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Final Report of the FOSTER project

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LUONNONVARAKESKUS

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Tiivistelmä

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Suomen metsiin kohdistuu ilmastonmuutoksen ja puustotuhojen mukanaan tuomia haasteita sekä odotuksia ja vaatimuksia monipuolisten ekosysteemipalveluiden tuottamisesta. Tarvitsemme ilmastokestäviä metsiä, jotka pystyvät turvaamaan erilaiset ekosysteemipalvelut. Tulevaisuuden monitavoitteiset metsät ja niihin kohdistuvat riskit muuttuvassa ilmastossa (FOSTER) -hankkeessa tutkittiin ilmaston ja erilaisten tuhonaiheuttajien sekä erilaisten metsänhoitoskenaarioiden vaikutuksia metsiin ja niiden tuottamiin ekosysteemipalveluihin.

Tuhonaiheuttajien ja ilmastonmuutoksen vaikutukset metsiin havaittiin merkittäviksi. Tärkeimpien tuhonaiheuttajien (tuuli, kirjanpainaja ja hirvieläimet) vaikutusten lisääntyminen nykytasosta on todennäköistä tulevaisuudessa. Muuttuva ilmasto myös voimistaa esimerkiksi kirjanpainajan vaikutuksia metsissä merkittävästi. FOSTER-hankkeessa tutkimme myös mikroilmaston mahdollisia vaikutuksia metsädynamiikkaan, mikroilmaston huomioimisen vaikutusta makroilmastoon sekä sitä, miten mikroilmasto voidaan ottaa huomioon erilaisissa simulaatiomalleissa. Simuloimme kahdella metsien kasvua ja dynamiikka kuvaavalla mallilla erilaisia metsänhoidon ja maankäytön skenaarioita sekä maisematasolla (pitkän aikavälin simulaatiot, joihin sisältyy ilmastonmuutos ja puustotuhot) että aluetasolla (lyhyen aikavälin simulaatiot, joissa vallitsee nykyinen ilmasto). Simulaatiotulokset osoittivat, että ilmastonmuutoksen hillintään tähtäävä metsänhoito voivat lisätä hiilivarastoja ja tukea luonnon monimuotoisuutta, mutta siihen liittyy korkeampi tuhoriski ja hakkuumäärien vähentyminen. Toisaalta sopeutumiseen tähtäävä metsänhoito pienentää metsien hiilivarastoja ja monimuotoisuutta hakkuumäärien kuitenkin kasvaessa suhteessa nykymetsänhoitoon. Sopeutumisskenaariot vähensivät tehokkaasti kirjanpainajariskiä muuttuvassa ilmastossa.

FOSTER-hankkeessa yhdistettiin metsien häiriö-, ilmastonmuutos- ja metsänhoitoasiantuntemusta ja sovellettiin monimutkaisia mallinnusmenetelmiä Suomen metsien tulevaisuuden ymmärtämiseksi. Tulokset osoittavat, että muuttuvan ilmaston ja häiriöiden vaikutukset voivat olla huomattavia. Tulevaisuuden metsänhoidon tuleekin olla yhdistelmä ilmastonmuutoksen hillintää ja siihen sopeutumista ja varautumista.

Asiasanat: metsänhoito, monitoimisuus, metsätuhot, ilmastonmuutos, mikroilmasto, hirvieläintuho, ilmastonmuutoksen hillintä, tuhoriskien ennakointi, ekosysteemipalvelut, metsämallit

Abstract

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Finnish forests are facing challenges from climate change and increasing natural disturbances while demands for the provisioning of diverse ecosystem services should be ensured. Resilient, multifunctional forests are therefore needed for the future. Future multipurpose forests and their disturbance risk in the changing climate (FOSTER) -project investigated the impacts of climate change and natural disturbance agents on forests as well as the synergies and trade-offs between ecosystem services under multiple alternative forest management scenarios.

We found significant impacts of disturbances and climate change on forests. Impacts of disturbance agents, such as wind, spruce bark beetle, and ungulate browsers, are likely to increase in the future. Impacts of deer species (whitetail deer, roe deer) with expanding distribution ranges and increasing populations may have unexpected impacts on forest ecosystems. Climate change interacts with disturbances and exacerbates disturbance effects, specifically in the case of bark beetles. FOSTER also explored the potential effects of micro-climate on forest disturbances and how to take them into account in modelling. Using a multi-model approach, various forest management and land-use scenarios were simulated for both smaller landscapes (long-term simulations including climate change and disturbances) and larger regions (short-term, current climate simulations). The simulation results indicate that mitigation management can increase carbon storage and support biodiversity but carry higher disturbance risks and considerably reduce harvested volumes. Conversely, adaptation-focused management was less beneficial for carbon storage but yielded higher harvests. The adaptation scenarios aimed to reduce disturbance risks were effective in reducing bark beetle risk under climate change.

The FOSTER project has brought together forests disturbance, climate change and forest management expertise and applied complex modelling approaches to understand the future of Finnish forests. The results show that impacts of changing climate and disturbances may be substantial. Thus, the future forest management should include actions to not only mitigate climate change, but also prepare for adaption to the dramatic changes it may bring in order to ensure resilient ecosystem-provisioning in the future.

Keywords: forest management, multifunctionality, disturbances, climate change, microclimate, browsing, mitigation, adaptation, ecosystem services, forest models

Contents

1. Introduction

1.1. Objectives

FOSTER – "Future multipurpose forests and their disturbance risk in the changing climate" -project was funded by the Ministry of Agriculture and Forestry in 2021 as part of the Catch the Carbon Research and Innovation Programme (R&I programme). The overall aim of the FOSTER project was to provide solutions to foster forest resilience with forest management, game and wildlife policies and efficient land use while taking into account the changing forest disturbances. Specifically, the main research questions were; 1) How resilient forests are to the risks posed by climate change? 2) What are the synergies and tradeoffs between different forest management?

1.2. Overview

Forests and their ability to uptake and store carbon are crucial on Finland's road to reach carbon neutrality in 2035. The important role of forests in mitigating climate change has been acknowledged nationally, and at European and global scale. Different choices of forest management practices and land-use decisions can enhance the carbon fluxes and storage significantly. On the other hand, forest disturbances have increased in Europe over the past decades and they are predicted to increase even more in the future with the changing climate. Such development is threatening the mitigation potential of forests. In addition to carbon uptake, forests provide numerous other ecosystem services, such as timber and recreational values. The role of forests is also significant for conserving biodiversity, the foundation of ecosystem services.

The FOSTER project was aimed to provide solutions to foster forest resilience with forest management, game and wildlife policies, and efficient land use while taking into account the changing climate and forest disturbance regimes. In FOSTER, we simulated different forest, land-use, and game management scenarios at landscape, regional and national scales and assessed their economic, social, and ecological impacts using metrics for different ecosystem services. We analyze both short- and long-term changes and resilience of forests as well as their ability to adapt to the changing climate and the forest disturbances.

The FOSTER project was divided into seven work packages with different specific objectives. Ungulate impacts on forest ecosystems were studied with literature review, GPS-collar data and remote sensing data, and simulation modelling. These results are introduced here first in Chapter 2 ”Browsing by cervids in Finland”. Changing climate was an integral part of the FOSTER project where future climate change scenarios were needed to study the impacts of changing disturbance regimes to forests. In addition, we initiated a collaboration effort to implement microclimate effects into simulation model workflow. Methods and materials for climate change scenarios as well as for the microclimate work are presented in Chapter 3 ”Changing climate”. Finally, the third large entity in the FOSTER project was the simulations of future dynamics of multifunctional forests in landscape and regional scale under different forest management and land-use scenarios. Simulations were carried out with two different state of the art simulation models and the results for the simulations are presented in Chapter 4 ”Simulating future multifunctional forests”.

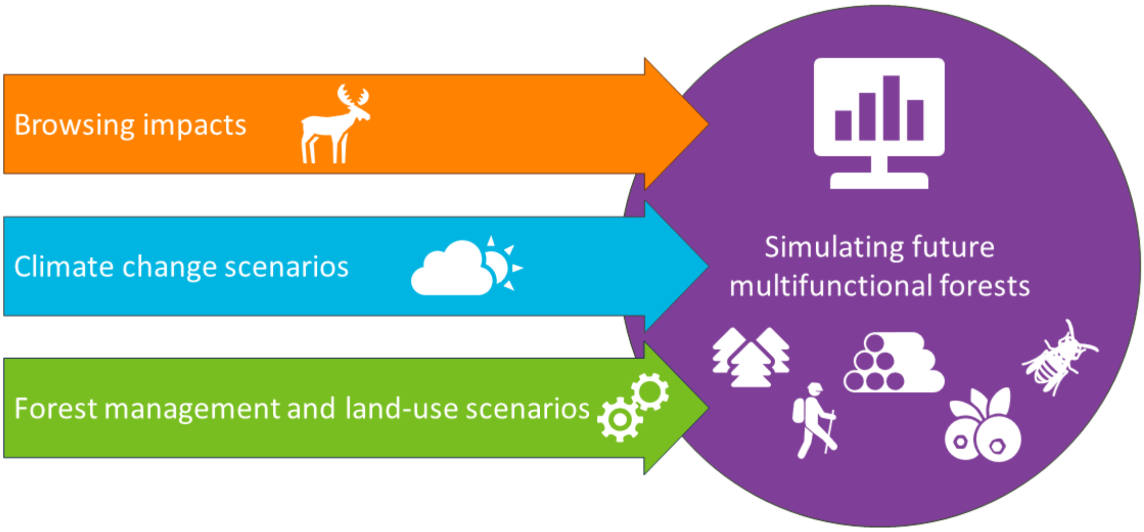


Figure 1. Overview of FOSTER project and its objectives.

2. Browsing by cervids in Finland

2.1. Cervids and forests in Finland

In Finland, there are six species of browsing cervids which form varying compositions of cervid assemblages in different parts of the country. In the south-western part of country the highest populations consists of white-tailed deer (*Odocoileus virginianus* Zimmermann), moose (L.) and roe deer (*Capreolus capreolus* L.); in central and eastern areas moose is present with highest numbers accompanied by locally significant populations of roe deer; and in the north the most numerous cervid species are moose and semi-domesticated reindeer (*Rangifer tarandus* L.) (Finnish Natural Resources Institute 2023, Reindeer Herders' Association 2023). In addition, there are smaller local populations of fallow deer (*Dama dama*, Niemi et al. 2015) and wild forest reindeer (*Rangifer tarandus fennicus*). All these cervids have potential to influence regeneration and early succession of their preferred browse trees (see e.g., Ammer 1996, Heikkilä & Tuominen 2009, den Herder & Niemelä 2003, Ramirez et al. 2018, Rooney 2001). The species that can have biggest effects on Finnish forests are in the order of currently assumed importance moose, white-tailed deer and roe deer. However, there is lack of knowledge regarding the many exact effects and importance of deers in Finnish forests.

Effects of moose on boreal forests have been rather thoroughly researched for a long time. High moose (*Alces alces* L.) populations have caused extensive forest damage in the Fennoscandian boreal forests in recent decades (Markgren 1974, Lavsund et al. 2003, Bergqvist et al. 2014, Nevalainen et al. 2016). In Finland, the results of the 10th National Forest Inventory (NFI; 2004–2008) showed some symptoms of moose damage on 990,000 hectares, or 4.9% of the total forest area (Nevalainen et al. 2016). Moose damage is partly determined by their population density, as well as factors related to available browse and suitable habitat (Hörnberg 2001a,b, Nikula et al. 2019, 2021). The clearest connections between moose population and forest damages so far have been shown by Nikula et al. (2021) who developed regional models to predict the area damaged by moose as a function of their population and forest characteristics observed in the NFI. For moose it has now been possible to take a next step and attempt to adapt prediction models for moose damage to forestry modelling and thus make more realistic forestry projections for future including this marked disturbance.

