known about forest owners' attitudes toward ambiguity worldwide, and nothing is known in the Swedish context. The literature on forest-related insurance is also limited and largely does not measure the link between attitudes toward risk and insurance choices (Brunette and Couture, 2023; Brunette et al, 2020b; Deng et al, 2015). For Sweden, *there is no evidence on how risk and ambiguity attitudes affect decision-making, including insurance choices.* This gap is notable, given that the purpose of insurance is to manage income risks from forest damage.

In summary, no study has explicitly examined how forest owners' attitudes to risk or ambiguity relate to insurance choices. This represents a significant knowledge gap for understanding risk management and anticipating how forest owners will address increasing economic risks in the future.

6.3 Economic Models for Assessing Large-scale Forest Damage

Events such as storms, fires, and pest infestations can cause significant economic damage to forests, initially to local wood supply and wood markets in the immediate aftermath. However, the impact may also persist over time, extend into neighbouring regions through market linkages, and influence harvesting decisions in the long term.

For instance, consider the effects of a regional wind disturbance. One is the sudden influx of damaged timber into regional mills, which may depress product prices immediately. However, this effect can turn into a scarcity of products within a few years, driven by the delayed regeneration and harvesting post-storm, as seen after hurricanes (Johnston et al, 2022; Caurla et al, 2015). If large-scale disturbances increase in the future, it will be crucial to model regional wood markets, their linkages, and the long-term effect on regeneration and harvesting (Henderson et al, 2024).

Forest sector models integrate forestry and forest industries, as well as supply and demand for wood products. Specific product markets like sawlogs, pulpwood and fuelwood are modelled separately (Gong and Guo, 2020). Several models can also account for how supply and demand evolve over time, such as the French Forest Sector Model (Caurla et al, 2013), and the Norwegian NorFor (Sjølie et al, 2011). These models are developed for large-scale policy questions such as bio-energy demand, carbon storage and non-timber benefits, and conservation set-asides. They are tied to specific countries and/or regions, since forest characteristics, ownership and supply and demand patterns may vary significantly. These models may also assess the effects of large-scale forest disturbances, either by applying them at high spatial resolution or by judiciously complementing them with alternative approaches. For instance, Henderson et al. (2022) applied the U.S. Sub-regional Timber Supply (SRTS) model to predict the implications of Hurricane Michael on forest markets.

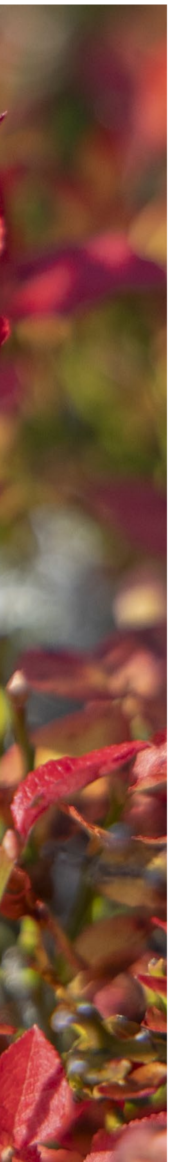
To assess economic damage from disturbances, Sweden *needs a standardised national or regional forest sector model, and a framework linking this model to specific damage-causing events.* Two Swedish forest sector models have been developed in the past: the STIMM (Gong et al, 2013) and variants of the SFSTM (Carlson, 2012), along with a sub-regional model for Norrbotten (Olofsson, 2019). However, they lack standardisation, ongoing maintenance, and updates, and would require considerable time and resources to restore to operational use. Currently, Sweden has neither an operational national model nor sub-national models of wood markets.

