How restrictions of forest management affect landscape level wind damage risk

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Abstract

Current forest management seeks to reconside timber harvesting while aims to improve forest diversity and halt biodiversity loss. Novel approaches as optimization of forest management regimes, increasing proportion of set-aside forest stands, or novel management approaches such as continuous forest cover emerge. However, novel ways of forest management shape structures of the forest stands over the landscape which will in turn affect the vulnerability to resist to more frequent climatic disruptions, such as windthrows. To understand how will the traditional (rotation forestry, RF) and novel forest managements techniques (continuous cover forest, CCF) 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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Introduction

Adaptive forest management aims to balance between forest productivity, provision of non-woody ecosystem services, and biodiversity. Existance of biodiversity, mostly attached to existence of deadwood, is limited by harvesting levels. Intensive logging activities fragment forested landspaces. To balance between biodiversity and economic gain from timber, the propostion 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 of 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 carefull landscape level planning of the management actions balancing between set-aside (unmanaged forests), intensive management and continuously present forest cover.

Optimal management scenarios fullfil 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. Althought the optimization process does not necessary 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 opportiunities 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 specuies, advocate for shortening of the minimal stand age (Latvia REF). This however poses further pressure on the multifucntionnal 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 mutlipel decades (from 1950) homogenized stands structureal diversity, homogenized landscapes and increased forest fragmenetations. 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 landcspeca level wind risk combined with the forest growth simulator and long-term consequences of he 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 affects landscape level wind risk.

We hypothesized that RF would increase wind damage risk dues to increasing number of open edges while CCF would lower wind risk over the landscape. Further, we hypothetize that higher levels of timber extraction would increase wind risk. Lastly, we hypothetized than increasing amount of set-aside stands, over the landscape together with CCF management would increase wind damage risk due to larger present timber volume, and due to more frequent thinning activities. We investigated wind risk in terms of available timber volume, specifically saw and log timber volume. Lastly, we explored the trends of wind risk relevant to stands height, changes and species compositions.

Methods

Study area. Our study area represents a typical Finnish production forested landscape with relatively structurally homogenous forests stands. In total, we used 1475 forests 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 currents stand conditions in 2016.

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

Forest stand development under different regimes. We simulated the development of the forests 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 stands depended

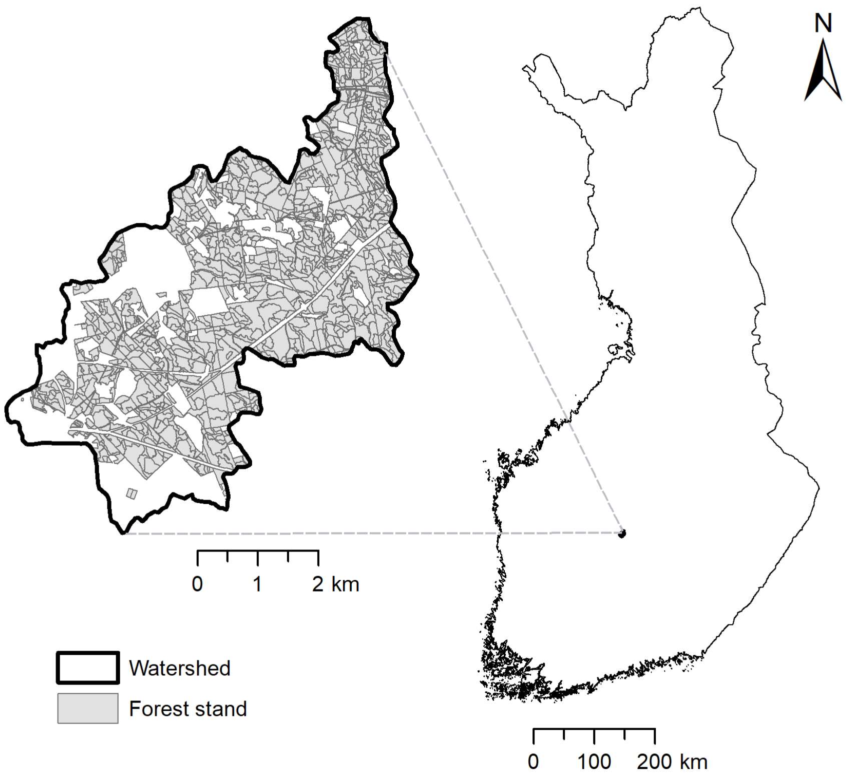

Figure 1: The study area located in Central Finland (watershed 14.534) comprising 1475 forest stands.