The role of smaller deer with currently high numbers, white-tailed and roe deer, has so far been under rather limited research Finnish forests. Their population growth has happened recently and their possible role as forest disturbance factor has therefore risen also just in recent years. However, their impact on forests in their established range is well known (e.g., Ammer 1996, Rooney 2001) and as regards roe deer it has been studied in Sweden and Norway which provides results for similar conditions than at least in southern Finland. In rare Finnish studies they have been shown to prefer rather similar forest trees and dwarf shrubs as moose (Andersson & Koivisto 1980, Helle 1980) but their preferences on habitats here and their impacts on forestry remains unstudied.

Due to the increase in the number and further spread of smaller cervids, the combined effect of multi-species and abundant cervids in terms of forest damage, future forest management goals and forest development becomes an even more important issue (Spitzer et al. 2020, Huuskonen et al. 2020). An interesting indication of the indirect effect of small deer is provided by a recent Swedish study (Pfeffer et al. 2021), which found that large numbers of smaller deer consume the ground vegetation favoured by all species to such an extent that moose are forced to use even more pine as winter food, which further increases moose damage in forests. In a study conducted in Finland, the moose density per pine sapling stands was not so good predictor for the forest damage in areas where there is higher densities of white-tailed and roe deer as compared elsewhere in the country (Nikula et al. 2021). This raises the question of whether in Finland, too, could the food competition between white-tailed deer and roe deer against moose be partial explanation to forest damage along with their direct consumption of tree saplings. In any case, we need more analysis on their role as disturbance factors in order to model forest development scenarios taking into account the impact of the multi-species deer community (De Jager et al. 2017, Ramirez 2018).

2.2. Consumption of browse trees by cervids with highest populations in Finland

Consumption of browse species and amount by cervid species makes it possible to evaluate how cervids impact on forest regeneration. In more detail, it is possible to estimate the proportion of coniferous and deciduous trees in the diets of deer to understand the potential role of deer herbivory for the dynamics of mixed species forests.

At the moment, we have good knowledge on moose food consumption and browse species preferences but there is very limited knowledge on these for white-tailed deer and roe deer in their current common range in Finland or even in similar boreal conditions. In FOSTER-project, we have reviewed the current scientific literature on the food diet preferences and food consumption of white-tailed deer and roe deer in boreal and temperate regions and evaluate the potential role of these species on forest regeneration and resilience of boreal forests in Finnish conditions (Poutanen et al. 2024, manuscript).

Our review showed that deciduous trees and forbs were the two most important group of food species categories of both white-tailed deer and roe deer diet during the entire year. For white-tailed deer diet, the third food category was coniferous trees but for roe deer the third category was shrubs. When consumption was evaluated by season, deciduous trees and forbs remained the two most important food groups in both species' diet in spring, summer and autumn. In winter, deciduous trees are still among the three most important food sources for both deer but coniferous trees comprised the biggest part of the diet for both species. When deciduous and coniferous trees were evaluated together, trees formed the majority (69%) of winter diet for white-tailed deer. Tree browse is important also in roe deer winter diet, but it is not the major component as 38% of their browse is trees (Poutanen et al. 2024, manuscript)

Most of the literature originated from temperate regions and thus information was also focused on deciduous trees. In species-poor Finnish conditions the potential browse species composition is different, and this might also lead to different selection and use. However, the result of both deer species preferring deciduous trees over conifers, except for the wintertime, is likely to hold also in boreal conditions, whenever deciduous trees are available. This can have a negative effect on promoting more deciduous-mixed forests in the boreal as an adaptive management to increasing natural disturbances and promoting biodiversity. (Poutanen et al. 2024, manuscript)

The impact of cervid food consumption onto vegetation is related to size of the animals through differences in daily biomass consumption. Our review (Poutanen et al. 2024) gives possibility to make comparisons between our main deer species in this respect as we now have estimates also to white-tailed and roe deer on their daily consumption. Our review showed that white-tailed deer consume about 2 kg of fresh biomass per individual per day and the average dry weight estimate of daily consumption was 1.5 kg. For roe deer, the daily consumption of food was 1.6 kg fresh weight per individual and 0.70 kg dry weight per individual. In comparison to these, moose daily consumption as averaged over seasons is 22.5 kg fresh weight food (Persson et al. 2000).

Taking into account the population sizes of different deer species we can compare the impact of deers in total. The Finnish moose population size is approximately 77 000 individuals (Pusenius 2023). The moose diet is estimated to be composed on 54% of deciduous trees and 39% of coniferous trees (Mysterud et al. 2000). Based on these numbers the Finnish moose population would eat 1 732 500 kg of fresh biomass daily (935 550 kg deciduous trees and 675 675 kg coniferous trees). Based on the estimates on our review, the white-tailed deer population (120 000 individuals, Aikio & Pusenius 2023) would eat in total 252 000 kg of fresh biomass daily (71 820 kg deciduous trees and 41 200 kg coniferous trees). The population size of roe deer is not evaluated in Finland, but the rough estimate can be 100 000 individuals (pers.comm. Sami Aikio & Jyrki Pusenius). Thus, the roe deer population would eat 156 000 kg of fresh biomass daily (29 796 kg deciduous trees and 16 536 kg coniferous trees). Thus, in comparison to moose, white-tailed deer and roe deer together would consume 11% of the deciduous tree biomass and 9% of the coniferous tree biomass. This indicates that moose still have a significantly larger effect on forest regeneration in general than smaller cervids in Finland. However, as both smaller deers are highly concentrated into southwest Finland their effect locally in their most dense range there is proportionally higher.

One notable phenomenon on deer food consumption is that there is a substantial supplemental wintertime feeding of game animals in Finland. It is estimated that there is 17.6 million kg per year supplementary food provided by hunters targeting especially to white-tailed deer (Pellikka et al., 2020). This is presumably already compensating for the effect of winter restrictions on food availability and promoting deer survival and reproduction (Ozoga and Verme, 1982, Rodriguez-Hidalgo et al., 2010, Milner et al., 2013). Based on our review (Poutanen et al. 2024, manuscript), white-tailed deer consume about 2 kg of fresh food daily. Thus, the artificial feeding would be quantitatively enough to completely fulfil the dietary requirements of 50 000 individuals over the winter. Furthermore, these feeding stations also support roe deer and other ungulate populations during winter. More research is needed on the effect of artificial feeding on deer populations and consequently on the possible impacts of feeding-influenced population growth and behavioural changes to local forest regeneration.

2.3. New information on habitat selection of white-tailed and roe deer in their sympatric range

Knowledge on habitat use of cervids is needed for both successful management of their population and also in analysis for their impacts on land-use, especially forestry and agriculture. To fill knowledge gaps on habitat use of white-tailed deer and roe deer in Finland, it was analysed in FOSTER-project by using location data collected earlier by GPS-collared deer (Graf et al. 2024, manuscript). For habitat analysis, we had GPS-location data of 35 roe deer and 31 white-tailed deer. Habitat use and composition was analysed using Kernel Density Estimation at Multi-Source National Forest inventory (MS-NFI) data, which is a spatially explicit data product generalizing the information from the NFI field plots using Landsat and Spot satellite images, and digital maps of roads, agricultural land, and other non-forest land. In addition to habitat composition and availability of resources we also evaluated the impact of habitat configuration (patch and edge density) in the landscape (Graf et al. 2024, manuscript).

In our analysis (Graf et al. 2024, manuscript), average home ranges of roe deer varied from about 220 ha to 480 ha in summer and from 120 ha to 230 in winter. White-tailed deer had home ranges between 180-420 ha in summer and 270-360 ha in winter. It was a bit surprising that roe deer had larger home ranges in summer than white-tailed deer, but this might be explained by the fact that species were located in different landscapes and roe deer were located in more northern and less productive environments where more movement might be necessary in search for food and shelter. Both species showed preference for agricultural lands, but there were seasonal differences as white-tailed deer did not prefer agricultural lands during winter. Deciduous seedling stands were found to be important for both species during summer and young pine forest were important in winter. As there also was effect on patch density on habitat selection, it might be that forest seedling stands close to forest edges near agricultural land might be at higher risk of browsing damage when forage on agricultural land becomes scarce in the winter. As agricultural land was important habitat the effects of various agricultural crops on habitat selection and browsing damage in adjacent seedling stands should be investigated in future studies.

2.4. National scenarios of moose damages in forestry scenario modelling

Several risks are expected to influence future forests and forestry in Finland. One main damage agent that cause damages regularly on wide areas is moose. To make reasonable projections on development of forests in future, these damages should be included forestry models and the models should also be able to predict the susceptibility of projected in forest structures to browse damage.

Recently, Nikula et al. (2021) formulated a prediction model where moose damage was region-specifically dependent on the total forest area, proportions of seedling stands and mature forests, and moose population density per land area. In FOSTER-project we developed this modelling further and augmented the European Forestry Dynamics Model (EFDM) for the area of seedling stands damaged by moose (Vauhkonen et al. 2023). The augmented model was tested in projecting both forest resources and moose damage for 18 million hectares of forest land in Finland, based on input data from the National Forest Inventory (NFI). Modelling the area of seedling stands damaged as a function of moose population density, forest characteristics, and region-specific interactions of these variables was found to work realistically for 30 years, predicting that the area of seedling stands damaged by moose would increase by up to a third from the last NFI observation. Our work laid the groundwork for future to model consequential, large-scale ecological and socio-economic effects of moose browsing on forests. Next steps towards more comprehensive analysis would be introduction of models that describe growth and quality losses (Heikkilä and Löyttyniemi 1992; Wallgren et al. 2014; Matala et al. 2020) in these damaged stands and analyze which would be the economic losses due to impaired further development in forests damaged by moose in the long run.

3. Changing climate

3.1. Climate change scenarios

The climate scenarios used in this study were based on the EURO-CORDEX model simulations (Kotlarski et al. 2014, Jacob et al. 2020). The EURO-CORDEX is the European branch of the Coordinated Regional Climate Downscaling Experiment (CORDEX) initiative to provide dynamically downscaled high-resolution climate scenarios for the European domain. The dynamical downscaling consists of running a limited area regional climate model (RCM) over a selected domain of interest for long continuous simulation times driven by lateral boundary conditions obtained either from a global climate model (GCM) simulation or global reanalysis of weather observations. The most recent EURO-CORDEX simulations which are currently publicly available are based on the Coupled Model Intercomparison Project phase 5 (CMIP5) GCM simulations (Taylor et al. 2012, Flato et al. 2013), as the dynamical downscaling of the CMIP6 GCM simulations (Eyring et al. 2016) is still undergoing. The results of the EURO-CORDEX simulations are available for numerous meteorological variables from a bunch of model simulations.