Bärris. Foto: Theres Svensson

Consequently, *the absence of a consistent economic model framework connecting forestry and forest products markets, as well as different types of damaging agents and abiotic factors, makes it challenging to predict economic implications of forest disturbances.*

6.4 Forest decision-making when information is very uncertain

Assessing forest damage requires understanding how different damaging agents and abiotic factors evolve, interact, and affect the forest. Forest owners can only respond effectively if the links between the biophysical aspects of damaging agents and factors and management strategies are established. Yet these links are often uncertain or unknown, creating a dilemma: decisions must still be made despite persistent uncertainty. Common approaches include structured decision-making, scenario planning, and adaptive management (Vanderhoeven et al, 2017), but decision makers nonetheless need to *quantify* the distribution of key unknown parameters in each case. Such problems (e.g. estimating storm probabilities) frequently stem from gaps in empirical data at relevant spatial scales and the inherent complexity of biophysical systems. In these contexts, *drawing solely on data* is rarely feasible.



When statistics are insufficient for decision analysis, *expert elicitation* ("asking experts") is both common and prudent (Colson & Cooke, 2018). The method has been applied increasingly in forest damage contexts (see Appendix for details), including wildfire susceptibility and fuel management (Martins et al, 2021; Scott et al, 2013) and a very early estimation of the impact of climate change on forest ecosystems (Granger Morgan et al, 2001).

In the Nordic countries, however, "asking experts" has rarely been used to systematically assess the range of uncertainty in the estimated effects of climate change on specific damaging agents and factors. Such an approach can shed light on how important the degree of uncertainty is to decision-making. Disagreements between experts do not always lead to different probability distributions, and when they do, this does not necessarily affect important decisions. However, without quantifying these differences, it is difficult to both prioritise "filling in the knowledge gaps" and provide a systematic scientific basis for decision-making.

In any case, while expert judgements are hardly a substitute for definitive scientific research, they can nonetheless provide important insights and help forest owners and societies make decisions when faced with incomplete scientific knowledge. *Despite the salience of incomplete scientific knowledge regarding future forest damage, the lack of quantitative frameworks developed, or used, to address this question for Sweden represents a major knowledge gap.*

6.5 Areas of priority for future research

Based on the lack of economic models and the gap in fundamental knowledge regarding forest owner behaviour identified here, the following areas of research may be the most pressing to address and the quickest to yield broadly applicable knowledge:

1. **Economic risk management and small forest owners.** Develop quantitative understanding of: forest owners' attitudes toward risk and its implications for insurance and forest management; forest owners' response to climate change and climate-related risks.

2. **Economic Models for assessing consequences of large-scale forest damage.** Develop: a static, market-level supply-demand model of forest products to evaluate how forest owners' and product buyers' decisions affect market responses; and a framework to link this model to large-scale disturbances, to trace the effects on different stakeholders in forestry.

3. **Dealing with uncertainty, optimal response to multiple damage risks:** Develop quantitative economic models to: *understand* how to optimally respond to multiple risks in forestry, and the interaction between forest owners' risk attitudes and optimal responses; provide decision support for situations where scientific knowledge is incomplete, e.g. invasive species risk; assess long-term impacts of insect-borne and fungal disease outbreaks on forest economics.

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7. Storm Damage Quantification at the Landscape Level

An illustration using the Heureka Decision Support System

7.1 Introduction

Chapters 1-5 have outlined the gaps in knowledge regarding a variety of damage sources, while Chapter 6 provided an overview of the gaps in the ability to model many of these sources of damage, using decision support systems (DSS). The main objective of this chapter is to demonstrate how the current gaps in knowledge and DSS modelling affect our ability to assess damage risk, using storm as an example.

A core concept is the use of 'downscaled' climate data. This means coarse global climate data transformed to higher spatial or temporal resolution to better reflect local conditions. As detailed in the Appendix, downscaled wind data are challenging to use with DSS for at least two reasons: first, the mismatch in time-scale between a DSS and the wind load that actually leads to damage; and second, the difficulty in modelling many biophysical effects, such as edge effects, in spatially aggregated DSS. These drawbacks are amplified when future wind scenarios from downscaled data from regional climate models (RCMs) are used. Detailed statistical wind load-damage relationships at an appropriate spatial scale may yield better estimates (Zeppenfeld et al, 2023). Yet, these are bespoke and limited in spatial scale, and unavailable in Sweden. Consequently, the only approach available to us is scenario analysis. Heureka is an advanced DSS widely used for management planning in Swedish forestry and developed by SLU (Lämås et al, 2023). However, Heureka is unable to account for stochastic risks, such as wind damage. Thus, we take the scenario approach to illustrate how knowledge gaps in DSS modelling and future wind loads interact.

