Scandinavian Journal of Forest Research

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/sfor20

Specified resilience value of alternative forest management adaptations to storms

Thomas Hahn, Jeannette Eggers, Narayanan Subramanian, Astor Toraño Caicoya, Enno Uhl & Tord Snäll

SCANDINAVIAN JOURNAL OF FOREST RESEARCH
2021, VOL. 36, NOS. 7–8, 585–597
https://doi.org/10.1080/02827581.2021.1988140

Specified resilience value of alternative forest management adaptations to storms

Thomas Hahn [a], Jeannette Eggers [b], Narayanan Subramanian [c], Astor Toraño Caicoya[d], Enno Uhl[d] and Tord Snäll [e]

[a]Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden; [b]Department of Forest Resource Management, Swedish University of Agricultural Sciences, Umeå, Sweden; [c]Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences, Lomma, Sweden; [d]TUM School of Life Sciences, Technical University of Munich, Freising, Germany; [e]SLU Swedish Species Information Centre, Swedish University of Agricultural Sciences, Uppsala, Sweden

ABSTRACT

Resilient ecosystems provide natural insurance value, or resilience value, to the landowner and to society at large. In response to global calls for integrating biodiversity in sector policy and planning, we analysed the specified resilience value by simulating three storm regimes and five management scenarios: Business As Usual/BAU (spruce-dominance), Spruce Monoculture, More Broadleaves, Continuous Cover Forestry (CCF), and No Thinnings. The forest decision support system Heureka RegWise was used to simulate the effects of storms on forest dynamics and Net Present Value (NPV). No Thinnings, CCF and More Broadleaves were more resilient to storms (reduced damage cost) compared to BAU. BAU had the highest NPV only if storms are ignored, a common assumption in today's forest planning. Given storms, No Thinnings maximises NPV on landscape level. On the 20% most vulnerable plots the NPV was much higher for No Thinnings and slightly higher for CCF and More Broadleaves, compared to BAU. CCF and More Broadleaves also provide nature-based solutions (co-benefits) including public goods. However, forestry adaptations to storms are slow in Sweden, in contrast to e.g. German state forestry which emphasises maximising tree growth and resilience to several stresses and disturbances rather than NPV optimisation.

ARTICLE HISTORY
Received 18 May 2021
Accepted 28 September 2021

KEYWORDS
Insurance value of ecosystems; insurance value of biodiversity; ecosystem services; ecosystem resilience; social-ecological systems; forest adaptations; mixed forests

Introduction

The resilience value of ecosystems

The idea that resilient ecosystems offer humans a form of insurance, a natural insurance value, can be traced back to the ecology literature in the mid-1950s (Green et al. 2016). This was later developed by empirical research revealing that the earth's life-supporting ecosystems indeed provide functions critical to human wellbeing and resilience (e.g. Ehrlich and Mooney 1983; Odum 1989; De Groot 1992; Folke et al. 1996).

The Economics of Ecosystems and Biodiversity (TEEB) defined insurance value of ecosystems as "the value of ensuring that there is no regime shift in the ecosystem with irreversible negative consequences for human well-being" (Pascual et al. 2010). However, insurance value is not limited to regime shifts between alternative stable states or trajectories but can be more generally defined as the value of resilience, i.e. sustained production of ecosystem services in the face of uncertainty, including enhancing options for adaptations (Holling et al. 2002; Pascual et al. 2015; Hahn et al. 2018). Such a conceptualisation is appropriate for boreal forests which tends to regenerate after a disturbance or clear-cutting rather than undergoing a regime shift.

Recently, it has been noted that the term "insurance value" may be confusing in interdisciplinary discussions. "Insurance" is a well-defined concept in economics and the value of insurance is the subjective value of risk reduction for a risk averse decision-maker. The original conceptualisation of the "insurance value" and subsequent development presented above have not been consistent with the literature on insurance and financial economics; in particular, the degree of risk aversion, i.e. the fundamental aspect of insurance, has not been analysed (Baumgärtner and Strunz 2014). Hence, there seems to be two schools of insurance value: one more metaphorical that was developed by ecologists and one which is consistent with insurance and financial economics. The former focuses on the expected (objective) scientifically assessed value of resilience, while the latter is a measure of the subjective value of risk reduction, which is zero for risk neutral persons (Baumgärtner and Strunz 2014).

This study springs from the original ecological understanding that resilient ecosystems provide insurance to human societies. Besides the ability to persist disturbance (e.g. storms), resilience of social-ecological systems also concern learning, adaptation and regeneration (Folke 2006). To avoid confusion we use the concept "resilience value" (Vergano and Nunes 2007) which we operationalise as risk reduction. The resilience value has nothing to do with subjective risk aversion, but is the expected increased present discounted value accrued from reduced risk "due a unit increase in the concurrent resilience stock" (Mäler and Li

CONTACT Thomas Hahn thomas.hahn@su.se Stockholm Resilience Centre, Stockholm University, Kräftriket 2B, Stockholm 10691, Sweden
Supplemental data for this article can be accessed at https://doi.org/10.1080/02827581.2021.1988140.

2010, p. 717). In this study, the resilience stock is increased (or decreased) by a change in management.

Empirical analysis of resilience typically focuses on *specified* resilience in relation to specified kinds of disturbances and shocks, which can be contrasted to *general*, broad-spectrum resilience in relation to various kinds of shocks, especially unexpected ones (Carpenter et al. 2012). Our study is an operationalisation of the specified resilience value concerning storm risks in forestry. Storms are a major disturbances affecting European forests; they caused more than half of the total damage to forest resources in Europe during the last decades (Schelhaas et al. 2010).

Environmental policy integration is about halting the drivers of biodiversity loss and climate change by addressing policy inconsistencies (IPCC 2018). The Aichi Biodiversity Targets clarified the goal that "biodiversity values have been integrated into national (…) planning processes" (CBD 2013). Net Present Value (NPV) simulations and optimisation are very common approaches informing European forestry policy and planning (Yousefpour et al. 2012; Tahvonen and Rämö 2016). Our approach to policy integration is to target the forest policy implementation and planning, by internalising the risk of storm and management adaptations in NPV calculations, which is rarely done today (Knoke et al. 2008; Knoke et al. 2017a).

Operationalising resilience value on storm risk in forestry

The resilience value in forestry has never been operationalised in quantitative or monetary terms. Adaptations to reduce storm damage in forests are expected to lower vulnerability, i.e. increase the specified resilience value. Boreal forests are one of the dominant biomes on earth constituting one-third of the world's total forest area and almost half of the world's timber stock (Astrup et al. 2018). Sweden is one of the largest provider of wood products to the global market (SFI 2019). Boreal forests are not only important for their vast timber resource but also for biodiversity, climate regulation and other ecosystem services that are essential for human wellbeing (Pan et al. 2011; Gauthier et al. 2015).

Climate change is one of the biggest challenges facing forestry and adapting to climate change is a pressing policy concern (Seidl et al. 2017; Luyssaert et al. 2018). Of all forest biomes, climate change projections suggest that the boreal biome will face the largest increase in temperature of 3–5°C by the end of the twenty-first century (Price et al. 2013). As a result, the intensity and frequency of catastrophic extreme weather events may increase with changing climate, especially extreme storm events (Stott 2016; Balaguru et al. 2018).

The storms Kyrill (2007), Klaus (2009) and Vaia (2018) over Germany were all more intense (wind speed) than Storm Gudrun (2005) over Sweden but cannot match the forest damage (cubic metres) of Storms Lothar (1999) and Gudrun, which are the two most forest devastating storms in Europe since Storm Vivian (1990).[1] The average intensity of the most destructive storms has tripled since the 1990s in Europe, resulting in vast damages to the forest growing stock (Gregow et al. 2017). Notably, the Storms Vivien and Lothar uprooted around 100 and 200 million m^3 of growing stock, respectively (Hanewinkel et al. 2011). The European net biome production was reduced by around 30% in the aftermath of Storm Lothar (Lindroth et al. 2009). There is a large consensus that for most European forests the impacts of both periodic stresses (e.g. drought episodes) and disturbances (e.g. storms, fires, insects outbreaks) are expected to increase with climate change (Coll et al. 2018). For example, increased winter precipitation and reduced frequency of sub-zero winter temperatures due to climate change may weaken tree anchorage and increase storm damage in the future (Hanewinkel et al. 2011).

In Sweden, Storm Gudrun grounded more than 70 million m^3 timber volume in 2005, a volume almost equal to the normal national-level annual cut (Valinger et al. 2014). Norway spruce (*Picea abies* (L.) Karst.) is the most common tree species in Sweden constituting around half of the total growing stock (SLU 2018). Most of the storm-felled trees in the Storm Gudrun were Norway spruce, and the storm damage led to a major bark beetle outbreak in the following years (Valinger and Fridman 2011).

The net income of forest owners is reduced after a storm event because parts of the trunks are broken and harvesting costs per cubic metre increase (Szewczyk et al. 2014; Kärhä et al. 2018). Storms also result in harvesting of trees at a non-optimal time, entailing economic losses (Pukkala et al. 2016). Economic losses may increase further due to an increased risk for bark beetle attacks after storms (Eriksson et al. 2005; Økland et al. 2016).

