

Effects of forest management and harvest intensity on landscape level wind damage risk

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Abstract

Future forest management needs to balance between sustainable timber, supporting non-woody ecosystem services and shelter biodiversity. Novel approaches as optimization of forest management to certain goals, increasing proportion of set-aside forest stands, or novel management approaches such as continuous forest cover emerge. However, novel ways of forest management shape forest stands structures over the landscape and will define the stand vulnerability to more frequent climatic disruptions, such as windthrows under hardening climate change. To understand how will the traditional (rotation forestry, RF) and novel forest managements techniques (continuous cover forest, CCF) combined using optimal management alternate the risk of wind damages over the harvest intensity gradient (ranging from completely setaside to highest harvesting rates), we combined the forest growth simulator under ranges of management regimes (RF, CCF and combined: ALL), optimized over the range of harvesting levels to calculate stand and landscape level wind damage risk for alternative paths of the forest management and harvesting levles over 100 years. We found that higher harvest intensity in RF lowers wind risk, whereas the wind risk increased under CCF and ALL scenarios. More intensive harvesting using RF produced more pulp, while CCF provided higher volumes of the standing and harvested log wood, which likely explains higher values of wind risk probability. RF slightly increased the number of stands with open edge, which remained stable under CCF and ALL regimes. Intensive harvesting may change species composition to favour Norway spruce which will further increase probability of wind damage in the future. Therefore, we suggest that forest managers should consider the target forest species composition to mitigate wind risk if aimed to support production of log wood over the pulp.

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1. Introduction

Future forest ecosystems need to simultaneously provide timber, non-woody ecosystem services such as carbon storage or human recreation, and shelter biodiversity. Adaptive forest management strives to balance between timber production, provision of non-woody ecosystem services, and biodiversity. Existence of biodiversity, mostly attached to existence of deadwood, is limited by harvesting intensity. Intensive logging activities fragment forested landscapes. To balance between biodiversity and timber economic gains, the proportion of set-aside forests within commercial forests emerges, and new forest management approaches are explored, such as continuous forest cover (Eyvindson et al., 2021) and traditional harvesting regimes are becoming controversial or requested to ban (...). The increase of the set aside forests within the commercial forests, as well as development of the new management techniques affect landscape level structural diversity, timing of the thinning, presence or absence of the final cuts in rotation forestry or development of the larger trees within continuous cover forestry or in set-aside forestry. The fundamental is the careful landscape level planning of the management actions balancing between set-aside (unmanaged forests), intensive management and continuously present forest cover.

Optimal management scenarios fulfil the specific objectives of the society of forest owners to provide certain timber value, improve provision of timber and non-timber ecosystem services, or improve overall forest multifunctionality of the landscape. As such, optimization provides the combination of the specific forest management regimes on stand level. Although the optimization process does not necessarily involve the spatial configuration of the stands, it specifically assigns the particular regimes to individual stands and therefore allows to recreate alternative dynamics landscapes shaped by forest managements aggregated by optimal scenarios. As such, the spatial configuration of the management regimes allows to estimate the subsequent characteristics such as landscape level risk of wind damage.

The risk of the wind damage increases with current climate change and it creates the major risk to the stability of the forest production. Windthrows are unpredictable climatic disruption that shapes forest structure and composition, and if left unsalvaged could create opportunities for deadwood dependent species and support local biodiversity. From economical point of view, however, windthrows massively abrupt the continuity of the timber supply, lowers timber quality from log to pulp, increases the prices of unplanned salvage harvesting (REF). To lower the risk of wind risk damage, current suggestions include shortening the rotation period, promoting/avoiding the wind resistant vs. wind prone tree species, advocate for shortening of the minimal stand age (Latvia REF). This however poses further pressure on the multifunctional and multiple objective oriented landscapes, which will provide habitats for endangered species, support non-timber services and forest recreational use.

Traditional forest management regimes specialized in promoting timber revenues while minimizing costs. In Fennoscandia, over the decades, the traditional rotation forestry with multiple thinnings and final cuts that over just multiple

decades (from 1950) homogenized stands structural diversity, homogenized landscapes and increased forest fragmentation. On the other hand, forest management supporting multifunctional landscapes, and promoting non-timber ecosystem services requires implementation of the diverse set of management regimes (Mönkkönen et al., 2014; Triviño et al., 2017). Furthermore, provision of the endangered species habitats and non-woody ecosystem services are provided on different scales where the planning scale should match or overcome the scale that provided ecosystem (Pohjanmies et al., 2019).