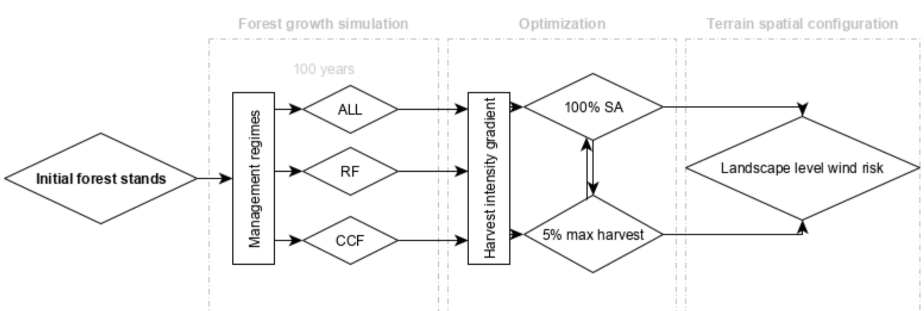

Figure 2: The study workflow from collecting initial stand conditions (2016) throught forest simulation growth under various ranges of forest management, and construiction of teh harvesting intensity gradient using optimization to landscape level stand configurations.

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.

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 reffered 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 multifunctionnality, 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 manamement 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.

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 strongs 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).

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 means of dynamic 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.

Results

Landscape level wind risk under management restriction and harvest intensity scenarios. 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.

Timber volume at wind 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 is produced by CCF regimes, while RF dominates in harvesting pulp timber @ref(fig:fig_4_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 teh total standing volume See figure @ref(fig:fig_5_proportion_V_pulp_log) NEW FIG @ref(fig_5_proportion_V_pulp_log).

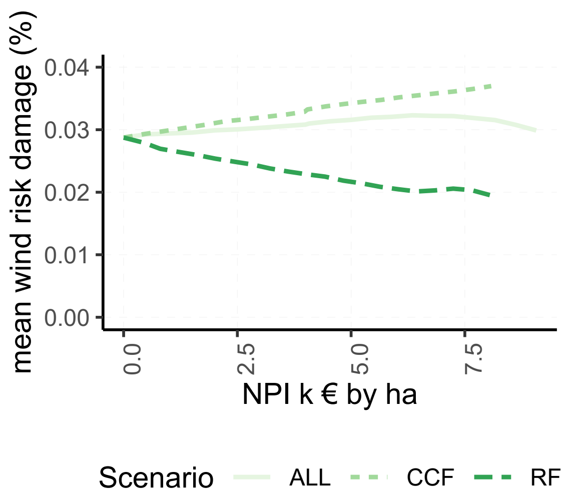

Figure 3: Mean wind risk damage for three types of management regimes over harvest intensity gradient

Dynamic parameters contributing to wind risk

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.

Dominant tree heights. 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.

Frequency of open stands. RF regimes increase the amount of stands with open edge with increasing harvest intensity while CCF regimes maintain the same amount of open stands over the harvest intensity gradient. Intensive RF increases number of stands with open edge by 5%.

Thinning frequency.

```
##                 id year Age cash_flow        BA        V V_stand_log V_stand_pulp
##       1: 12515084 2016  51         0 15.92991 121.9846    50.43912     69.03075
##       2: 12515084 2021  56         0 15.97570 122.4578    50.81278     69.09368
##       3: 12515084 2026  61         0 16.02149 122.9315    50.94787     69.39531
##       4: 12515084 2031  66         0 16.06730 123.4057    51.08273     69.69723
##       5: 12515084 2036  71         0 16.11311 123.8802    51.21737     70.11885
##      ---
## 1852196:  6691970 2091 165         0 14.02046 149.2695   126.53544     21.80980
```