Factors increasing the risk for storm damage include late thinning, increased tree height, increasing proportions of spruce and mature even-aged stands; however, vulnerability may also increase during the conversion phase from even to uneven-aged forests (Gardiner 2013). Spruce monocultures are particularly vulnerable to storm disturbances (Schelhaas et al. 2010) while deciduous trees are considered less storm-sensitive as most storms in northern Europe occur during winter (Schindler et al. 2016). Nature-based solutions therefore focus on these factors. Nature-based solutions and similar concepts (ecosystem-based adaptation and ecosystem-based disaster risk reduction) are management practices that promote the maintenance, enhancement, and restoration of ecosystems as a means to address multiple concerns simultaneously (Kabisch et al. 2016). Management adaptations resulting in more storm-resilient forests include a mix of site-adapted tree species, avoiding late thinnings, and conversion into uneven-aged forests (Continuous-cover forestry, CCF) (Holecy and Hanewinkel 2006; Hanewinkel et al. 2014). Forest owners can thus influence the vulnerability to storm by adapting their management.

Despite projected risks and recent experience, neither forest companies nor private forest owners in the Nordic countries have paid much attention to climate change adaptation, not even in the aftermath of Storm Gudrun (Lidskog and Sjödin 2014; Andersson et al. 2018). This is because forest owners in Southern Sweden have developed local knowledge on spruce management and perceive changing to other tree species as increasing the risk of grazing damage by moose (*Alces alces* L.) and roe deer (*Capreolus capreolus* L.) (Valinger et al. 2019). Swedish forestry thereby differs from e.g. German forestry, where managing for stand resilience in general, and adaptations to storm in particular, have been institutionalised (Govt of Germany 2016). For example, the proportion of forests managed as CCF is less than one per cent in Sweden and about 30 per cent in Germany (Mason et al. 2021).

From this theoretical framework on resilience value and policy integration, as well as the empirical problem on storm damage risks to forestry, we analyse the financial costs and benefits for the forest owner of adapting forest management to become more resilient to storms. The overall aim is to facilitate policy integration by illustrating the trade-offs for the forest owner, in monetary terms, between the resilience value (reduced risks for storm damage) and reduced expected NPV. Specifically, we answer the following questions, recognising the different decision contexts for large forest companies (mainly concerned about average effects for the total area) on the one hand, and small, private forest owners on the other:

(i) What is the average opportunity cost and specified resilience value of alternative forest management scenarios given different storm regimes?
(ii) Are the effects of management adaptations different on the most vulnerable individual forest stands compared to the average stand?

Methods

Methodological approach

We take a pragmatic approach where the management choice is either business as usual (BAU) with high expected NPV in the absence of storms but high expected storm damage risk; or an alternative forest management which may reduce the storm damage risk at the expense of lower expected NPV. This is a realistic choice situation since forestry adaptations to storms, e.g. mixed-species forestry, have been shown to reduce storm damage risks at the expense of profitability, i.e. reduce both expected income and its standard deviation (Knoke et al. 2017a). Hence a trade-off between profitability and resilience can be expected.

The monetary expression of the resilience value in this study is intended to be an illustration only, not capturing the huge uncertainty involved in these estimations and not assuming that the resilience value can easily be substituted for, just because it is expressed in monetary terms. Profitability is estimated only for the private forest owner, although nature-based solutions typically generate co-benefits as a mix of private and public good (Paavola and Primmer 2019).

In empirical work risk reduction is often used as a proxy for resilience but there is no agreement on how risk reduction is defined or how it is measured (Dallimer et al. 2020). In this study we define the specified resilience value as the expected risk reduction (reduced damage cost) for the private owner provided by an alternative management compared to the risk in BAU (Equation 1). We also calculate the opportunity cost, i.e. the loss in expected NPV for the alternative management for each storm regime (Equation 2). Rather than assigning probabilities, we use three storm regimes to make decisions under uncertainty explicit, i.e. the subjective weighting of opportunity costs and risk reduction.

$$\mathrm{SRV} = \mathrm{DC}_{\mathrm{Alt}} - DC_{\mathrm{BAU}} \quad (1)$$

SRV = Specified resilience value; $\mathrm{DC}_{\mathrm{Alt}}$ = Damage cost under Alternative management; $\mathrm{DC}_{\mathrm{BAU}}$ = Damage cost under BAU: Damage cost is defined, for each management scenario, as (NPV for one of the storm regimes – NPV for No storm).[2]

$$\mathrm{OC}_{\mathrm{Alt/S}} = \mathrm{NPV}_{\mathrm{Alt}} - NPV_{\mathrm{BAU}} \quad (2)$$

$\mathrm{OC}_{\mathrm{Alt/S}}$ = Opportunity cost for alternative management under each storm regime; $\mathrm{NPV}_{\mathrm{Alt}}$ = NPV for alternative management; $\mathrm{NPV}_{\mathrm{BAU}}$ = NPV for BAU.

Whereas the opportunity cost (forgone net benefit) concerns the overall private profitability, resilience value only measures risk exposure, in terms of reduced expected damage cost. The damage cost is included in the opportunity cost. Future storms are difficult to project. For example, forest damage has increased by a factor of five in Germany in recent years, from 8 million m^3/year (2011–2017), to 39 million m^3/year (2018–2019), mainly due to bark beetles and storms (Statistisches Bundesamt Deutschland 2020). Therefore, the genuine uncertainty facing forest owners cannot be reduced to conventional risk calculations, by predicting storm damage and assigning probabilities (Nikinmaa et al. 2020). Hence, risk aversion is not calculated in this study but addressed in a disaggregated and transparent way by the subjective weighting: the trade-off between the opportunity cost and the resilience value.

Study region

The study region, Jönköping County (Figure 1), is located in southern Sweden, where current management practices favour the plantation of Norway spruce. This area is expected to be at risk from storm damage given its historic storm regime. The managed, productive forest land in Jönköping County is 624,000 ha but here we focused on the 380,000 ha of managed spruce-dominated productive forest, represented by 670 plots (radius 7–10 m) from the National Forest Inventory (NFI) (Fridman et al. 2014). This area excludes nature reserves, voluntary set-asides and retention patches. Our simulations started from the state of the forests in 2010. We simulated forest dynamics, using different management scenarios and storm regimes, for 100 years into the future, divided into 20 five-year time steps.

Simulation approach and software

We used the Heureka RegWise model version 2.12.0.1 to simulate the scenarios. RegWise is a simulation model especially suited for impact analysis on a national or sub-national level (Wikström et al. 2011). The central drivers of