Here, we selected at first data from seven pairs of GCM-RCM simulations (Table 1) under the Representative Concentration Pathway (RCP) scenarios RCP4.5 and RCP8.5 (Riahi et al. 2011, Thomson et al. 2011, van Vuuren et al. 2011). Regarding the global greenhouse-gas emissions, RCP4.5 is an intermediate pathway assuming that the emissions peak before the year 2050 whereas in the high-end RCP8.5 pathway the emissions continue to rise throughout the 21st century. In the CMIP6 simulations the RCPs were replaced by homologous Shared Socioeconomic Pathway (SSP) scenarios (Riahi et al. 2017). By the end of the current century, the increase in global mean temperature relative to the preindustrial level falls very likely within the range from 2.1 °C to 3.5 °C under SSP2-4.5 and between 3.3 °C and 5.7 °C under SSP5-8.5 (IPCC, 2021). Thus, both pathways will lead to a considerably higher level of warming compared to the target of the 2015 Paris agreement to limit the increase in global mean temperature preferably to 1.5 °C. This is, however, a very challenging target (Samuelsson et al. 2016, IPCC 2022). In fact, the global greenhouse-gas emissions between 2005 and 2020 tracked most closely the RCP8.5 pathway (Schwalm et al. 2020). Consequently, Schwalm et al. (2020) argued that RCP8.5 should be considered as a useful risk assessment tool, although it also has been argued that given the current climate policies, RCP8.5 should be clearly labelled as a highly uncertain worst-case scenario (Hausfather & Peters 2020).

In Finland, like elsewhere in the high northern latitudes, the rate of warming has clearly exceeded the global average within the recent decades (Rantanen et al. 2022). Also in the future, the mean temperature is projected to increase substantially more rapidly in Finland compared to the global average, although the ratio of the warming rate in Finland to the global mean warming rate is projected to somewhat decrease and converge towards ~1.6 by the end of the current century (Ruosteenoja & Jylhä 2021). Relative to the period 1981–2010 this would mean that under the SSP5-8.5 pathway the annual mean temperature in Finland would likely increase by nearly 6 °C by the late 21st century with 90% confidence interval from 3.3 °C to 8.6 °C. Under SSP2-4.5 the corresponding temperature increase would be very likely within the range from 1.7 °C to 5.6 °C. For the upper part of the distribution of possible temperature changes these are slightly higher estimates than those based on the CMIP5 model simulations under the RCP8.5 and RCP4.5 pathways (Ruosteenoja et al. 2016).

Moreover, the mean temperature is projected to increase more rapidly in winter than in summer. Nevertheless, with the global warming levels of only 1–2 °C the occurrence of extreme summertime heatwaves in Finland, for instance, is expected to multiply (Ruosteenoja & Jylhä 2023).

In addition to temperature increase, also precipitation levels are projected to increase in Finland. The increase in annual precipitation level from 1981–2010 to 2070–2099 ranges under SSP5-8.5 very likely from 7% to 31% and under SSP2-4.5 from 1% to 20% (Ruosteenoja & Jylhä 2021). These estimates are very close to those based on the earlier RCP pathways. It is very likely that the precipitation levels will increase in winter but in summer the direction of the change is uncertain, particularly in the southern half of Finland, yet the precipitation levels will more likely slightly increase than decrease also in summer. However, the possible increase in summer precipitation has been attributed to an intensification of heavy precipitation events (Myhre et al. 2019). Accompanied with enhancing evaporation and a general tendency towards more extreme and variable precipitation conditions in a warmer climate (Giorgi et al. 2011, Lehtonen & Jylhä 2019), this may lead to an increase also in drought occurrence (Ruosteenoja et al. 2018).

Anticipated changes in other climate variables in Finland include slightly increasing solar radiation in summer and early autumn and decrease in diurnal temperature range in winter (Ruosteenoja & Jylhä 2021). Little changes are projected both for mean and extreme wind speeds (Ruosteenoja et al. 2019, Ruosteenoja & Jylhä 2021), but decreasing soil frost (Lehtonen et al. 2019) may contribute to increasing wind damage in winter.

Although due to their finer resolution RCM simulations tend to outperform GCM simulations in capturing many regional-scale climatic features, direct application of RCMs in many impact modelling studies is hampered by model biases (Casanueva et al. 2016). Overall, the EURO-CORDEX simulations tend to be often too cold, too wet and too windy (Vautard et al. 2021). Thus, in this project we performed a statistical bias correction on the model data by applying a distributional-based quantile mapping technique. It is a routinely applied technique in atmospheric sciences to correct biases of RCM simulations compared to observational data (Maraun 2013). In quantile mapping, cumulative probability distributions of simulated time series of daily weather variables are fitted to the observed distributions within the calibration period, separately for each month. Eventually, the monthly probability distributions of corrected model variables become identical with the observed distributions within this period. Then, the same corrections are applied to the whole simulation period. A detailed description and evaluation of quantile mapping for correcting simulated temperature time series was presented by Räisänen and Räty (2013) and for precipitation time series by Räty et al. (2014). However, quantile mapping can be used for correcting biases also in other simulated weather variables, like demonstrated, e.g., by Wilcke et al. (2013). Here, we used a version of quantile mapping that is referred to as quantile mapping with smoothing where the extreme tails of the probability distributions are not precisely fitted (Räisänen & Räty 2013, Räty et al. 2014).

The bias correction was performed for the following variables: daily minimum, mean and maximum air temperatures at 2 m height, daily precipitation level, daily mean wind speed at 10 m height, daily global radiation and daily relative humidity at 2 m height. For relative humidity, the bias correction was performed relative to ice in subzero temperatures, but the corrected values were transformed relative to water. The vapor pressure deficit needed in the iLand simulations was calculated from the corrected mean temperature and relative humidity.

The bias correction was performed separately for each variable and for temperature variables the corrected values were finally adjusted, if needed, so that daily maximum temperature could not be lower than the minimum temperature and by checking that the maximum and minimum temperatures on adjacent days behaved reasonably. As our observational data set for temperature variables, precipitation, global radiation and relative humidity in the bias correction procedure, we used gridded daily climatology produced by the Finnish Meteorological Institute that covers Finland at the spatial resolution of 10 km × 10 km (Aalto et al. 2016). Water vapor deficit was calculated based on the daily means of air temperature and relative humidity. In correcting the wind speed, we used interpolated values from the ERA5 reanalysis data (Hersbach et al. 2020) that were previously used in creating a gridded evapotranspiration data for Finland (Pirinen et al. 2022). As our calibration period in the bias correction procedure, we used the years 1971–2005 corresponding to the historical period of the climate model runs. During the process, we also interpolated the model data from its original grid approximately at 12.5 km × 12.5 km to the same grid with the observational data at 10 km × 10 km.

As input for the iLand model simulations, we selected a total of four model runs from the ensemble of bias-corrected climate model runs. Two model runs were selected under RCP4.5 and two runs under RCP8.5. The selection was based on the projected changes in annual mean temperature and precipitation level among the model simulations. Additionally, only one simulation from each individual GCM and RCM was selected. The selected simulations under RCP4.5 were the RCA4 model run driven by lateral boundary conditions from the global model MPI-ESM-LR and the REMO2015 run driven by boundary conditions from the NorESM1-M model. Under the RCP8.5 pathway, we selected the run by CCLM4-8-17 with boundary conditions from the EC-Earth model and the run by WRF381P with boundary conditions from the IPSL-CM5A-MR model. The IPSL-CM5A-MR_WRF381P model run in the selection represents a warm and extreme wet scenario under RCP8.5, while the EC-Earth_CCLM4-8-17 run represents a relatively dry scenario in the context of RCP8.5. The NorESM1-M_REMO2015 run represents an average scenario under RCP4.5 and the MPI-ESM-LR_RCA4 run under RCP4.5 represents a scenario with overall low-end climate change signal. The annual course of mean temperature in Finland in the selected bias-corrected model runs from 1971 to 2100 is shown in Figure 2 and the same for precipitation level in Figure 3. For the purpose of the iLand model simulations, the selected model runs were finally bilinearly interpolated onto a 1 km × 1 km grid.

Table 1. The complete list of the EURO-CORDEX model runs for which the statistical bias correction onto a 10 km × 10 km grid was performed. The four model runs that were selected as input for the *iLand* model simulations are shown in bold. The last two columns show the changes in annual mean temperature and precipitation level in Finland from 1981–2010 to 2070–2099 under RCP4.5/RCP8.5 in the bias-corrected model runs, respectively. More information about the driving GCMs can be found in Flato et al. (2013) and about the RCMs in Diez-Sierra et al. (2022).

Driving GCM	Ensemble	RCM model	Downscaling realisation	Temperature change	Precipitation change
EC-Earth	r12i1p1	CCLM4-8-17	v1	+3.0 °C / +5.0 °C	+11.1% / +11.2%
EC-Earth	r1i1p1	RACMO22E	v1	+3.2 °C / +5.1 °C	+4.4% / +15.2%
EC-Earth	r12i1p1	RCA4	v1	+3.2 °C / +5.3 °C	+12.7% / +16.9%
IPSL-CM5A-MR	r1i1p1	WRF381P	v1	+4.2 °C / +5.9 °C	+21.6% / +40.1%
MPI-ESM-LR	r1i1p1	CCLM4-8-17	v1	+2.3 °C / +4.7 °C	+7.7% / +23.4%
MPI-ESM-LR	r1i1p1	RCA4	v1a	+2.3 °C / +4.9 °C	+8.8% / +27.2%
NorESM1-M	r1i1p1	REMO2015	v1	+3.2 °C / +5.2 °C	+13.8% / +18.2%

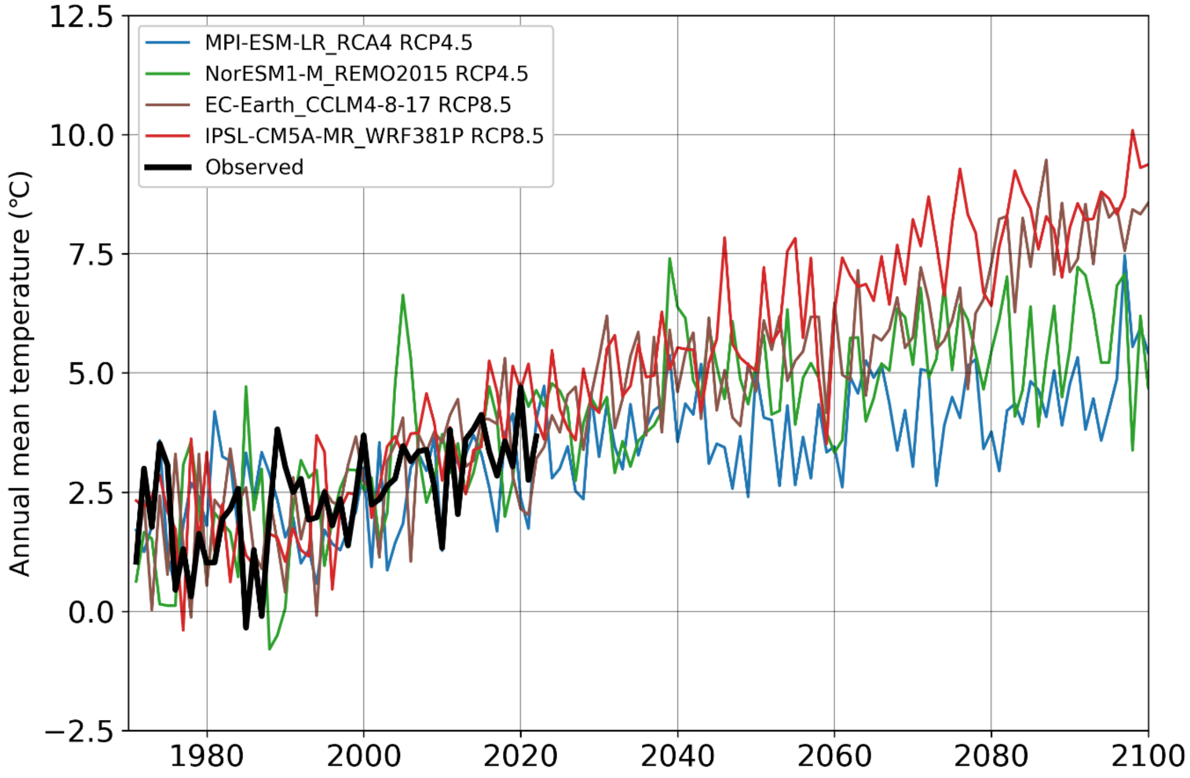


Figure 2. Annual countrywide mean temperatures in Finland in 1971–2100 in the four bias-corrected model runs that were selected as input for the simulations with the *iLand* model are shown with coloured curves. The thick black curve depicts the observed annual mean temperature in Finland in 1971–2022.