Here we explore how the restriction of forest management practices, along with the increasing level of harvest levels over the landscape affects landscape level damage of wind risk and how much timber value is put on risk under alternative regimes and extraction levels. Our study for the first time evaluates the landscape level wind risk combined with the forest growth simulator and long-term consequences of the applied forest management practices. Therefore, we first calculate the stand level wind risk over alternative landscapes and further explore the likely drivers of the wind risk levels. We investigated how restriction of forest management regimes combined with levels of intensity of timber extraction will affect landscape level wind risk.

Our study aims to understand how types of forest management and harvesting intensity affect stand and landscape level wind risk over time, and how much timber volume is at the risk at time. We hypothesized that RF will increase stand level wind risk due to accumulated timber volume before the final cut, and increase wind risk in landscape due to increasing number of stands with open edges after the final cuts. On the other hand, the CCF will likely homogenize the amount of timber volume over landscape; therefore at any given time, the exposed timber volume to wind damage will be lower in CCF compared to RF management. We will consider the pulp and log volume of the standing volume. We further investigate the dynamics of simulated stand characteristics as stand dominant height, dominant tree species by stand, age, number of trees by stand, frequency of open edge stands and thinning frequency over the landscape over the harvest intensity gradient and time. We further differentiate between the dynamics of the volume and wind risk in managed and set-aside forests.

2. Methods

2.0.1. Study area

Our study area represents a typical Finnish production forested landscape with relatively structurally homogenous forest stands. In total, we used 1475 forest stands aggregated within a single watershed (number 14.534) in Central Finland, covering 2242 ha (Fig. 1). Initial stand conditions were collected as open source data from the Finnish Forest Centre (available on www.metsaan.fi) providing current stand conditions in 2016.

Our input dataset includes initial stand conditions (2016), alternative forest growth under the range of forest management regimes over 100 years and a set of optimal solutions balancing between intensifying harvest levels and

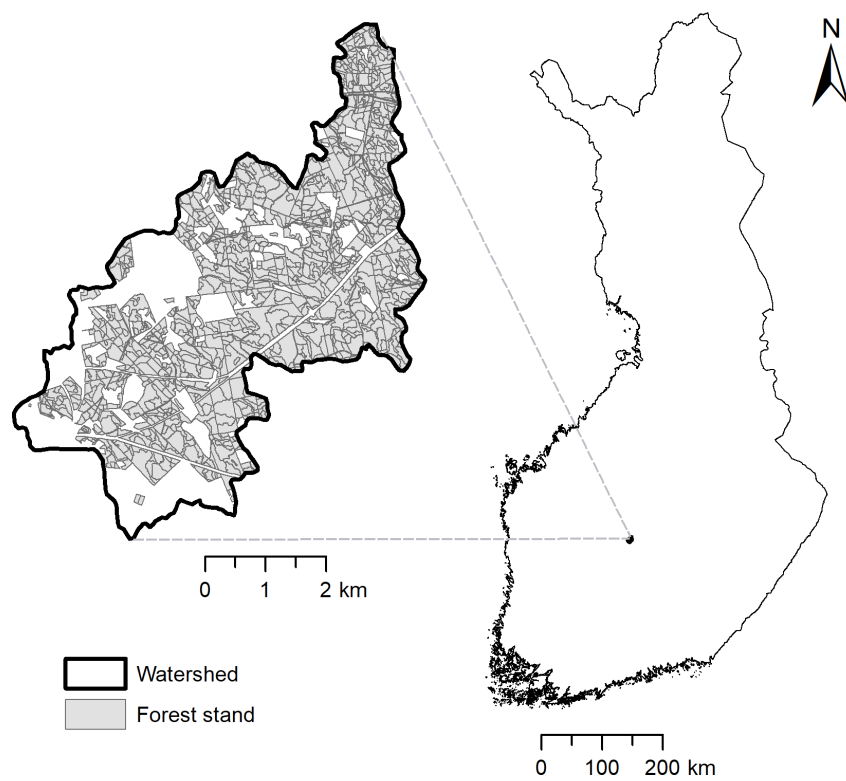


Figure 1: The study area located in Central Finland (watershed 14.534) comprising 1475 forest stands.

