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Degree project/Master thesis • 30 hp
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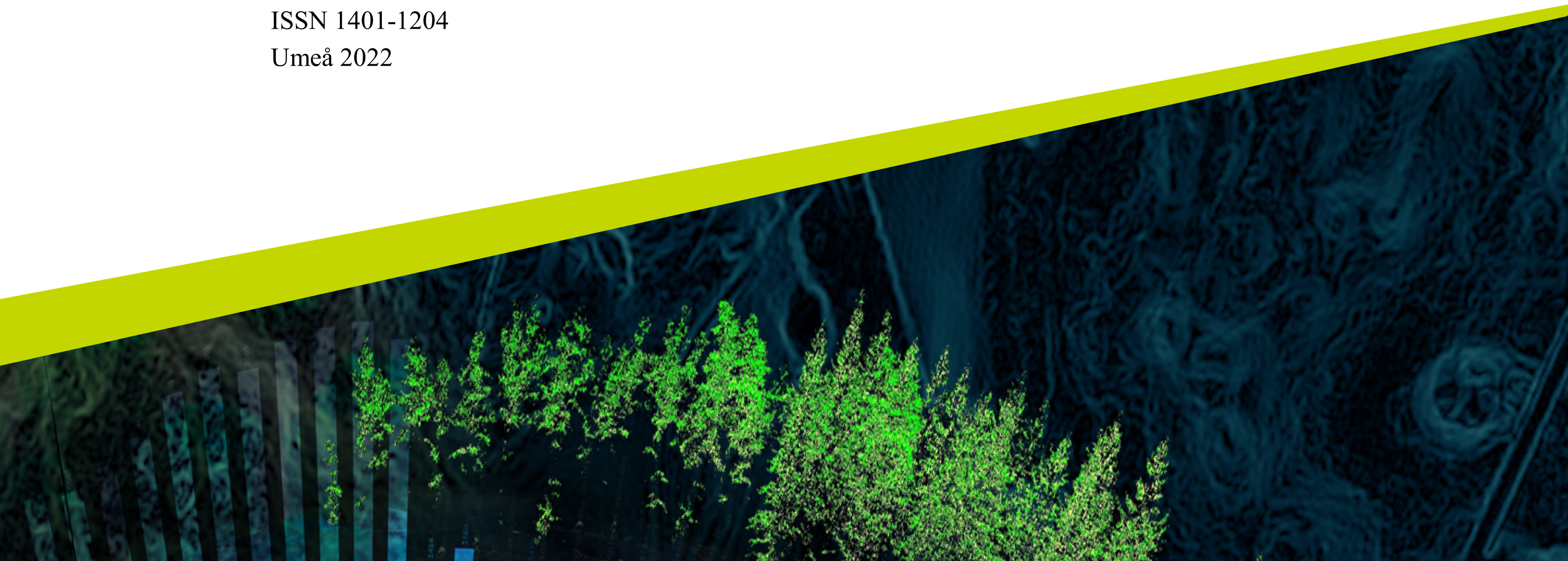
Arbetsrapport/ Sveriges lantbruksuniversitet, Institutionen för skoglig resurshushållning, 535
ISSN 1401-1204
Umeå 2022



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Credits:	30 hp
Level:	Master´s level, A2E
Course title:	Master's thesis in Forest Science, A2E - Forest Resource Management
Course code:	EX0965
Programme/education:	MSc in Forestry/Jägmästarprogrammet
Course coordinating dept:	Department of Forest Resource Management
Place of publication:	Umeå
Year of publication:	2022
Cover picture:	Swedish University of Agricultural Sciences
Title of series:	Arbetsrapport/ Sveriges lantbruksuniversitet, Institutionen för skoglig resurshushållning
Part number:	535
ISSN:	1401-1204

Keywords: changing climate, decision support system, forest damage, forest management, storm, trade-off, wind

Swedish University of Agricultural Sciences
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Department of Forest Resource Management

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Abstract

With a changing climate, the risk for damage to the forest will increase. In Sweden, large storm damages have been more common under the 20th century and are also the damaging event that has resulted in the largest damages in Europe. The aim of the thesis is to investigate how various indicators for sustainable forestry and forest management are affected if the management objective is to minimize the risk for storm damages 100 years in future. Data from the national forest inventory was used in the decision support system Heureka PlanWise for a trade-off analysis between the risk for storm damage and indicators representing forest economy, production, nature conservation, biodiversity, carbon storage and recreation. The study areas were Lycksele municipality and Växjö municipality.

All indicator values were reduced when the storm damage risk was minimized, for both Lycksele and Växjö municipalities. Higher standing volume, age and height, and active thinning management were some of the forest characteristics that increased storm damage risk. The optimal combination of management strategies when minimizing storm damage risk included most management without thinnings, which was relatively uncommon when managing the forest for other objectives. There are possibilities to adapt forest planning and forest management to reduce the risk for storm damage, especially when considering forest management objectives such as high net revenue, harvested volume, and growth.

Keywords: changing climate, decision support system, forest damage, forest management, storm, trade-off, wind

Sammanfattning

Med ett förändrat klimat kommer risken för skador på skogen att öka. Skador orsakade av storm står för störst andel av skadad skog i Europa och mer omfattande stormskador har blivit allt vanligare i Sverige. Syftet med arbetet är att ta reda på hur skogsskötsel och olika indikatorer för hållbart skogsbruk påverkas om målet med skogen är att minimera risken för stormskador. Data från riksskogstaxeringen används i beslutsstödsystemet Heureka PlanVis för en avvägningsanalys mellan risken för stormskador och indikatorer som representerar ekonomi/produktion, naturvård och biologisk mångfald, kolinlagring samt rekreation. Två områden är inkluderade, Lycksele kommun och Växjö kommun.

Alla de undersökta indikatorerna fick lägre värden då risken för stormskador minimerades, både i Lycksele och Växjö kommun. Risken för stormskador ökade med ökad ålder, höjd, stående volym samt aktiv skötsel med gallringar. Den optimala kombinationen av skogsskötselstrategier för att minimera risken för stormskador inkluderade främst en skogsskötsel utan gallringar, vilket var relativt ovanligt om skogen sköttes utifrån andra mål. Det finns möjligheter att anpassa skogsbruket för att minska risken för stormskador, detta även om målet med skogen är hög nettointäkt, hög avverkad volym eller hög tillväxt.

Nyckelord: avvägning, beslutsstödsystem, klimatförändring, skador i skog, skogsbruk, storm, vind

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Abbreviations

AI_cohort	Allometric relationship Index
BA	Basal Area
BAU	Business as usual (here equal with commercial clear-cut management)
CAI	Current Annual Increment
CCF	Continuous cover forestry
DSS	Decision Support System
ha	Hectare
h/dbh-ratio	Ratio between the height of the tree and the diameter at breast height for the same tree
HI_cohort	Height Index on tree level
m^3fub	Forest volume in cubic meter under bark
m^3sk	Forest volume in cubic meter standing volume
NFI	National Forest Inventory
RSI/RSI_patch	Root Stability Index
SKA15	Forest Impact Assessment in 2015 (Skogliga konsekvensanalyser 2015)
SLU	Swedish University of Agricultural Sciences
SQL	Structured Query Language (programming language)
TSI (or SI_cohort)	Total Sensitivity Index
yr	Year

1. Introduction

1.1. Global climate change and risk of damages to forests

Forest covers a large part of Sweden and the role of forest in climate change is central for the world. One aim for the forest in Sweden is to be sustainably managed and for example produce bio-based materials which replace oil-based products to reduce greenhouse gases (Lundmark et al. 2014). In a forest that is harvested, carbon dioxide is released into the atmosphere but then the growing forest at the same time sequester carbon dioxide into the biomass (Skogsstyrelsen 2021b). Sustainable forestry is one of several important factors to reduce global climate change. This has been shown in several studies, for example, in Sweden the boreal forest acts as a carbon sink when using the harvested wood in biobased products (Lundmark et al. 2014; Chi et al. 2020). Sustainable forestry requires a forest policy that regulates forestry towards a common goal - a society without a noticeable climate impact (Skogsstyrelsen 2021b).

The global climate change is expected to increase the average temperature in Sweden, and more in the northern part of the country and in the winter than in the summer. The growing season is expected to be one to two months longer and the precipitation is expected to increase by 15-20% until the next century. It is expected to be wetter in the whole country during winter and spring, but also a higher risk for drought in the summer (Eriksson et al. 2016; Kårén et al. 2018). The wind climate will probably not be affected by global climate change, but this is uncertain (Blennow & Olofsson 2008; Alexandersson 2010; Kårén et al. 2018). There is some evidence that the severity and intensity of storms will increase in the future, due to higher wind speeds and climate change (Gardiner et al. 2013), and this especially in the south of Sweden (Blennow & Olofsson 2008; Alexandersson 2010; Gardiner et al. 2013; Eriksson et al. 2016; Kårén et al. 2018). The difference in the probability of high wind speeds (higher in south Sweden than in north Sweden (Alexandersson 2010)) is expected to remain in the future (Blennow & Olofsson 2008). The climate could also affect the wind direction, which, for example, could affect the risk for wind damage in forests (Blennow et al. 2010b; Gardiner et al. 2013). It has been shown that storms from south-west and south-east will be more common and result in increased storm damage to forests, beyond the most common wind damaging directions such as west to the south-west (Blennow & Olofsson 2008; Gardiner et al. 2013). As there are many uncertainties about the future wind climate, it is meaningful to investigate the possibilities for flexible forest management solutions for the future with a changing climate (Blennow & Olofsson 2008).

With a changing climate, higher growth in the boreal forests is expected (Blennow et al. 2010a; Skogsstyrelsen 2021b), but at the same time, the risks of damage to the forest will also increase (Peltola et al. 2010; Gardiner et al. 2013; Eriksson et al. 2016; Kårén et al. 2018; Skogsstyrelsen 2021b). The longer growing season and elevated carbon dioxide levels result in increased growth (Gardiner et al. 2013). The forest growth will increase more in the northwest of Sweden and less in the southeast, in percentage terms. Some calculations have resulted in an increased growth of 25% until the end of the century (Eriksson et al. 2016; Kårén et al. 2018), but the higher risk of damages must also be considered. The storm Gudrun, in Sweden 2005, felled 100 million cubic meters of forest (Skogsstyrelsen 2006) which resulted in a reduced growth of approximately 10% of the remaining forest in the most affected areas over the following three years (Seidl & Blennow 2012).

Forest damages, as a risk to the forest resource, occur often suddenly and without warning. Sometimes the damages are local, but in other cases, they can be over large scales. Trees that often are affected by abiotic damages, such as storm damages, are often multi-damaged because damaged trees are often attacked by insects and pests (Kårén et al. 2018).

Depending on who or what that is affected by the damaging event the consequences will be different.

> *"Risk is the combination of the probability of a damaging event and the consequences if such an event occurs."* (Gardiner et al. 2013).

For example, the consequences after a storm damaging event will be different depending on if you are a private individual, a forest owner, a sawmill owner, or the regional or national government. The probability of a damaging event is the same independent of who it affects but because of the diversity in the consequences, the risk will be different for different stakeholders (Gardiner et al. 2013).

With an increased risk of damage to the forest in the future, due to climate change, there is a clear need for an impact assessment to see how much these damages could affect the forest as a valuable resource both nationally and internationally. Should storms be considered a natural element in forest succession or should the forest silviculture be adapted to minimize the risk for storm damage? Will it be possible to minimize the risk of storm felling in the future and at the same time prioritize climate change mitigation, together with other values in the forest.

Increased risk for damages in the forest can affect biodiversity by changing competition between species, darker forests, and increased grazing. Also, increased risk for damages in forests can decrease the recreational values in them (Eriksson et al. 2016). A changing climate with variable weather and a higher risk for extreme events will in this way not only affect timber production, but also non-timber forest products and services (Couture et al. 2016; Witzell et al. 2017b). Minimizing the risk for damage is therefore of interest to a broad target group, for anyone concerned about the sustainability of the forest and forestry sector (Gardiner et al. 2013).

There are possibilities to adapt different management strategies to decrease the risk for storm damage. This can be efficient from the economic perspective and sufficient in the future where biobased products are becoming even more important. One strategy which fulfils the aim for economic values can though be in conflict with other objectives, for example, wood production, biodiversity, and carbon sequestration. This issue requires consideration and trade-offs between many different objectives (Gardiner et al. 2013), which can be connected to forest planning and forest management.

1.2. Decision support system: Heureka – PlanWise

With a decision support system (DSS) it is possible to analyse the development of different indicators in the forest over a long time. With a DSS it is possible to "solve complex and long term forest management planning problems" (Wikström et al. 2011). The DSS is a support for decision-makers and can be changed depending on the decision-maker's objectives (Wikström et al. 2011). Different management strategies contribute to different objectives in various grades and it is of interest to study how different management strategies affect different forest objectives (Eggers & Öhman 2020).

One DSS developed at the Swedish University of Agricultural Sciences (SLU), named "Heureka" was released in 2009 and has several applications for different issues and different users (Wikström et al. 2011; Eggers & Öhman 2020), including researchers, students and forest companies (Eggers & Öhman 2020). Heureka is used for "long term forest level planning" and includes a simulation part on both stand level and regional level together with an optimization module. The Heureka system uses empirical models to project the dynamics in the forest such as growth, but it also simulates forest management treatments and estimates recreation values, carbon sequestration and habitat suitability. All this can be made under different climate scenarios (Wikström et al. 2011).

One of the main components in Heureka is the "treatment program generator" which simulates alternative treatment schedules for a treatment unit (for example a stand) (Wikström et al. 2011). In the treatment program generator, the development of the forest and ecosystem services is projected from specified settings and is simulated with different models (Eggers & Öhman 2020). In what way different forest management actions affect the risk for storm damage can be simulated with this DSS. If the risk for storm damage should be minimized, the most optimal management strategy for that objective could also be chosen with an optimization tool in the DSS.

When using the optimization function in a DSS, the best alternative from a large number of management schedules is selected based on the decision-maker's objective together with restrictions of the problem (Eggers & Öhman 2020). In the optimization module in Heureka, it is possible to formulate and solve both linear and mixed-integer programming problems. The optimization module is using the ZIMPL programming language (Wikström et al. 2011).

The Heureka application PlanWise is a tool designed for long-term planning on a landscape level. With the help of Heureka PlanWise, it is possible to simulate different management strategies on stand level and choose the most optimal management depending on the defined objectives and constraints. With Heureka PlanWise it is possible to assess different indicators and ecosystem services for forests and to assess trade-offs between different forests objectives in conflict (Eggers & Öhman 2020).

1.3. Aim

The main aim of this work is to evaluate how a storm damage risk index affects various indicators for sustainable forestry. In a trade-off analysis, indicators for sustainable forestry will be considered and the goal is to identify how much a mitigation strategy for storm damages affects other perspectives on the forest.

This work aims to:

- Show the consequences of optimizing forest management to minimize the risk of storm damage over a long time and in various geographic areas.
- Analyse how consideration to storm damage risk affects net revenue, harvested volume, growth, deadwood, coarse trees, older broadleaf-rich forest and old forest, carbon storage and social values (recreation).

- Indicate whether more consideration should be given to the risk of storm felling in the planning and management of forests.
- Evaluate the risk index developed for storms in PlanWise and the test version of PlanWise that has been developed including the risk index.

1.3.1. Questions

- How does an adaptation of forest management to storm damage risk affect various indicators for sustainable forestry in northern and southern Sweden, respectively?
- How does the optimal combination of forest management strategies change when you minimize the risk of storm damage compared to when you do not consider storm damage risk?
- Is there a need for adapted forest planning/management based on risk for storm damages?