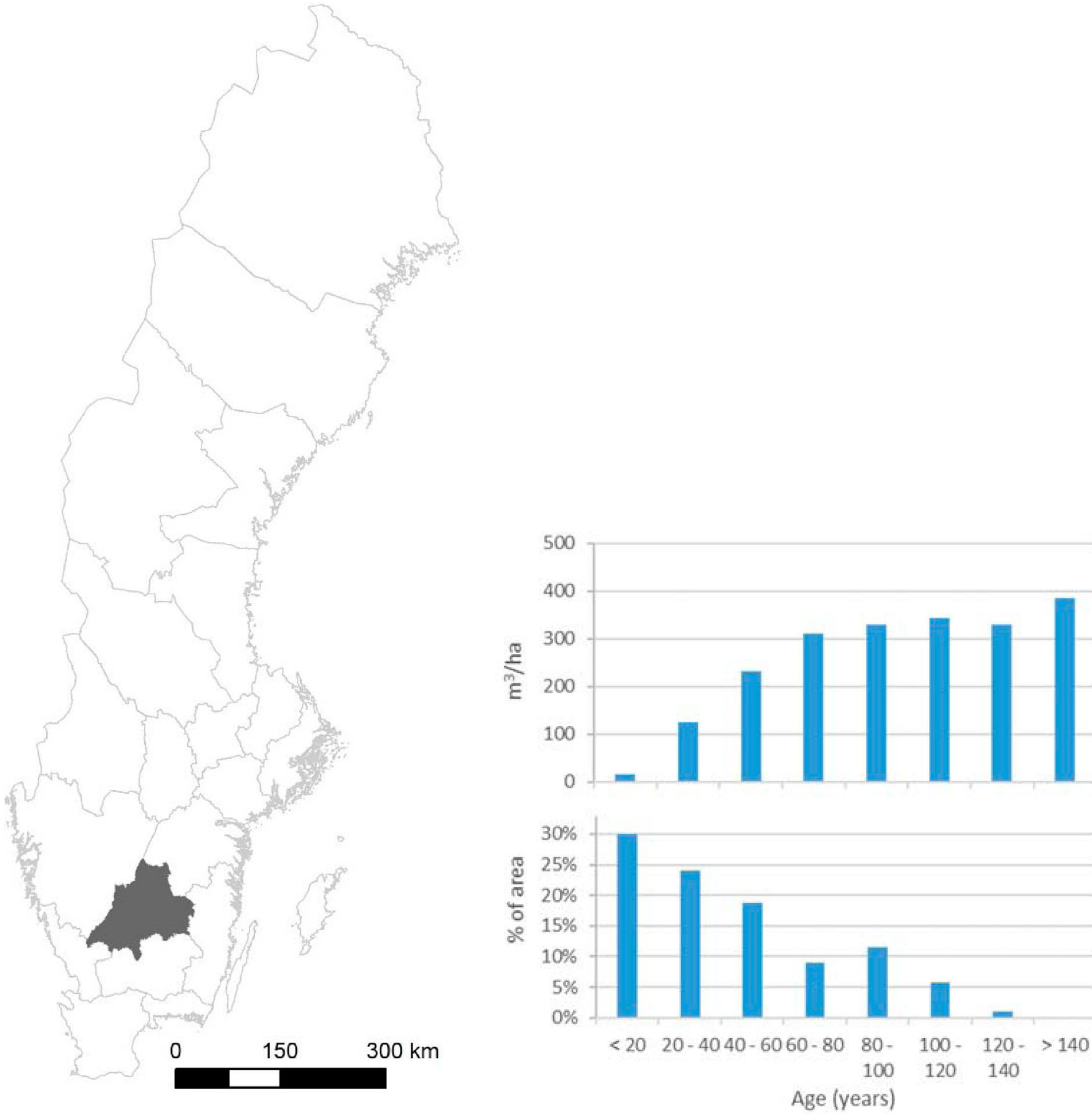

Figure 1. Map of counties in Sweden with the Jönköping county shown in grey, and initial age class distribution (area and volume) of managed, spruce-dominated plots.

the Heureka system are empirical growth and yield models, mainly developed using data from the NFI and applicable for the dominant Swedish tree species. The models are applicable also for mixed species plots and have been shown to provide reliable growth predictions for up to 100 years (Fahlvik et al. 2014). The growth models are complemented by models regulating, inter alia, natural mortality (Fridman and Ståhl 2001), in-growth (Wikberg 2004), and the probability of silvicultural activities being undertaken.

The phenomenological windthrow model implemented in Heureka RegWise was parameterised based on a mechanistic model (Lagergren et al. 2012). In Heureka RegWise, the user determines the year and intensity of storms in advance. For an in depth description of the storm module, see SI-B. After a storm event, the whole forest plot is final felled (clear-cut) if the storm felling in the plot exceeds 35% of the standing volume. If the storm felling is below 35%, only the storm-felled proportion is extracted during a subsequent thinning. Around 8% of the storm-felled volume is left in the plot as deadwood. The storm-felled volume in future storms depends partly on the wind-load calculated from historic storms and partly on the forest state at the time when a storm takes place. Based on Szewczyk et al. (2014), we assume that the cost of harvesting after a storm doubles per cubic metre, compared to a normal final felling or thinning. This cost estimation includes potential price deductions for damaged timber.

Three storm regimes

We used three storm regimes (Figure 2): *No storm*, *Historic storm* and *30% Increased storm intensity*. There were nine

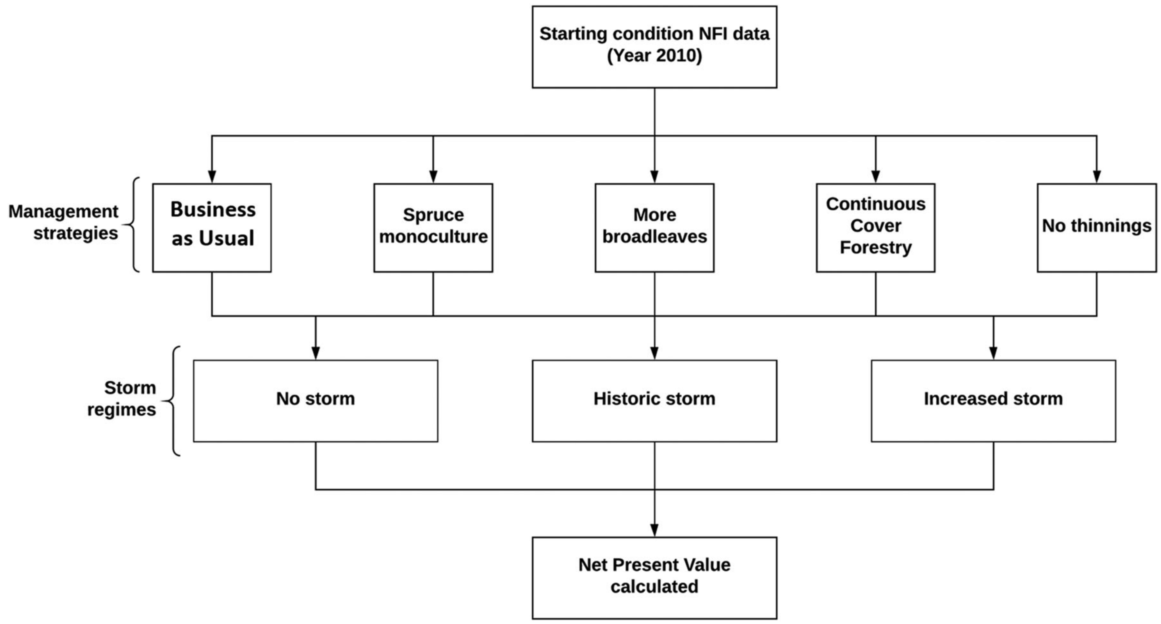

Figure 2. Schematic illustration of forest management scenarios and storm regimes simulated for the spruce forest of Jönköping county 2010–2110.

storm events of various intensity recorded in Jönköping county during 1953–2012 (60 years), and for *Historic storm* we replicated their intensity and frequency for the years 2011–2110 (Figure SI-1). In Increased storm intensity, frequency is identical to Historic storm regime but the intensity of each storm is increased by 30%.

These three storm scenarios were appropriate to answer our research questions on specified resilience value, although future storm frequency and intensity are highly uncertain. As storms are one of the most damaging natural disasters in general, there is a very large interest in predicting their future trends. However, projecting the future trends of stochastic extreme weather events is highly uncertain, especially under changing climate (Rummukainen 2012). Reviews of global and regional climate simulations conclude that the storm intensity may increase in the future, but could not find a common trend in the storm frequency (Feser et al. 2015; Mölter et al. 2016). Moreover, very few of those studies (eight out of 82) focus on the Scandinavian/Baltic region, and the majority indicate an increased storm intensity but reduced frequency (Feser et al. 2015; Belusic et al. 2019). Therefore, we decided not to include a scenario with different storm frequency, or a combination of different storm frequency and intensity. Typically, the studies above assumed future storm intensity to increase by 30%, which is why we choose this value. Note though also that the average intensity of the most destructive storms in Europe has tripled since the 1990s (Gregow et al. 2017), so 30% is probably conservative. This serves as an illustration to calculate resilience value; projections on how forestry responds to climate change are outside the scope of this paper because monetary (NPV) calculations can hardly capture the complexity and uncertainty of climate change. The study illustrates how NPV and resilience value change with different management adaptations, when simple and clear assumptions about storms are accounted for in the standard planning tools.

Five management scenarios

We simulated five scenarios varying the management of the spruce-dominated plots (Table 1, for definitions of spruce-dominated, see SI-A). *The Business as usual (BAU) scenario* is based on the national scenario simulation work conducted by the Swedish Forest Agency (Claesson et al. 2015). In this scenario, spruce-dominated plots are mainly regenerated using planting, with natural regeneration being applied on about 12% of the area. The share of broadleaves retained after cleanings (pre-commercial thinnings) and thinnings is between 10 and 20%. After cleanings, one or two thinnings are made. The minimum final felling age depends on site type, in Jönköping ranging from 45 years for the most productive sites, to 90 years for the least productive sites. A plot reaching the minimum final felling age is not necessarily final-felled immediately. Instead, priority functions determine which plots are harvested.

The other four management scenarios constituted adaptations of the BAU scenario (Table 1). First, in the *Spruce Monoculture scenario*, spruce-dominated plots were regenerated exclusively by planting, and no broadleaves were retained in cleanings and thinnings. Second, in the *More Broadleaves scenario*, we adapted cleanings and thinnings to increase the admixture of broadleaves to 40%. We also reduced the planting density of spruce by about 20%. Third, in the *Continuous Cover Forestry (CCF)* scenario, all spruce-dominated plots were managed by a series of selection fellings without a clear-cut phase. The minimum time between two selection fellings was 20 years. In a selection felling, 20-40% of the standing volume was removed, mainly the biggest trees (thinning from above). The minimum diameter of cut trees was 8 cm. A function

Table 1. The five management scenarios simulated for the spruce-dominated forest of the study Jönköping County.