7.2 Storms and Swedish Forestry

It has been predicted that climate change will promote growth and biomass production in Swedish forests, leading to increased harvests and shorter rotation lengths in managed forests. However, climate change is also expected to increase the intensity and frequency of extreme weather events such as storms. Storms are a major problem for forestry across Europe, having caused vast damage in the last three decades and accounting for a total of about 46% of all damage during the past 70 years (mean 24 Mm3/year, Patacca et al. 2023; Blennow and Olofsson 2008; Hanewinkel et al. 2011; Wallentin and Nilsson 2014). Indirect effects of climate change can also increase storm damage in the future. Both increased precipitation and shorter periods of frozen ground during winter will weaken tree anchorage (Hanewinkel et al. 2011).

Several changes in management practices have increased the likelihood of future storm damage. These include increasing the prevalence of conifer monoculture (Drössler et al. 2014) and the standing volume in the forests (Hanewinkel et al. 2011). Future changes in management practices will need to take into account both the productive capacity of the forest landscape, and its resilience against extreme weather events (Lucash et al. 2017). Previous studies on the impacts of climate change and its risk factors at the stand level have shown that storm damage can be mitigated by using adaptation strategies such as avoiding thinning and reducing rotation lengths, and by avoiding Norway spruce monocultures (Keskitalo et al. 2011; Wallentin and Nilsson 2014; Subramanian et al. 2016a).

Promoting alternative species also improves biodiversity, increases resistance to root rot (Heterobasidion annosum [Fr.] Bref.) and bark beetle (Ips typographus L.) infestations (Subramanian et al. 2016a), and may create opportunities to use new and more productive indigenous or exotic tree species in commercial forestry (Bolte et al. 2009; Mason et al. 2012; Meason and Mason 2014).

7.3 Methodology and Data

7.3.1 Broad Outline

Our goal here is to illustrate how future wind loads and management strategies affect the magnitude of wind damage using Heureka, the most widely used DSS in Swedish forestry. For our purposes, which is an illustration of key aspects (rather than a comprehensive exploration), we choose the following sets of scenarios: climate change scenarios RCP4.5 ("optimistic") and RCP8.5 ("business as usual") (see Appendix for details); two management scenarios (even-aged with and without thinning); and three wind speed metrics (maximum, mean, and 75th percentile of wind load), in total 12 different scenarios. To deal with the ambiguity about which metric of wind load best corresponds to damage to the stand (at our temporal aggregate of 5 years), we use three different and possibly equally reasonable metrics.

With a DSS that could model optimal response to stochastic risks, the decision maker could respond to the risk of any storm in advance. That is not possible with Heureka today, which models risk outside of the decision-making process (meaning that damage risk does not affect management choices such as rotation period or thinning schedule). In order to sidestep these disadvantages, we visualise the future, for each climate scenario, as many realisations of one wind load metric. This visualisation is partly necessitated by the lack of significant variability in 5-year-aggregate of wind load, as we discuss later on. In any case, for each climate scenario and management choice, the state of wind load is represented by a random reordering of the actual wind load derived for that specific scenario. 50 such wind loads are drawn for each climate-management scenario and metric, Heureka is run for each of these 50 scenarios, and the full distribution of outcomes is presented. This approach has a major benefit over providing an aggregate outcome (e.g. a mean across the 50 simulations): it allows the entire range of outcomes within each scenario to be visualised. In particular, this approach helps answer the question: given that any one of the 50 time-paths of wind loads are equally likely, what is the likely storm damage over the next century, and how widely does this vary? It is important to emphasise that storm damage depends both upon the wind load and the timing of occurrence (e.g., if it occurs during winter, whether the ground is frozen, time since last thinning), an interplay that may be visible in the simulation results. For stakeholders such as forest owners, this approach can help visualise not merely the "average damage" pattern under a climate scenario, but more importantly the range of damage under a given scenario, e.g. what is the worst-case outcome?