2. Background (literature review)

2.1. Storm and its damage on forests

Wind is the disturbance that has resulted in the largest damages to European forestry under the 20th century (responsible for 51% of all forest damages in Europe which is recorded) (Schelhaas et al. 2003; Gardiner et al. 2013). The damages from storms in Europe occurs often in the winter (Gardiner et al. 2013). The damages from wind are varying between years but larger damages have been more common (Gardiner et al. 2013) under the 20th century in Sweden (Nilsson et al. 2004; Eriksson et al. 2016), although relatively low variation in the wind climate (Bärring & Fortuniak 2009).

The amount of damaged forest has varied between approximately 0-75 million m^3 per year over the last 100 years, but the damages tend to increase over time, mainly because old and wind sensitive forest with a high timber volume has increased over time (Schelhaas et al. 2003; Gardiner et al. 2013; Witzell et al. 2017a; Kårén et al. 2018). The standing timber volume has increased, both due to changing climate and nitrogen deposition but also due to different management activities such as ditching, reforestation on earlier agricultural land and a more developed silviculture (Eriksson et al. 2016). Storms in Sweden have been more common in the southern part of the country (Nilsson et al. 2004; Bergh 2012). This is due to the windier climate (Nilsson et al. 2004) and "higher volume of standing forest" in southern Sweden compared to northern Sweden (Blennow et al. 2010a). It is therefore likely that it is both due to changed forest management and a changing climate that the forest is more sensitive to storm damages (Blennow et al. 2004, 2010b; Gardiner et al. 2013).

Regarding the impact of climate change, only stronger winds do not have to lead to an increased risk of wind damage in forests (Witzell et al. 2017a). Other factors also lead to increased storm felling such as:

- Warmer winters with a higher groundwater level during the winter and a more often absent frost in the ground which reduces root anchorage and tree stability (Peltola et al. 2010; Gardiner et al. 2013; Eriksson et al. 2016; Kårén et al. 2018).

- Increased proportion of Norway spruce (*Picea abies* (L.) H. Karst) dominated forests (Schelhaas et al. 2003; Valinger & Fridman 2011). This as a result of increased game grazing damaging on other species, which favours spruce (Senn et al. 2002) (spruce is relative to other species sensitive to wind damages because of more shallow roots, as one explaining factor (Peltola et al. 2000)).
- Higher growth of the forest to higher heights and standing volumes, where the risk of storm felling increases (Blennow et al. 2004, 2010a; b; Eriksson et al. 2016; Witzell et al. 2017a; Kårén et al. 2018; Skogsstyrelsen 2021a).

2.2. Storm damage and consequences for the society

Natural disturbances such as storms and storm felling are a part of the dynamics of a natural forest ecosystem (Gardiner et al. 2013). Storm damaged forests contributes to an increased amount of deadwood in the forest, but the damaged forests also lead to an increased cost for forestry (Peltola et al. 2010; Bergh 2012; Witzell et al. 2017b). It was estimated that the storm Gudrun incurred a cost of 15 billion SEK to the forestry. Costs for damages to the forest can be divided into “lost ecosystem services”, “lost refining value”, “compensation and contributions to forest owners from society”, “replanting and regenerating costs” and a “lost timber value” (Witzell et al. 2017b). Storm damages result in high costs for harvesting, storing and transporting the felled trees which often are spread in the terrain (Peltola et al. 2010; Kårén et al. 2018). In addition to this, the high flow of wood from storm fellings to the market will also affect the timber value, which will decrease (Gardiner et al. 2013; Loisel 2014). The increased cost to forestry can also include the cost for different management actions that are taken to reduce the risk for storm damage and mitigate the damage before the event (Gardiner et al. 2013).

Except for the damage and cost of the forest, felled trees by a storm can also negatively affect the society, for example, infrastructures such as closed roads, power interruptions, telecommunication services and private properties could be affected (Gardiner et al. 2013; Kårén et al. 2018). Other effects from storm damage in forests can be connected to carbon balance (Lindroth et al. 2009; Gardiner et al. 2013), the quality of wildlife habitats, biodiversity, recreation (Gardiner et al. 2013) and increased impacts from insects and pests such as the Spruce bark beetle (*Ips typographus* L.) (Schelhaas et al. 2003). Some of these effects are more difficult to evaluate in economic terms than others (Gardiner et al. 2013).

2.3. Factors affecting the risk for storm damage

The risk for storm damages and the susceptibility to storm damage for a forest differ between different parts of the landscape and depends on various tree, stand, management, site and climate factors (Figure 1) such as:

- Tree/stand characteristics
  - Composition of tree species (Blennow et al. 2010a; Peltola et al. 2010; Valinger & Fridman 2011; Gardiner et al. 2013; Kårén et al. 2018)
  - Tree height (Blennow et al. 2010a; Peltola et al. 2010; Valinger & Fridman 2011; Gardiner et al. 2013; Kårén et al. 2018) and height variation at stand level (Valinger & Fridman 2011)
  - Even-aged/uneven-aged forest structure (Gardiner et al. 2013)
  - Stand age (Lohmander & Helles 1987; Bergh 2012; Gardiner et al. 2013)
  - Height/diameter at breast height ratio (h/dbh) (Valinger & Fridman 1999; Schelhaas 2008; Blennow et al. 2010a; Peltola et al. 2011; Gardiner et al. 2013; Stoltz 2016)
  - Amount of standing volume (Schelhaas et al. 2003) and amount of forest cover (Nilsson et al. 2004)
  - Number of stems per hectare (Blennow et al. 2004, 2010a) and stand density (Peltola et al. 2010; Gardiner et al. 2013)
  - Root characteristics (Nilsson et al. 2004; Gardiner et al. 2013). Reduced root depth can increase the risk of storm damage (Gardiner et al. 2013).
- Forest management of stands (Gardiner et al. 2013)
  - Time since last thinning (Blennow et al. 2010a; Stoltz 2016) or different thinning regimes (Nilsson et al. 2004) (Lohmander & Helles 1987; Valinger & Fridman 2011).
- Site conditions (Peltola et al. 2010)
  - Soil/ground characteristics and site index (Blennow et al. 2010a; Peltola et al. 2010; Gardiner et al. 2013; Stoltz 2016). Soil with restricted oxygen availability and soils with the occurrence of waterlogging or peaty/very wet humus forms increase the risk for

storm damage, and the soil water balance affects. Acidic soils increase the risk for storm damage (Gardiner et al. 2013).

    - Topography (Blennow & Olofsson 2008; Peltola et al. 2010; Gardiner et al. 2013). Passes between mountains, valleys running from west to east and the first westerly slopes on mountain ranges have all increased risk for storm damage (if the westerly wind is assumed) (Gardiner et al. 2013).

- Wind climate (Nilsson et al. 2004; Blennow et al. 2010a; Peltola et al. 2010; Gardiner et al. 2013)
    - Wind direction (Blennow et al. 2010b)
    - Wind speed/wind load (Lagergren et al. 2012)
    - Wind intensity (Nilsson et al. 2004)
    - Wind frequency (Nilsson et al. 2004)

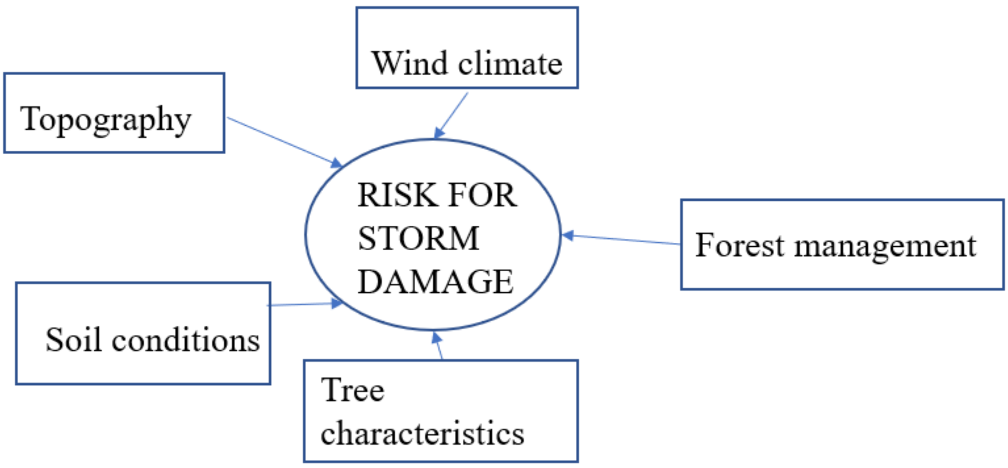

Figure 1. Factors affecting the risk for storm damage in a forest. A more detailed figure can be seen in Stoltz (2016) (Only in Swedish) (Stoltz 2016).

It has been shown that site characteristics and wind speeds have less impact on the vulnerability of a tree or stand, compared to stand and tree characteristics, which affect the risk for storm damage more (Gardiner et al. 2013).

2.3.1. Possibilities to reduce the risk for storm damages with forest management

Today, the forest in Sweden is predominantly managed with even-aged forestry with cleaning, one or several thinnings, a final felling, and then soil preparation and planting or sowing regeneration. The current forest management strategy in a future with a changing climate has been shown to increase the sensitivity of the forest to wind, both in the north and south of Sweden (Blennow et al. 2010b; a). The sensitiveness for storm damage in even-aged stands are often connected to past thinning history (Gardiner et al. 2013). A possible management strategy to increase wind stability is with large spacing at planting and an early and heavy thinning. This will lead to low h/dbh-ratio which increases stability but can decrease the timber quality due to higher knottiness (if no pruning occurs) (Gardiner et al. 2013).

Thinning increases the risk for storm damage instantaneous but the risk decreases after some years (Blennow et al. 2004; Valinger & Fridman 2011; Bergh 2012; Gardiner et al. 2013; Valinger et al. 2014; Eriksson et al. 2016; Kårén et al. 2018). This is because the wind force is spread on fewer tree crowns which have no stability from the surrounding tree crowns (Nielsen 1995; Gardiner et al. 2013; Eriksson et al. 2016). The remaining trees are affected by greater wind loads and need some time to adapt to the new wind climate (Gardiner et al. 2013). The instability after thinning is also explained by a changed growth pattern that needs adaption. In the earlier dense stand, the height growth was prioritized, but after the thinning the diameter growth could be prioritized due to more space for each tree (Lagergren et al. 2012), and a favoured root anchorage (Gardiner et al. 2013). The favoured diameter development is a positive effect to mitigate the risk for storm damage, compared to an unthinned stand (Gardiner et al. 2013).

Thinning affects the h/dbh-ratio more than the height due to the favoured diameter development (Stoltz 2016). In northern Europe, h/dbh-ratio is of higher importance compared to variation in tree height (which is more important in central Europe) to assess the risk for storm damage (Gardiner et al. 2013). Gardiner et al. (2013) mean though that a low h/dbh-ratio does not always mean better stability for stands because a low h/dbh-ratio also correlate with larger crowns and older trees and with that higher risk for storm damage (Gardiner et al. 2013).

Early thinning and last thinning before the dominant height is over 20 m could reduce the risk for storm damages. Late thinnings in the stand development increases the risk for storm felling due to increased height of the stand (Blennow et al. 2004; Elfving 2010b; Valinger & Fridman 2011; Gardiner et al. 2013; Eriksson et al. 2016; Kårén et al. 2018). Early thinnings are especially important in Norway spruce dominated forests, due to the sensitiveness for storm felling in spruce stands (Slodicak & Novak 2006; Valinger & Fridman 2011; Gardiner et al. 2013; Eriksson et al. 2016).

Increased thinning grade also decreases the stability of the remaining stand to storm damages, especially when the thinning is made late in the rotation period. Thinnings should be implemented at regular intervals and with a light grade to reduce the storm damage risk (Gardiner et al. 2013). An example of actions is a first thinning at a height of 12-14 m with a thinning grade between 25-35% of the basal area followed by a second thinning when the height is 20 m with a thinning grade of 20% of the basal area (Kårén et al. 2018). In the context of thinnings, the forest could also be managed without any thinnings, which could decrease the risk for wind damages (Valinger & Pettersson 1996).

2.3.2. Possibilities to spread the risk for storm damages with forest management

One way of spreading risk connected to forest damage, is with a higher variation in the forestry management, for example, with management that promotes mixed forests (Blennow 2012; Gardiner et al. 2013; Eriksson et al. 2016; Kårén et al. 2018). Increasing the area with broadleaved forest and mixed forest of broadleaf and conifer species reduces the damage risks in several ways and at the same time, biodiversity is increased (Eriksson et al. 2016). The storm Gudrun in 2005 caused less storm damage to mixed stands than to homogenous stands especially when birch (*Betula spp.* (L.) Linné) or other broadleaved trees were in mix with Norway spruce. Broadleaved species in a mix with Norway spruce showed a larger decrease of storm damage risk compared to Scots pine (*Pinus sylvestris* (L.) Linné) in a mix with Norway spruce (Valinger & Fridman 2011; Valinger et al. 2014). When broadleaved trees are found in the upper canopy layer, a mixed forest with 25-30% of broadleaved species can reduce the risk for storm damage by approximately 50% (Valinger & Fridman 2011). In general, a higher proportion of Norway spruce increases the risk of storm damage (Schütz et al. 2006; Valinger & Fridman 2011; Albrecht et al. 2012).

The positive impact of broadleaved trees to reduce storm damage risk is due to that the species have no leaves in the autumn and winter (Bergh 2012; Gardiner et al. 2013) when storms are common. Of concern is though that in a warmer climate the leaved season for broadleaved species will be longer and the risk for storm damages to broadleaved species will increase (Eriksson et al. 2016). A negative effect of increasing the broadleaved forest in Sweden is the slower growth and reduced harvest volume, which will have a negative impact on the economy in the long run for the forestry (Bergh 2012).

Other ways of spreading risk could be to have forest stands in different age classes and to use continuous cover forestry. Continuous cover forestry (CCF), “single-tree selection forestry” and forests with uneven-aged and irregular stand structures are in general less sensitive to storm damages, compared to commercial clear cut and even-aged stands. On sites with moderate wind exposure, trees in uneven-aged stands develop good stability (Mason 2002; Valinger & Fridman 2011; Gardiner et al. 2013; Hanewinkel et al. 2014; Couture et al. 2016; Eriksson et al. 2016). Uneven-aged stands have a more open canopy structure and the present understory absorbs some of the wind exposure on the stand (Gardiner et al. 2013). For dominant trees in uneven-aged stands, the h/dbh-ratio is lower and therefore more stable. The dominant trees are also more stable due to the usually greater wind load they are affected by and adapted to (Mason 2002; Gardiner et al. 2013). CCF is also advantageous if storm felling occurs because no planting is required for regeneration (Gardiner et al. 2013). If CCF would be used over large areas, the area of sensitive stand edges will also be reduced (Eriksson et al. 2016).

It is also possible to spread risks by using different management objectives to different forest stands (Gardiner et al. 2013). One example mentioned by Gardiner et al. (2013) is "by managing some stands for a high economic return but with a high risk of damage while keeping other stands at a lower risk but with an acceptance of a lower economic return" (Gardiner et al. 2013).

2.4. Earlier similar studies

A study by Blennow et al. (2010b) "simulated how possible changes in wind and ground-frost climate and state of the forest due to changes in the future climate may affect the probability of exceeding critical wind speeds expected to cause wind damage within one northern and one southern study area in Sweden, respectively". The simulations showed that the probability of storm damage was higher in the southern area of Sweden than in the northern. This was due to differences in for example tree species composition. It was also suggested that there is a need for further analysis such as "of the effects of different management options on the probability of wind damage and what modifications of Swedish forest management are possibly warranted" (Blennow et al. 2010b).

Another study, comparing storm damage effects in one southern and one northern area in Sweden was made by Bergh (2012). The result from the comparison, in this case between Småland and Jämtland, showed that a management of the forest without thinnings resulted in a slightly reduced or even better economy (Jämtland). In addition to this, the damages by storm (and also Norway spruce bark beetle and root rot) were reduced if no thinnings are made, which also is positive for the economy (Bergh 2012). But management without thinnings also has negative effects, which have been described earlier (Bergh 2012).