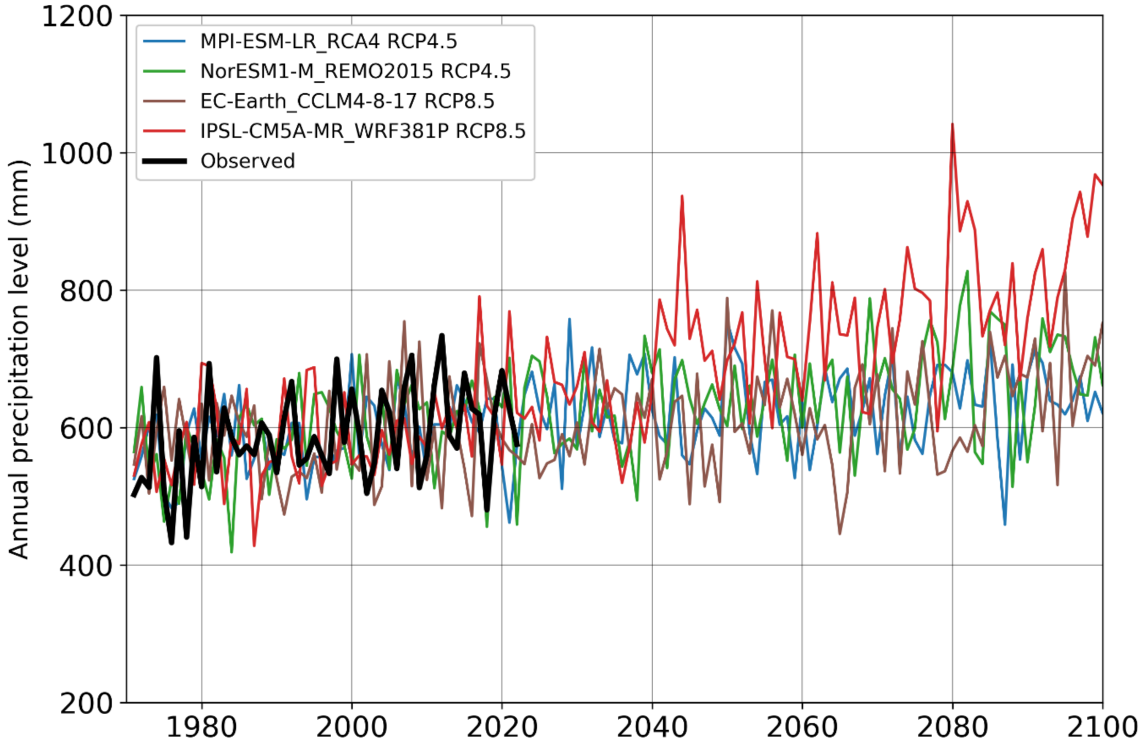


Figure 3. Annual countrywide precipitation levels in Finland in 1971–2100 in the four bias-corrected model runs that were selected as input for the simulations with the *iLand* model are shown with coloured curves. The thick black curve depicts the observed annual precipitation level in Finland in 1971–2022.

3.2. Importance of microclimate

3.2.1. Background and objectives

Microclimatic conditions inside forests differ from macroclimates in several ways (Lenoir et al. 2016, De Frenne et al. 2021). *Macroclimate* refers to large-scale climate patterns that affect entire regions, while *microclimates* are localized climate conditions within a forest, including air and soil temperature and soil moisture. Forest climates are influenced by various drivers, such as tree cover and canopy structure, topography, and proximity to water bodies (Aalto et al. 2022). Forest climates exhibit significant spatial and temporal variations due to factors like shading, wind sheltering, and ground cover. They often exhibit smaller i.e., buffered temperature and humidity variations compared to open areas (Figure 4; De Frenne et al. 2019). Due to the *buffering* effect, forests can potentially mitigate extreme weather events such as heat or drought episodes, providing more stable and moderated temperatures and humidity levels, and wind speeds compared to open areas, benefiting the biota dwelling within forests (De Frenne et al. 2021). The characteristics of forest microclimates and their impacts of forest dynamics have so far remained largely unclear, because conventional coarse-resolution macroclimate data commonly used in ecosystem and impact models (spatial resolution ≥ 1km^2) does not describe conditions inside forests and high-resolution microclimate data is not often available.

Forest management modifies microclimates as forest structure, density and species composition are altered (Ehbrecht et al. 2017). For example, clear-cutting and forest regeneration, associated with even-aged forestry traditionally implemented in Finland, can impact microclimates by altering energy and water cycles at the start of forest rotation. During the rotation, gradual changes in stand density, structure and composition may amplify or impede the effects of macroclimate on microclimate and further on various ecosystem services. For the multi-target mitigation and adaptation, future forest management could benefit of considering microclimatic and fertility gradients that control forest dynamics at landscape level. One deficit of current operative forest planning systems in Finland (e.g., *MELA* and *SIMO*) is that their forest dynamics (i.e., growth, mortality) library and soil carbon models ignore microclimatic variability by using only long-term average temperature and precipitation metrics as climatic inputs.

In FOSTER WP2 one of the aims was to investigate the effects of forest structure on microclimate, namely on temperature and humidity variability close to ground surface. This information and produced spatial layers were then used in WP4 to examine the sensitivity of the *iLand* model on microscale climate information and show the potential added value of incorporating microclimate data into model of forest landscape dynamics. All in all, this novel model integration enables us to explore forests' long-term (and likely non-linear) response to macro- and microclimate change.

3.2.2. Microclimate modeling

To generate high-resolution microclimate data, we used the open-source mechanistic microclimate model *microclimf* (Maclean 2023), version 0.1.0, developed for the R software environment (R core team 2022). In brief, *microclimf* estimates near-ground air and soil temperatures principally based upon the net energy flux density absorbed by surfaces (vegetation, soils; Figure 5) and momentum as modified by the local environment e.g., local topography. A combination of gridded climate data, remote sensing and model-derived data products were used to parameterize the *microclimf* model:

Weather, FMI Climgrid (Aalto et al., 2016), ERA5 (Hersbach et al., 2020)

- Temperature (°C)
- Relative humidity (%)
- Atmospheric pressure (kpa)
- Total shortwave radiation received by a horizontal surface (W/m^2)
- Diffuse radiation (W/m^2)
- Sky emissivity (range 0 to 1)
- Wind speed at reference height (m/s)
- Wind direction (in degrees)

Topography from digital surface and terrain models (National Land Survey of Finland)

- Elevation (meters above sea level)
- Aspect (in degrees)
- Slope angle (in degrees)

Vegetation

- Plant area index (unitless)
- Vegetation height (m)
- Ratios of vertical to horizontal projections of leaf foliage
- Maximum stomatal conductance (mol/m^2/s)
- Degree of canopy clumpiness (0 = even, 1 = highly clumped)
- Leaf reflectance values for shortwave radiation (0 – 1)
- Leaf diameters (m)
- Leaf transmittance values for shortwave radiation (0 – 1)

Soil

- Soil type (e.g. sand, silt, clay)
- Soil reflectance values for shortwave radiation (0 – 1)

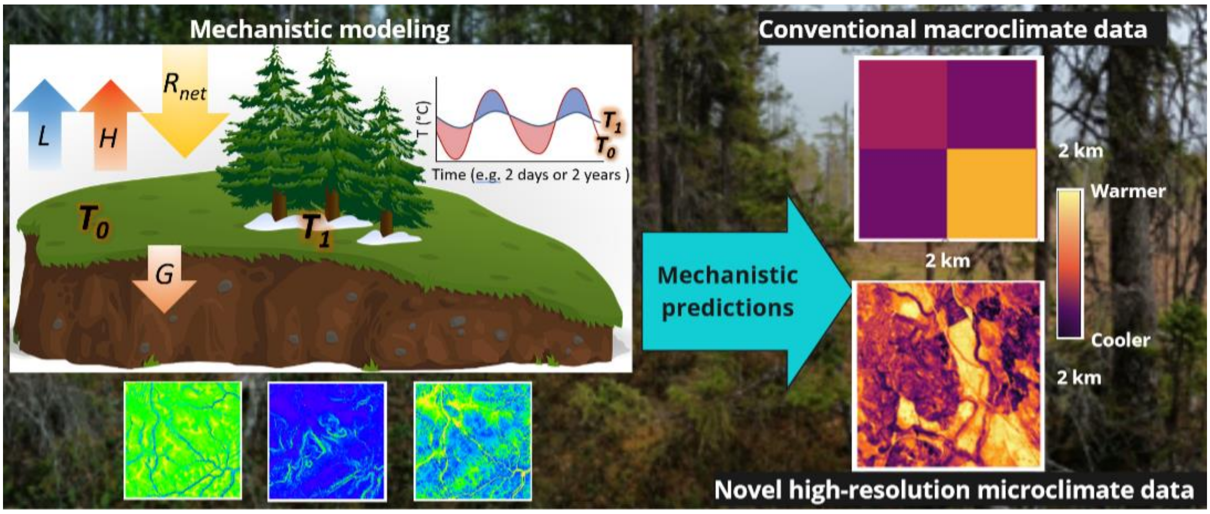


Figure 4. Conventional, coarse-resolution macroclimate data does not represent conditions inside forests (T_0=conditions outside forest, T_1=conditions inside forests). In FOSTER, we used sophisticated mechanistic modeling, and spatial environmental to produce data of microclimate at very high-resolution to be integrated with the *iLand* dynamic forest landscape model. L=latent heat flux, H=sensible heat flux, G=soil heat flux, R_{net}=net radiation.

The key outputs of the model include spatiotemporal estimates of:

- Air temperatures at requested height (°C)
- Leaf temperatures at requested height (°C)
- Ground surface temperatures (°C)
- Soil moisture fractions in the top 10 cm of the soil (m^3 / m^3)
- Relative humidity at requested height (%)
- Wind speed at requested height (m/s)
- Downward direct shortwave radiation incident on horizontal surface (W/m^2)
- Downward diffuse shortwave radiation incident on horizontal surface (W/m^2)
- Downward longwave radiation incident on horizontal surface (W/m^2)
- Upward shortwave radiation fluxes (W/m^2)
- Upward longwave radiation fluxes (W/m^2)

3.2.3. Model implementation

R environment as implemented in library *microclimf* at 10 x 10 m spatial resolution produces hourly estimates 2011–2020 from April to September. Model runs were performed in a supercomputing environment of the CSC (IT center for science) PUHTI system. The general modeling pipeline is presented in Figure 5. Due to large computational burden, the model runs were divided into two-day segments. This allowed for running the model on multiple computation nodes, lowering overall run times, and lowering the memory requirements of each of the model runs. The prediction domain was selected as a 10 x 10 km area with the following specifications (left, bottom, right, top): (299349,4 | 6766634 | 309349,4 | 6776634) – coordinates in ETRS89 / TM35FIN, EPSG:3067.