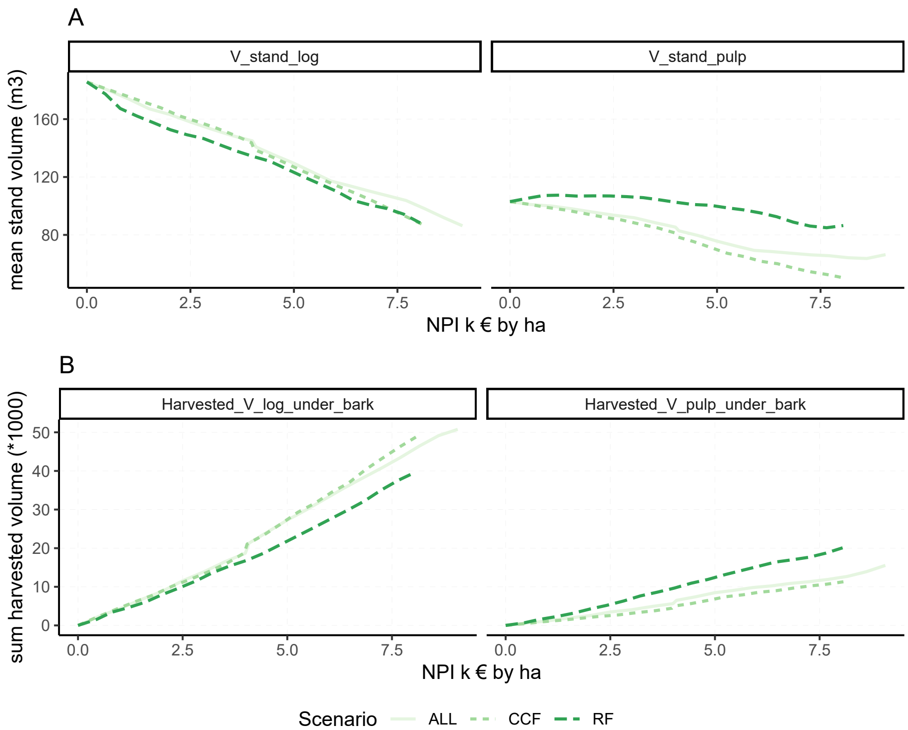

Figure 4: A. Mean standing and B. harvested pulp and log timber under three types of management regimes over harvest intensity gradient

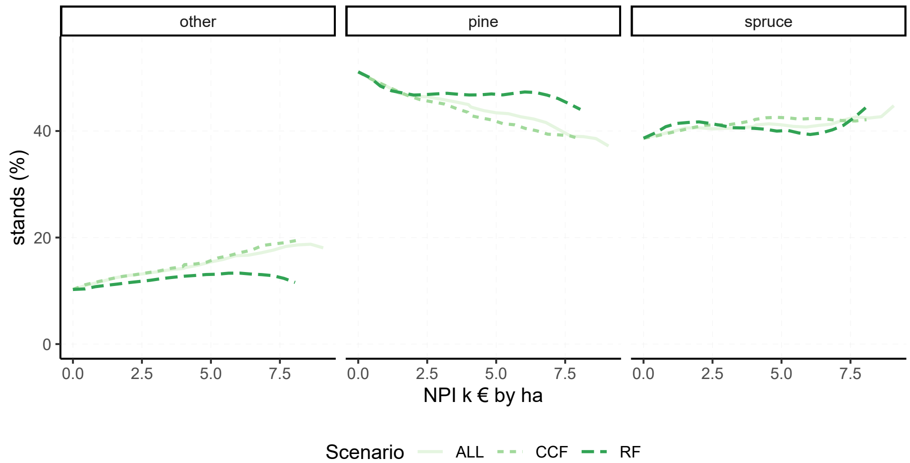

Figure 5: Changes in species composition under different management groups and harvest intensity. (The ALL scenario leads to highest economic gain, tehrefore values for CCF and RF are missing from plot)

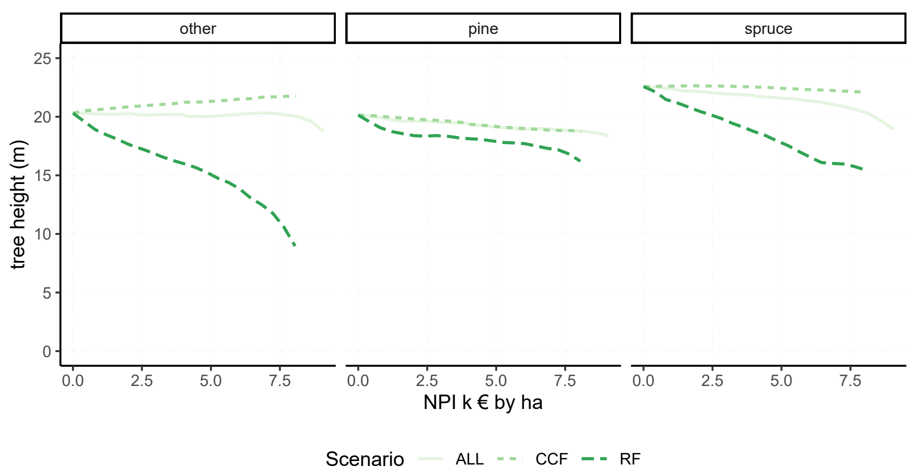

Figure 6: Mean dominant tree height under different management groups and harvest intensity.