The study by Blennow et al. (2004) uses a model called "WINDA" (Blennow & Sallnäs 2004) which calculates the probability for storm damages for each stand over a landscape. With the model "WINDA", Blennow et al. (2004) evaluate different forestry practices and the effect of a changing climate on storm damages (Blennow et al. 2004).

After investigating how the current wind climate and the probability of high wind speed affect forests and forest management Peltola et al. (2010) proposed that similar studies should be made for different future scenarios with a changing climate because a "clearer picture about the expected risks by wind in the future" is needed. Effects of forest management which is adapted to forest productivity and both biotic and abiotic damages to forests should be analysed in connection to different scenarios of a changing climate. This is sufficient to also produce ecosystem services in the future and therefore damage risk to forests should be incorporated in models for growth and yield production (Peltola et al. 2010).

Common to all silvicultural strategies adapted for reducing the risk of damage in the forest is an increased cost or decreased growth. It is therefore important to make trade-offs to find the most optimal strategy to manage the forest (Kårén et al. 2018).

3. Materials and methods

3.1. Materials

Input data are sample plot data from the National Forest Inventory (NFI) inventoried between 2014 to 2018. The data only covers productive forest areas. NFI has collected data in Sweden since 1923 and has developed to include data valuable to follow up many functions of the forest, for example, provision of timber to industry, biodiversity and carbon storage. The sample plots inventoried are both permanent and temporary (Fridman et al. 2014).

The plot-level data represent a certain proportion of forest and indicators connected to a tree layer do not need an exact location. With NFI plots it is not possible to do analyses that need “wall-to-wall spatial data”. With this data, analyses of how a certain forest type change over time or analyses with trade-offs between different indicators for sustainable forestry can be made (Eggers & Öhman 2020). In this thesis, a trade-off will be made.

Lycksele and Växjö municipality was subjectively chosen as study areas and to represent forests both in northern and southern Sweden (Figure 2). Växjö municipality was selected because it is a municipality in southern Sweden but at the same time, it does not include as many noble broadleaved forests (long-lived broadleaves such as oak, beech, maple, elm) as other areas in the south, for example, Skåne county. This makes the forest in Växjö municipality more similar to the forest in Lycksele municipality and reduces the uncertainty in PlanWise of handling noble broadleaves.

Each NFI plot in each municipality represents a specific area, in PlanWise represented by the weight “AdjustedAreaFactor”. The “AdjustedAreaFactor” (area weight factor depending on the number of inventoried years used) for NFI plots in Lycksele municipality range from 111.92 ha to 1704 ha and in Växjö municipality the “AdjustedAreaFactor” range from 49.9 ha to 722.84 ha.

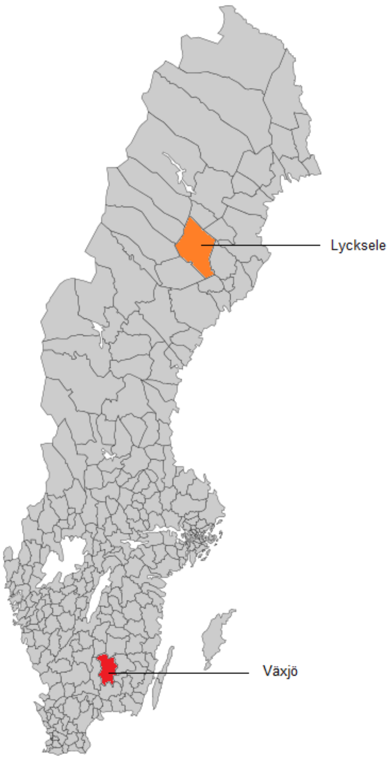

Figure 2. Map over selected geographical areas, Lycksele municipality and Växjö municipality. CC BY-SA 2.5, (Wikimedia Commons 2007) Edited by: Linnea Larsson.

The data representing Lycksele municipality consists of 320 plots which represent 418 000 ha productive forest land, has an average growing stock of 106.1 m^3sk/ha, average age of 64.9 years (volume-based) and a forest area age-class distribution as in figure 3. The main tree species are Scots pine (approximately 58% of volume), Norway spruce (approx. 26%), Birch (approx. 13%) and Lodgepole pine (*Pinus contorta* (L.) Bol.) (3%) (Figure 4). About 23% of the productive forest is spruce dominated area. The average site productivity is 3.35 $m^3sk \cdot ha^{-1} \cdot year^{-1}$.

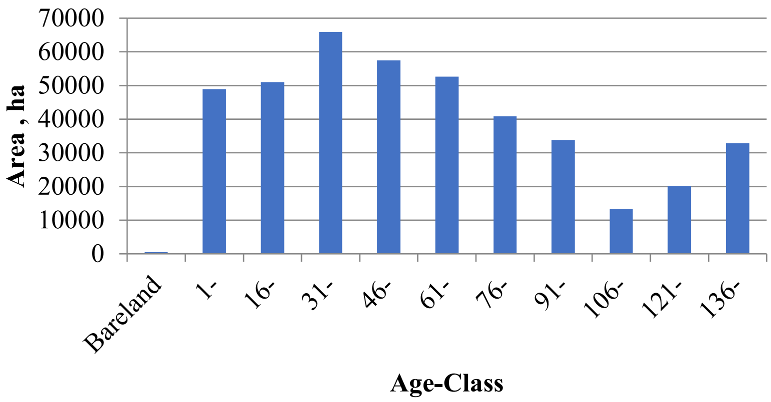

Figure 3. Productive forest area age-class distribution in Lycksele municipality, ha.

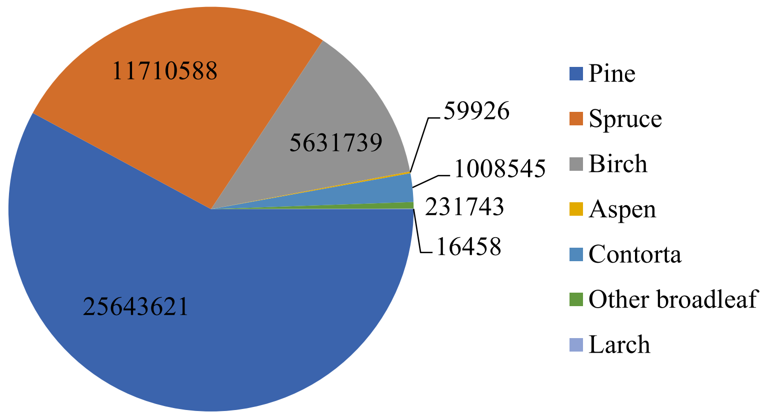

Figure 4. Growing stock distributed on tree species in Lycksele municipality, m^3sk.

The data representing Växjö municipality consists of 250 plots which represent 136 000 ha productive forest land, has an average growing stock of 149.4 m^3sk/ha, average age of 41.2 years (volume-based) and a forest area age-class distribution as in figure 5. The main tree species are Norway spruce (approx. 56% of volume), Scots pine (approx. 25%), Birch (approx. 12%), and some other broadleaved species (Figure 6). About 56% of the productive forest is spruce dominated area. The average site productivity is 9.35 $m^3sk \cdot ha^{-1} \cdot year^{-1}$.

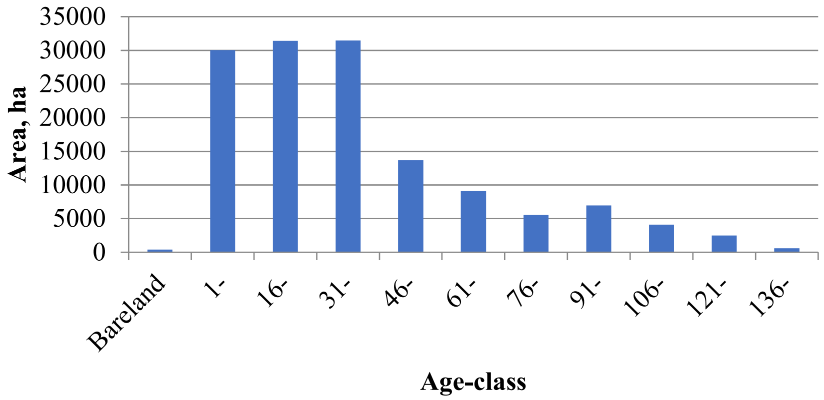

Figure 5. Productive forest area age-class distribution in Växjö municipality, ha.

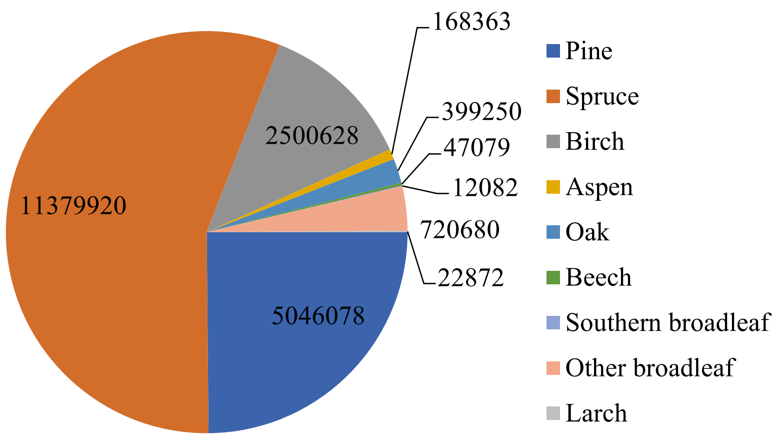

Figure 6. Growing stock distributed on tree species in Växjö municipality, m^3sk.

3.2. Method

To analyse how an adaption to the risk of storm damage affects the forestry and different ecosystem services a simulation and optimization were made in Heureka PlanWise.

3.2.1. Indicators

Indicators for forest production, nature conservation and biodiversity, carbon storage and recreation were subjectively chosen to indicate how the relationship between a change in storm damage risk and ecosystem services could be in the future. For these indicators, a trade-off analysis was made.

Following indicators were chosen (detailed description in 3.2.2 - 3.2.6):

- Forest economy and production:
    - Net revenue (SEK/ha).
    - Harvested volume: Roundwood volume harvested including timber, pulpwood, fuel wood and log cull ($m^3fub \cdot ha^{-1} \cdot yr^{-1}$).
    - Growth: CAI Net (All species), current annual increment (net) during the last period ($m^3sk \cdot ha^{-1} \cdot yr^{-1}$).

- Nature conservation and biodiversity:
    - Deadwood: Downed and standing deadwood (m^3/ha).
    - Coarse trees: Density of trees with a diameter in breast height > 40 cm (number of trees/ha).
    - Older broadleaved-rich forest: Area of forest with broadleaved species (birch, aspen, oak, beech, southern broadleaf and other broadleaf) representing > 25% of the total basal area. In southern Sweden with an age > 60 years, in northern Sweden with an age > 80 years (ha).
    - Old forest: Area of forest with age > 120 years in southern Sweden and age > 140 years in northern Sweden (ha).
- Carbon storage:
    - Carbon in biomass and deadwood (ton C): Total carbon in Deadwood + Total carbon in living trees incl. tree crown (excl. stumps and roots) + Total carbon in stumps and roots.
- Recreation:
    - Recreation index: Index between 0 and 1 describing a plots' suitability for recreation, a higher index value denoting higher suitability for recreation.
- Damage risk:
    - Storm Index Without Exposure (without proxies for exposure). Index between 0 and 1, a higher index value denoting a higher risk for storm damage.

3.2.2. Indicators for forest production

High economic revenue is one of the main objectives for forest management and forest industries. To substitute fossil-based products with biobased products, net revenue, harvested volume and growth are all therefore interesting indicators to analyse. Two important parts of sustainable forestry are to not harvest more than the growth and to regenerate after harvesting which makes the forest a renewable resource. In the Swedish Forestry Act from 1993, it is stated that the production and environmental values should be equally valued in the forestry sector (Regeringen 2014). Production values can also be connected to the bioeconomy which is included in the national forest program of Sweden (Näringsdepartementet 2018). Net revenue, harvested volume and growth is one way to interpret these production values.

3.2.3. Indicators for nature conservation and biodiversity

Deadwood, coarse trees, older broadleaf-rich forest and old forest is in this thesis used to describe nature conservation values and biodiversity (Pilstjärna & Hannerz 2020). These four indicators are also indicators for the environmental goals in Sweden (Pilstjärna & Hannerz 2020; Sveriges miljömål 2021). The definition of coarse trees in this thesis is set to all trees with a diameter > 40 cm, based on the nature conservation value assessment by Skogsbiologerna AB ("Skogsbiologernas naturvärdesbedömning") (Lundberg & Lundkvist 2019). Other definitions of coarse trees vary between 30 to 45 cm in diameter, depending on which tree species that are included (SLU 2020; Sveriges miljömål 2021).

Numerous studies support the fact that deadwood is one of the most important substrates for species richness and preserved biodiversity in boreal forests (Lassauce et al. 2011; Pilstjärna & Hannerz 2020). In this thesis, both downed and standing deadwood were included.

During the last century, there has been a change in the landscape structure where conifer species (pine and spruce) have become more dominant. This has led to a situation where biodiversity connected to the presence of broadleaved trees are under pressure (Felton et al. 2016). For example, the southern broadleaved forest contains many threatened species, for several organism groups (both cryptogams, vascular plants, invertebrates, and vertebrates) (Berg et al. 1994).

The older broadleaf-rich forest is described as:

> "In stands with a mean height >=7m: broadl. are more than 3/10 of the basal area. In stands with a mean height <7m: broadl. are more than 3/10 of the number of stems. Definition of older forest: Forest >80 years in the Boreal region, Forest >60 years in the Boreonemoral and Nemoral region" (Pilstjärna & Hannerz 2020; SLU 2020; Sveriges miljömål 2021).

Large and old trees are important substrates for red-listed species in boreal forests. The level of species richness can be connected to the characteristics of the old forest. Old forests are critical for vertebrates, invertebrates, and cryptogams (Berg et al. 1994). The definition of old forest (including all tree species) is over 120 years in Växjö municipality (Boreonemoral and Nemoral region) and over 140 years in Lycksele municipality (Boreal region) (Pilstjärna & Hannerz 2020; SLU 2020; Sveriges miljömål 2021).

3.2.4. Indicator for carbon balance and its connection to storm damage

The impact of storm damage on carbon storage can be divided into two parts. First, damages from storms can reduce the living biomass and with that reduce the capacity of carbon sequestration (reduce the photosynthesis). Second, wind damage results in an increased decomposition of coarse woody debris, soil organic carbon and litter due to increased heterotrophic respiration (Gardiner et al. 2013). The indicator for carbon storage in this thesis represents the carbon in biomass and deadwood (the carbon in the soil and the substitution effect from wood products are excluded in this study).

3.2.5. Indicator for recreation

As an indicator for recreation, an index between 0 and 1 is used in Heureka PlanWise. The recreation index is describing a plot's suitability for recreation, based on the type of forest (bare land, young forests and mature forests). The recreation index for the mature forest is based on variables such as average height, trees/ha, and tree species distribution. The recreational value in forests are becoming more and more important due to urbanization, and it is the municipalities responsibility to provide recreational areas for the inhabitants (Eggers et al. 2018).

3.2.6. Storm damage risk index (sensitivity index for storm damage)

The storm damage risk index (sensitivity index for storm damage) which was used in this thesis, "Storm index without exposure", was recently developed for PlanWise (2021). The storm damage risk index is based on the earlier developed storm module implemented in Heureka RegWise. The storm module is based on the article by Lagergren et al. (2012). The storm damage risk index only estimates the sensitivity of the stand for storm damages and is presented as an index between 0 and 1. This storm damage risk index does not estimate wind damaged forest or storm felled timber volume (personal communication with J. Eggers, 2021).