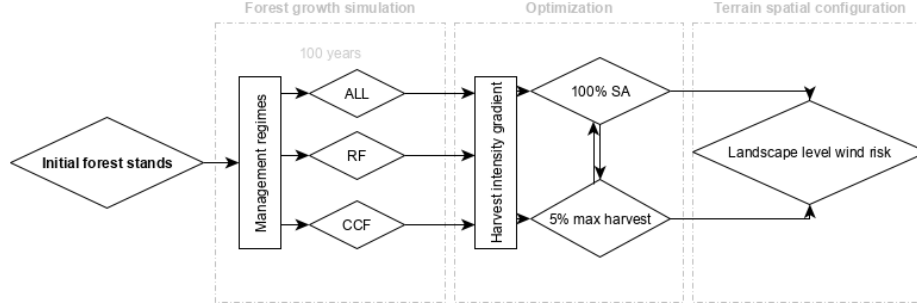


Figure 2: The study workflow from collecting initial stand conditions (2016) through forest simulation growth under various ranges of forest management, and construction of the harvesting intensity gradient using optimization to landscape level stand configurations.

multifunctionality (from completely set-aside, i.e. no management to maximal harvest gains). From the set of optimal solutions we have calculated stand-level probability of wind damage (for full details, please refer to Eyvindson et al. (2021) study. Fig. 2) represents study workflow.

2.0.2. Forest stand development under different regimes

We simulated the development of the forest stands using SIMO forest growth simulator (???) over 100 years, separated into 20 5-year sequences. Each stand could be managed by up to 58 different management regimes (the total number of regimes per stand depended on the initial stand conditions), including 17 regimes for rotation forestry (RF), 40 variations of continuous cover forest (CCF) and one set-aside (SA), where no management actions were taken. RF regimes differed in timing of final felling, optional thinning (present/absent), and increase in number of retained green trees after final cut (more details in Eyvindson and Kangas (2018)). Basic CCF management follows rules from Äijälä et al. (2014). To increase the range of CCF managements, we varied two rules defining the timing of harvest: (i) site-specific basal area and (ii) timing of the first thinning. We modified the pre-defined site-specific basal area requirement (16m²/ha for less fertile sites to 22m²/ha for fertile sites) prior to harvesting by -3, ±0, +3, +6, and delayed the timing of the first harvest in 5 year increments up to a delay of 45 years.

2.0.3. Optimization

The optimal forest management explores the trade-offs between net present income (NPI) and forest multifunctionality. NPI represents economic value of the forests estimated by Metsähallitus (the Finnish governmental organization managing state owned forests). Higher NPI presents higher timber extraction and opposes the proportion of the set-aside forest stands (i.e. without active harvesting) over the landscape. Optimization process over the NPI gradient was run using only RF, only CCF management types, or all possible managements (RF and CCF, further referred as ALL) included over the gradient of NPI values,

from 0 (representing completely set-aside or no management in all stands) to maximal amount of extracted timber (leaving up to 5% of SA stands). The optimization balances between harvest intensity and landscape-level multifunctionality, including non-woody ecosystem services (climate change mitigation), recreational activities and vertebrate and non-vertebrate endangered species. The optimization resulted in 63 alternative collections of RF, CCF and ALL management regimes. We converted the optimal solutions back to the development paths for every stand under alternative management given group of management allowed (CCF, RF, ALL) and levels of timber extraction (21). Each stand has only one management regime by scenario. This allowed to reconstruct stand structure on particular stand under given management regime at specific time.

2.0.4. Wind risk calculation

We have calculated the probability of wind damage based on Suvanto et al. (2019) binomial generalized linear model with logit-link function for each stand for every time step at each scenario. Suvanto et al. (2019) model calculates the probability of the wind damage considering available relevant open-access datasets including dominant tree species, dominant tree height, time since thinning, predicted levels on maximal wind speed, temperature sums, evaluated if stand has open edge, soil type, mineral soil depth, site fertility and temperature sum (see Suvanto et al. (2019) for all details). The final probability of wind damage shows relative differences between stands, whereas the damage can be only partial to the stand, but neglects the explicit spatial locations of the future strong winds. The parameters of the dominant tree species, tree height, open edge and time since thinning were dynamics under simulated management regimes. Parameters of maximal predicted wind speed and temperature sums, as well as soil characteristics, remained stable during our 100 years simulation. We processed the datasets, calculated damage probability models, and visualized results using R Development Core Team (2019).