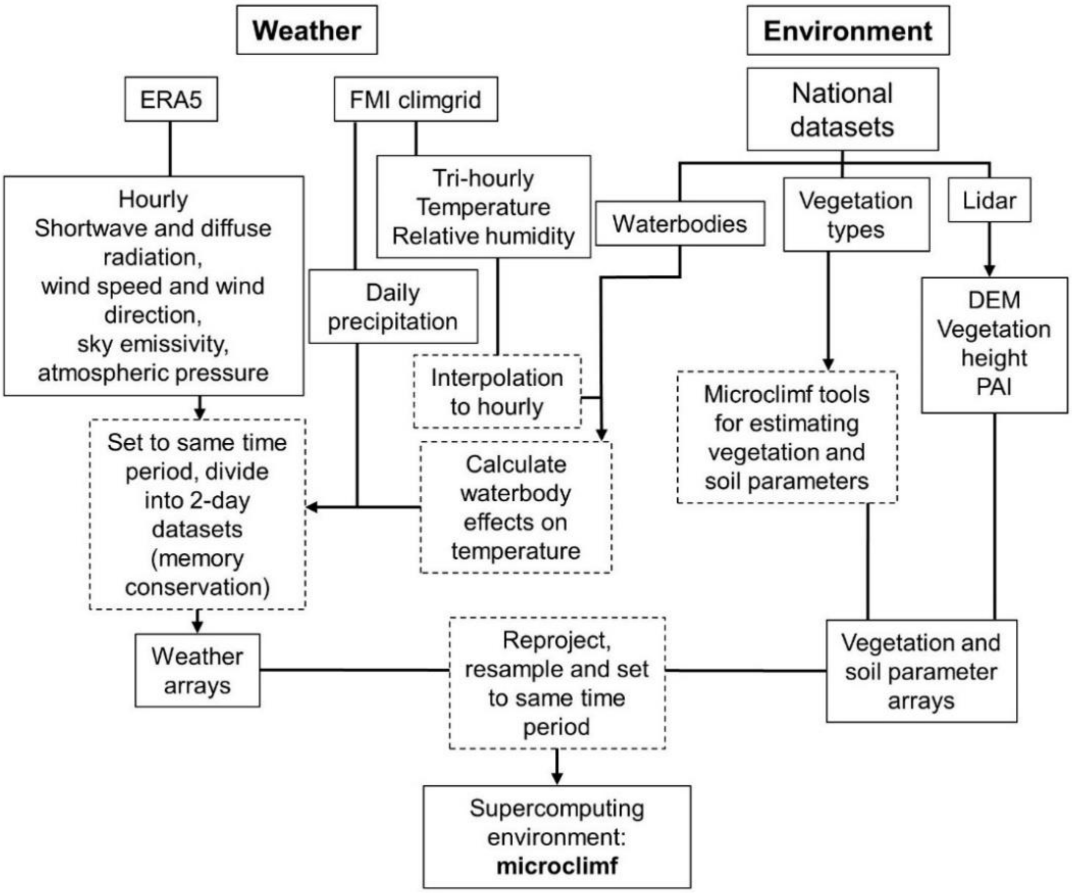


Figure 5. Summary of the modeling pipeline, taken from Kolstela et al., (under review).

3.2.4. Prediction performance

Recently, Kolstela et al. (under review) conducted cross-validation of the near-surface air temperature predictions during May-August 2020 against a comprehensive set of in-situ microclimate observations over boreal three boreal landscapes in Finland (Lohja, Hyytiälä and Värriö). The analysis suggested a reasonable predictive performance of the model with root mean square error (RMSE) between three-hourly predicted and observed temperatures across all landscapes ca. 3.3 °C. The predictive performance was found to vary between the areas and with environmental characteristics with the prediction error in general being smaller inside forest canopies compared to open areas. Figure 6 exemplifies model outputs by presenting maximum near-surface air temperature variability in Lohja area aggregated over the summer 2020.

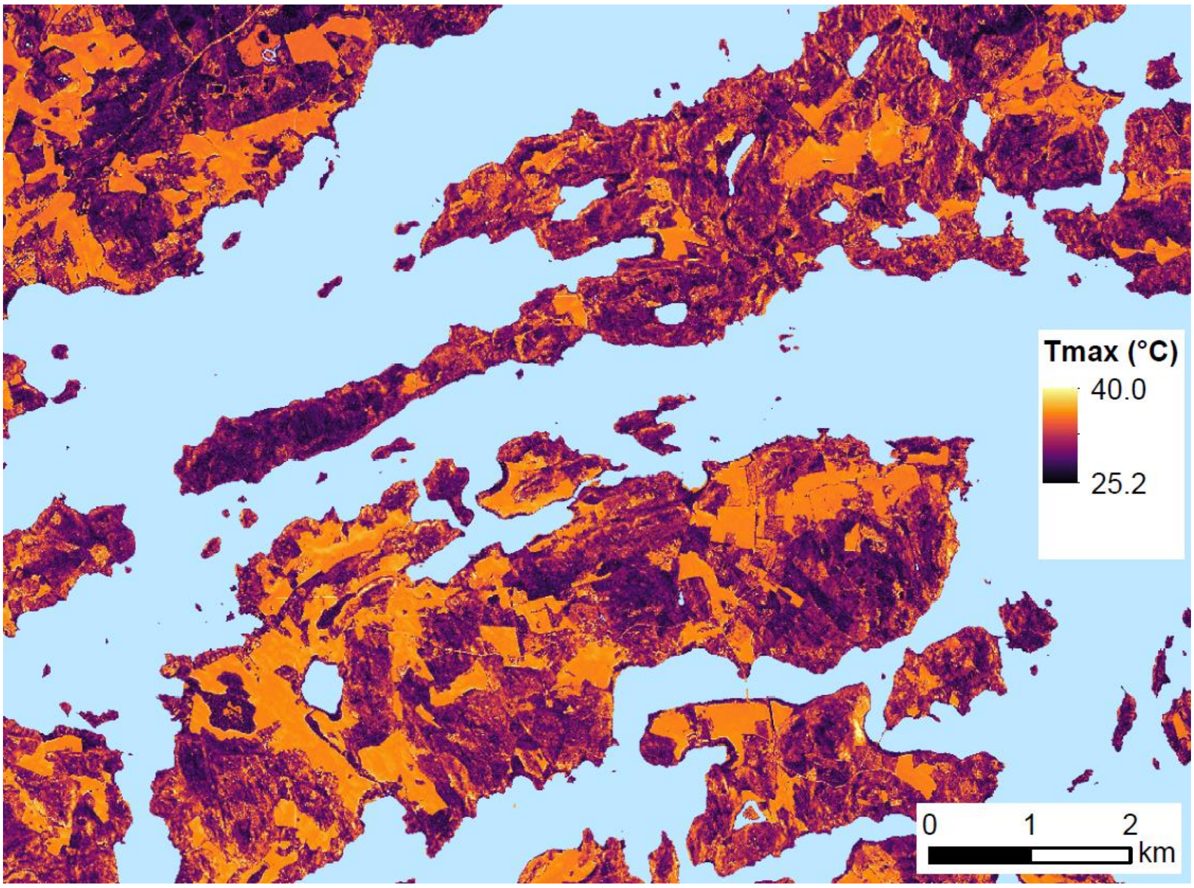


Figure 6. An example of microclimate layer produced using the *microclimf* model. The map depicts spatial variation in absolute maximum temperature close to ground surface over the summer of 2020 in Lohja region, southern Finland, at the spatial resolution of 10 × 10 m.

3.2.5. Investigating ecosystem dynamics using microclimate data

In FOSTER, we took first steps to integrate the mechanistic *microclimf* model with the dynamical forest landscape model *iLand* (Seidl et al. 2012, see also Section 4.1.4 for a more detailed description of the model). Ecosystem models generally use relatively coarse-scale (both spatial and temporal) climate data and model parameters are parametrised based on macroclimate. However, when investigating the development of forests under climate change and disturbance, particularly the crucial processes of forest recovery and re-organisation after disturbance (Seidl & Turner 2022), it becomes increasingly important to consider the impact of microclimatic variation on ecosystem processes in models (De Frenne et al. 2021).

There are multiple potential avenues towards better representation of microclimatic variation in ecosystem models, from empirically parametrised offset functions (e.g., modifying climate variables based on topography, forest structure, etc. based on empirically observed data) to fully integrating mechanistic modelling of local interactions of climate and forest. As a first step towards a more mechanistic approach, we here tested the possibility of establishing an interaction between the *iLand* forest landscape model and *microclimf*. Forest conditions generated from simulations from *iLand* (under macroclimatic conditions) were used as input data for *microclimf* which in turn provided microclimate as an output.

This resulted in two sets of climate inputs: i) conventional gridded data interpolated from weather station observations (spatial resolution of 1 × 1 km, neglecting microclimatic processes) and ii) high-resolution microclimate surfaces accounting for e.g. the effects of vegetation cover on local temperature and humidity (spatial resolution of 10 × 10 m), showing the potential variability in local climate which is currently not represented in simulation modelling (Figure 7) We then explored the range of differences between these two datasets, with a particular focus on climate variables relating to processes of forest disturbances and forest development, e.g. key *iLand* parameters related to regeneration establishment, bark beetle development and overwintering, as well as decomposition processes of deadwood and litter.

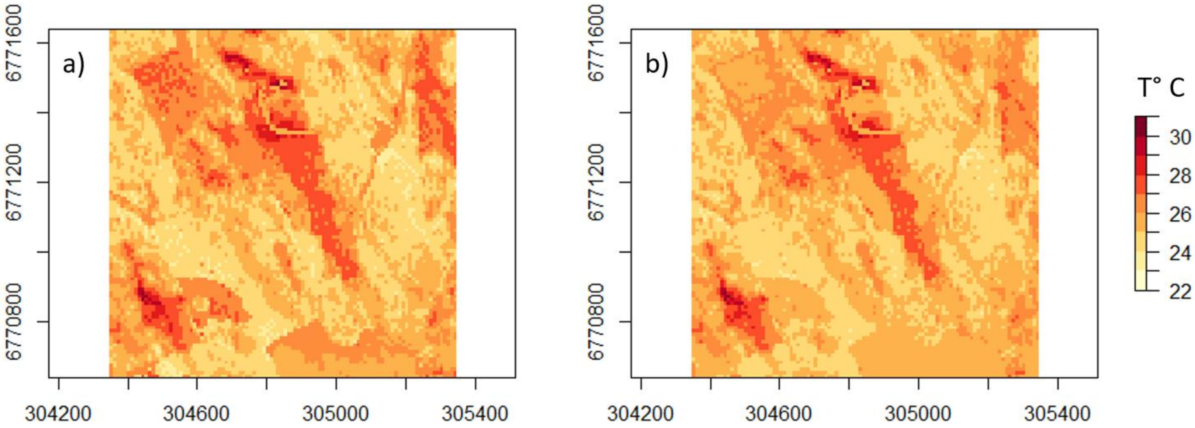


Figure 7. An example 1 km^2 from the center of the simulated landcapes showing the local differences in temperature when running *microclimf* on *iLand* vegetation output. In the macro-climate driven simulation, this entire area would have homogenous climate. Shown is average daily maximum temperature for July 2018 15 cm (a) and 150 cm (b) above ground.

4. Simulating future multifunctional forests

4.1. Scenarios and study landscapes

We applied two models for simulating the future of multifunctional forests. First, to investigate effects of climate change, disturbances, and management at a landscape level in the next 80 years, we used *iLand* ("the individual-based forest landscape and disturbance model", Seidl et al. 2012a). Second, to analyze the effects of mitigation and adaptive management in larger areas and in the short term (30 years), corresponding forest management options were simulated with *Motti* ("simulator for forest development forecasts", Hynynen et al. 2015). The short-time horizon was chosen to provide information on the effects of forest management option with time horizon relevant for meeting Finland's Carbon Neutrality Goal by 2050, whereas the long-time simulations provide insight into the long-term effects of changing forest management strategies on forest ecosystem services and biodiversity under multiple scenarios of climate change.