This is vital to emphasise since the link between a specific climate scenario and realisation of extreme events like high wind load is unclear and the wind load under a specific climate scenario generated by any Regional Climate Model (RCM) should not be treated as data. We turn next to some of the details of our methodology and data. See the Appendix for further details of the climate scenarios and of the simulations.

7.3.2 Study area

Given that historically wind damage in Sweden has varied widely across regions, we focus our analysis on three counties representing different conditions: one county prone to wind events and associated damage (Kronoberg), and two less prone (Dalarna and Västerbotten). Regional/county-level (for representative counties across regions) analyses are carried out with a view to evaluating variability, across scenarios, in damage across Sweden. We use the National Forest Inventory (NFI) data from these three counties as initial forest data for simulation. Our analysis uses the Swedish Forest DSS Heureka and the landscape simulation application RegWise (Lämås et al, 2023) for simulating storms under a matrix of different combinations of management, climate and wind speed scenarios.

7.3.3 Simulations using the Heureka model

We simulated the storm-felled volume and total growth for the time period 2025-2100. We evaluated 12 storm-including scenarios (2 climates (RCP4.5 and RCP8.5) × 3 wind metrics (maximum, mean, and 75 % wind load) × 2 managements (thinned and unthinned), each with 50 resamples, plus 2 baseline BAU scenarios without storms (one per climate), for a total of 602 runs. We report here the cumulative storm-felled volume for each five-year period during the simulation period. In the Appendix, we show the total annual growth over the same period. Total annual growth was calculated by multiplying Current Annual Increment m3ha-1yr-1 with the representative area of each NFI plot (Area factor).

7.4 Simulation Results

We briefly analyse the mean wind load in the two climate scenarios (Figure 3). The 20-year mean wind load is higher in the RCP8.5 scenario in all three counties. No specific trend was found across the four time periods. The highest increase in 20-year mean wind load was under the RCP8.5 scenario during the 2041-2060 time period in northwest Dalarna where the 20-year mean wind load was predicted to increase by 800%. The percentage change in 20-year mean wind load was higher in Västerbotten and Dalarna than in Kronoberg. Overall, the changes in mean wind load are moderate, with sporadic increases for certain regions and certain time periods.

7.4.1 Cumulative storm-felled volume

Due to the moderate change in wind load, we do not anticipate major changes in damage patterns but do anticipate changes in the cumulative storm-felled volume for the three counties (Figures 3-6). We found similar patterns across the entire time period, for all three counties, regardless of management and climate scenarios. This makes wind load the single most important factor affecting the amount of storm-felled volume. The cumulative volume was highest in the maximum wind load scenario, followed by the 75th percentile, and lowest in the mean wind load scenario. The cumulative storm-felled volume was higher in the RCP8.5 climate during the beginning and middle simulation periods. However, especially after 2080, the volume increased in the RCP4.5 scenario.