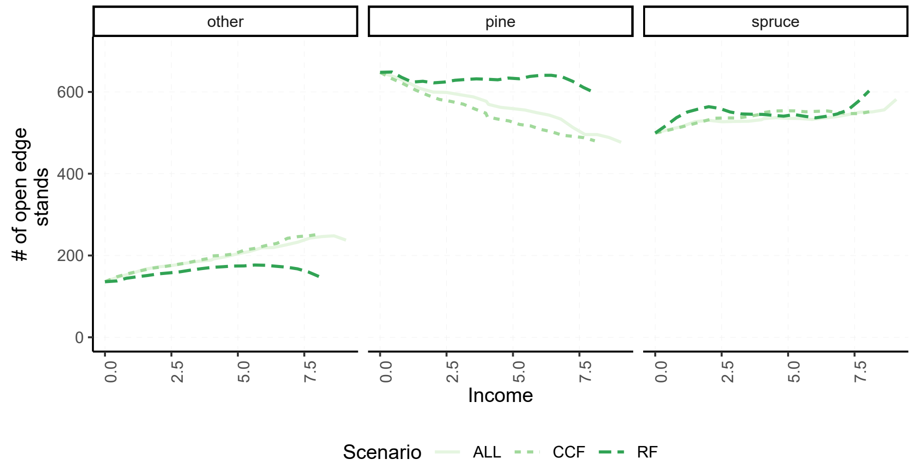

Figure 7: Yearly count of stands with open edge over the intensity gradient

```
## 1852197:  6691970 2096 170         0 13.75152 146.9029   126.40365      19.62537
## 1852198:  6691970 2101 175         0 13.57640 145.4288   125.87290      18.73834
## 1852199:  6691970 2106 180         0 13.47255 144.6260   125.76314      18.08305
## 1852200:  6691970 2111 185         0 13.42110 144.3109   126.50326      17.01734
##          Harvested_V Harvested_V_log_under_bark Harvested_V_pulp_under_bark
##       1:           0                          0                           0
##       2:           0                          0                           0
##       3:           0                          0                           0
##       4:           0                          0                           0
##       5:           0                          0                           0
##      ---
## 1852196:           0                          0                           0
## 1852197:           0                          0                           0
## 1852198:           0                          0                           0
## 1852199:           0                          0                           0
## 1852200:           0                          0                           0
##          Biomass        N THIN PEAT    H_dom     D_gm income_biomass
##       1:       0 697.8802 <NA>    1 167.9335 18.70460              0
##       2:       0 696.3087 <NA>    1 168.1394 18.73898              0
##       3:       0 694.7542 <NA>    1 168.3448 18.77329              0
##       4:       0 693.2163 <NA>    1 168.5497 18.80752              0
##       5:       0 691.6946 <NA>    1 168.7540 18.84168              0
##       ---
## 1852196:       0 251.7209 <NA>    0 260.0189 29.40783              0
## 1852197:       0 241.5970 <NA>    0 260.4277 29.55030              0
## 1852198:       0 233.8745 <NA>    0 260.8226 29.69387              0
```

```
## 1852199:       0 228.0484 <NA>    0 261.2026 29.83591             0
## 1852200:       0 223.6549 <NA>    0 261.5679 29.97626             0
##          CARBON_STORAGE name_new branching_new avohaakut THIN_included
##       1:             NA       SA          <NA>        SA         FALSE
##       2:             NA       SA          <NA>        SA         FALSE
##       3:             NA       SA          <NA>        SA         FALSE
##       4:             NA       SA          <NA>        SA         FALSE
##       5:             NA       SA          <NA>        SA         FALSE
##     ---
## 1852196:       267558.7       SA          <NA>        SA         FALSE
## 1852197:       262147.2       SA          <NA>        SA         FALSE
## 1852198:       256662.0       SA          <NA>        SA         FALSE
## 1852199:       251972.7       SA          <NA>        SA         FALSE
## 1852200:       247921.1       SA          <NA>        SA         FALSE
##          mainRegime scenSimpl2 scenNumb landscape difference time_thinning
##       1:         SA        ALL        0 2016_ALL0         NA           >10
##       2:         SA        ALL        0 2021_ALL0         NA           >10
##       3:         SA        ALL        0 2026_ALL0         NA           >10
##       4:         SA        ALL        0 2031_ALL0         NA           >10
##       5:         SA        ALL        0 2036_ALL0         NA           >10
##     ---
## 1852196:         SA         RF        9  2091_RF9         NA           >10
## 1852197:         SA         RF        9  2096_RF9         NA           >10
## 1852198:         SA         RF        9  2101_RF9         NA           >10
## 1852199:         SA         RF        9  2106_RF9         NA           >10
## 1852200:         SA         RF        9  2111_RF9         NA           >10
##          avoh_Simpl simpleScen open_edge      area siteFertility
##       1:         SA        ALL      TRUE 10218.091          poor
##       2:         SA        ALL      TRUE 10218.091          poor
##       3:         SA        ALL      TRUE 10218.091          poor
##       4:         SA        ALL      TRUE 10218.091          poor
##       5:         SA        ALL      TRUE 10218.091          poor
##     ---
## 1852196:         SA         RF      TRUE  2479.115       fertile
## 1852197:         SA         RF      TRUE  2479.115       fertile
## 1852198:         SA         RF      TRUE  2479.115       fertile
## 1852199:         SA         RF      TRUE  2479.115       fertile
## 1852200:         SA         RF      TRUE  2479.115       fertile
##          soilDepthLess30       soilType species   windRisk twoRegm      NPI
##       1:           FALSE        organic    pine 0.02327795      SA 0.000000
##       2:           FALSE        organic    pine 0.02332427      SA 0.000000
##       3:           FALSE        organic    pine 0.02337051      SA 0.000000
##       4:           FALSE        organic    pine 0.02341666      SA 0.000000
##       5:           FALSE        organic    pine 0.02346272      SA 0.000000
##     ---
## 1852196:           FALSE mineral coarse  spruce 0.05105826      SA 3.622254
```