	BAU	Spruce Monoculture	More Broadleaves	CCF	No Thinnings
Planting vs. Natural regeneration	Mainly (88%) planting	100% plantation	As in BAU, but 20% lower planting density	n.a.	As in BAU
Cleanings	Yes	Yes	Yes	n.a.	Yes
Commercial thinnings	Yes	Yes	Yes	Yes (selection fellings)	No
Percentage of broadleaves after cleanings	15%	0%	40%	At least 15%	15%
Percentage of broadleaves after thinnings/ selection fellings	10% (private) 20% other forest owners	0%	40%	20%	n.a.
Minimum final felling age	According to legislation	Acc. to legislation	Acc. to legislation	n.a.	Acc. to legislation

defined the target volume after selection felling. The cost function was the same as in thinnings. Fourth, the *No Thinnings scenario* was the same as BAU for the first 25–30 years after regeneration, including cleanings, but thereafter no thinnings were applied.

We simulated the dynamics and development of the forest under each management scenario and storm regime for 100 years, divided into 20 five-year periods. Since the starting point was the actual forests plots in 2010, the five management scenarios were identical until the first thinning or harvest was conducted. By the time of the most severe storm, simulated to occur during the 11th period, after 50–55 years (Figure SI-1), most plots had been shaped by the new managements simulated. Due to some stochasticity in the forest management and storm simulations (regarding when a management intervention occurs and exactly which plots are hit by a storm), we repeated each management scenario and storm regime combination three times and calculated the average. Since the results of these three replicates were very similar (the timing of the storms was not changed), we deemed that adding more replicates was not necessary. Financial effects were calculated as NPV, i.e. the sum of discounted revenues minus costs, for the 100 year simulation period. Acknowledging that there is no correct discount rate for simulations of climate change (Pindyck 2017), we used a relatively low discount rate (1.5%) assuming a high future value of natural capital (Sterner and Persson 2008; Knoke et al. 2017b).

Two spatial scales of analysis

The simulations described above were conducted for all the 670 plots representing 380,000 ha of managed spruce-dominated productive forest. Additionally, we analysed the effects of storm on NPV and resilience value for all management scenarios on the individual plots hit by *the most severe storm* under the BAU scenario and historic storm regime. This aimed to illustrate the worst-case scenario for an individual forest owner rather than NPV for an average forest stand in the whole study region (corresponding to the second research question above). The rationale is to address risk aversive individuals, which has often been ignored in the literature on ecosystems' insurance or resilience value (Baumgärtner and Strunz 2014).

The most severe storm occurred after 50–55 years of simulation, and mimics the severity of the storm Gudrun that took place in 2005. Specifically, we first calculated, for each management scenario, the proportion of all 670 plots that was hit by this storm (in any of the three repeated simulations). Under the BAU Historic storm regime, 136 plots (20.3% of all 670 plots) were hit either considerably or moderately by that storm and henceforth we refer to these plots as being most vulnerable. In reality, it is difficult to know which forest stands are most vulnerable. It depends partly on the age and whether it was recently thinned.

Results

Simulations on the total forest area (all plots)

The BAU scenario, which represents the current management, provided the highest NPV only under the no storm regime (Figure 3(a)). For Spruce Monoculture, the NPV was reduced considerably under the historic storm regime and it had the lowest NPV of all management scenarios given increased storm intensity.

The No Thinning scenario had the highest NPV under both the historic and increased storm intensity, indicating that adapting thinning practices is the most profitable strategy to minimise storm damage. More Broadleaves resulted in lower revenues since broadleaves in Sweden are mainly used for pulp and firewood, which are lower priced than conifers used for sawn timber. CCF is less profitable than BAU as it results in lower growth and thus lower wood production on average, partly due to natural regeneration and non-bred material (instead of planting seedlings with higher growth rate) (Lundmark et al. 2016).

The NPV of More Broadleaves and CCF was much lower than BAU if we abstract from storms but this difference decreased when storms were accounted for. The opposite was observed for Spruce Monoculture: the disadvantage compared to BAU increased with storm (Figure 3(b)).

Relative to BAU, the damage cost of storm was lowest for No Thinnings and CCF (Figure 4). In other words, the specified resilience value was highest for these two management scenarios. For CCF, this is because the NPV for No storm was very low, resulting in very low storm damage cost.

Note that for all management scenarios except for CCF, a similar proportion of the forest – around 50% – was older than 40 years and thus susceptible to storms in 2050, right

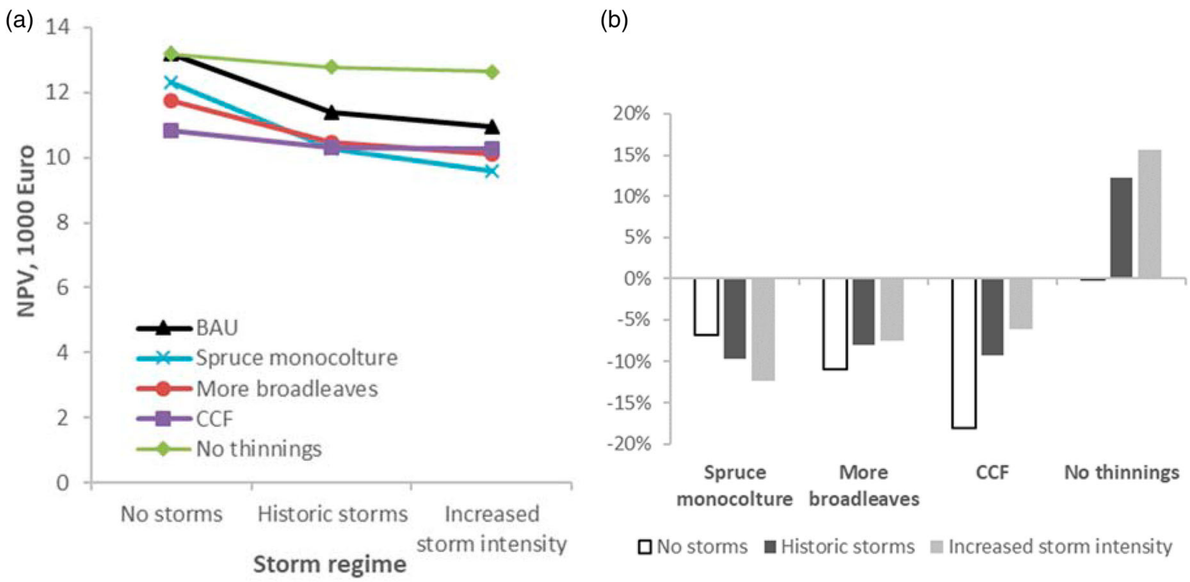

Figure 3. (a) NPV in euro per hectare for the five management scenarios given three storm regimes. (1 Euro = 10 SEK). (b) Relative difference in NPV for all 670 plots compared to BAU.

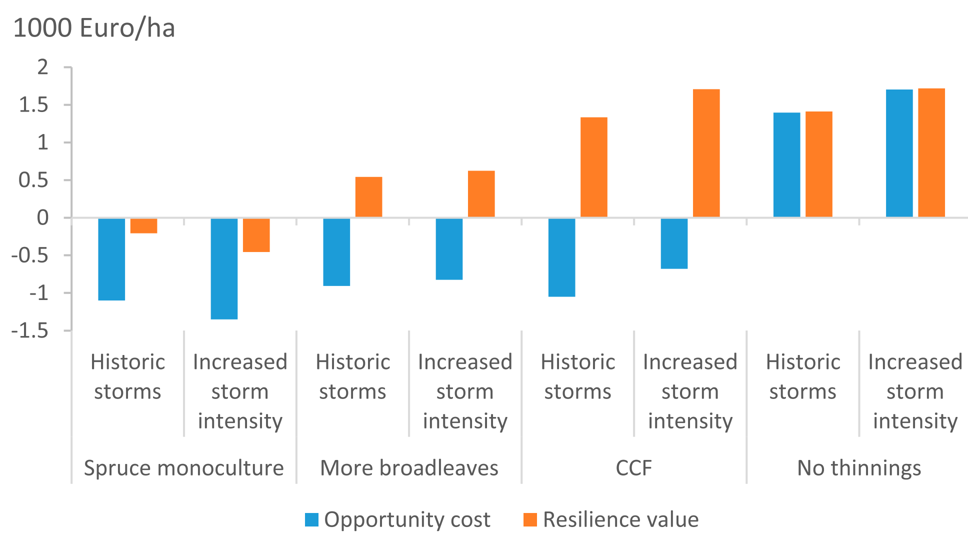

Figure 4. Opportunity cost (difference in NPV) and resilience value compared to BAU for all 670 plots.

before the Gudrun-like storm (Figure 5). In No Thinning, forests get very dense and are therefore felled earlier than when thinnings are done.

Simulations on the most vulnerable forest land (subset of plots)

The BAU simulation for Historical storm regime resulted in 136 plots being hit by the most severe storm. This storm affected 84 plots considerably, requiring final felling, and 52 plots moderately, requiring thinning. Altogether 136 of 670 plots (20.3%) were affected by the most severe storm under BAU. An even larger proportion of Spruce Monoculture was affected by the most severe storm while the other management scenarios were more robust area-wise (Figure 6). As expected, as storm intensity increases the proportion of the damaged forests area also increases, for all management scenarios.

The damage cost per hectare increased for all management scenarios when focusing on the most vulnerable plots. Spruce Monoculture experienced over 50% losses in NPV for the Increased storm intensity regime while No Thinnings, CCF and More Broadleaves had relatively less damage than BAU, resulting in a higher NPV compared to BAU under both historic and increased storm regimes (Figure 7).