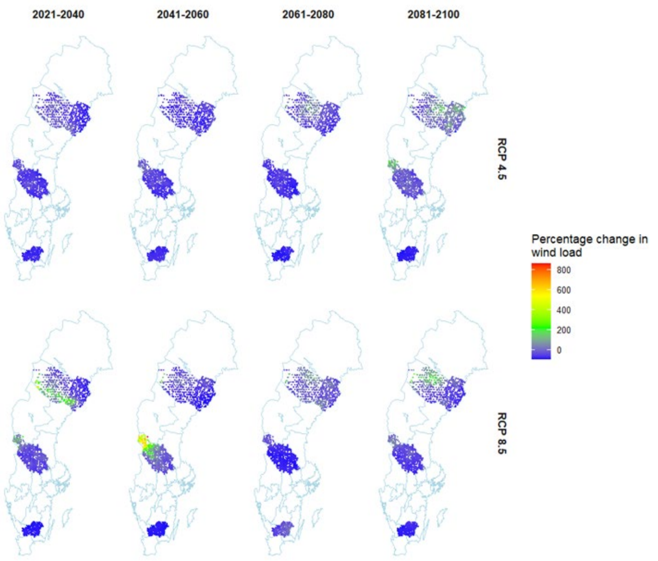

Figure 3. Percentage change in 20-year mean wind load during 2021-2040, 2041-2060, 2061-2080 and 2081-2100 in comparison to the 20-year mean wind load during the time period 2001-2020 under two future climate scenarios RCP4.5 and RCP8.5 in three counties in Sweden: Västerbotten, Dalarna and Kronoberg. The wind load calculation is optimized using NFI data and therefore wind load does not include wind data from climate grids outside productive forest area

It decreased under the unthinned regime in all counties under all climate and wind scenarios. The total annual growth is discussed in the Appendix and shows greater variation than storm felling.

7.5 Discussion and Conclusions

Our findings suggest that an unthinned management regime increases storm resilience in all counties under all climate and wind load metrics. Total annual growth was also better under unthinned management during the whole simulation period in Dalarna and Kronoberg counties, but not until the 2080s in Västerbotten. These results may suggest that unthinned regimes, which in essence reduce the volume-at-risk, are one way to attain "resilience". Nonetheless, this must be weighed against the possible reduction in Net Present Value (NPV). This was not considered in this study but will be in the future. It is difficult to assess how climate change affects the frequency and severity of storms, because their relatively rare occurrence requires long-term observations (Senf and Seidl, 2021). Recent increases in forest disturbances have triggered debates on the need for adaptation measures (Hahn et al, 2021; Senf and Seidl, 2021). Our simulation study suggests that the inability to model forest dynamics under stochastic damage risk such as storm, is a major impediment. This is because non-optimal decisions not only provide an incomplete or misleading picture but can also lead to false trade-offs. In our case, the trade-off between "resilience" and NPV (if it exists at all) is an artefact of an inability to appropriately consider changes in windthrow risk when making both harvesting and thinning decisions. Some studies have used a stochastic optimisation approach to find the optimal forest management solution by maximizing NPV under future storms (Eyvindson et al, 2024). This is not yet implemented in the Heureka model. Our analysis also stresses the problem that major windthrow events are on a much finer time scale than many DSSs are built for. Statistical models for specific regions may yield more tailored scenarios than those presented by coarse DSSs.

The storm model currently implemented in Heureka combines coarse and fine-scale modelling to simulate the probability of storm damage at a given time. For example, the length of exposed forest edges and the difference in mean height between neighbouring stands are calculated at the county scale for simplicity (Lagergren et al, 2012). In reality, mean height should be compared to the actual adjacent stands. Similarly, in this study, the length of exposed stand edges remains the same even after storm felling, which is not the case in reality. But addressing this needs a spatially explicit modelling approach which is not currently possible in Heureka. The effects of future climate scenarios on forest growth and on wind speed are considered as two separate effects; this study does not consider any interaction between them. We have used one value for wind load among all the grid points lying within the county border while building our wind scenarios. Ideally, the wind load in each grid cell within the county should have been calculated separately based on the predicted gust wind speed. Currently, Heureka is not equipped with that facility. It is being improved, but much more work is needed.

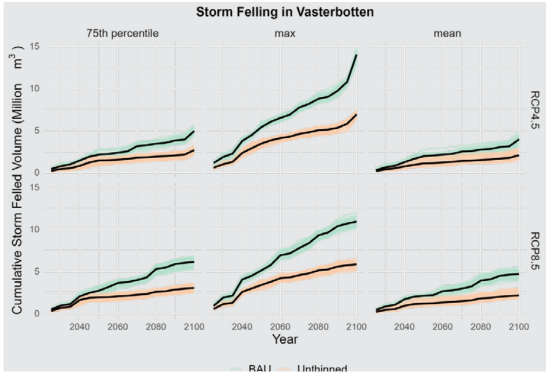

Figure 4: Cumulative Felled Volume (Million m3) predicted in Västerbotten county under BAU (black line and green confidence interval), unthinned management (black line and orange confidence interval), two different climate scenarios (RCP4.5 and RCP8.5) and three different wind speed scenarios (75th percentile, maximum and mean wind load).