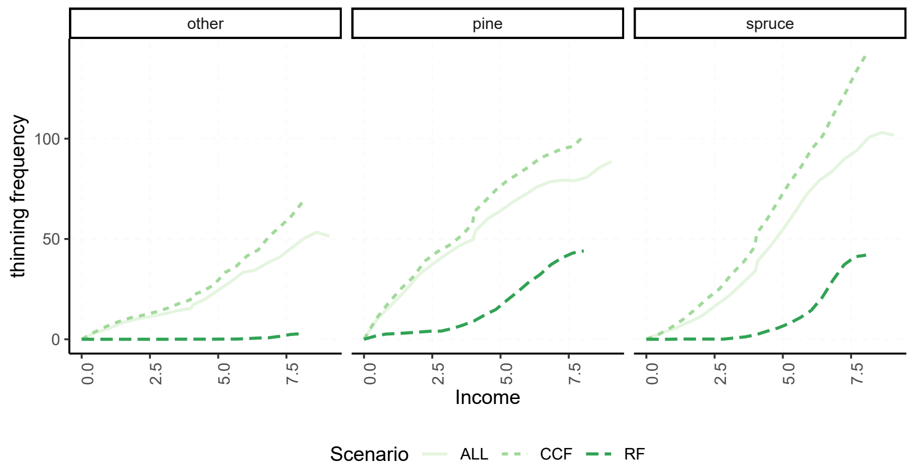

Figure 8: THe frequency of the thinnings by management groups, species and harvest intensity gradient

```
## 1852197:           FALSE mineral coarse  spruce 0.05130966      SA 3.622254
## 1852198:           FALSE mineral coarse  spruce 0.05155323      SA 3.622254
## 1852199:           FALSE mineral coarse  spruce 0.05178835      SA 3.622254
## 1852200:           FALSE mineral coarse  spruce 0.05201497      SA 3.622254
##               MF stands_n   SA_prop THIN2
##       1: 1.81712     1470 100.00000  <NA>
##       2: 1.81712     1470 100.00000  <NA>
##       3: 1.81712     1470 100.00000  <NA>
##       4: 1.81712     1470 100.00000  <NA>
##       5: 1.81712     1470 100.00000  <NA>
##      ---
## 1852196: 1.74564      894  60.81633  <NA>
## 1852197: 1.74564      894  60.81633  <NA>
## 1852198: 1.74564      894  60.81633  <NA>
## 1852199: 1.74564      894  60.81633  <NA>
## 1852200: 1.74564      894  60.81633  <NA>
```

Discussion

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 valuesm, 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 uncertainities in future wind occurences

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