We simulated with both models in total of nine different forest management and land-use options, which formed three overarching themes: business-as-usual (BAU), climate change mitigation (MIT), and climate change adaptation (ADA). Business-as-usual scenario followed the current good practice guidance for forestry in Finland (Rantala 2011). The MIT and ADA scenarios were modifications of BAU by adjustments in rotation lengths and regenerated tree-species selections, allocation of set-aside areas and share of continuous cover forestry (CCF) (Table 2). In mitigation scenarios rotation periods were prolonged to allow the trees to grow larger, store carbon *in-situ* for an extended time and produce also more litter input to soil (Liski et al. 2001, Repo et al. 2015). In these options, the set-aside areas were selected prioritizing old stands or high volume stands to increase carbon storage in the landscape (Pregitzer & Euskirchen 2004, Repo et al. 2021). In adaptative scenarios the rotation lengths were shortened to reduce the risk of loss of timber because of disturbances (Zimová et al. 2020), and birch was planted in former spruce stands after clearcuts to reduce the risks from bark beetle outbreaks by lowering the share of the primary host species (Honkaniemi et al. 2020). Increasing the share of broadleaf trees is also seen as beneficial to biodiversity (Felton et al. 2021). Set-aside areas were implemented as connected areas with a random starting point to minimize edge effects and provide large continuous protected areas, which have been seen as beneficial to conservation (Fahrig et al. 2022). In *iLand* all forest management options were simulated in five different climate scenarios (historical climate and two scenarios each under RCP 4.5 and RCP 8.5), in *Motti* the current climate conditions were applied.

Table 2. Definition of different forest management scenarios with *iLand* and *Motti*.

Scenario	Rotation length	Set Aside	Broadleaf Share	CCF
BAU	Target >60-90 years in *iLand* and corresponding stand diameters in *Motti*, depending on site type.	None	Max 10% admixed but not actively added	None
MIT_1	+10%	15% of area (old/high volume stands)	As in BAU	5% of herb-rich sites (OMT)
MIT_2	+10%	30% of area (old/high volume stands)	As in BAU	5% of herb-rich sites (OMT)
MIT_3	+30%	15% of area (old/high volume stands)	As in BAU	5% of herb-rich sites (OMT)
MIT_4	+30%	30% of area (old/high volume stands)	As in BAU	5% of herb-rich sites (OMT)
ADA_1	-10%	15% of area, continuous area randomly placed, different location for each replicate	50% of spruce substituted by broadleaves	none
ADA_2	-10%	15% of area, continuous area randomly placed, different location for each replicate	100% of spruce substituted by broadleaves	none
ADA_3	-30%	15% of area, continuous area randomly placed, different location for each replicate	50% of spruce substituted by broadleaves	none
ADA_4	-30%	15% of area, continuous area randomly placed, different location for each replicate	100% of spruce substituted by broadleaves	none

4.1.1. Simulations with iLand

For the *iLand* simulations, we selected two forest landscapes in Finland (Figure 8). The first landscape is centered around the municipality of Urjala at the border of the Pirkanmaa and Kanta-Häme regions (61°04′ N, 23°27′ E) and covers a total of 53 510 ha. The landscape is a mixture of forests, agricultural land, and lakes, of which we simulated the 30 584 ha of forests with *iLand* (only upland/mineral soils, excluding peatlands). The landscape is located in the southern boreal zone (SYKE, 2015), is dominated by Norway spruce, and characterized by relatively fertile forest sites (Table 3).

The second landscape is located in the Central Finland region, in Äänekoski and neighbouring municipalities (62°38' N 25°38' E). It is straddling the border of the Southern boreal and Middle boral forest vegetation zones (Figure 8) and covers a total area of 60 436 ha, of which 30 248 are classified as forest area and simulated here. Compared to Urjala, Äänekoski landscape has poorer sites and higher shares of Scots Pine (Table 3). The initial state of the forest vegetation was derived from Metsäkeskus stand-level data (Metsäkeskus 2021) and represents an approximation of the forest state in the year 2020. *iLand* simulations were run for 80 years each, with each scenario combination being replicated 10 times to take into account stochastic variation in model processes (e.g., tree mortality, bark beetle spread).

To design the management scenarios, we first defined the Business-as-Usual scenario based primarily on Tapio Best Practice Guidelines for Sustainable Forest Management (Rantala 2011, TAPIO 2022) therefore representing the current recommendations for planting, thinning, and final harvests (in *iLand*, final harvests are currently primarily based on age rather than mean diameter as in *Motti*) for each site type and landscape (following recommendations for Southern Finland for Urjala and Central Finland for Äänekoski). To create the alternative management scenarios, final fellings were scheduled earlier or later according to scenarios, thinnings were not altered. For the ADA scenarios, planting targets were altered, replacing 50 or 100% of previous spruce targets with birch. For the MIT scenarios where CCF management was added, this was done primarily in young stands, which were transformed towards uneven aged stands through a series of selection cuttings, following a similar approach to Shanin et al. (2016). To select set-aside areas in the MIT scenarios with a focus on high-volume stands, stands on each landscape were ranked by volume per hectare in a descending order and iteratively set aside until the target of 15 or 30% of forest area was reached. In the ADA scenarios, 15% of the forest area were set-aside as one continuous forest area. The location of this area varied in each of the 10 replicates. This was done by selecting 10 center points randomly in each landscape and iteratively growing the protected area around them until 15% of the forest area was set-aside. The set-aside areas were not managed in any way and trees killed by disturbance were not salvaged.

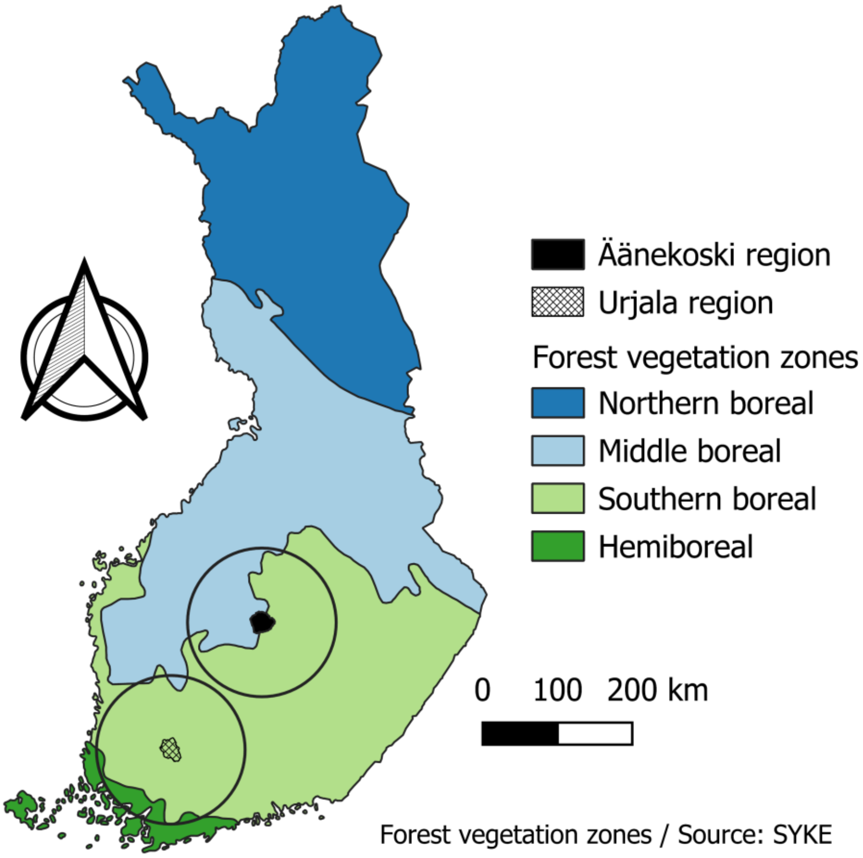
All management scenario combinations were simulated in *iLand* under 5 different climate scenarios (historical, 2 RCP 4.5 scenarios 2 RCP 8.5 scenarios, see section 3.1.1. for details on climate scenarios).

4.1.2. Simulations with Motti

For extending landscape-level results produced by *iLand* to the larger geographical areas, scenario analysis with National Forest Inventory (NFI) data and *Motti* stand simulator was carried out.

First, we defined two circular study-regions with 100 km radius and with Urjala (Region 1) and Äänekoski (Region 2) as their focal points. Then, we selected NFI12-sample plots (fieldwork 2014–2018; Korhonen et al. 2021) located inside the circles, totaling 5 371 and 5 855 plots in Regions 1 and 2, respectively. Each NFI-plot represents app. 350 ha of productive or non-productive forest land, resulting ca. 1.8 and 2.2 million hectares in Regions 1 and 2, respectively (Table 4). The detailed information of the forest sites and stands measured from each NFI-plot produced a representative view to the current stage of forests in the study-regions and served as an input for the simulations.

In the *Motti*-simulations, stand projections of NFI-sample-plot stands were predicted for 30 years according to pre-defined management regimes. Several alternative regimes were simulated to cover the variation in forest management practices currently in use. In Region 1, altogether 535 670 different stand projections were simulated, and in Region 2, the number was 663 321.



Forest vegetation zones / Source: SYKE

Figure 8. Location of study areas in Finland. Smaller shaded areas represent the *iLand* simulation landscapes (Urjala and Äänekoski), while the circles around them represent the regions simulated with *Motti* (Region 1 centered around Urjala, Region 2 centered around Äänekoski).

Table 3: Forest and site characteristics in the two study areas in *iLand* simulations.

Landscape (iLand simulation area)	**Urjala**	**Äänekoski**
Area (ha)	30 584	30 248
Site types (% coverage)		
Herb rich (OMT)	32.5	14.0
Mesic (MT)	56.2	52.0
Subxeric (VT)	7.3	30.1
Xeric (CT)	4.0	3.9
Tree species (% share of volume)		
Norway Spruce	59.4	48.4
Scots Pine	23.5	36.9
Other (Broadleaves)	17.1	14.7

Table 4: Forest and site characteristics in the two study areas in *Motti* simulations.

	Region 1 (Urjala)		**Region 2 (Äänekoski)**	
Area	**mill. ha**	**%**	**mill. ha**	**%**
Total	1.83		2.23	
Production forests		88.2		91.9
Strictly protected		5.6		3.6
Other		6.2		4.5
Mineral soils	1.46		1.64	
Herb rich (OMaT, OMT), %		23.8		19.3
Mesic (MT), %		38.9		38.4
Subxeric (VT), %		13.4		14.0
Xeric (CT, ClT), %		3.9		2.0
Peatlands	0.37		0.58	
Herb rich (Rhtkg), %		4.3		3.0
Mesic (Mtkg), %		8.4		8.1
Subxeric (Ptkg), %		3.2		9.6
Xeric (Vatkg, Jätkg), %		4.2		5.6
Volume	**mill. m^3**	%	**mill. m^3**	%
Total	307		329	
Production forests		86.5		90.9
Strictly protected		7.4		4.6
Other		6.1		4.4
Mineral soils	248		252	
Peatlands	59		77	
Tree species, share of volume		%		%
Norway Spruce		43.3		31.9
Scots Pine		43.4		58.4
Other (Broadleaves)		13.3		9.7

The forest management scenarios (BAU, MIT, and ADA) were defined same way for the *Motti*-simulations as for the *iLand* simulations (see Table 2 in chapter 4.1.).