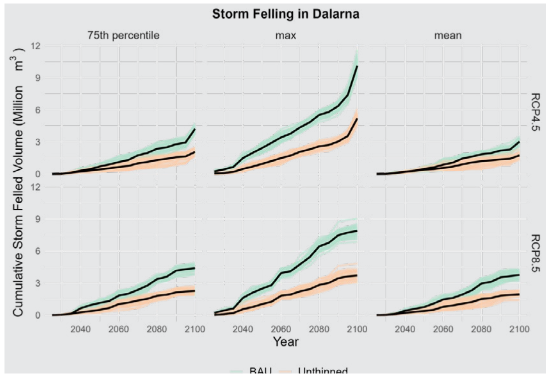

Figure 5: Cumulative Felled Volume (Million m3) predicted in Dalarna county under BAU (black line and green confidence interval), unthinned management (black line and orange confidence interval), two different climate scenarios (RCP4.5 and RCP8.5) and three different wind speed scenarios (75th percentile, maximum and mean wind load).

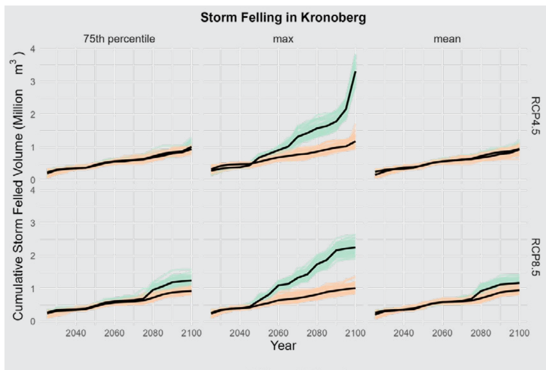

Figure 6: Cumulative Felled Volume (Million m3) predicted in Kronoberg county under BAU (black line and green confidence interval), unthinned management (black line and orange confidence interval), two different climate scenarios (RCP4.5 and RCP8.5) and three different wind speed scenarios (75th percentile, maximum and mean wind load).

Finally, we note that high-resolution spatial and temporal wind load data are needed for future climate scenarios, if we are to generate appropriate statistical distributions of wind load. These distributions could then be used for finer-scale DSS models of wind damage. This study used a naïve bootstrap across time (where each wind load was assumed independent over the study period), but even more sophisticated resampling strategies cannot help solve the problem of time aggregation inherent in DSSs such as Heureka.

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8. Synthesis: Common Issues and Overarching Gaps

Five important aspects form a common thread running through this report: (i) inter-related disturbances or disturbances that reinforce one another; (ii) invasive species spread and dynamics; (iii) the ability to account for the entire chain of economic effects at a variety of scales (from individual forest owner to market level) and their relation to the scientific gaps identified; (iv) decision-making under imperfect scientific knowledge of damage risk; and (v) the ability to appropriately model identified disturbance patterns in a decision support system (DSS) for forest planning and in other economic frameworks, e.g. cost-benefit analysis, for policy-making and forest planning purposes. We provide a perspective on these aspects here, discussing inter-connections while highlighting challenges that arise from these interactions.

8.1 Disturbance Interactions

Different disturbances interact in complex ways, with a high degree of uncertainty due to many external factors. Abiotic disturbances often act as a precursor for biotic disturbances; for instance, windthrow or drought stress can allow spruce bark beetle outbreaks to reach epidemic levels. Hence, large-scale forest damage is usually the result of a confluence of factors that often involve more than one disturbance agent or factor. The frequency and severity of abiotic disturbance events are likely to change as a result of the changing climatic conditions. Severe drought events are predicted to occur more frequently in the future. Drought has a direct effect on tree biomass production and tree survival, but also affects mortality indirectly via increased susceptibility to insects, pathogens, and fire.