For the most vulnerable forest plots, all management alternatives except Spruce Monoculture were more profitable (higher NPV) than BAU when storms were accounted for. No Thinnings, CCF and, to some extent, also More Broadleaves showed very high resilience value, between 1,800 and 5,000 Euros/ha (Figure 8), which is much higher than for the average area of Jönköping, the 670 plots (Figure 4). Again,

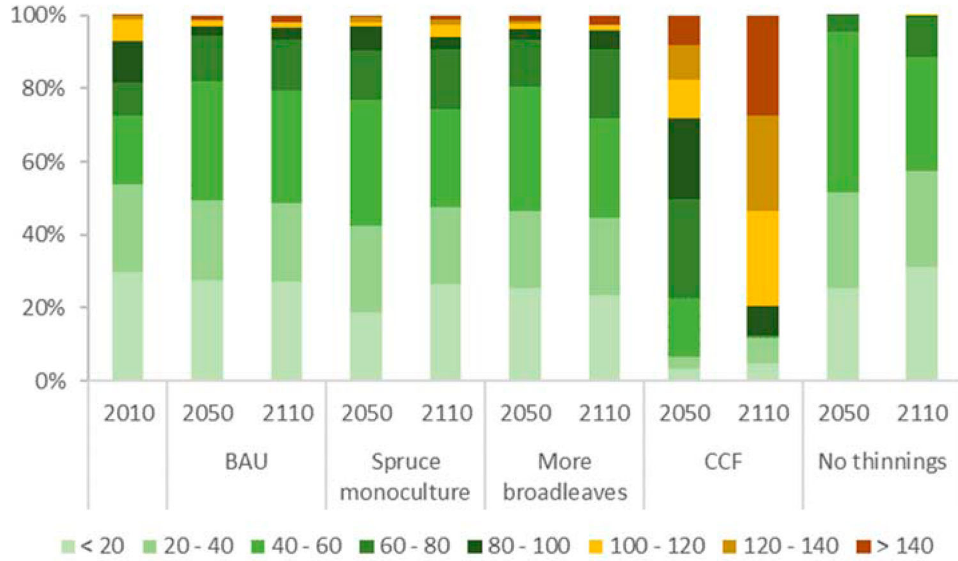

Figure 5. Age class distribution (area, % of total) in 2010 (initial situation), 2050 and 2110, for the historic storm regime.

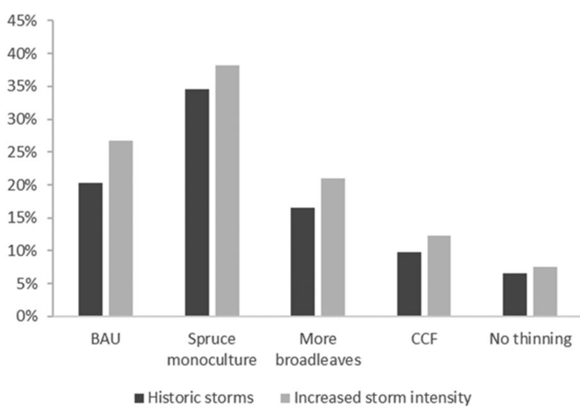

Figure 6. Proportion of plots with partial or severe storm felling in period 11.

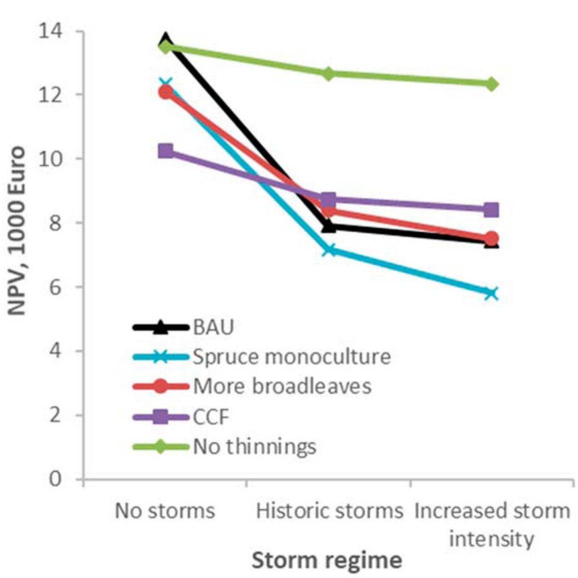

Figure 7. NPV in euro per hectare for the five management scenarios for the 136 most vulnerable plots, given three storm regimes. (1 Euro = 10 SEK).

in the case of CCF, the high resilience value mainly resulted from a low NPV, under the No storm regime.

Discussion

No thinning – pros and cons

Based on the assumption in our simulations, No Thinnings and CCF have the highest specified resilience value and are therefore most effective for forest owners who want to minimise the damage cost of storm. Since newly thinned spruce forests are very susceptible to storm, management without commercial thinnings reduces the damage risk from storms. No Thinnings has also the highest profitability given storms, which is supported by Subramanian et al. (2016). These results are the same whether we take a landscape perspective (relevant to forest companies and the government) or focus on individual vulnerable forest stands (relevant to small risk averse private owners). Since CCF is very unusual in Sweden, the empirical data for modelling CCF is limited, and the results for the CCF scenario are more uncertain compared to the other scenarios that are based on conventional even-aged management methods (Lundmark et al. 2016). This might explain the low NPV of CCF.

Our results should be interpreted with caution since we only investigated the financial effects for the forest owners of one disturbance. For example, No thinnings has several drawbacks and is not recommended by the Swedish Forest Agency (Agestam 2015). Compared with BAU, it reduces the rotation period (Figure 5) resulting in less old trees. No thinnings result in dense forests which decreases the supply of lichens for reindeer forage (Strengbom et al. 2018), the attractiveness for recreation and the supply of other ecosystem services (Gundersen and Frivold 2008; Eggers et al. 2018). Increasingly denser forests also result in forest species becoming red-listed, although clearcutting is the main cause (SLU 2020).

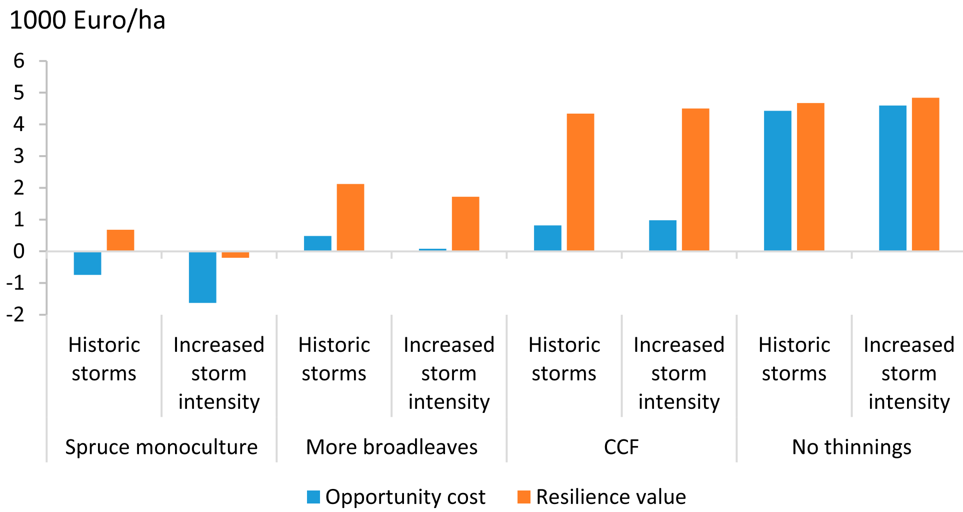

Figure 8. Opportunity cost (difference in NPV) and resilience value compared to BAU for the 136 most vulnerable plots.

Mixed forests and CCF provide co-benefits

Our results on More Broadleaves indicate reduced damage (higher resilience value) compared to BAU but at the expense of lower economic returns on average land. This is supported by Knoke et al. (2017a). However, for the analysis of the 20% most vulnerable plots the NPV was slightly *higher* for More Broadleaves and CCF compared to BAU. Therefore, risk averse forest owners have private economic reasons to consider mixed forests and CCF, either if they focus on reduced expected damage cost or if they want to maximise the outcome if hit by a storm, i.e. Rawlsian maximin strategy (Rawls 1974). From a societal perspective, there are several studies reporting higher levels of biodiversity and multiple ecosystem services (e.g. recreation, berries and fodder for wildlife that is hunted) in mixed forests (Gamfeldt et al. 2013), if correctly mixed (Jonsson et al. 2019). Mixed forests and CCF are also likely to be more resilient to pest outbreaks than BAU (Felton et al. 2016; Tahvonen and Rämö 2016). Broadleaves further enhance surface albedo and therefore reduce global warming (Astrup et al. 2018).