The basic scenario **"Business As Usual" (BAU)** was first constructed from simulated datasets via linear programming (LP) using software J (Lappi & Lempinen 2014) to represent recent forest management activity in the study regions. The same simulation-LP method has recently been applied in several regional scenario analyses (e.g., Hynynen et al. 2015, Haikarainen et al. 2021). In BAU, we adjusted harvesting removals and areas of silvicultural treatments to the level of recent years (2017–2021) according to the forest statistics (Luke 2023a, 2023b) by using them as constraints in LP. The final solution for BAU included one single management regime for each sample plot. The regional results were calculated on the basis of the area represented by each sample plot.

After defining BAU, we constructed **the other scenarios (MIT1-4, ADA1-4)** by replacing specific BAU regimes with other options better reflecting the new scenarios. For example, in MIT1 the rotation length aimed to be 10% longer compared to BAU, the area of CCF in OMT-sites aimed to be 5%, and set-aside area in old stands 15% (Table 2). More specifically, regime with standard final-cutting time was replaced with the otherwise similar regime but later final-cutting time, regime including cuttings was replaced with the "no-treatments"-regime representing set-aside strategy, and the even-age regime was replaced with the CCF-regime.

The changes in rotation lengths (i.e., timing of final cuttings) were based on the stand mean diameter at the time of final cutting. The simulated regimes included several alternative mean diameters (varying around the final-cutting stages suggested in guidelines and defined separately by sites and tree species, about 2 cm intervals). Thus, we were able to replace regime initially selected for BAU with the regime including smaller or larger diameter for final cutting. However, using diameters instead of stand ages means that the differences between scenarios initially defined with years, were not exactly reached. Especially in MIT scenarios the intended lengthening was not perfectly achieved, whereas in ADA, intended shortening was better achieved.

Management regimes for both rotation forestry and CCF were included in a set of management alternatives. We set **the area of CCF-management** zero in BAU and ADA, whereas in MIT-scenarios the CCF management was applied in 5% of randomly selected mineral soil herb rich (OMT) sites.

The selection of set-aside areas was carried out differently for MIT and ADA scenarios. In MIT, the selection was allocated primarily to the old and/or high-volume stands, whereas in ADA all kind of stands had equal possibility to be selected. For ADA, we picked 10 different, randomly selected subsets of the NFI-plots for both study-regions. After resolving them separately, we used averages of the results as final results. Both in MIT and ADA, the total of selected set-aside plots was set to be large enough to fulfil the targeted total area of protected forests in each scenario (i.e., 30% in MIT2 and MIT4 and 15% in MIT1, MIT2, and ADA-scenarios).

The increasing share of the birch stands following regeneration in ADA-scenarios were calculated separately. The sites, where spruce is used for planting are also suitable for growing birch. Therefore, we replaced the initial annual area regenerated for spruce with birch (50% in ADA1 and ADA3 and 100% in ADA2 and ADA4).

4.1.3. Effects on ecosystem services and biodiversity

To study the interlinkages between forest management and land-use options as well as biodiversity and ecosystem services we included a set of indicators in our study (Table 4). In *iLand* simulations we used the number of large trees, share of broadleaved trees, and deadwood as indicators of biodiversity, because the link between these key forest structures and biodiversity is well established (Felton et al. 2017, Gao et al. 2015 Hyvärinen et al. 2019, Johansson et al. 2013, Siitonen 2001). As indicators for ecosystem services we used total carbon storage, harvested timber, bilberry yield (Miina et al. 2016), and scenic beauty of forest (Pukkala et al. 1988). The scenic beauty index increases with the age and size of trees, with share of pines and deciduous trees, and with openness of stand. Since there are no bilberry models for broadleaf-dominated stands, models for pine stands were applied for birch-dominated stands (pers. communication J. Miina). In *Motti* simulations, the studied variables for biodiversity were volume of broadleaved trees, deadwood volume, and a combined diversity indicator calculated from several deadwood types and qualities (Table 4). Forest ecosystem services are described through the volume of growing stock, carbon storage of living trees, harvested sawlog and pulpwood volumes, and the economic indicators of incomes from harvests, costs of silvicultural treatments, and net present value (Table 4).

Table 4. Indicators for ecosystem services by models.

Indicator	**Unit**	**Description**
iLand		
Total carbon	tC ha^{-1}	Includes stems, branches, foliage, coarse and fine roots, regeneration, snags, downed wood, litter and soil
Harvested timber volume	m^3 ha^{-1} year^{-1}	Included both regular planned and salvage harvests
Annual disturbed volume	m^3 ha^{-1} year^{-1}	Volume killed by bark beetle and wind disturbance
Deadwood carbon	tC ha^{-1}	Includes stems, branches and coarse roots of standing dead trees and downed woody debris
Share of broadleaved trees	%	Basal area share of broadleaved trees
Large trees	N ha^{-1}	Number of trees with a diameter at breast height larger than 30 cm
Bilberry yield	kg ha^{-1} year^{-1}	Annual yield of Billberries, according to Miina et al., 2016
Scenic beauty	Index (0-10)	Index of perceived scenic beautyc, according to Pukkala et al. 1988
Motti		
Volume of growing stock	Mill. m^3	Stem volume
Carbon storage of living trees	tCO$_2$eq ha^{-1}	Includes stems, branches, coarse roots, fine roots
Harvested timber volume (cutting removals)	Mill. m^3 a^{-1}	Volume of merchantable wood (sawlogs and pulpwood)
Incomes	Mill. €	Stumpage earnings from cuttings
Costs	Mill. €	Costs of silvicultural treatments
Net present value	Mill. €	Value of future net revenues discounted to present
Volume of broadleaved trees	Mill. m^3	Stem volume
Deadwood volume	Mill. m^3	Includes snags (standing) and logs (downed) dead trees
Diversity	Index	Based on the number of dead tree species, types of deadwoods (e.g., snags and logs), size-classes and decaying stage of deadwood

4.1.4. Model descriptions

The alternative management strategies were simulated using two complimentary modelling approaches. *iLand* integrates climate change and disturbances in smaller landscapes, focusing particularly on longer term interactions of these factors with forest management. *Motti* delivers robust forecasts of forest management effects (including profitability) for larger regions, focusing on shorter term development under the current climate.

iLand – the individual-based forest landscape and disturbance model

iLand, a process-based forest landscape model was developed as a research tool to investigate forest dynamics under the influence of climate, natural disturbances, and forest management. The forest is represented as individual trees and forest dynamics directly emerge from their demographic processes (regeneration, growth, mortality, competition) and their interaction with the environment (daily climate, soil conditions). Because of this, the effects of climate change can be directly included by using future climate data generated by climate models and it is particularly suitable to investigate long-term interactions of forest dynamics, natural disturbances, climate change, and forest management and their combined effects on forest ecosystem services. *iLand* is a spatially explicit model, including landscape-scale processes such as seed dispersal and spread of disturbance agents (Seidl et al. 2012). The model has been previously applied both in Europe and North America. For the application in Finland, we tested and parameterized it with Finnish data (Repo et al. 2024, manuscript). *iLand* includes modules for both abiotic (Seidl et al. 2014a, 2014b) and biotic (Honkaniemi et al. 2021, Seidl & Rammer 2017) natural disturbances. We simulated the effects of the disturbance agents wind and European spruce bark beetle as well as their interactions with climate and forest management. The various management scenarios are implemented through the agent-based management engine within *iLand* (Rammer & Seidl 2015). *iLand* is freely available under the GNU General Public License and the full model documentation as well as a downloadable version can be found at: https://iland-model.org/

Motti – an efficient and versatile simulator for forest development forecasts

Motti is an empirically based simulation tool for assessing the impacts of different forest management practices on stand dynamics and forest management profitability as well as for comparing alternative management strategies (Salminen & Hynynen, 2001; Salminen et al., 2005). A large set of tree-species specific stand-level and tree-level models are incorporated in *Motti*, separately for mineral soil and peatland stands (e.g., Hynynen et al, 2014, Repola et al., 2018). Components of stand dynamics, like regeneration, growth, and mortality, can be predicted in different stages of stand development and in different circumstances (i.e., site fertilities, climatic conditions, and with or without silvicultural treatments (Hynynen et al., 2015). The technical details of *Motti* are described in Salminen et al. (2005).

4.2. Landscape scale results (iLand)

4.2.1. Future forest development and forest disturbances

The interplay between changing climate and forest management practices significantly influenced the projected trajectory of forest development within the study landscapes (Figure 9, Figure 10). Mitigation scenarios generally resulted in larger total carbon stocks compared to adaptation or business-as-usual scenarios due to longer rotation times and forest protection. Conversely, shorter rotation periods in the adaptation scenarios lead to increased harvesting and lower carbon stocks particularly in the short term relative to BAU and mitigation scenarios. The general trends were similar in both studied landscapes. The impact of management options on carbon stocks was greater than that of climate change. For instance, in the Urjala region, climate change alone increased total carbon stocks by an average of 5% in RCP 4.5 climate and 11% in the RCP 8.5 climate in the long-term compared to business-as-usual management in historical climate, while the combined effect of climate change and mitigation management increased total carbon stocks correspondingly by 15–23% and 20–28% depending on the management option.

Climate change increased disturbances, especially bark beetle invasions compared to historical climate (Figure 11, Figure 12). The annual disturbed volumes increased over time, with the largest volumes being observed in the RCP 8.5 climate change scenarios and mitigation options (Figure 11, Figure 12). For example, in the long term, the average annual disturbed volumes increased up to 2.2 m^3 ha^{-1} a^{-1} in Urjala, while in Äänekoski, the increase was 0.2 m^3 ha^{-1} a^{-1}. (Table 5, Table 6). In the Urjala landscape, the disturbed volumes can be explained by higher larger standing volume, more productive forest stands, higher trees and higher spruce share compared to Äänekoski. Management had both positive and negative effects on disturbed volumes, which became more noticeable over time, particularly with climate change.

Wind damages dominated disturbances in both BAU and ADA climate scenarios (Figure 9, Figure 10) while in MIT options, bark beetle damages were also significant. For example, in Urjala under the MIT4 RCP 8.5 scenario, bark beetle invasions accounted for over 60% of the total disturbed volumes in the long-term. In contrast, the ADA scenarios reduced the impact of bark beetles by reducing the spruce share and shortening rotation times. Hence, despite wind disturbances, the disturbed volumes in ADA3 and ADA4 were lower under RCP8.5.

Disturbances affected both managed and set-aside areas. In historical climate over 70% of the disturbed volumes were in protected areas in Urjala. However, the more severe the climate change, the smaller proportion of total disturbed volumes came from protected areas. In adaptive options there were only small differences in the share of disturbed volume from protected areas between climate scenarios.