Attempts to limit one damaging agent or abiotic factor may result in increased susceptibility to another, as processes following disturbances are intrinsically linked. For example, browsing damage can be mitigated by planting spruce on less suitable soils. This may increase browsing pressure on the pines that remain in other stands, but may also result in stands regenerated with spruce on soils more suitable for pine. Such stands will be more susceptible to drought and subsequent attacks from spruce bark beetles.

Other such interactions include snow or wind damage and pest/pathogen infections or insect attacks. When the trees' structural integrity is compromised by one damaging agent, susceptibility to stem breakage or uprooting by others is increased. Extensive insect attack can increase the risk of high-intensity forest fires. Conversely, wind damage can facilitate the reproduction of insect species or the establishment of new infections. In addition, insects can sometimes be vectors of pathogens, facilitating their spread and establishment in new forest areas. To summarise, there are numerous interactions among different disturbance agents and abiotic factors, and their study is often complex due to biotic agents' ecology intertwined with forest characteristics and species composition.

8.2 Invasive species

Globalization and trade in wood products increase the chances of introducing invasive species, whose effects on forest health and on other disturbance agents are initially unknown. EU-wide vigilance and monitoring of quarantine species are important for early detection and for understanding the risk of these species arriving in Sweden. Societal responses to changes in such risks are equally important, but quantitative assessments of such changes are rare. The uncertainty and the dynamics surrounding invasive species risk suggest that more quantitative frameworks are needed to be able to assess them. Decisions related to minimising these risks are to be made on a contingent basis and revised periodically as new information arises, using appropriate quantitative models.

8.3 Economic effects, models, and decision-making

The overarching theme from Part I of the report, which discussed biotic damaging agents and abiotic factors, is the effect of climate change on the altered pattern of disturbance agents and the increased salience of multiple disturbances. This can have significant economic effects on both production forestry and biodiversity values. A better understanding of the economic consequences of these changes is needed, not only pertaining to changes in volume of wood and revenue but also in costs associated with changes in management practices and preventive actions.

A few implications are worth highlighting. First, quantitative models linking disturbances, forest growth, and economic models of forest management are more important now than ever, but are also more challenging to develop when multiple damaging risks are involved. Second, forest-related decisions are to be made continuously, taking into account the current state of knowledge regarding damage-related risks. Thus, a greater damage risk increases the need to understand decision-making at many levels, including that of the forest owner. This understanding is particularly relevant to more formal economic risk management, such as insurance. Many gaps remain in our understanding of these aspects, and their salience is increasing.

Third, the ability to understand the effect of large-scale damaging events, e.g. storms or pest outbreaks, on the next harvest and future management, is lacking. The absence of standardised forest sector models remains a major obstacle. Finally, the economic impacts of damaging agents are likely underestimated. While direct losses from timber degradation and tree mortality are quantifiable, the indirect costs are more difficult to assess, such as reductions in ecosystem services, biodiversity loss, and long-term forest productivity. In addition, the broader economic implications of pathogen spread, treatment efficacy, and forest vulnerability are not fully captured in existing models. Data on the cumulative economic significance of emerging diseases is sparse, and cost–benefit analyses for preventive measures are rarely available, which limits the ability to plan and prioritize effective responses.

8.4 Climate-induced alteration in patterns of disturbances, disturbance interactions and decision support systems

This discussion highlights the uncertainty regarding the effects of climate change on individual disturbance agents, and on the interactions between them. Consequently, forest management should anticipate a range of forest damage scenarios, and consider the widest possible alternatives to minimise damage on both production and biodiversity. It is necessary to develop forest management models that allow the simulation of disturbance agent development, interactions among them, or the quantification of forest susceptibility to damage under different future scenarios. These tools may build on economic models but include additional aspects, especially spatial detail, as in many DSS.