Variables from Heureka used in the storm module (Heureka Wiki contributors 2014) in RegWise are: diameter at breast height (cm), height (m), tree species grouped into three groups (pine, spruce, birch), thinning grade (share of the basal area which is thinned) and time since thinning. These variables were also used for the storm damage risk index model implemented in PlanWise.

The storm damage risk index in PlanWise used for these analyses was "without proxies for exposure" and therefore was no spatiality included. This storm damage risk index is calculated with a root stability index (RSI_patch), a height index on tree level (HI_cohort) and an index for allometric relationship (AI_cohort). This results in a total sensitivity index (TSI or SI_cohort) which is on tree level and needs to be summarized to represent a stand or a plot. The summarizing is made by calculating a basal area-weighted mean ("grundytevägt medelvärde") for TSI. The TSI is the value that is implemented as a result variable in Heureka PlanWise (test version) under "Damage risks" → "Before" → "Storm Index Without Exposure".

The root stability index (RSI_patch) is calculated with a modified formula from Lagergren et al. (2012).

$$RSI_i = a + b * e^{c*t_i}$$

i = index for patch
a, b and c are coefficients from table 1
t = time since last thinning (in years)
If no thinning has been made earlier, RSI = 0,1.

Table 1. Parameters for calculating RSI together with the time since last thinning (t, years).

Thinning grade (%)	a	b	c	r^2
20	0.2978	0.4573	-0.2465	0.74
30	0.2001	0.7559	-0.1242	0.79
40	0.1538	0.9959	-0.0932	0.82

The original formula for RSI_patch (Equation 10 in Lagergren et al. (2012)) is based on yearly calculations from "current fine-root biomass" and the "fine-root biomass at the time of the most recent thinning" (Lagergren et al. 2012).

The thinning grade (%) is used as an input variable in table 1 and is calculated as follows:

$$Tgrade_i = \frac{BA_{out_i}}{BA_{bt_i}} * 100$$

I = index for patch
BA_{out} = basal area for thinned trees on the patch (m^2/ha)
BA_{bt} = basal area of the patch before thinning (m^2/ha)

The basal area is calculated as follows:

$$BA = \sum_{j=1}^{n} \frac{\pi * d_{j^2}}{4}$$

j = index for tree
n = number of trees
d = diameter in breast height (cm)

The height index on tree level (HI_cohort) is described by Lagergren et al. (2012) as “an index of how much a given cohort emerges above the other cohorts in a patch” (Lagergren et al. 2012). The height index on tree level (HI_cohort) is calculated as follows (Equation 12 in Lagergren et al. (2012)):

$$HI_{cohort_{ij}} = \frac{h_{ij} - hgv_{patch_i}}{30} + 1$$

i = index for patch
j = index for tree
h = height of the tree (m)
hgv_{patch} = height weighted over the basal area for the patch (m)

The height index on tree level implies a higher risk for the highest tree in unmanaged forests or continuous cover forestry compared to the highest tree in an even-aged managed forest. In an even-aged managed forest, the HI_cohort for the dominant tree will get close to 1 and the index has therefore low significance. This is due to the increased sensitivity for a tree to storm damage if the surrounding neighbouring trees are shorter (Lagergren et al. 2012).

The index for allometric relationship (AI_cohort) describes how sensitive trees in a cohort are to wind independent of other factors, such as neighbouring trees, patches or the topography (Lagergren et al. 2012). AI_cohort represents the relationship between tree height and stem diameter (h/d-ratio) (Lagergren et al. 2012), which have been shown to correlate with risk for storm damage (Valinger & Fridman 1999; Schelhaas 2008; Blennow et al. 2010a; Peltola et al. 2011; Gardiner et al. 2013; Stoltz 2016).

The index for allometric relationship (AI_cohort) is calculated as follows (Equation 13 in Lagergren et al. (2012)):

$$AI_{cohort_{ij}} = \frac{h_{ij} - 5}{d_{ij} - 12} * k_{species}$$

i = index for patch
j = index for tree
h = height of the tree (m)
d = diameter of the tree (cm)
$k_{species}$ = coefficient which varies with different groups of species ($k_{pine} = 0.85$, $k_{spruce} = 1.70$, $k_{broadleaves} = 0.17$)[1]. If h<5 m or d<12 cm, AI_{cohort} is set to 0.

[1] Note! In Lagergren et al. (2012) $k_{species}$ was set to “1.0 for Norway spruce, 0.5 for Scots pine and 0.1 for the remaining species”.

The total sensitivity index (TSI or SI_cohort) is calculated as follows (Equation 14 in Lagergren et al. (2012)):

$$TSI = RSI_{patch_i} * HI_{cohort_{ij}} * AI_{cohort_{ij}}$$

i =index for patch
j=index for tree
If TSI<0, TSI=0 and if TSI >1, TSI=1.

3.2.7. Analysis in PlanWise

The analysis was made in a test version of Heureka PlanWise: "PlanWise Test DamageRisk" (Version 2.17.6.5). The analysis covered 20 periods of 5 years in each period, resulting in a total time of 100 years.

To find the optimal solution, seven different forest management strategies per plot were simulated and then an optimization was made to find the most optimal management program depending on specific goals.

Eggers and Öhman (2020) describe the steps of making an analyse in PlanWise as follows:

1. Import data
2. Define management strategies
3. Treatment generation (simulation)
4. Define goals and constraints and the treatment selection (optimization)
5. Analyse results

The first step was to import the plot-level data from the NFI into the PlanWise application. The data was imported from a forest database that covered productive forest areas from 2014 to 2018. All five years were included in the analysis and the average forest condition was represented as the year 2016. The start year (year 1) for the analysis was therefore set to 2017.

3.2.8. Management strategies

In PlanWise, different management strategies were defined for the simulation of different future scenarios. The focus with the different management strategies was on different thinning methods and alternatives with more mixed forests. This derives from detected ways to reduce or spread the storm damage risk through forest management activities. Except for different thinning strategies and strategies which includes more broadleaves, other management strategies included in the analyses were CCF, commercial clear cut (business as usual (BAU)) and an unmanaged alternative, all described below. Management settings in PlanWise used default values if not changed as described below.

- Commercial clear-cut management (BAU)

Standard management actions, regeneration through planting, cleaning, thinnings and final felling with 10 retention trees and 3 high stumps per hectare. The maximum height at thinning could be performed was 25 meters.

- No thinning

Includes planting, cleaning, final felling with 10 retention trees and 3 high stumps per hectare, no thinnings (max number of thinnings = 0).

- Max one thinning

Maximum one thinning and performed before 18 meters mean height (Bergh 2012). This management strategy also included a more exact time of thinning with no delay in time and an increased thinning grade. The thinning grade was set to between 30-50% instead of the default values of 20-40%. Includes planting, cleaning, final felling with 10 retention trees and 3 high stumps per hectare.

- Continuous cover forestry (CCF)

Managed with a series of selection fellings. The management system was set to "Uneven-aged" (CCF) instead of "Even aged". After selection felling, 10 single retention trees and 3 high stumps were left. Max height of the stand for a thinning that could be made was set to 20 meters. This strategy was only applied in spruce-dominated forests.

- Unmanaged

The forest is left for free development. No management at all. The management system was set to "Unmanaged".

- 30% broadleaves

Increased share of retained broadleaved species in cleaning and thinning operation (share after cleaning and thinning was set to 30% broadleaved trees (the thinning model Hugin was used for thinning settings)). The management system was "Even aged" and there will be 20 single retention trees and 6 high stumps after final felling. The maximum height where a thinning can be made was set to 20 meters.

- 70% broadleaves

Same settings as for the management strategy of 30% broadleaves but instead the share of broadleaved trees was set to 70% after cleaning and thinning.

3.2.9. Treatment generation (simulation)

After defining the different management strategies, the simulation of management programs followed. All management strategies were simulated for each plot, except for CCF, which only was simulated for spruce-dominated forests. 20 treatment programs were simulated for each management strategy. In the settings of the simulation, the period midpoint was chosen to represent the result value, and the maximum number of periods was set to 21 (20 periods (1 to 20) + period 0 (which was the starting year (2016), representing the starting value)). The discount rate was set to 2.5% and the default pricelist (Mellanskog 2013) was used.

3.2.10. Optimization and trade-offs in PlanWise

The optimization in PlanWise consisted in this thesis of a trade-off analysis. The trade-off analysis was made between two different objectives, and one of them was minimizing storm damage risk. One way of doing trade-offs is with "pareto-optimal" plans, plans which need that if one objective is to be improved, the other outcome from another objective needs to be lower. The method in this thesis of making "pareto-optimal" plans is presented in the report by Eggers and Öhman (2020) and they describe the following:

> "…this can be done by first maximizing (or minimizing) each objective separately, to find out the maximum potential for each of them. In the next step, one of the objectives is maximized (or minimized), and the other objective is included as a constraint. By step-wise changing the required amount of that objective to be reached, a number of pareto-optimal solutions can be found… …Then, the indicator values can be plotted against each other…" (Eggers & Öhman 2020).

The optimization model in this analysis included a constraint about evenness in the harvested volume between periods. From one period to another the harvested volume must be +/- 10% of the previous period. No lower limit of harvested volume was specified, which makes it possible to have an unmanaged management strategy. In this optimization model, the decision variable Xij was set to "Custom" instead of "Binary". This made it possible for PlanWise to divide one plot into several parts and that each part could be managed with different management strategies. This was suitable in this analysis due to the relatively large area each plot represented.

Step one in the optimization was to maximize (or minimize) each indicator separately. The optimization, or "treatment selection", was made with the solver Gurobi 9.1 and no rounding off to integer was used. In the first step, the objective function was set to maximize total value over all planning periods for each indicator separately. For each indicator, the summarized value over time was optimized (for period 1 to period 20, covering 100 years).

Step two was to maximize (or minimize) one indicator, here the risk for storm damage was minimized, and at the same time gradually decrease the demand for maximizing other indicators to create trade-off curves. In this second step, a constraint of each indicator was needed. The constraint was formulated as that the summarized value over time (the optimized value) must be over a certain percentage of the maximum potential value (which was calculated in the first step). With this constraint, it was possible to minimize the storm damage risk and at the same time maximize the indicator, to a certain level. This step was made several times but with the change of the percentage of the maximum potential value of the indicator. The percentage was stepwise decreased from 0.99, 0.95, 0.90 and continued until a further decrease did not change the result anymore (here seen as when the lowest possible value for storm damage risk was achieved). With this principle, it was possible to make trade-off optimizations and visual trade-off curves for the different indicators of interest against storm damage risk. The formulas for the optimization model in general terms can be found in Appendix 1.

All results were presented with tables and graphs in PlanWise, showing the summarized value, the average value per hectare or the summarized area of an indicator. All result tables were exported to Microsoft Office Excel where average values for all 100 years were calculated (per 5-year period or per year). The result was calculated without period 0, and no starting values were included. In Excel, tables and graphs were created to visually present the results.

4. Result

4.1. Maximal potential for each indicator

To investigate how silviculture adapted to storm damage risk affects various indicators for ecosystem services and sustainable forestry, each indicator was maximized and compared with the corresponding value for when the storm damage risk was minimized (Table 2 and 3).

The results showed that the minimum storm damage risk was 0.022 for Lycksele (Table 2) and 0.036 for Växjö (Table 3). When aiming for minimized storm damage risk all indicators were decreasing, both in Lycksele and in Växjö municipalities. The highest storm damage risk was occurring when maximizing the number of coarse trees per hectare (0.054 for Lycksele, 0.116 for Växjö). The second highest storm damage risk was when the recreation values were maximized. The difference between the highest and lowest storm damage risk was 0.032 for Lycksele municipality and 0.080 for Växjö municipality.

In addition, all indicators that were maximized led to an increased storm damage risk, compared to the minimum storm damage risk. This was shown for both Lycksele and Växjö (Table 2 and 3).

Table 2. Results after maximizing or minimizing (storm damage risk) each indicator for Lycksele Municipality. Values are the average over all periods, excl. period 0, with the constraint of +/- 10% in harvest level between periods.

	Indicator									
	Max									Min
Indicator	Net Revenue	Harvested volume	Growth	Deadwood	Coarse trees	Older broadleaf-rich forest	Old forest	Carbon storage	Recreation	Storm damage risk
Net Revenue (SEK/ha)	**3565**	3367	1513	17	1093	1800	42	0	449	2117
Harvested volume (m^3fub·ha^{-1}·yr^{-1})	3.26	**3.42**	1.70	0.02	1.42	2.04	0.04	0	0.51	2.31
Growth (CAI Net) (m^3sk·ha^{-1}·yr^{-1})	3.52	3.55	**3.92**	3.23	3.09	3.35	3.17	3.21	3.12	3.35
Deadwood (m^3/ha)	17.7	13.2	15.8	**34.6**	21.3	13.8	34.2	34.6	30.1	13.3
Coarse trees (stems/ha)	3.4	3.3	3.3	15.2	**17.3**	4.6	15.5	15.5	15.7	2.7
Older broadleaf-rich forest (1000 ha)	18.4	14.1	26.6	45.7	24.7	**84.3**	45.8	45.7	39.9	13.0
Old forest (1000 ha)	13.8	6.0	13.5	114.7	70.2	19.7	**117.2**	117.2	109.3	6.0
Carbon storage (mill. ton C)	22.2	19.7	25.3	42.5	28.1	21.6	41.8	**42.6**	37.7	17.9
Recreation (index 0-1)	0.45	0.44	0.45	0.55	0.51	0.45	0.56	0.55	**0.58**	0.40
Storm damage risk (index 0-1)	0.043	0.050	0.047	0.042	0.054	0.049	0.043	0.042	0.052	**0.022**

Table 3. Results after maximizing or minimizing (storm damage risk) each indicator for Växjö Municipality. Values are the average over all periods, excl. period 0, with the constraint of +/- 10% in harvest level between periods.

	Indicator									
	Max									Min
Indicator	Net Revenue	Harvested volume	Growth	Deadwood	Coarse trees	Older broadleaf-rich forest	Old forest	Carbon storage	Recreation	Storm damage risk
Net Revenue (SEK/ha)	**9948**	9632	6326	33	2271	5370	0	15	2097	7171
Harvested volume (m^3fub·ha^{-1}·yr^{-1})	7.16	**7.33**	4.97	0.03	1.80	4.19	0	0.02	1.63	6.11
Growth (CAI Net) (m^3sk·ha^{-1}·yr^{-1})	7.94	8.01	**8.43**	6.02	6.09	6.86	5.98	6.02	6.04	7.48
Deadwood (m^3/ha)	24.7	20.2	20.0	**67.8**	51.5	27.0	67.8	67.8	52.0	19.5
Coarse trees (stems/ha)	8.1	6.8	8.3	56.8	**61.1**	16.1	57.5	56.9	57.9	5.0
Older broadleaf-rich forest (1000 ha)	7.5	7.8	10.8	28.3	23.9	**48.5**	28.8	28.1	23.7	4.7
Old forest (1000 ha)	0.7	0.3	0.9	29.7	26.7	5.9	**30.4**	29.6	28.3	0.7
Carbon storage (mill. ton C)	12.3	11.3	12.4	24.8	20.4	13.9	24.8	**24.8**	20.5	9.8
Recreation (index 0-1)	0.44	0.43	0.44	0.59	0.61	0.47	0.59	0.59	**0.63**	0.37
Storm damage risk (index 0-1)	0.090	0.092	0.097	0.075	0.116	0.078	0.076	0.075	0.114	**0.036**

For Lycksele and Växjö municipalities, the highest mean age per ha was found when maximizing deadwood, old forest and carbon storage (Figure 7 and 8). The same indicators gave the largest average of forest area which had a mean height of over 20 meters, for both Lycksele and Växjö (Figure 9 and 10). But these indicators do not have the highest storm damage risk (Table 2 and 3).

Coarse trees and recreation which have the highest storm damage risk have a relatively high mean age per ha and a relatively high average area with a mean height over 20 meters, but not the highest of each of the factors (Figure 7, 8, 9 and 10).