2.0.5. Data processing

We calculated the probability of wind damage for each stand, scenario and time intervals. Further, we averaged the wind risk values over the scenarios to allow comparison between RF, CCF and ALL management regimes groups over the harvesting gradient. We explored the mean wind risk (%) given the management groups and over harvest gradient (from set-aside to maximal harvest levels). In addition, we investigated the mean levels of the standing log and pulp timber volumes (m³) for scenarios, and total sum of harvested pulp and log timber over simulation run (XXX). We further investigated the changes in dynamics parameters (tree species, dominant tree height, frequency of open edges and time since thinning) over the harvest intensity gradient to understand how they contributed to predicted wind risk values. As different tree species varied in wind risk probability, we further grouped this variable by species to understand differences between species. Specifically, we calculated mean proportion of individual tree species (%), mean tree heights (m), proportion of

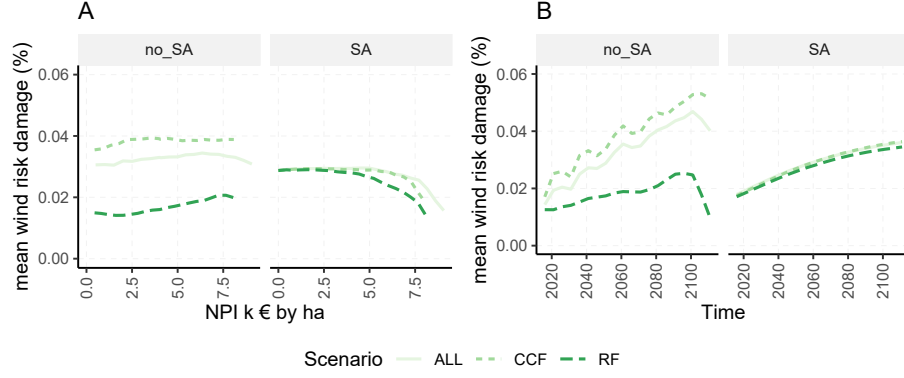


Figure 3: (#fig:fig_meanRisk_time_NPI) Mean wind risk damage for three types of management regimes over A: harvest intensity gradient and B: over time.

the stands with open edge from total amount of stands by species and mean thinning frequencies by year.

3. Results

3.0.1. Wind damage probability

The set-aside landscape level management resulted at the same mean landscape level risk for all management regimes (Fig. 2). However, intensifying harvesting triggers different responses under groups of management regimes and intensification of the timber extraction. Sole use of the RF managements lowered the wind risk with increasing harvest intensity. On the other hand, both ALL and CCF scenarios increased the wind risk where CCF monotonically increased with increasing harvesting rates, while ALL regimes have slightly humpened curve shape, culminating around inteinsity of 7.5K by ha. The CCF increases monotonically while maximal harvesting increase the wind risk by 25% compared to completely set-aside stands. @ref{fig_meanRisk_time_NPI}

3.0.2. Timber volume at wind risk

Question: how much timber is at risk????

Increasing harvesting levels lowers the amount of the available timber at any time step to be lost due to windthrows. Interestingly, the CCF regimes produces higher logs volumes, while RF has higher production of the pulp wood, which is in high demand by cheaper then log wood. The same trends are visible for harvested log and pulp volumes. For ALL management regimes, using all available management regimes, is located between two extremities. The highest mean log timber volume as available for the wind damage at lowest harvesting levels. Interestingly, under RF, low levels of timber extraction increase levels of the pupl standing volume. The highest amount of harvested log wood