These models are needed for forest decision support and must build on fundamental research. Current scientific literature on these subjects is both small and far too specific, providing an insufficient basis for broadly applicable decision-support tools. It is a challenge to develop full models that causally and quantitatively connect management actions to changes in damage patterns from multiple damaging agents or abiotic factors, but in the meantime, existing imperfect models may be altered to better map out the interaction between different climate scenarios, the effect on one or more damaging agents or factor, and management alternatives. At a minimum, such frameworks can provide an informed basis for ongoing decision-making, which cannot wait on the development of the quantitative, causal models referred to previously.

8.5 Priority Areas for Future Research

Based on the foregoing and the discussion in the respective Chapters, the following research areas of priority emerge:

1.Develop the Heureka DSS along the following directions:

- integrate risk indices for forest damage in Heureka for damaging agents and abiotic factors not already modelled
- integrate overall forest resilience, accounting for multiple damage risks
- integrate models for alternative forest management enabling an assessment of alternative management strategies focusing on future potential risk of different types of damage
- enhance wind damage modelling by considering orographic features, and enabling the use of stochastic optimisation which allows management actions in response to storm risk

2.Develop

- quantitative economic models to understand how to optimally respond, via changes in management strategies, to multiple damage risks in forestry
- risk and disease detection models for invasive species and emerging pathogens
- quantitative understanding of forest owners' attitudes to climate-related risks and their implications for insurance and forest management
- quantitative economic models to assess optimal response to multiple damage risks and its relation to forest owners' risk attitudes; provide decision support where scientific knowledge is lacking; and evaluate the economic consequences of the long-term impacts of insect-borne and fungal disease outbreaks
- models and methods to evaluate risk of drought and fire that can be included in DSS, such as Heureka, and used for mapping damage risk at local, regional and national levels

3. Improve biological control methods, identify naturally resistant trees through forest breeding programmes, and implement ecosystem-based approaches to reduce the spread of forest diseases

4.Quantify

- impacts of insects other than spruce bark beetle, which is already a priority area
- long-term trends in insect populations of interest
- the limitations on yields in forestry from browsing in young stands
- the effects of browsing on future stand composition
- dependence of drought and fire spread on forest characteristics, management methods and weather conditions

5. Assess trade-offs and synergies between different drought and fire mitigation methods and their relation to other forest management goals (e.g. biodiversity, monetary value, carbon) and other damaging agents and factors

6. Strengthen monitoring systems in forests and urban areas using systematic data collection, integration of climate and ecosystem dynamics, and the development of risk and disease detection models for invasive species and emerging pathogens.

7. Develop a better understanding of stand-level management effects on landscape-level diversity.

8. Improve communication and outreach to the sector based on current scientific knowledge and existing quantitative models and DSS.

8.6 Conclusion

Future forest management will need to account for multiple disturbances. Otherwise, actions targeting one disturbance could lead to adverse effects with respect to another. Simultaneously, a balance needs to be struck between economic, ecological and social management goals, with an explicit focus on risk reduction. Better tools for both research and for more applied forest planning and decision-making are needed to reduce and manage the risk of damage from multiple disturbances. The current state of knowledge is insufficient for many of these forest-related decisions. A more systematic synthesis of knowledge across different damaging agents and abiotic factors and their relationship to forest management is needed to understand the consequences of different climate-change adaptation strategies for Swedish forestry.

While the focus of Swedish forestry is generally on production of woody biomass, well-functioning ecosystems may reduce the forests' susceptibility to damaging events. Adequate provision of these ecosystem services may ultimately also benefit the production of woody biomass. Such synergies, or potentially trade-offs, may be identified by models that quantify how biodiversity and the functioning of forest ecosystems affect forest damage, especially from multiple agents or factors simultaneously. This report has highlighted how we currently lack the scientific knowledge and the model frameworks needed for carrying out such assessments.

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