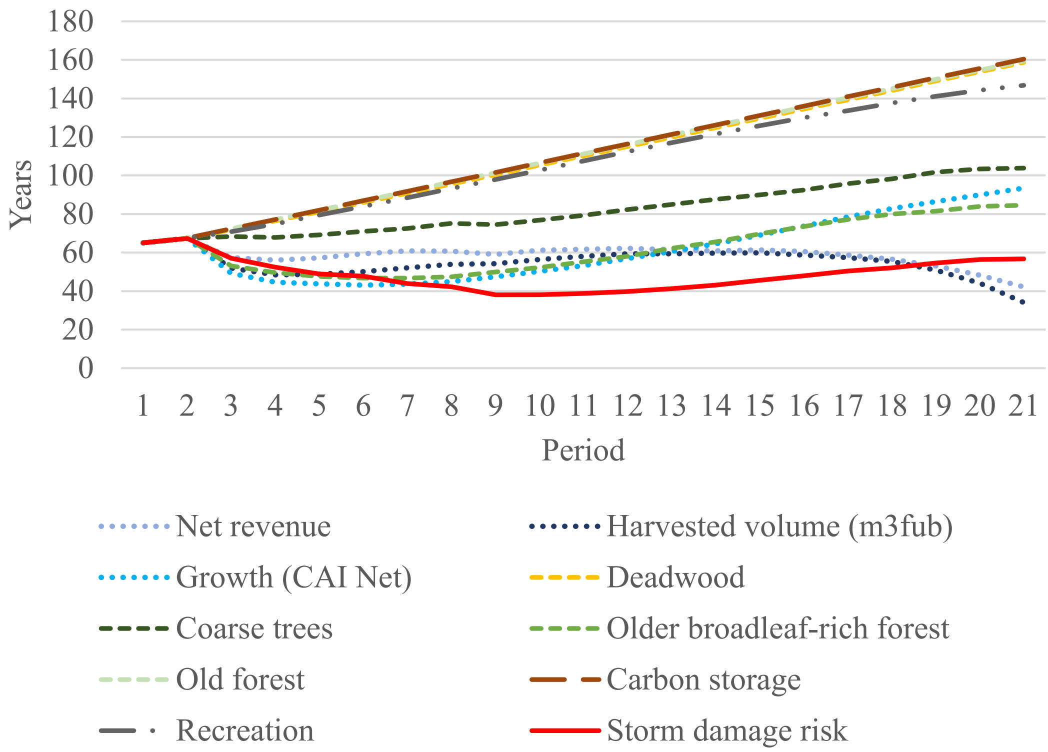

Figure 7. Mean age over time for different maximized or minimized indicators in Lycksele municipality, years.

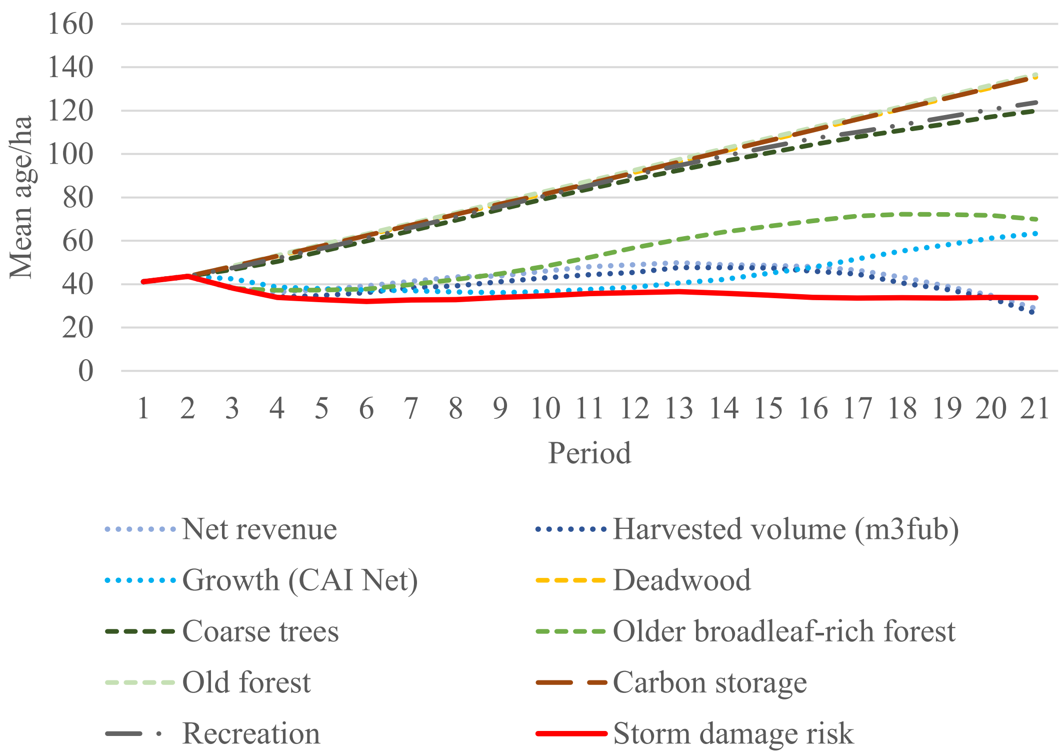

Figure 8. Mean age over time for different maximized or minimized indicators in Växjö municipality, years.

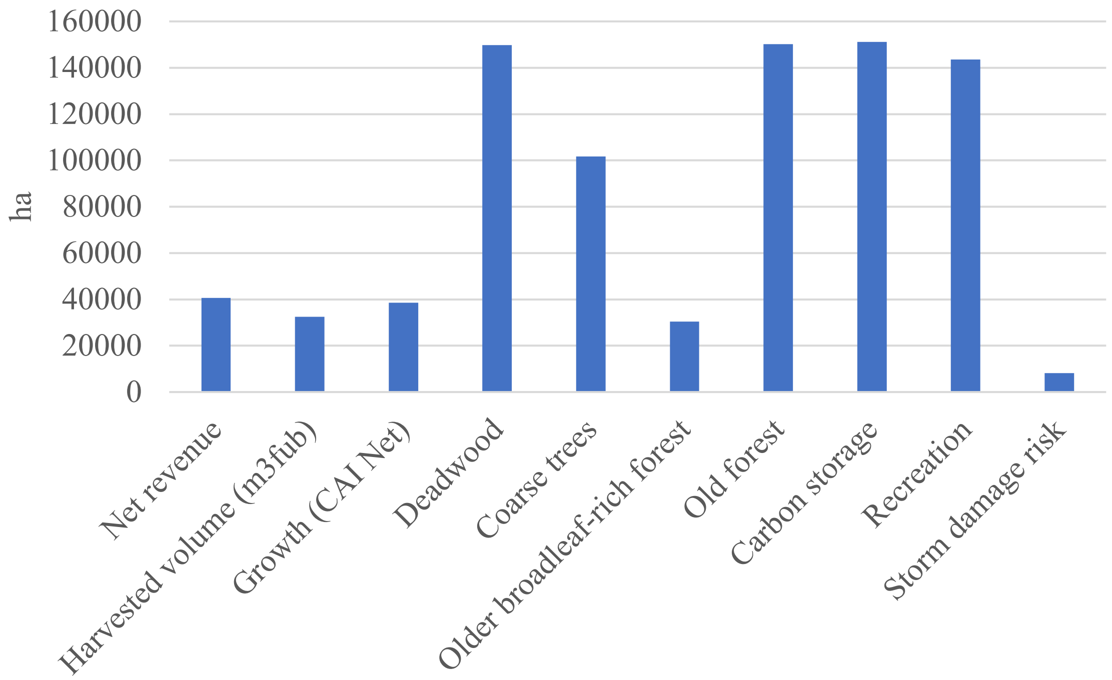

Figure 9. Average forest area with a mean height over 20 meters in Lycksele municipality, ha.

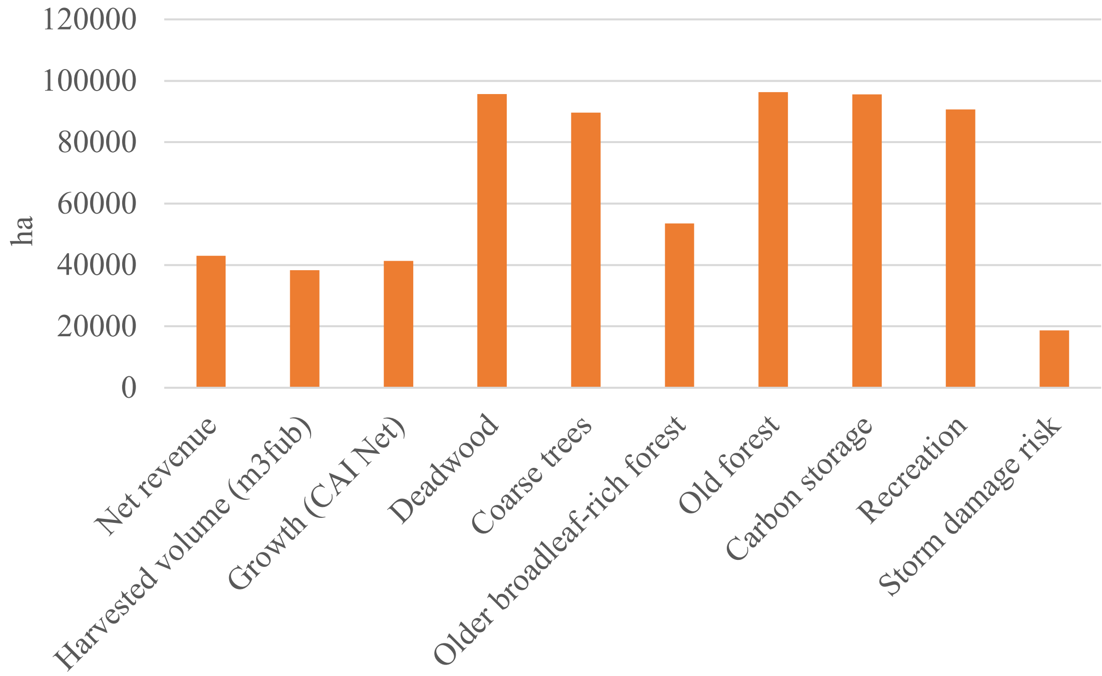

Figure 10. Average forest area with a mean height over 20 meters in Växjö municipality, ha.

4.2. Management strategies when maximizing each indicator

The lower net revenue when minimizing storm damage risk, compared to the maximal possible net revenue (Table 2 and 3) depends on changes in the proportion of management strategies (Figure 11 and 12). When maximizing the summarized value for net revenues for 100 years in the future, the forest would mainly be managed with no thinnings, max one thinning and BAU (commercial clear cut) in both Lycksele and Växjö municipalities (Figure 11 and 12). When instead minimizing storm damage risk, the increased amount of the no thinning strategy leads to less harvested volume and with that also a lower net revenue. But the net revenue is not at the lowest level when minimizing storm damage risk. Some of the lowest net revenue occurs when maximizing the deadwood, old forest or carbon storage (Table 2 and 3) which can be connected to the large area of unmanaged forests (Figure 11 and 12) when maximizing those indicators.

The storm damage risk is lower when maximizing net revenue compared to when maximizing harvested volume, for both Lycksele and Växjö municipalities. This is mainly due to the lower area of forest which is managed with commercial clear cut (BAU) when maximizing net revenue compared with maximizing harvested volume (Figure 11 and 12).

When maximizing the growth (CAI Net) for Lycksele the productive forest included in this thesis would be managed with the unmanaged alternative, commercial clear cut and with max one thinning (Figure 11). When maximizing growth for Växjö the management strategies were mainly commercial clear cut and max one thinning (Figure 12).

If the objective was to maximize deadwood, old forest or carbon storage, the forest in Lycksele and Växjö would mostly be unmanaged. Some small areas would though be managed with no thinning in addition to the unmanaged forests (Figure 11 and 12). The unmanaged management strategy resulted in the second lowest storm damage risk when maximizing deadwood and carbon storage (Table 2 and 3).

When maximizing coarse trees in these municipalities, the optimal management strategy varied between case study areas. In Lycksele, the management strategies were mainly unmanaged, commercial clear cut, 30% broadleaves and 70% broadleaves (Figure 11). In Växjö, the unmanaged strategy and CCF were the most common (Figure 12).

The management strategy when maximizing older broadleaf-rich forests consisted of all possible management strategies included in this simulation. For Lycksele, the management strategies with 70% broadleaves followed by commercial clear cut (BAU) were the most common (Figure 11). Also, for Växjö, the most common management strategy was 70% broadleaves, but here followed of unmanaged management (Figure 12).

If recreation would be the main objective for the analysed forests, the result showed that after maximizing recreation, the forest would mostly be unmanaged (Figure 11 and 12). For Växjö municipality, CCF was also common (Figure 12). Other management strategies occur but in minor areas.

The result showed that when minimizing storm damage risk most areas were managed without any thinnings, for both Lycksele and Växjö (Figure 11 and 12). The second most used management strategy to reduce the risk for storm damage was 70% broadleaves in Lycksele municipality, corresponding to approximately 15% of the total area (Figure 11). For Växjö municipality the second most used management strategy was max one thinning (Figure 12).

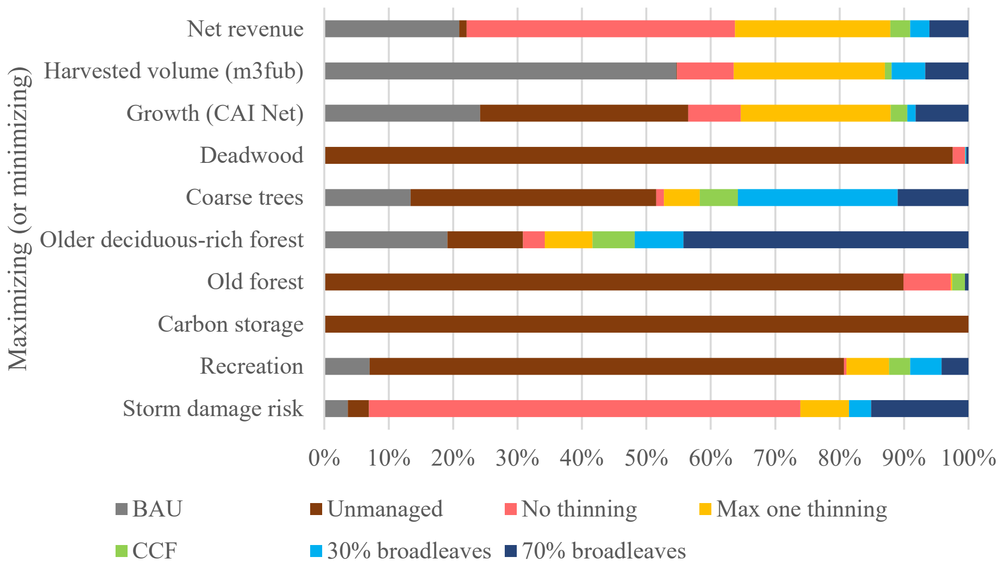

Figure 11. Combinations of different management strategies for different maximized (or minimized) indicators in Lycksele municipality. Each NFI plot was possible to divide into subplots, and separate subplots could be managed with individual management strategies.