In related studies, transformation to CCF and mixed forests has been regarded as a natural insurance or nature-based solutions. First, these management systems increase the specified resilience value by reducing the damage cost of storms for the private forest owner and, second, they enhance public goods in terms of other ecosystem services and biodiversity (Felton et al. 2016; Knoke et al. 2017a; Jonsson et al. 2019). Nature-based solutions' co-benefits for society provide arguments to incentivise forest owners to adopt more resilient forest management (Eyvindson et al. 2021) with a mix of policy tools including legislation, like in Germany (Borrass et al. 2017), and payments for ecosystem services (Pascual et al. 2015; Riguelle et al. 2016; Paavola and Primmer 2019).

Slow adaptation in Sweden compared to Germany

The adoption of mixed-species forestry and CCF has been very slow in Sweden (Lidskog and Sjödin 2014; Andersson et al. 2018) even though our results indicate similar profitability on vulnerable land. The Swedish Forest Agency supports mixed forests on vulnerable forest land and other adaptations to enhance resilience (Skogsstyrelsen 2019) but spruce remains dominant since the storm risk is typically ignored in NPV calculations.

This is in contrast to Germany where state-owned forests have been gradually converted from spruce-dominated clear-cutting management to a combination of mixed tree species and CCF systems since the 1980s, in order to enrich the structure, improve recreation value, and increase general resilience to several stresses and disturbances (Fichtenrichtlinie 2009). These ecological and social values are difficult to account for in NPV calculations but German forest owners emphasise maximising and stabilising tree growth rather than NPV optimisation (Brukas and Weber 2009).

Some factors may explain the conversion of German forest management. First, Germany experienced huge damage costs from acid rain in the 1970s, which created a collective awareness of vulnerability. Second, clear-cuts, if not prohibited, are maximally 1–2 hectares in size according to the federal nature protection law and in Bavaria also according to the forest state law (Foerst et al. 2018). Third, forest state laws explicticly prohibit any reduction in the forest resilience against storms (Burschel and Huss 1997; Foerst et al. 2018). Legislation and experiences of alternative management, especially in state owned forests, have thereby served as examples also to private forest owners on how to account for resilience and what the effects of management adaptations are.

Limitations of the study

The occurrence of future storms was simulated as a recurring historical pattern, with a major storm occurring after 50–55 years. Given the uneven age class structure in the input data, the proportion of forest susceptible to wind damage fluctuates over time (Figure 5), which may bias our results to some extent. However, the scope of the study was not to make an exhaustive, fully generalisable study of future storm risks for Nordic forests, but to explore and illustrate opportunity costs and resilience value of different management scenarios.

We did not include all future impacts of climate change on forest dynamics and management in our simulations, as no forestry decision support system enables that, although some models allow for more complex interaction of disturbances projected by climate change (Seidl et al. 2014). For example, we did not include effects of increased tree growth that further leads to increased storm fellings as tree height is a key variable determining the wood volume felled (see SI-B) by storms. Adverse effects of future drought episodes that can reduce the tree growth in future are also not considered here. However, another recent study using a similar methodology and assuming climate-change induced increased tree growth and accounting for the effect of future drought episodes came to similar conclusions, specifically that no thinning is, in purely financial terms, the best adaptation option to storms (Subramanian et al. 2019). Moreover, large wind fellings are often followed by bark-beetle infestations, as not all wind-felled trees can be salvage-logged in time and this damage may increase with a warmer climate (Seidl et al. 2017). Our simulations did not account for that. We nevertheless believe that minimising the risk for storm felling through adaptive management is likely to also decrease the risk for large-scale bark beetle infestations (Jactel and Brockerhoff 2007).

Our forestry and hence NPV simulation tool, Heureka RegWise, allows investigating effects of storms on existing forest stands. However, the standard planning approach is NPV optimisation based on linear programming (Nilsson et al. 2013), which makes it difficult to directly account for stochastic events such as storms. While several studies have explored ways to include disturbances in forest planning (e.g. López-Andújar Fustel forthcoming), disturbances are not yet routinely included in decision support systems for forest management (Pasalodos-Tato et al. 2013; Orazio et al. 2017). Our simulations present one approach to overcome the common shortcoming of ignoring storms in NPV-calculations.

NPV and monetary calculation

Monetary (NPV) simulations are not ideal for analysing adaptations and resilience. First, although simulations can stretch over centuries, NPV calculations have been criticised for not being dynamic in the sense of learning and revising management based on previous periods (Knoke 2017). Therefore, the expected storm damage over the forest cycle has to be factored in *ex ante* based on pre-conceived assumptions on management adaptations, not allowing any further management adaptations. Second, analysis in monetary terms (NPV) has also been criticised for reducing uncertainty to risk calculations (Pascual et al. 2010). Nevertheless, our methodological approach suggests that monetary (NPV) analysis of social-ecological resilience may be helpful for decision-makers if four conditions are met: the distinction between general and specified resilience is clarified; ecological causes of resilience and vulnerability are addressed; co-benefits are emphasised; and the monetary analysis uses the same framework as the ordinary sector planning, to facilitate policy integration.

Conclusion

The specified resilience value is operationalised, in this study from Southern Sweden, as reduced damage cost of storm in an alternative management scenario compared to BAU. The aim to facilitate policy integration by illustrating the tradeoffs for the forest owner, in monetary terms, between the resilience value (reduced risks for storm damage) and reduced expected NPV. Mixed forests and CCF produce co-benefits to society and are therefore nature-based solutions. As expected they increase specified resilience at the expense of private profitability (NPV) at landscape level. However, on the most vulnerable forest stands, mixed forests and CCF are more profitable for the individual forest owner than BAU, when storms are accounted for. This suggests that risk averse forest owners have incentives to adapt their management from BAU to mixed forests or CCF. Our results also suggest that management with no commercial thinnings generates very high NPV and also reduces storm damage costs more than the other scenarios. However, management with no thinnings is not a nature-based solution (no large co-benefits).

Adaptations to mixed forests or CCF are rare although they are welcomed by the Swedish Forest Agency. We describe the German context as a contrast to the slow adaptation in Sweden. Two differences were identified. First, German forestry emphasises maximising and stabilising tree growth rather than NPV optimisation. Second, managing for stand resilience in general, and adaptations to reduce storm damage in particular, have been institutionalised in Germany, not only recommended.

Our simulation provides a pedagogic example of environmental policy integration in the forest sector by including the effects of one disturbance, storm, in the dominant planning approach. More disturbances and more ecosystem services need to be addressed to fully account for the general resilience value of forest ecosystems.

Notes

1. https://www.europeandatajournalism.eu/eng/News/Data-news/Forests-of-Europe-a-stormy-future.
2. For example: SRV (storm+30%)$_{CCF}$ = (NPV storm + 30% – NPV No storm)$_{CCF}$ – (NPV storm + 30% – NPV No storm)$_{BAU}$ = (10,260–10,810) – (10,940–13,200) = 1710 Euro/ha.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research was supported by the 2015–2016 BiodivERsA COFUND Call (project GreenFutureForest) with the national funders Formas [2016-01949]; Formas [2019-01078]; joint grant from Mistra [DIA 2019/28] and

Formas via the national research programme on climate [2021-00416]; and German Federal Ministry of Education and Research BMBF [BMBFLC1610B].

ORCID

Thomas Hahn http://orcid.org/0000-0002-6649-5232
Jeannette Eggers http://orcid.org/0000-0003-1530-2581
Narayanan Subramanian http://orcid.org/0000-0003-2777-3241
Tord Snäll http://orcid.org/0000-0001-5856-5539

References

Agestam E. 2015. Skogsskötselserien – Gallring. Skogsstyrelsen. https://www.skogsstyrelsen.se/globalassets/bruka-skog/skogsskador/skogsskotselerisen—gallring.pdf.

Andersson E, Keskitalo ECH, Bergstén S. 2018. In the eye of the storm: adaptation logics of forest owners in management and planning in Swedish areas. Scand J Forest Res. 33(8): 800–808.

Astrup R, Bernier PY, Genet H, Lutz DA, Bright RM. 2018. A sensible climate solution for the boreal forest. Nat Clim Change. 8:11–12.

Balaguru K, Foltz GR, Leung LR. 2018. Increasing magnitude of hurricane rapid intensification in the central and eastern tropical atlantic. Geophys Res Lett. 45(9):4238–4247. doi:10.1029/2018GL077597.

Baumgärtner S, Strunz S. 2014. The economic insurance value of ecosystem resilience. Ecol Econ. 101:21–32.

Belusic D, Berg P, Bozhinova D, Lars B, Döscher R. 2019. Climate extremes for Sweden: state of knowledge and implications for adaptation and mitigation. SMHI. doi:10.17200/Climate_Extremes_Sweden.

Borrass L, Kleinschmit D, Winkel G. 2017. The "German model" of integrative multifunctional forest management – analysing the emergence and political evolution of a forest management concept. Forest Policy Econ. 77:16–23. doi:10.1016/j.forpol.2016.06.028.

Brukas V, Weber N. 2009. Forest management after the economic transition – at the crossroads between German and Scandinavian traditions. Forest Policy Econ. 11:586–592.

Burschel P, Huss J. 1997. Grundriß des Waldbaus : ein Leitfaden für Studium und Praxis, 2., neubearb. und erw. Aufl. ed, Pareys Studientexte. Berlin: Parey.