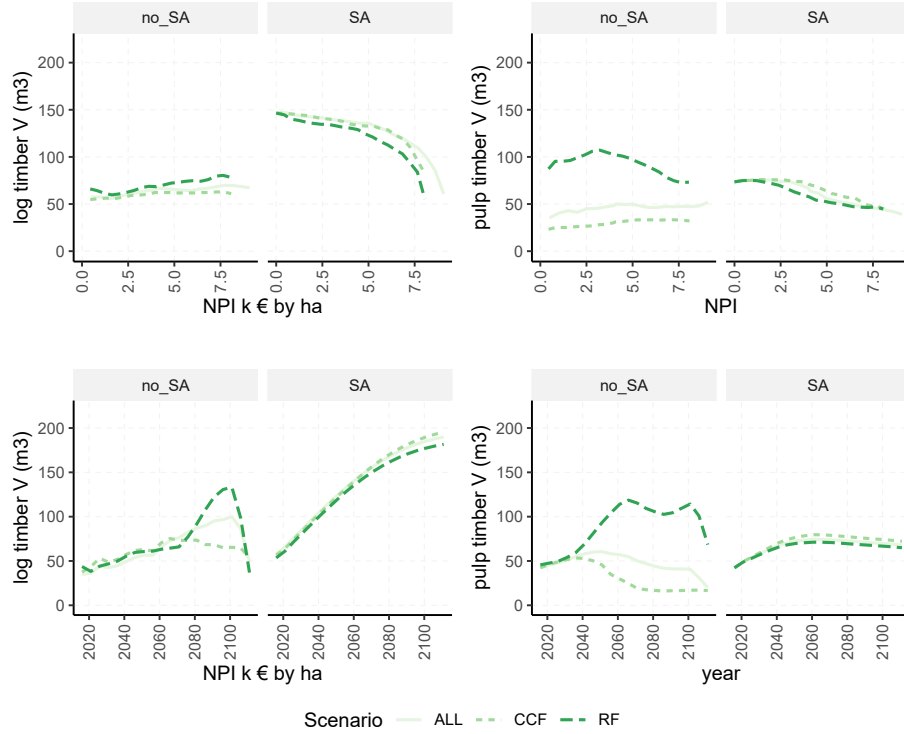


Figure 4: Mean log (left) and pulp (right) timber volume of the top tree layer in the stands over management groups over harvesting intensity gradient (top) and over years (bottom)

is produced by CCF regimes, while RF dominates in harvesting pulp timber @ref(fig:plot_V_timber).

The intensification of the harvesting levels increases the proportion of the pulp wood compared to log wood, especially in RF. In CCF, the proportion among standing log and pulp volume remains at the same rate (65:30) where the production of the log timber dominates. At the highest intensity of timber extraction, pulp wood creates up to 50% of the total standing volume. See figure @ref(fig:proportion_V_pulp_log) NEW FIG @ref(proportion_V_pulp_log).

In spruce dominated forests, the proportion of the log wood from top stratum lowers by 50% with increasing harvesting rate in all management regimes applied. Interestingly, RF maintains the high production of the pulp wood with increasing harvest intensity. For all species, the proportion of the stand and top stratum volumes lowers by 47% (spruce, RF), while pulp lowers in CCF and ALL management (41) and remained the same (mean 100 m³/ha) in RF with increasing harvesting rates.

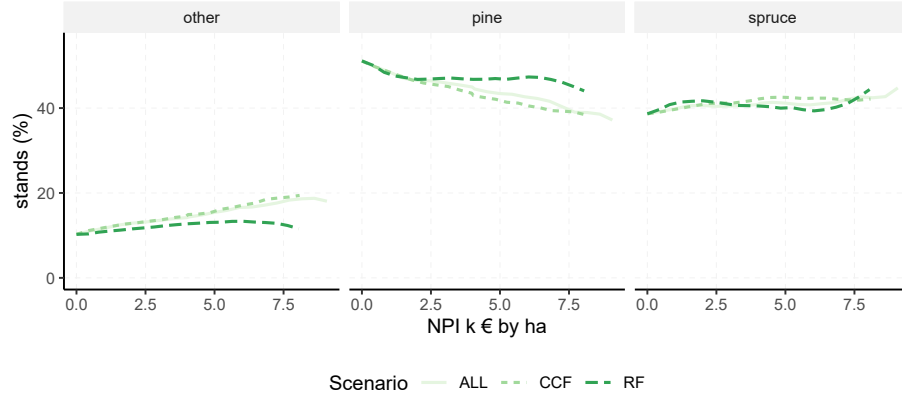


Figure 5: (#fig:species_change)Changes in species composition under different management groups and harvest intensity.

3.0.3. Changes in wind risk

3.1. Dynamic parameters contributing to wind risk

3.1.1. Species composition

The intensification of the harvesting changes the stand species composition over time (Fig. ??). Intensification of the harvesting favorize the proportion of the Norway spruce and others (deciduous) tree species instead of Scots pine, which likely in turn increases wind risk over the stands. Proportion of the pine lowers with higher harvest intensities.