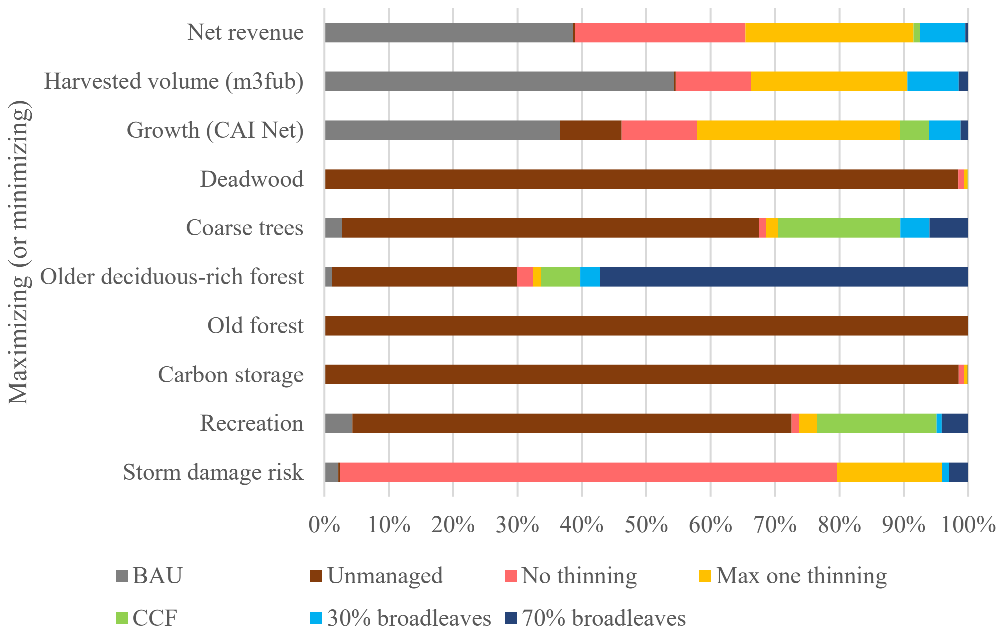

Figure 12. Combinations of different management strategies for different maximized (or minimized) indicators in Växjö municipality. Each NFI plot was possible to divide into subplots, and separate subplots could be managed with individual management strategies.

4.3. Trade-offs between indicators and storm damage risk

The results from the trade-off analysis show that the effect of decreasing the risk for storm damage affected various indicators in various ways. A longer part of a more linear effect showed the potential of decreasing the storm damage risk to a relatively small reduction in the indicator included in the trade-off. This was seen for net revenue, harvested volume and growth, for both Lycksele and Växjö (Figure 13, 14 and 15).

The trade-off for coarse trees versus storm damage risk (Figure 17) showed also possibilities to reduce the risk for storm damage with a small reduction in amount coarse trees, this was though not as clear as for net revenue, harvested volume and growth (Figure 13, 14 and 15). It was also shown that when minimizing storm damage risk, the number of coarse trees was relatively similar for both Lycksele and Växjö. The number of coarse trees/ha when minimizing storm damage risk was 2.7 per ha for Lycksele and 5 per ha for Växjö.

For deadwood and older broadleaf-rich forest (Figure 16 and 18), the effect of decreasing the storm damage risk affected the amount of deadwood and area of older broadleaf-rich forest relative early (compared with trade-offs with net revenue, harvested volume or growth (Figure 13, 14 and 15)), exclusive the older broadleaf-rich forest in Lycksele, which had a more linear curve until a certain point.

The trade-off between area old forest and storm damage risk (Figure 19) differed depending on which geographical area you look into. For Lycksele, the area of the old forest decreased with reduced storm damage risk, and this occurred relatively immediately. The decreasing effect was increased as lower the storm damage risk was. Instead, for Växjö, the result for area old forest was not affected in the same way of a reduced storm damage risk, until a certain point where the storm damage risk is relatively low.

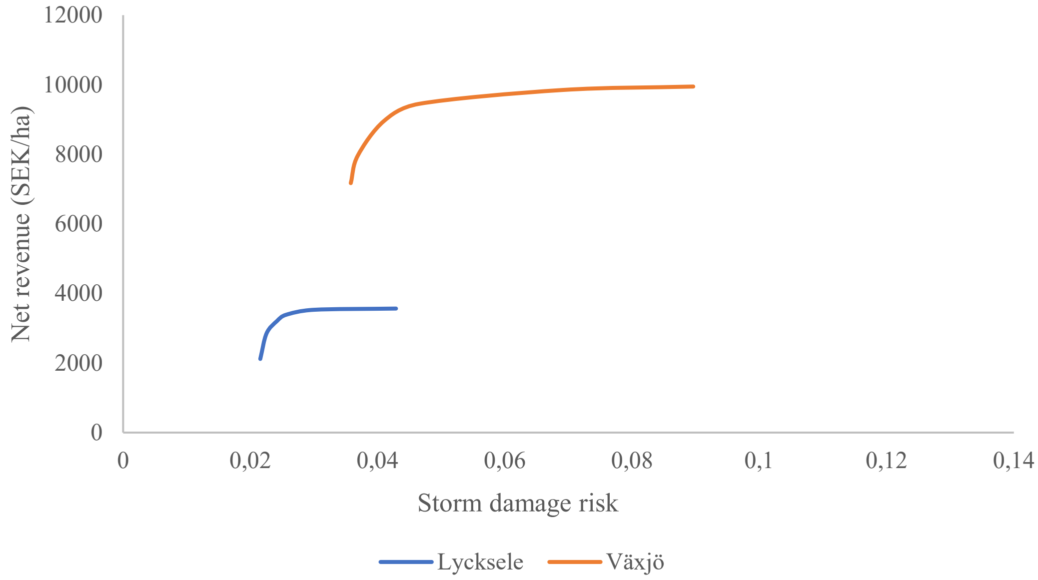

Figure 13. Trade-off between average net revenue (SEK/ha) and average storm damage risk, over all periods excl. period 0, with the constraint of +/- 10% in harvest level between periods.

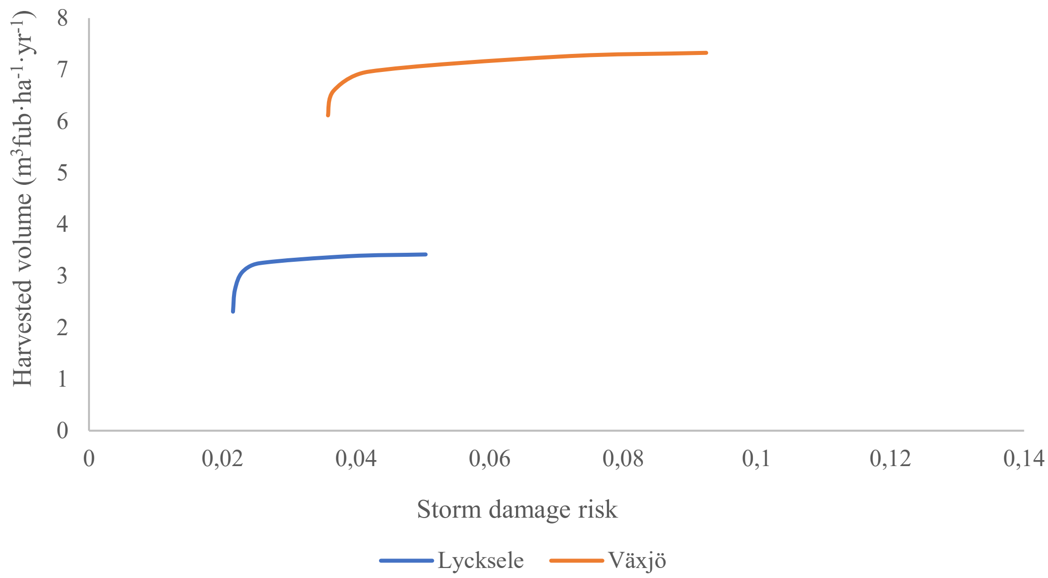

Figure 14. Trade-off between average harvested volume ($m^3fub \cdot ha^{-1} \cdot yr^{-1}$) and average storm damage risk, over all periods excl. period 0, with the constraint of +/- 10% in harvest level between periods.

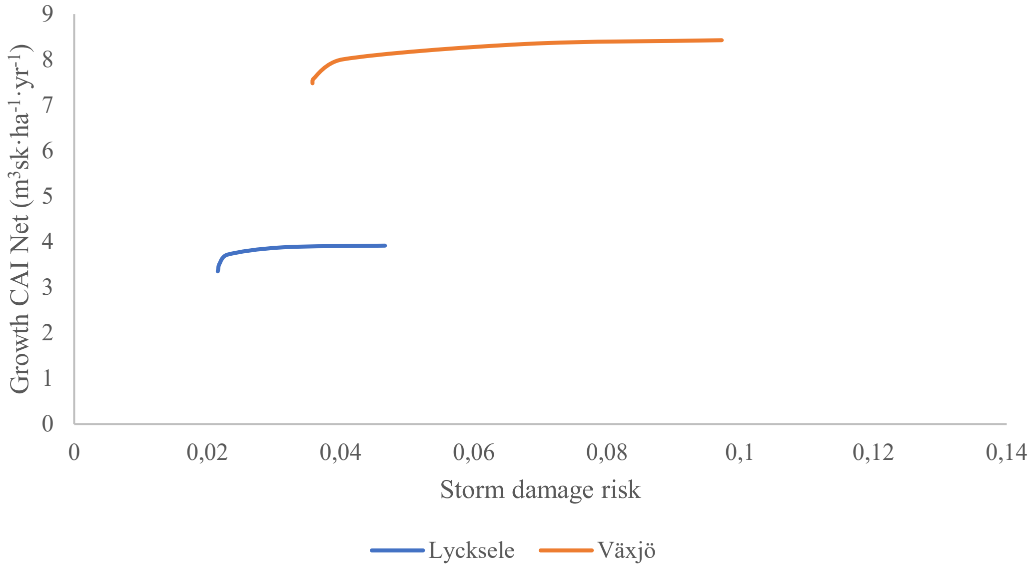

Figure 15. Trade-off between average growth (CAI Net) ($m^3sk{\cdot}ha^{-1}{\cdot}yr^{-1}$) and average storm damage risk, over all periods excl. period 0, with the constraint of +/- 10% in harvest level between periods.

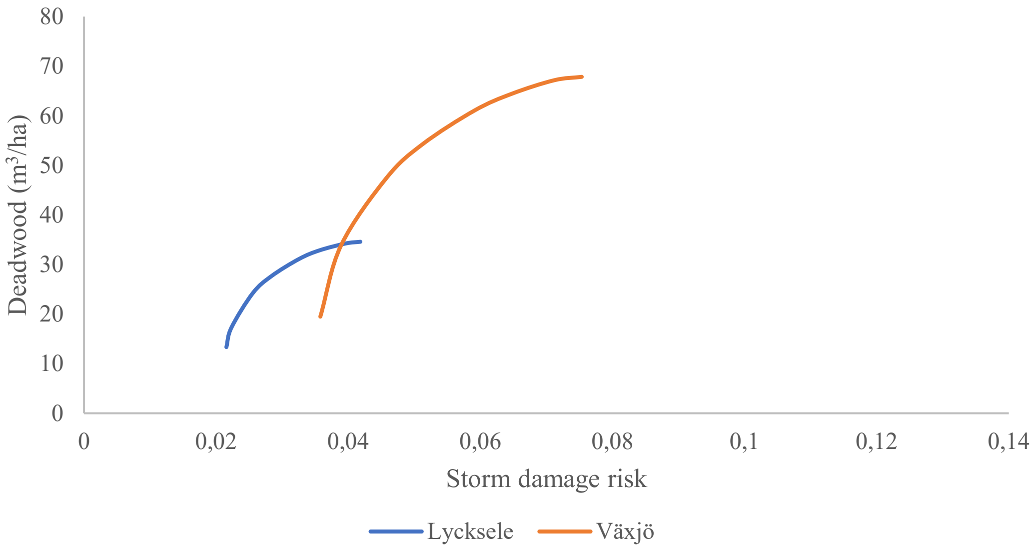

Figure 16. Trade-off between average deadwood (m^3/ha) and average storm damage risk, over all periods excl. period 0, with the constraint of +/- 10% in harvest level between periods.

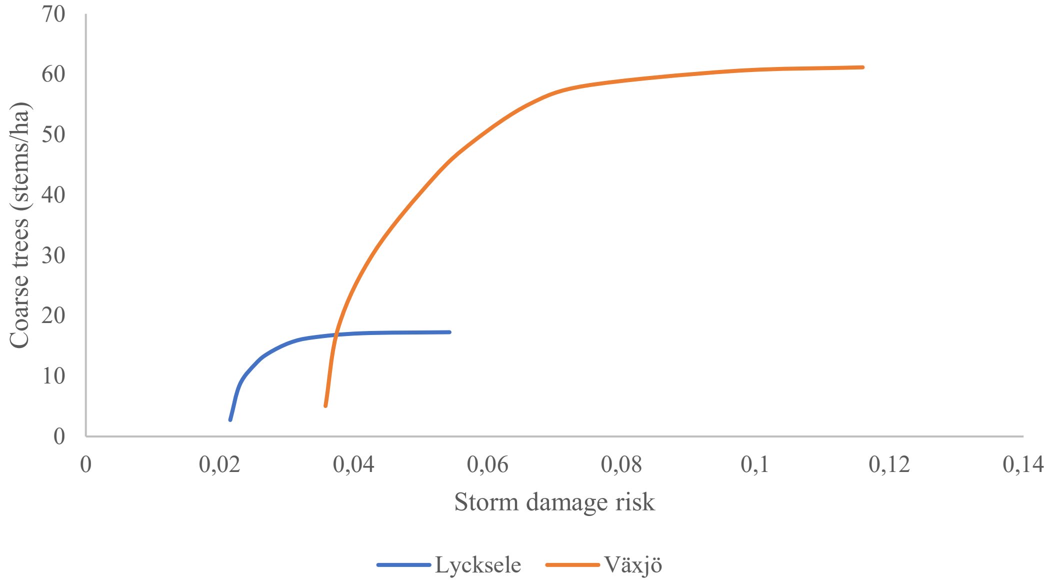

Figure 17. Trade-off between average coarse trees (stems/ha) and average storm damage risk, over all periods excl. period 0, with the constraint of +/- 10% in harvest level between periods.

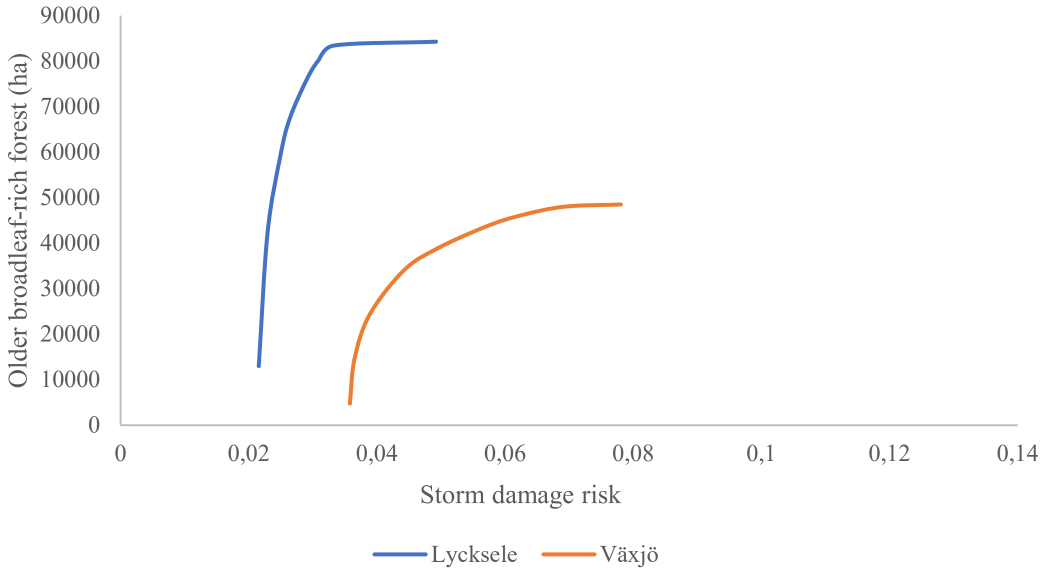

Figure 18. Trade-off between average older broadleaf-rich forest (ha) and average storm damage risk, over all periods excl. period 0, with the constraint of +/- 10% in harvest level between periods.