Carpenter SR, Arrow KJ, Barrett S, Biggs R, Brock WA, Crépin AS, Engström G, Kautsky N. 2012. General resilience to cope with extreme events. Sustainability. 4:3248–3259.

CBD. 2013. Quick guides to the Aichi biodiversity targets. Convention on biological diversity. https://www.cbd.int/nbsap/training/quick-guides/.

Claesson S, Duvemo K, Lundström A, Wikberg PE. 2015. Skogliga konsekvensanalyser 2015 - SKA15 (Forest Impact Analysis) In Swedish (No. 10). Skogsstyrelsen and Swedish University of Agricultural Sciences, Jönköping, Sweden.

Coll L, Ameztegui A, Collet C, Löf M, Mason B, Pach M, Barreiro S. 2018. Knowledge gaps about mixed forests: what do European forest managers want to know and what answers can science provide? For Ecol Manag. 407:106–115.

Dallimer M, Martin-Ortega J, Rendon O, Afionis S, Bark R, Gordon IJ, Paavola J. 2020. Taking stock of the empirical evidence on the insurance value of ecosystems. J Ecol Econ. 167:106451.

De Groot RS. 1992. Functions of nature: evaluation of nature in environmental planning, management and decision making. Amsterdam: Wolters-Noordhoff BV.

Eggers J, Lindhagen A, Lind T, Lämås T, Öhman K. 2018. Balancing landscape-level forest management between recreation and wood production. Urban Forestry Urban Green. 33:1–11. doi:10.1016/j.ufug.2018.04.016.

Ehrlich PR, Mooney HA. 1983. Extinction, substitution, and ecosystem services. BioScience. 33:248–254.

Eriksson M, Pouttu A, Roininen H. 2005. The influence of windthrow area and timber characteristics on colonization of wind-felled spruces by Ips typographus (L). For Ecol Manag. 216(1–3):105–116. doi:10.1016/J.FORECO.2005.05.044.

Eyvindson K, Duflot R, Triviño M, Blattert C, Potterf M, Mönkkönen M. 2021. High boreal forest multifunctionality requires continuous cover forestry as a dominant management. Land Use Policy. 100:104918.

Fahlvik N, Elfving B, Wikström P. 2014. Evaluation of growth functions used in the Swedish forest planning system Heureka. Silva Fennica 48. doi:10.14214/sf.1013.

Felton A, Nilsson U, Sonesson J, Felton AM, Roberge J-M, Ranius T, Ahlström M, Bergh J, Wallertz K. 2016. Replacing monocultures with mixed-species stands: ecosystem service implications of two production forest alternatives in Sweden. Ambio. 45(Suppl. 2):124.

Feser F, Barcikowska M, Krueger O, Schenk F, Weisse R, Xia L. 2015. Storminess over the North Atlantic and northwestern Europe – a review. Q J R Meteorol Soc. 141:350–382. doi:10.1002/qj.2364.

Fichtenrichtlinie. 2009. Accessed May 2, 2020. https://www.baysf.de/fileadmin/user_upload/04-wald_verstehen/Publikationen/Fichtenrichtlinie.pdf.

Foerst C, Stöckel H, Beck R, Nüßlein S, Pratsch S, Leopold TM, Brinkmann D. 2018. Forstrecht in Bayern. ISBN: 978-3-555-50115-4.

Folke C. 2006. Resilience: The emergence of a perspective for social–ecological systems analyses. Global Environmental Change. 16:253–267.

Folke C, Holling CS, Perrings C. 1996. Biological diversity, ecosystems, and the human scale. Ecol Appl. 6:1018–1024.

Fridman J, Holm S, Nilsson M, Nilsson P, Ringvall A, Ståhl G. 2014. Adapting national forest inventories to changing requirements – the case of the Swedish National Forest Inventory at the turn of the 20th century. Silva Fennica 48. doi:10.14214/sf.1095.

Fridman J, Ståhl G. 2001. A three-step approach for modelling tree mortality in Swedish forests. Scand J Forest Res. 16:455–466. doi:10.1080/02827580152632856.

Gamfeldt L, Snäll T, Bagchi R, Jonsson M, Gustafsson L, Kjellander P, Ruiz-Jaen MC, Philipson CD. 2013. Higher levels of multiple ecosystem services are found in forests with more tree species. Nat Commun. 4:1340.

Gardiner B. 2013. Living with storm damage to forests. Joensuu: European Forestry Institute.

Gauthier S, Bernier P, Kuuluvainen T, Shvidenko AZ, Schepaschenko DG. 2015. Boreal forest health and global change. Science. 349(6250):819–822. doi:10.1126/science.aaa9092.

Govt of Germany. 2016. Accessed May 2, 2020. https://www.bmel.de/EN/Forests-Fisheries/Forests/_Texte/Waldstrategie2020.html.

Green TL, Kronenberg J, Andersson E, Elmqvist T, Gomez-Baggethun E. 2016. Insurance value of green infrastructure in and around cities. Ecosystems. 19:1051–1063.

Gregow H, Laaksonen A, Alper ME. 2017. Increasing large scale windstorm damage in western, central and Northern European forests, 1951–2010. Sci Rep. 7(1):46397. doi:10.1038/srep46397.

Gundersen V, Frivold LH. 2008. Public preferences for forest structures: a review of quantitative surveys from Finland, Norway and Sweden. Urban Forestr Urban Green. 7:241–258. doi:10.1016/j.ufug.2008.05.001.

Hahn T, Heinrup M, Lindborg R. 2018. Landscape heterogeneity correlates with recreational values: a case study from Swedish agricultural landscapes and implications for policy. Landsc Res. 43i:696–707.

Hanewinkel M, Hummel S, Albrecht A. 2011. Assessing natural hazards in forestry for risk management: a review. Eur J For Res. 130:329–351.

Hanewinkel M, Kuhn T, Bugmann H, Lanz A, Brang P. 2014. Vulnerability of uneven-aged forests to storm damage. Forestry. 87:525–534. doi:10.1093/forestry/cpu008.

Holecy J, Hanewinkel M. 2006. A forest management risk insurance model and its application to coniferous stands in southwest Germany. Forest Policy Econ. 8:161–174.

Holling CS, Carpenter S, Brock WA, Gunderson LH. 2002. Discoveries for sustainable futures. In: Gunderson L.H., Holling C.S, editor. Panarchy. understanding transformations in human and natural systems. Washington, DC: Island Press; p. 395–418.

IPCC. 2018. Special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Summary for policymakers. https://www.ipcc.ch/srccl-report-download-page/.

Jactel H, Brockerhoff EG. 2007. Tree diversity reduces herbivory by forest insects. Ecol Lett. 10:835–848. doi:10.1111/j.1461-0248.2007.01073.x.

Jonsson M, Bengtsson J, Gamfeldt L, Moen L, Snäll T. 2019. Levels of forest ecosystem services depend on specific mixtures of commercial tree species. Nat Plants. 5:141–147.

Kabisch N, Frantzeskaki N, Pauleit S, Naumann S, Davis M, Artmann M, Haase D, Knapp S, Korn H, Stadler J. 2016. Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. Ecol Soc. 21(2):39.

Kärhä K, Anttonen T, Poikela A, Palander T, Laurén A, Peltola H, Nuutinen Y. 2018. Evaluation of salvage logging productivity and costs in windthrown Norway spruce-dominated forests. Forests. *9*(5):280.

Knoke T. 2017. Economics of mixed forests. In: Pretzsch H., Forrester D. I., Bauhus J., editor. Mixed-species forests. Springer, Berlin; p. 545–577.

Knoke T, Ammer C, Stimm B, Mosandl R. 2008. Admixing broadleaved to coniferous tree species: a review on yield, ecological stability and economics. Eur J Forest Res. 127:89–101. doi:10.1007/s10342-007-0186-2.

Knoke T, Messerer K, Paul C. 2017a. The role of economic diversification in forest ecosystem management. J Curr Forestry Rep. 3:93–106.

Knoke T, Paul C, Härtl F. 2017b. A critical view on benefit-cost analyses of silvicultural management options with declining discount rates. J Forest Policy Econ. 83:58–69.

Lagergren F, Jönsson AM, Blennow K, Smith B. 2012. Implementing storm damage in a dynamic vegetation model for regional applications in Sweden. Ecol Modell. 247:71–82.

Lidskog R, Sjödin D. 2014. Why do forest owners fail to heed warnings? Conflicting risk evaluations made by the Swedish forest agency and forest owners. Scand J Forest Res. 29:275–282. doi:10.1080/02827581.2014.910268.

Lindroth A, Lagergren F, Grelle A, Klemedtsson L, Langvall O, Weslien P, Tuulik J. 2009. Storms can cause Europe-wide reduction in forest carbon sink. Global Change Biol. 15(2):346–355. doi:10.1111/j.1365-2486.2008.01719.x.

López-Andújar Fustel T, Eggers J, Lämås T, Öhman K. forthcoming. Spatial optimization for reducing wind exposure of forest stands at the property level, Forest Ecology and Management (accepted).