3.1.2. Dominant tree heights

The intensification of the harvest reduce mean tree height for other species to half (from 20 m to 10 m) in RF, while CCF slightly increases mean tree heights. For pine and spruce trees, harvest intensification maintain the mean tree height of the stand to 20 m (other) to 22 m (spruce). Spruce is higher then pine and other stree species.

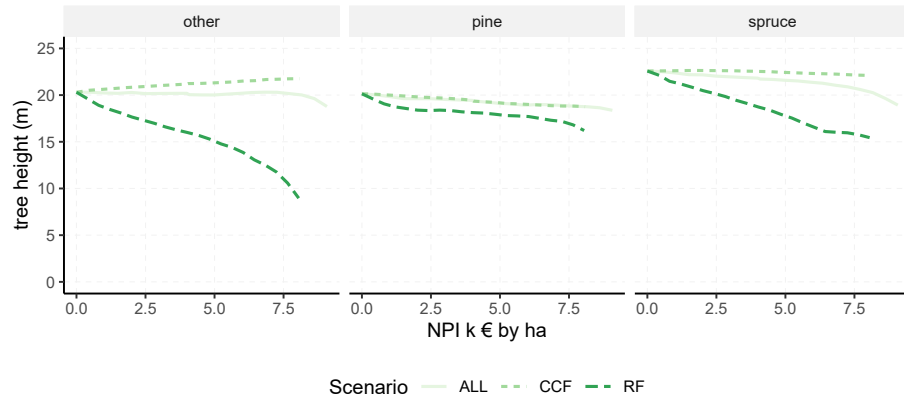
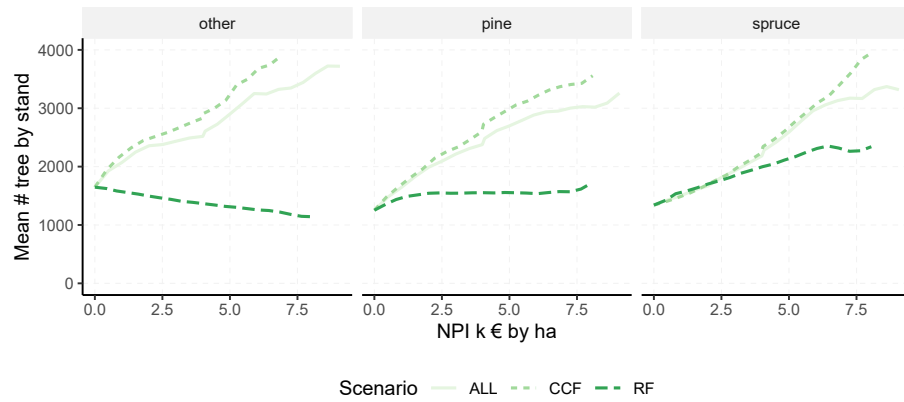


Figure 6: (#fig:res_D_tree_height) Mean dominant tree height under different management groups and harvest intensity.

3.1.3. Tree count



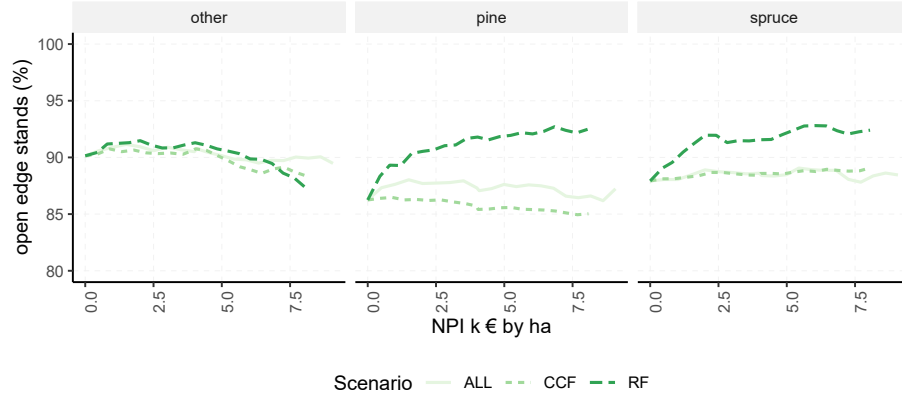


Figure 7: (#fig:fig_6_count_open_edge) Yearly proportion stands with open edge by species, management group and over the harvest intensity gradient. Note y axis starts at 80.