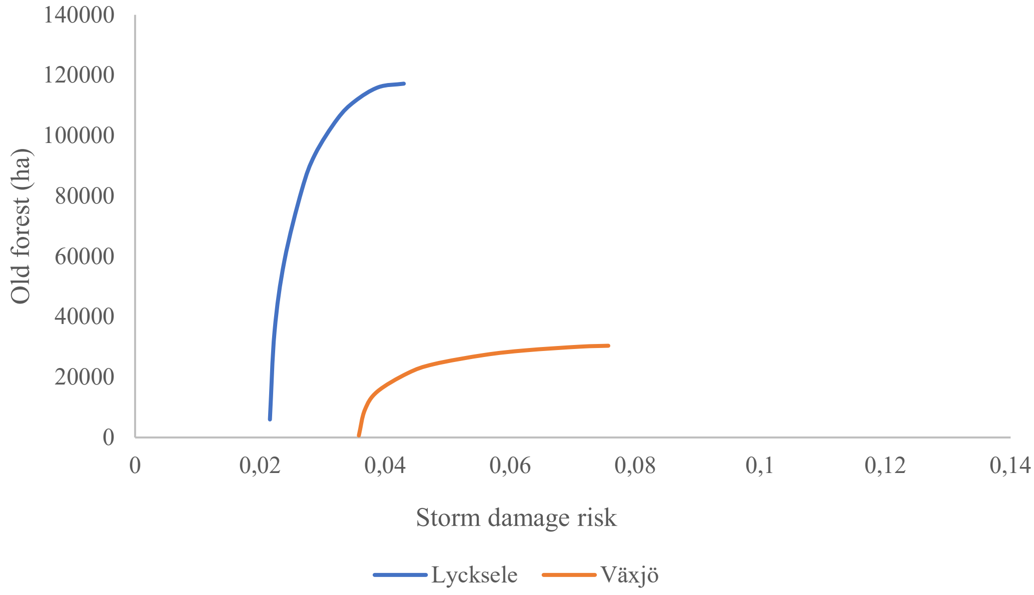

Figure 19. Trade-off between average old forest (ha) and average storm damage risk, over all periods excl. period 0, with the constraint of +/- 10% in harvest level between periods.

5. Discussion

In this thesis, the focus has been on different management strategies related to the risk of storm damage in forests and how different indicators could be affected if more adapted management to reduce storm damage risk would be introduced in forest practices.

5.1. Maximal potential of each indicator

All values for all indicators included in this thesis decreased when the storm damage risk was minimized and all indicators that were maximized led to an increased storm damage risk. This can be explained by a change in management strategies but also that all indicators have characteristics that increase the storm damage risk, seen for a time horizon of 100 years.

Harvested volume is interesting to include in this thesis because it represents the forest production service and can be argued to be a more direct indicator than net present value or net revenue for the production and economic objective in forestry. When looking for a time horizon of 100 years, the changes in economic values are uncertain but the harvested volume could give a better estimation of how the timber production would change. The harvested volume is important to include, due to other aspects such as social impacts, the environment, the forest culture and the forest policies (Gardiner et al. 2013). The reduction in harvested volumes depends on a changed proportion of management strategies when minimizing storm damage risk. The increasing proportion of unthinned forest area when minimizing storm damage risk reduces the possible harvested volumes that could be harvested in thinnings. This is the result for both Lycksele and Växjö. Commercial clear cut management (BAU) which is the most common management strategy when maximizing the harvested volume, and especially the even-aged stands that are developed, have been shown to increase the sensitivity of forest to wind (Blennow et al. 2010b; a). This statement can be confirmed in this thesis and also explain why the storm damage risk is lower when maximizing net revenue compared to when maximizing harvested volume. The lower area of forest which is managed with commercial clear cut (BAU) when maximizing net revenue results in a lower storm damage risk.

The growth is decreasing somewhat when the storm damage risk is minimized, compared to the maximum possible growth. The decreasing growth can be connected to that the storm damage risk is increasing with increasing volume in the stand (Schelhaas et al. 2003). Higher growth leads to higher wood stocks and higher volume in the forests, and to more forest that could be storm damaged, which is negative if the objective is to minimize the risk for storm damage.

The amount of deadwood was reduced when the risk for storm damage was minimized, due to higher storm damage risk with higher stand age. This could be connected to the change in management strategies with increased actions when the storm damage risk was minimized. When only maximizing deadwood the main management strategy was unmanaged which results in more deadwood compared to when the forest is managed in different ways. The occurrence of clear cuts, thinnings and other cuttings will decrease natural development and self-thinning which are needed for the development of deadwood. Although some deadwood could be created within forest actions, it will not be close to the possible amount of deadwood in natural development, seen over 100 years.

The result with decreasing amount of coarse trees, older broadleaf-rich forest and old forest when minimizing the risk for storm damage could be explained by the increased risk for storm damage in stands with increasing heights, increasing age and with increasing volume. This reasoning has also been proposed in earlier research (Lohmander & Helles 1987; Schelhaas et al. 2003; Peltola et al. 2010; Valinger & Fridman 2011; Bergh 2012; Gardiner et al. 2013; Kårén et al. 2018). Coarse trees, older broadleaf-rich forest and old forest have differently composed management strategies which all differ from the composition of management strategies when minimizing storm damage risk. The characteristics of the indicators themselves are not in line with a low storm damage risk. Coarse trees are relatively old, includes a high volume and is often relatively high. The coarse trees should have a relatively low h/dbh-ratio due to a large diameter. Therefore, the highest storm damage risk occurs when the number of coarse trees is maximized is somewhat surprising.

The older broadleaf-rich forest results in a higher storm damage risk than expected, due to older forest compared with for example when maximizing harvested volume. The effect of an increasing amount of broadleaved species would decrease the risk for storm damage, probably more than for old forests, but this is not the case. This could be explained by more thinning actions when maximizing older broadleaf-rich forest, compared with the unmanaged strategy when maximizing old forest. It is seen that older broadleaf-rich forest has a lower mean age and a smaller areal of forest with a height over 20 meters compared with old forest. This shows that the thinning action is more important for the storm damage risk index than the age and height of the forest.

The high storm damage risk when maximizing older broadleaf-rich forest could also be due to the limit that all forests where the basal area consists of more than 25% of broadleaved species is considered as broadleaf-rich forests. The limit of 25% could be too low to see an effect of the reduction of storm damage risk by a mixed forest because the forest could consist of 75% of conifers. And it is well-known that a higher proportion of Norway spruce increases the risk of storm damage (Schütz et al. 2006; Peltola et al. 2010; Valinger & Fridman 2011; Albrecht et al. 2012). Valinger & Fridman (2011) have though presented that when broadleaved trees are found in the upper canopy layer of a mixed forest, a mix with 25-30% of broadleaved species could reduce the storm damage risk by approximately 50% (Valinger & Fridman 2011).

The old forest has high volumes, high age and often a relatively high height. Therefore, the decreasing area of the old forest when minimizing the risk for storm damage is reasonable. The storm damage risk is lower when maximizing old forest compared to the older broadleaf-rich forest, which could be due to a higher h/dbh-ratio, long time since thinning and/or that trees that have become over 120 and 140 years have been adapted to high wind speeds during their life-time.

The increased risk of storm damage when maximizing carbon storage is discussed by Gardiner et al. (2013). With increased carbon storage, more forest volume will be at risk for storm damages (Gardiner et al. 2013), due to higher storage with higher forest volume (Schelhaas et al. 2003). The carbon is stored in the forest biomass, which must increase to increase the forest ability to store carbon. Therefore, the decrease in carbon storage when minimizing the storm damage risk is logical, due to higher storm damage risk in stands with higher volume.

Recreation values are higher for large trees than for small trees, it increases with increased tree size diversity and with a decreased amount of harvest residues left at the site, among other factors (Heureka Wiki contributors 2016). These structures are favoured by the unmanaged management strategy over time, which dominates when maximizing recreation, in comparison to the management strategy with no thinning which is dominant when the objective is to minimize the storm damage risk. Therefore, the recreation value is decreasing when minimizing storm damage risk. Notable is that the recreation index in PlanWise also can be affected by deadwood, the recreation value would decrease with increased abundance of deadwood, but this option has not been included in the analyses. Therefore, the result with unmanaged management when maximizing recreation is logical but could have been different if deadwood had been included. Another issue when discussing recreation is that no spatial relationships are used in this analysis, therefore the recreation index which should be dependent on the spatial distance to society could be doubtful.

Connected to storm damage some indicators also affect each other. For example, a high level of harvested volume and a large amount of deadwood is contradictory objectives, but both are affected by storm and storm damage preventive management (Gardiner et al. 2013). A high level of harvest volume results in high economic profit from the forest and at the same time, the risk for insect outbreaks is reduced. A high level of harvest volume could though affect the biodiversity negatively. Leaving more wood in the forest results in higher amounts of deadwood and a possible positive effect on biodiversity, but with increased risk for insect outbreaks (Gardiner et al. 2013).

It is also possible to notice in table 2 and 3 that the growth is higher than the harvested volume when the storm damage risk is minimized. This is one indication of that minimizing storm damage risk is sustainable over time due to harvest and growth levels.

5.2. Management strategies when maximizing each indicator

The risk for storm damage varies between different parts of Sweden (here Lycksele and Växjö), depending on factors such as tree species composition, the risk for high wind speeds, forest stand height and more. And therefore the management strategies could be different for different geographical areas (Kårén et al. 2018). Factors that affect the storm damage risk but cannot be affected is the climate, the topography, the soil/terrain conditions and the soil characteristics in the forest (Gardiner et al. 2013). Differences in climate, topography, soil/terrain conditions and soil characteristics could result in different management strategies in different geographical areas which affect the risk for storm damage. In the results some differences in the distribution of management strategies can be seen when comparing Lycksele and Växjö, for example, the strategies including more broadleaf-rich forest are more common in Lycksele when minimizing storm damage risk than in Växjö.

The proportion of commercial clear cut (BAU) is relatively small when minimizing storm damage risk, compared with maximizing harvested volume. This can be explained by the increased risk for storm damage within even-aged stands and especially to the thinning history (Blennow et al. 2010b; a; Gardiner et al. 2013), with several thinnings and thinnings in high heights of a stand.

“No thinning” was the most common management strategy to minimize storm damage risk, both for Lycksele and Växjö. A management strategy with no thinnings have been shown from other studies to be a possible management alternative when the risk for storm damage is high (Valinger & Pettersson 1996), but it has consequences. Consequences could be a shortening of the rotation period due to increased self-thinning and natural mortality, no early economic revenues from thinned timber, no possibility to change the composition of tree species after cleaning and negative forced actions if the stand would become damaged or sick (Bergh 2012).

When minimizing storm damage risk, the management strategy with max one thinning is more common in Växjö than in Lycksele. The reduced risk for storm damage could be due to a decreased risk for late thinnings with this management strategy. Late thinnings should be avoided due to the sensitivity to storm damage in high stands (Blennow et al. 2004; Elfving 2010b; Valinger & Fridman 2011; Gardiner et al. 2013; Eriksson et al. 2016; Kårén et al. 2018). The difference in the proportion of area that is managed with max one thinning between Lycksele and Växjö could be explained by the higher proportion of spruce stands in Växjö municipality. Several papers mention that it is especially important to thin early in spruce dominated stands, due to the sensitiveness for storm damage for spruce (Slodicak & Novak 2006; Valinger & Fridman 2011; Gardiner et al. 2013; Eriksson et al. 2016). Another explanation to the lower area which is managed with max one thinning in Lycksele municipality could be the lower growth which gives more time to thin two times before a final felling.

The effect of low h/dbh-ratio (low height and high diameter) after thinnings which is described to reduce the risk for storm damage is not so clear in the results. But the effect of a low h/dbh-ratio has also been discussed by researchers. Schütz et al. (2006) have shown no significant effect from h/dbh-ratio on the risk for storm damage, which goes in line with what Valinger & Fridman (2011) have stated. Gardiner et al. (2013) mean instead that the h/dbh-ratio is of high importance in northern Europe with clear cuts and monocultures to decrease the risk for storm damage. Due to the dominant management strategy with no thinnings, there was a negative effect of thinnings which destabilized the stand for some time.

A factor that could affect the result is the time since thinning, since longer time since thinning could decrease the risk for storm damage. It is shown that forest stands that were thinned recently (within the last five years) are at higher risk for storm damage (Valinger & Fridman 2011). This has though been shown to not have a significant effect on the risk for storm damage by Schütz et al. (2006). It is discussed that this contradiction could be a result depending on different thinning regimes (Schütz et al. 2006). The effect of time since last thinning is not included in this analysis and the effect is therefore still uncertain. The effect of thinning as a management action has though been seen to be a strong factor in the index for storm damage risk, due to the dominant management strategy with no thinnings when minimizing storm damage risk.

Continuous cover forestry (CCF) does not occur as an alternative management strategy to minimize storm damage risk in the result. This is contradictory to what research indicates. The risk for storm damage in CCF have been compared with the risk in even-aged stands, and the CCF is described as more stable and less sensitive to storm damage (Mason 2002; Valinger & Fridman 2011; Gardiner et al. 2013; Hanewinkel et al. 2014; Couture et al. 2016; Eriksson et al. 2016). The increased stability in uneven-aged stands must though also consider the wind climate, the site type and the root structure, not only the stand structure characteristics (Mason 2002; Gardiner et al. 2013). Some negative effects of CCF have been presented in earlier studies. For example, the sensitive period under the conversion from even-aged stands to uneven-aged stands could be long (Mason 2002; Gardiner et al. 2013; Eriksson et al. 2016), or, that CCF favours spruce which is the most storm sensitive species (Peltola et al. 2010; Eriksson et al. 2016). CCF which only is an alternative in spruce dominated stands in this thesis and at the same time favours spruce, make the result reasonable, due to the high risk for storm damage connected to spruce. CCF means in practice reoccurring thinnings, and the result with no CCF when minimizing storm damage risk also shows that the thinning action has a high impact on the storm damage risk index compared with the created stability with variation in age and height in uneven-aged stands.

Unmanaged forest to reduce the risk for storm damage is possible for a small area in both Lycksele and Växjö municipalities. As seen in the result, unmanaged forests favour old forests, carbon storage and to some extent also recreation. These indicators have characteristics such as high height, high age and high standing volume which increase the storm damage risk.

An alternative tested in this thesis was if the possibility of more broadleaved forest would decrease the risk for storm damage, which it could to some degree. This could have been an option to spread risks (Blennow & Olofsson 2008; Bergh 2012), and the results indicate that this could be the case for Lycksele, rather than Växjö. The proportion which is managed with 30% or 70% broadleaves is increasing for the forest in Lycksele when minimizing storm damage risk, compared with maximizing harvested volume. The result from this thesis cannot be said to support the potential in mixed species for reducing the risk for storm damage in Växjö, due to the relatively small proportion of area which would be managed with broadleaf management strategies. Other management strategies decreased the risk for storm damage more than 30 and 70% broadleaves, but the possibility to manage the forest with only one management strategy including more broadleaved forest was not investigated here which could have given other conclusions.

An increased variation in the forest with increased broadleaved and mixed forest have been proposed to result in a lower risk for storm damage in earlier studies (Blennow 2012; Gardiner et al. 2013; Eriksson et al. 2016; Kårén et al. 2018). This have been shown after the storm Gudrun in 2005, and the reduced risk with the mixed forest was greatest when birch or other broadleaves was in the mix with Norway spruce (Valinger & Fridman 2011; Valinger et al. 2014). It is though conflicting evidence from other research if the mix of a sensitive species (Norway spruce) with a less sensitive species (many broadleaves) will increase the stability of the stand compared with a homogenous stand of a sensitive species (Gardiner et al. 2013), this goes in line with the result from this thesis.