Lundmark T, Bergh J, Nordin A, Fahlvik N, Poudel BC. 2016. Comparison of carbon balances between continuous-cover and clear-cut forestry in Sweden. Ambio. 45:203–213.

Luyssaert S, Marie G, Valade A, Chen Y-Y, Njakou Djomo S, Ryder J, Otto J, et al. 2018. Trade-offs in using European forests to meet climate objectives. Nature. 562(7726):259–262.

Mäler KG, Li CZ. 2010. Measuring sustainability under regime shift uncertainty: a resilience pricing approach. Environ Dev Econ. 15:707–719.

Mason WL, Diaci J, Carvalho J, Valkonen S. 2021. Continuous cover forestry in Europe: usage and the knowledge gaps and challenges to wider adoption. Forestry. 1:1–12.

Mölter T, Schindler D, Albrecht A, Kohnle U. 2016. Review on the projections of future storminess over the North Atlantic European region. Atmosphere. 7:60. doi:10.3390/atmos7040060.

Nikinmaa L, Lindner M, Cantarello E, Jump AS, Seidl R, Winkel G, Muys B. 2020. Reviewing the use of resilience concepts in forest sciences. Curr Forestry Rep. 6(2):61–80. doi:10.1007/s40725-020-00110-x.

Nilsson M, Eriksson LO, Wästerlund DS. 2013. Strategy pattern creation in forest planning in Swedish forest-owning companies. Forests. 4:553–574. doi:10.3390/f4030553.

Odum EP. 1989. Ecology and our endangered life-support system. Sunderland, MA: Sinauer Associates.

Økland B, Nikolov C, Krokene P, Vakula J. 2016. Transition from windfall- to patch-driven outbreak dynamics of the spruce bark beetle Ips typographus. For Ecol Manag. 363:63–73. doi:10.1016/J.FORECO.2015.12.007.

Orazio C, Cordero Montoya R, Régolini M, Borges JG, Garcia-Gonzalo J, Barreiro S, Botequim B, Sallnäs O. 2017. Decision support tools and strategies to simulate forest landscape evolutions integrating forest owner behaviour: a review from the case studies of the European project, INTEGRAL. Sustainability. 9:599. doi:10.3390/su9040599.

Paavola J, Primmer E. 2019. Governing the provision of insurance value from ecosystems. J Ecol Econ. 164:106346.

Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA, Hayes D. 2011. A large and persistent carbon sink in the world's forests. Science. 333(6045):988–993. doi:10.1126/science.1201609.

Pasalodos-Tato M, Mäkinen A, Garcia-Gonzalo J, Borges JG, Lämås T, Eriksson LO. 2013. Assessing uncertainty and risk in forest planning and decision support systems: review of classical methods and introduction of new approaches. Forest Syst. 22:282–303. doi:10.5424/fs/2013222-03063.

Pascual U, Muradian R, Brander L, Gómez-Baggethun E, Martín-Lopéz B, Verma M. 2010. The economics of valuing ecosystem services and biodiversity. In: P. Kumar, editor. TEEB ecological and economic foundations. London: Earthscan; p. 183–240.

Pascual U, Termansen M, Hedlund K, Brussaard L, Faber JH, Foudi S, Lemanceau P, Jørgensen SL. 2015. On the value of soil biodiversity and ecosystem services. Ecosyst Serv. 15:11–18.

Pindyck RS. 2017. The use and misuse of models for climate policy. Rev Environ Econ Policy. 11:100–114.

Price D, Alfaro R, Brown K. 2013. Anticipating the consequences of climate change for Canada's boreal forest ecosystems. Environ Rev. 21(4):322–365. http://www.nrcresearchpress.com/doi/abs/10.1139/er-2013-0042.

Pukkala T, Laiho O, Lähde E. 2016. Continuous cover management reduces wind damage. For Ecol Manag. 372:120–127. doi:10.1016/J.FORECO.2016.04.014.

Rawls J. 1974. Some reasons for the maximin criterion. Am Econ Rev. 64:141–146.

Riguelle S, Hébert J, Jourez B. 2016. Integrated and systemic management of storm damage by the forest-based sector and public authorities. Ann For Sci. 73:585–600.

Rummukainen M. 2012. Changes in climate and weather extremes in the 21st century. Wiley Interdiscip Rev Clim Chang. 3:115–129.

Schelhaas M-J, Hengeveld G, Moriondo M, Reinds GJ, Kundzewicz ZW, ter Maat H, Bindi M. 2010. Assessing risk and adaptation options to fires and windstorms in European forestry. Mitig Adapt Strat Global Change. 15(7):681–701. doi:10.1007/s11027-010-9243-0.

Schindler D, Jung C, Buchholz A. 2016. Using highly resolved maximum gust speed as predictor for forest storm damage caused by the high-impact winter storm Lothar in Southwest Germany. Atmos Sci Lett. 17:462–469.

Seidl R, Rammer W, Blennow K. 2014. Simulating wind disturbance impacts on forest landscapes: tree-level heterogeneity matters. Environ Model Softw. 51:1–11. doi:10.1016/J.ENVSOFT.2013.09.018.

Seidl R, Thom D, Kautz M, Martin-Benito D, Peltoniemi M, Vacchiano G, Wild J. 2017. Forest disturbances under climate change. Nat Clim Chang 7(6):395–402.

SFI. 2019. Swedish forest industries, https://www.forestindustries.se/forest-industry/facts-and-figures/.

Skogsstyrelsen. 2019. https://www.skogsstyrelsen.se/bruka-skog/olika-satt-att-skota-din-skog/att-skota-blandskog.

SLU. 2020. Red-listed species in Sweden 2020. Uppsala: Artdatabanken, SLU. https://www.artdatabanken.se/publikationer/bestall-publikationer/.

SLU, Uppsala SLU. 2018. Forest statistics 2018. Umeå: Department of Forest Resource Management, Swedish University of Agricultural Sciences. https://www.slu.se /globalassets/ew/org/centrb/rt/dokument/skogsdata/skogsdata_2018_webb.pdf.

Statistisches Bundesamt Deutschland. 2020. Pressemitteilung Nr. N 041. https://www.destatis.de/DE/Presse/Pressemitteilungen/2020/07/PD20_N041_412.html.

Sterner T, Persson UM. 2008. An even sterner review: introducing relative prices into the discounting debate. Rev Environ Econ Policy. 2:61–76.

Stott P. 2016. How climate change affects extreme weather events. Science. 352(6293):1517–1518. doi:10.1126/science.aaf7271.

Strengbom J, Axelsson EP, Lundmark T, Nordin A. 2018. Trade-offs in the multi-use potential of managed boreal forests. J Appl Ecol. 55:958–966.

Subramanian N, Bergh J, Johansson U, Nilsson U, Sallnäs O. 2016. Adaptation of forest management regimes in southern Sweden to increased risks associated with climate change. Forests. 7:8. doi:10.3390/f7010008.

Subramanian N, Nilsson U, Mossberg M, Bergh J. 2019. Impacts of climate change, weather extremes and alternative strategies in managed forests. Écoscience. 26(1):53–70. doi:10.1080/11956860.2018.1515597.

Szewczyk G, Sowa J, Grzebieniowski W, Kormanek M, Kulak D, Stańczykiewicz A. 2014. Sequencing of harvester work during standard cuttings and in areas with windbreaks. Silva Fenn. 48:4. doi:10.14214/sf.1159.

Tahvonen O, Rämö J. 2016. Optimality of continuous cover vs. clear-cut regimes in managing forest resources. Can J For Res. 46:891–901.

Valinger E, Fridman J. 2011. Factors affecting the probability of windthrow at stand level as a result of Gudrun winter storm in southern Sweden. For Ecol Manag. 262(3):398–403. doi:10.1016/J.FORECO.2011.04.004.

Valinger E, Kempe G, Fridman J. 2014. Forest management and forest state in southern Sweden before and after the impact of storm Gudrun in the winter of 2005. Scand J Forest Res. 29:466–472.

Valinger E, Kempe G, Fridman J. 2019. Impacts on forest management and forest state in southern Sweden 10 years after the storm Gudrun. Forestry. 92:481–489. doi:10.1093/forestry/cpz005.

Vergano L, Nunes PALD. 2007. Analysis and evaluation of ecosystem resilience: an economic perspective with an application to the Venice lagoon. Biodivers Conserv. 16:3385–3408. doi:10.1007/s10531-006-9085-y.

Wikberg P-E. 2004. Occurrence, morphology and growth of understory saplings in Swedish forests (Doctoral thesis). Umeå: Swedish University of Agricultural Sciences.

Wikström P, Edenius L, Elfving B, Eriksson LO, Lämås T, Sonesson J, Öhman K, Wallerman J, Waller C, Klintebäck F. 2011. The Heureka forestry decision support system: an overview. Math Comput For Nat Res Sci. 3:87–95.

Yousefpour R, Jacobsen JB, Thorsen BJ, Meilby H, Hanewinkel M, Oehler K. 2012. A review of decision-making approaches to handle uncertainty and risk in adaptive forest management under climate change. Ann For Sci. 69:1–15. doi:10.1007/s13595-011-0153-4.