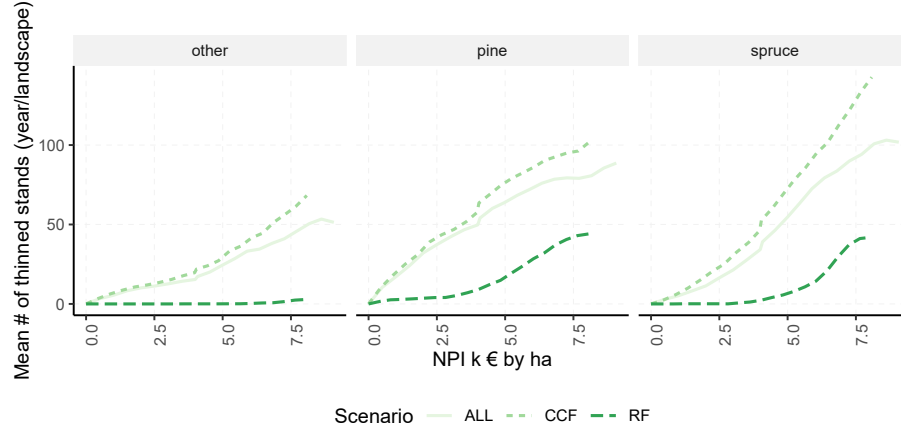
3.1.4. Frequency of open stands

The proportion of the open edge stands remains very high over whole simulation run, which is likely due to the fragmented landscape (85-95% of stands by species, Fig. 2, Fig. XX). However, increasing harvest intensity lowers number of stands with open edge when dominated by other species, whereas increases those numbers for pine and spruce dominated stands, especially under RF. The CCF and ALL management groups maintain the number of the open edge stands similar to completely set aside stands.

3.1.5. Thinning frequency

the highest frequency of thinnings is under CCF management regimes, which linearly increase with harvesting intensity for all tree species. Numbers of

thinnings in RF remains relatively low comparing to CCF and ALL, and strongly increases at high harvest intensity (from 3K for pine and from 5K for spruce). The frequency of thinnings in CCF increases 3-4 times in CCF comparing to RF.



4. Discussion

4.0.1. Wind risk dynamics

We found that intensification of the harvesting regimes have different consequences of resulting wind risk: where CCF management increases wind risk, and RF lowers wind risk with increasing intensity.

4.0.2. Wind risk drivers

4.0.3. Future questions to answer

4.0.4. Recommendation for future management

- SA vs. intensification of management
- management types: CCF, RF or ALL or something else???

Wind (10 years return level of max wind speed REF) are estimated the same over 100 years as well as temperature sums. How does could affects the results?

In spite of inherent stochasticity of the wind and damage phenomena at all spatial scales can be successfully modelled combining spatial spatial datasets and ground earth observation data (Suvanto et al. 2019). Interpret Suvanto's map: there are 3 limitations: use values as relative to each other - instead of exact probability values, interpret the map as relative differences in damage vulnerability. Damage probabilities do not refer to complete damage of the stand – damage can be only poartial, in some part of the stand (not spatially expicit) map erepresent the forest vulnerability to the wind, but it is impossible to predict the exact locations of future wind disturbances, given uncertainties in future wind occurences

- the glm takes into account the dominant tree species but neglects the stand structure. WE neglected the stand structure in applying the raster level based glm model to stand level information
- difficult to link the predicted wind risk to explicit wind damage volume as windthrows are unpredictable events in time and explicit locations.
- We need to understand what risks about current management decisions involves and if they bring another challenges, such as increasing risk of wind damage. On the other hand, the set-aside stands, if protected, the wind damage there should not be regarded as lost timber volume due to windthrow, as was not supposed to be logged anyway. However, if windthrow happen in SA stands, the risk of subsequent disturbances such as *Ips typographus* might increase the cost of the effective stand protection in following years.
- SA forests have clearly higher wind risk than intensively managed forests under RF. However, RF as highly specialized in provision of the single benefit - timber - while deterioration non-woody ecosystem services and destroying habitats for endangered species should be largely replaced over the landscapes by managements fulfilling multiple benefits Eyvindson et al. (2021).

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The shortening of the rotation period in Norway spruce forests might slightly lower the wind and subsequent bark beetle disturbances but has limited efficiencies and decreases under climate change (Zimová et al., 2020)

5. Conclusion

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