Gardiner et al. (2013) discuss the influence of past management, local soil condition, different growth dynamics and changes in structure which could alter the risk for storm damage from case to case. It is mentioned that a possible mix of a "slower growing species" and a "desired species" with an unthinned management strategy could lead to a reduced storm damage risk. This was due to the effect of self-thinning and competition where the desired species "suppresses" the slow-growing species and a natural thinning effect is reached (Gardiner et al. 2013). An alternative to a mixed forest with broadleaves and conifer species could therefore be a mix of conifers, such as Norway spruce and Scots pine (Valinger & Fridman 2011; Valinger et al. 2014), where the Norway spruce is suppressed by the desired Scots pine. The self-thinning effect reduced the risk for storm damage due to more stable trees and a lower h/dbh-ratio (Gardiner et al. 2013). This could be one more explanation to why the "no thinning" strategy was the most common.

5.3. Trade-offs between indicators and storm damage risk

There is a rising demand for ecosystem services from the forest, but the forest area is restricted. The occurrence of storms is natural, but with combinations of different management strategies over time, the "resilience" of the forest to storm damage could increase. This should be made at the same time as other ecosystem services are provided from the forest to the society (Gardiner et al. 2013). This leads to that a trade-off between different forest objectives will be necessary between different stakeholders.

The trade-offs between net revenue, harvested volume or growth and storm damage risk indicate that it is possible to reduce the risk for storm damage to only a slight decrease in net revenue, harvested volume and growth. This is comparable to a study by Bergh (2012), which shows that damage adapted spruce forest management (no thinnings and a shorter rotation period) could be used without too much impact on the economic return from the forest on a stand or regional level. Bergh (2012) has shown that this type of management would have a slight reduction in growth and harvest volumes over a long time (Bergh 2012). This has also been shown in this thesis. Bergh (2012) also showed that the demand from the forest industry could be possible to supply with this damage adapted management. Due to these perspectives, more consideration to storm damage risk is possible to include in forest planning and forest management, with little effect on the net revenue, harvested volume and growth.

Within the forest impact assessment SKA15 ("Skoglig konsekvensanalys" in 2015) a broad analysis was made for the impact of storm felling for Jönköping and Västerbotten county. The result from SKA15 was showing that silviculture to reduce storm sensitivity of forests could decrease the storm damage but at the same time, it could reduce the growth. Therefore, silviculture for reducing storm damage was recommended to only be used in areas where the risk for storm damage was high (Eriksson et al. 2015). The results from this thesis go in line with the results from SKA15, but with the difference that it is possible to minimize storm damage risk some, with only a slight reduction in growth.

When looking at indicators for nature conservation and biodiversity, decreasing the risk for storm damage affected those more immediately (for some more than others) compared with the net revenue, harvest and growth. If having high biodiversity as the main objective for the forest, the possibilities to adapt the forest planning and forest management to storm damage risk is lower. This is especially clear for indicators such as deadwood, both in Lycksele and Växjö, and old forest in Lycksele. These trade-off curves have a steeper slope and for each unit the storm damage risk is reduced, the amount of deadwood or area old forest will decrease more than the amount of net revenue as an example. These trends show that the nature conservation and biodiversity indicators are sensitive to changes in management strategies which are sufficient to reduce the storm damage risk.

This thesis does only cover some aspects of the need from society from forests and gives in that aspect not a whole picture of the issue with sustainable forestry. The objective for the forest could be several different values, except production and biodiversity. To achieve this, forest planning and forest management need to be individually specified for each forest owner and each forest stand. If more consideration to the risk for storm damage is desired, the forest cannot be managed as it is today, there is a need for adapted forest planning and management to affect the risk for storm damage. Different forest management strategies must be evaluated over the whole rotation period and the cost and benefits need to be balanced (Gardiner et al. 2013). An interesting analysis would be to investigate how non-industrial private owners are willing to manage their forests to decrease the risk for storm damage. It has been shown that few forest owners adapt the forest management after storms and continues to follow the "business as usual" strategy (Valinger et al. 2014).

5.4. Storm damage and cascade effects

This thesis only includes the risk for storm damage and possibilities to reduce the probability of storm damages. If a storm occurred, it would result in other effects to the forest that could not be covered in the simulations. As a consequence of storm damage, the amount of deadwood is increasing. This increase in deadwood can in the next step result in increased attacks by the Spruce bark beetle (*Ips typographus* (L.)) (SLU 2020). Damages by Spruce bark beetle are closely related to storm damages (Lagergren et al. 2012; Kårén et al. 2018; Venäläinen et al. 2020) because the damaged wood is a common breeding material and an increase of available breeding material could result in greater attacks (Peltola et al. 2010; Kårén et al. 2018). Problems with Spruce bark beetle attacks have been recognized when storm damages have occurred in protected forest areas and where the damaged wood have been left (Kårén et al. 2018). The Spruce bark beetle has commonly more offspring in storm felled wood than in standing trees (Eriksson et al. 2016). Management strategies that decrease the risk for storm damage could also decrease the risk for attacks by Spruce bark beetles (Eriksson et al. 2016), which is a growing problem in Sweden.

Also, the pine weevil (*Hylobius abietis.* (L.) Linné) is affected by storm damaged forests. If the edges of a recently harvested site are forced to be cut after storm felling or after attacks by Spruce bark beetles, this favours the populations of pine weevils (Eriksson et al. 2016).

Storm damage in forests can also affect social wellbeing, mainly negative. In a questionnaire made by the Swedish Forest Agency, one-third of the answers from non-industrial private forest owners indicated negative wellbeing after the forest had been storm damaged (Ingemarsson et al. 2006; Gardiner et al. n.d.). Storm damaged forests can create new habitats for game populations, but the accessibility for hunters is reduced due to storm felled trees. In the same way is the accessibility in the forest reduced for mushroom picking, trekking, sports activities and other recreation (Gardiner et al. n.d.).

Another possible effect after storm damage is the effect on soil chemistry, mainly due to the additional harvest of timber which results in an increased local mobilization and leaching of mercury (including methylmercury) in the soil. This change of the "environmental biogeochemistry of mercury" could also lead to an increased risk for accumulation in water (surface water, lakes and streams) (Munthe et al. 2007).

5.5. Strengths and weaknesses

The choice of using national forest inventory (NFI) plots was due to the possibility to do analyses for both the north and the south of Sweden. The data used in this thesis could easily be changed to other geographical areas because the data which the NFI is collecting is covering the whole of Sweden. NFI plots without spatial data were suitable to use in the analysis because spatiality was not included in the index for storm damage risk.

The two different geographic areas were decided to in some way represent southern Sweden and northern Sweden, even though the results only represent the studied municipalities. When analysing two different areas, led to differences in characteristics of the input data. For example, the differences in areal productive forest, average volume per hectare, average age and tree species distribution gives different input values. The most important difference is the distribution of spruce dominated area between Lycksele and Växjö, due to the sensitiveness in spruce stands. These differences made it also difficult to compare the results from Lycksele municipality and Växjö municipality. The result could though give some indication that an adaption to storm damage risk similarly affected the municipalities because all indicator values were reduced when the storm damage risk was minimized. A difference which was found between Lycksele and Växjö municipality was the difference between the highest and lowest storm damage risk. The difference was higher for Växjö municipality (0.080) compared with Lycksele municipality (0.032).

The input data covered productive forest, including both production forest and nature conservation areas, but no consideration have been taken to nature conservation areas in the simulation. If nature conservation areas would have been separated from the forest aimed for production, there would always have been an amount of old forest in the analysed areas. This would probably have increased the storm damage risk for all scenarios and all forest objectives. In this case, when analysing all forest together, more extreme differences between different forest objectives were possible to achieve, where for example all old forest was possible to remove.

When using Heureka PlanWise it is possible to find the optimal solution among a large scale of alternatives. As the simulation in PlanWise depends on growth models and other types of models (Elfving 2010a), the quality of these models is an issue for discussion. Growth models have been recognized to be reliable over 100 years, especially stand-level models (Fahlvik et al. 2014). Important is to be aware of, is that the reliability of the models and the evaluation of the models depends on the assumptions and the validity of them (Vanclay & Skovsgaard 1997).

The index for storm damage risk (sensitivity index for storm damage) was recently developed for PlanWise (2021) which makes the reliability of the index a bit uncertain. The underlying model to the storm damage risk index has been used for several years in RegWise and some test analyses have been made with this storm damage risk index in PlanWise which make the index to some extent reliable. One of the aims of this thesis was to evaluate the index for storm damage risk and to fulfil the purpose of this thesis the index has been sufficient/adequate. The implementation of the risk index for storm damage into PlanWise in the used test version has been user-friendly. To improve the use of the index for storm damage risk, spatial consideration would have been of interest due to the effect from clear-cut edges and how forest management planning could be considered in a landscape perspective with concern to storm damage risk. An alternative in future similar studies could be to discount (diskontera) the storm damage risk index, to take more consideration to the current situation than to the future. This has not been made here.

It is possible to protect forests from storm damages in several other ways except them which were possible to simulate in this thesis. The index for storm damage risk in Heureka PlanWise takes no consideration to spatiality and therefore misses the edge effect between recently harvested stands and mature old stands which increases the risk for storm damages. The edges after a final felling are exposed to high wind speeds and create turbulence (Morse et al. 2002; Gardiner et al. 2013), which can create damages to the now exposed forest stand (Eriksson et al. 2016). One way to mitigate the risk of storm damage is to cut the edges to a stand on the opposite side to the dominating wind direction (Blennow et al. 2004; Eriksson et al. 2016).

Important to be aware of is that noble broadleaved species (such as beech and oak) have been included in the simulations and optimizations. These noble broadleaved species have been tried to be avoided in choice of geographical areas, due to that Heureka PlanWise do not optimally handle them. PlanWise is though more sufficient for analysing broadleaved species such as birch and aspen. An improvement on the method could be to only include birch and aspen to represent older broadleaf-rich forests, or to choose geographical areas which contain no noble broadleaved species, to improve the reliability of the simulations and optimizations in PlanWise.

The possibility to have a harvested volume of 0 made it possible to have an unmanaged management strategy for the whole analysed period. This gave clear differences between different proportions of management strategies dependent on which objective the optimization had. But more realistic would have been to have a lower limit of harvested volume due to the need for biobased materials in the society.

In PlanWise there is an option to use different climate responses in the simulation step to see effects depending on the climate scenario. This is not included in this thesis, due to that Heureka only includes the climate change effect on growth but not the effect on the level of damages (personal communication with J. Eggers 2021). As the topic of the thesis is connected with the effect of future climate change with a possible increase in damaging events, it would have been interesting to investigate such effects.

One aspect which was discussed when the method was designed was the time which should be used. The rotation period is today decreasing, especially in southern Sweden, where a time horizon of 50 years maybe could have been more appropriate. Another aspect when discussing time is that this thesis only presents the result as total values over all 100 years. This gives a general picture of the future but the development and changes over time have not been possible to perceive.

In the simulation step, the default pricelist was used (Mellanskog 2013) for both Lycksele and Växjö. In forest practices, this is not the reality and there are more detailed and updated pricelists which are used. But to compare the economic perspective from the analysis between Lycksele and Växjö, the same pricelist was used. To use the same pricelist for different geographical areas is though not a notable limitation in this thesis due to the long timescale of 100 years. Over 100 years, the prices for timber, pulpwood and other assortments will vary. The default pricelist is used to indicate how the value of forest products could develop in the future.

This thesis does not include a compromise solution, where all indicators are set against each other. It would have been interesting to make an optimization where the maximal deviation from the maximal possible value (which have been recognized in this thesis) should be minimized, and this, for all indicators at the same time. A compromise solution of the effect of wood fuel harvesting instead of storm damage risk on different forest objectives can be found in the paper by Eggers et al. (2020).

5.6. Conclusion

- An adaption of forest management to storm damage risk affects various indicators for sustainable forestry negatively. All indicator values were reduced when the storm damage risk was minimized, both for Lycksele and Växjö municipalities. High standing volume, high age and high tree height were some of the characteristics of the forest which increased the storm damage risk.
- The optimal combination of management strategies when minimizing storm damage risk includes most management without thinnings, which is a management strategy that is relatively uncommon when managing the forest for other objectives. Active thinning management increases the risk of storm damage.
- There are possibilities to adapt forest planning and forest management to reduce the risk for storm damage, especially when considering forest management objectives such as high net revenue, harvested volume and growth. Indicators for nature conservation and biodiversity are more sensitive to changes and will be more affected if the forestry is adapted to minimize the storm damage risk.

Storm damages in forests affect the whole society, and this thesis only includes some forest objectives which are considered to be important for sustainable forests. More research is needed to fully understand the connection between the risk of storm damage and other objectives within the forests, and how it possibly could be handled with different forest management practices and forest policies in the future.

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Acknowledgements

I want to give special thanks to my supervisor Jeannette Eggers, in the Department of Forest Resource Management at the Swedish University of Agricultural Sciences, for the fantastic and straightforward support with both the writing and analyses in this thesis. I would also want to thank my assistant supervisor Karin Öhman, in the Department of Forest Resource Management at the Swedish University of Agricultural Sciences, for support with Heureka PlanWise. Thank you for your fast response both on questions and feedback of the report. I have developed my skills in both scientific writing and Heureka PlanWise, which not would have been possible without them. A last big thanks to my family and friends for the support during the whole work and during my five years of university studies. I have now wide knowledge in forestry and feel proud to finish my master exam with this thesis.

Appendix 1

Formulas for the optimization model in general terms:

Step 1. Maximizing each indicator separately. The maximum potential of each indicator a (with constraints for evenness in harvest volumes over time).

$$Objective\ function: Max\ (or\ Min)\ \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} a_{ijp} x_{ij}$$

Area constraint: all plots are assigned in total one treatment schedule.

$$Constraint\ 1: \sum_{j \in Ji} x_{ij} = 1 \quad \forall i \in I$$

$$x_{ij} = [0,1] \quad \forall i \in I \quad \forall j \in Ji$$

The constraint for evenness in harvest volumes between periods.

$$Constraint\ 2: (1 - \alpha) \sum_{i \in I} \sum_{j \in J} V_{ijp} x_{ij} \leq \sum_{i \in I} \sum_{j \in J} V_{ij(p+1)} x_{ij} \quad , where\ p = 1, \ldots, p - 1$$

$$Constraint\ 3: (1 + \alpha) \sum_{i \in I} \sum_{j \in J} V_{ijp} x_{ij} \geq \sum_{i \in I} \sum_{j \in J} V_{ij(p+1)} x_{ij} \quad , where\ p = 1, \ldots, p - 1$$

Step 2. The trade-off between storm damage risk and one indicator (with constraints for evenness in harvest volumes over time).

$$Objective\ function: Max\ (or\ Min)\ \sum_{i \in I} \sum_{j \in J_i} \sum_{p \in P} a_{ijp} x_{ij}$$

Including constraint 1, 2, 3 and

$$Constraint\ 4: \sum_{i \in I} \sum_{j \in J_i} \sum_{p \in P} ST_{ijp} x_{ij} > \beta_a * Max_a$$

x_{ij} = decision variable which takes value 0 or 1, indicates the proportion of a plot [i] which is assigned to a treatment schedule [j]
P = set of all periods
I = set of all NFI plots
J = set of all treatment schedules (management strategies)
J_i = set of treatment schedules for NFI plot i ($J_i \subseteq J$)
A = set of indicators

a_{ijp} = value of indicator a in NFI plot i, treatment schedule j and period p
V_{ijp} = harvested volume for NFI plot i, treatment schedule j and period p

α = accepted deviation in harvested volume between two periods. α was in this thesis set to 0.1

ST_{ijp} = indicator value for NFI plot i, treatment schedule j and period p, when at the same time minimizing the storm damage risk index
β_a = deviation from maximal value for indicator a
Max_a = maximal value for indicator a, calculated in step 1