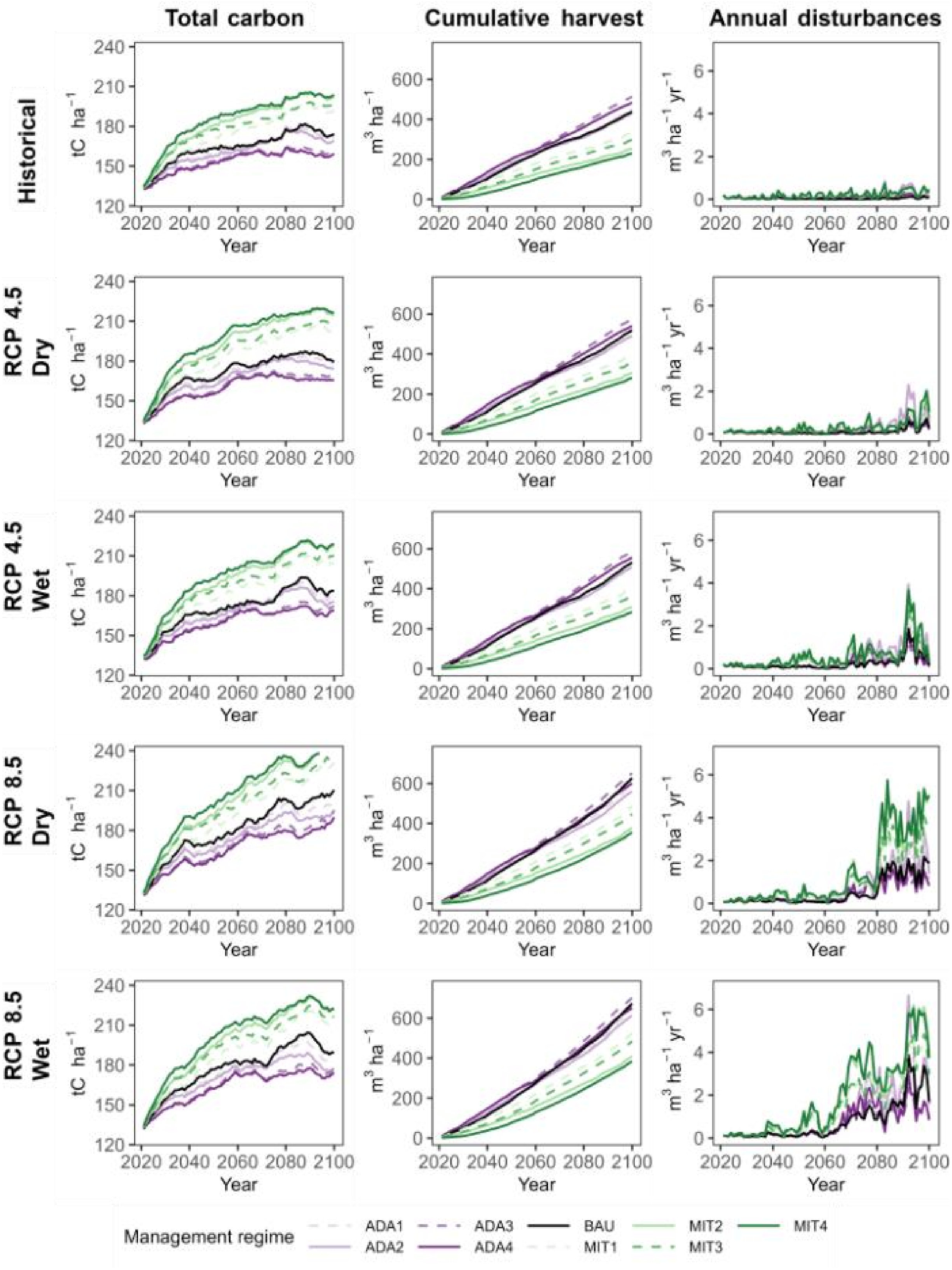


Figure 9. Development of total carbon stocks, cumulative annual harvests and annual disturbances in scenarios in Urjala. Climate scenarios are: RCP 4.5, dry=MPI, RCP 4.5, wet=NCC, RCP 8.5, wet=IPSL, RCP 8.5 dry=ICHEC. For abbreviations of management scenarios see Table 2. The values are averages over 10 simulation replicates.

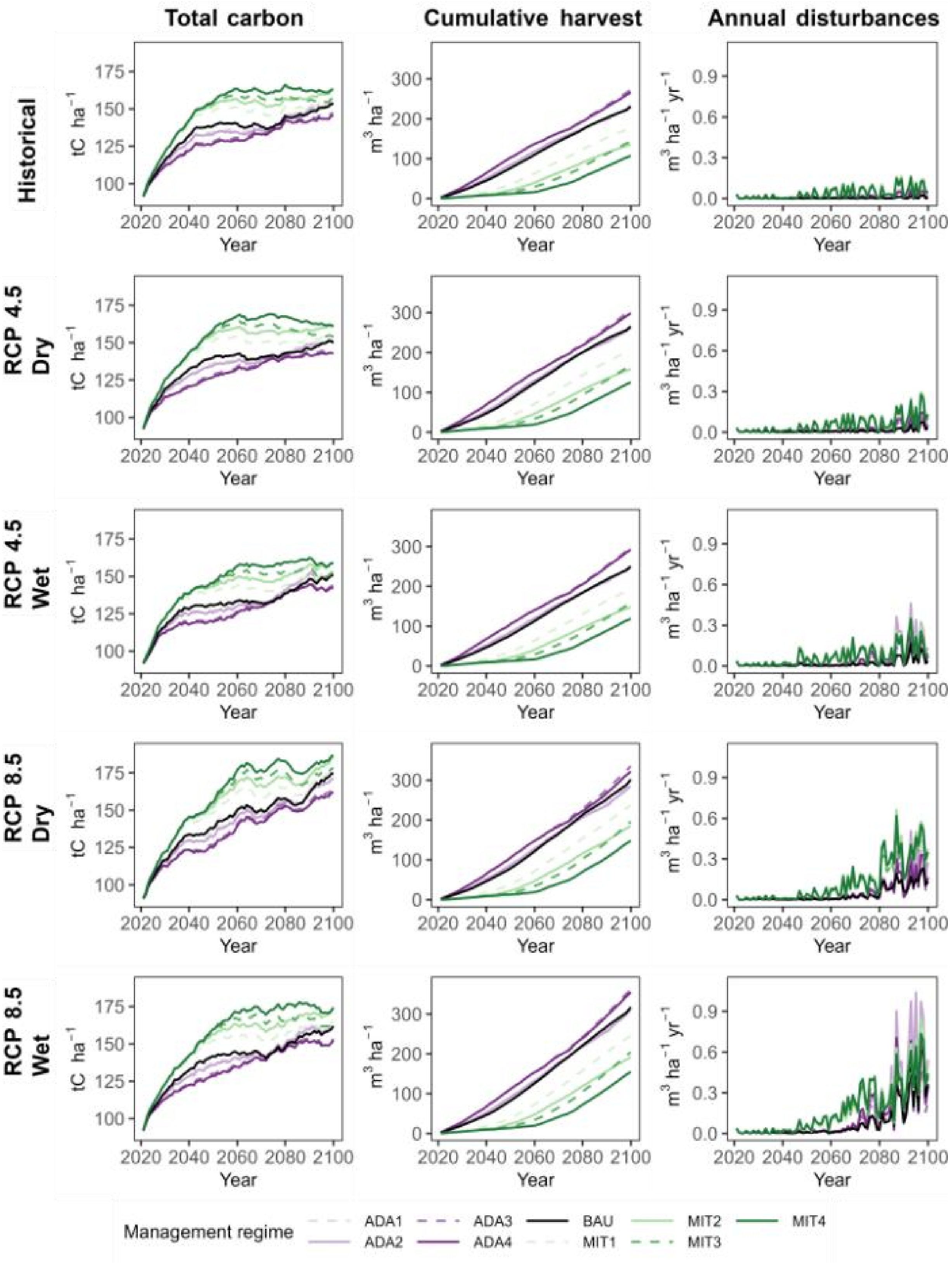


Figure 10. Development of total carbon stocks, cumulative annual harvests and annual disturbances in scenarios in Äänekoski. Climate scenarios are: RCP 4.5, dry=MPI, RCP 4.5, wet=NCC, RCP 8.5, wet=IPSL, RCP 8.5, dry=ICHEC. For abbreviations of management scenarios see Table 2. The values are averages over 10 simulation replicates.

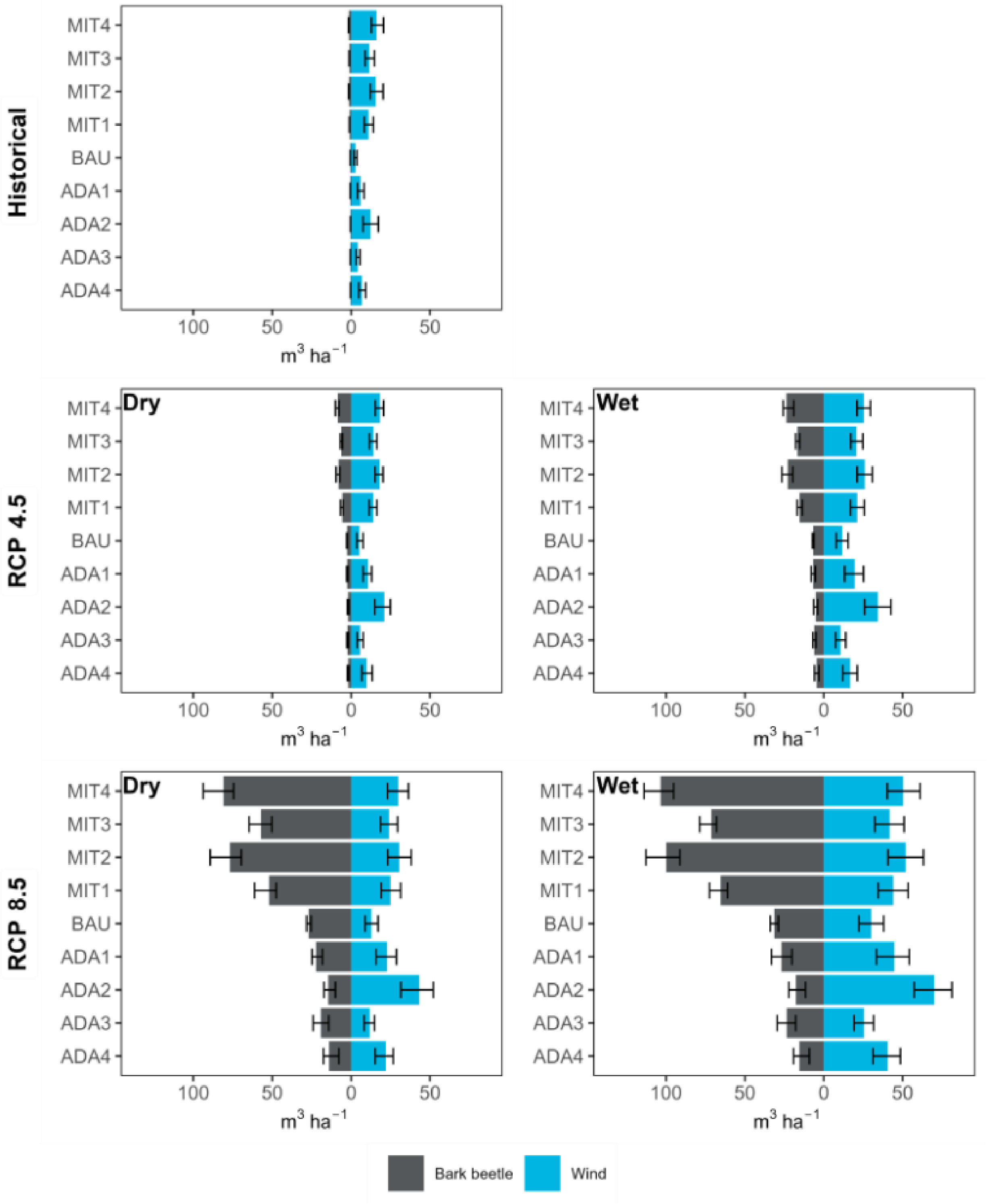


Figure 11. Accumulated disturbed volumes by barkbeetles and wind in 80 years of simulation in different management and climate scenarios in Urjala. Climate scenarios are: RCP 4.5, dry=MPI, RCP 4.5, wet=NCC, RCP 8.5, wet=IPSL, RCP 8.5=ICHEC. Bars show the mean of 10 replicates and whiskers show the maximum and minimum among replicates. For abbreviations of management scenarios see Table 2.

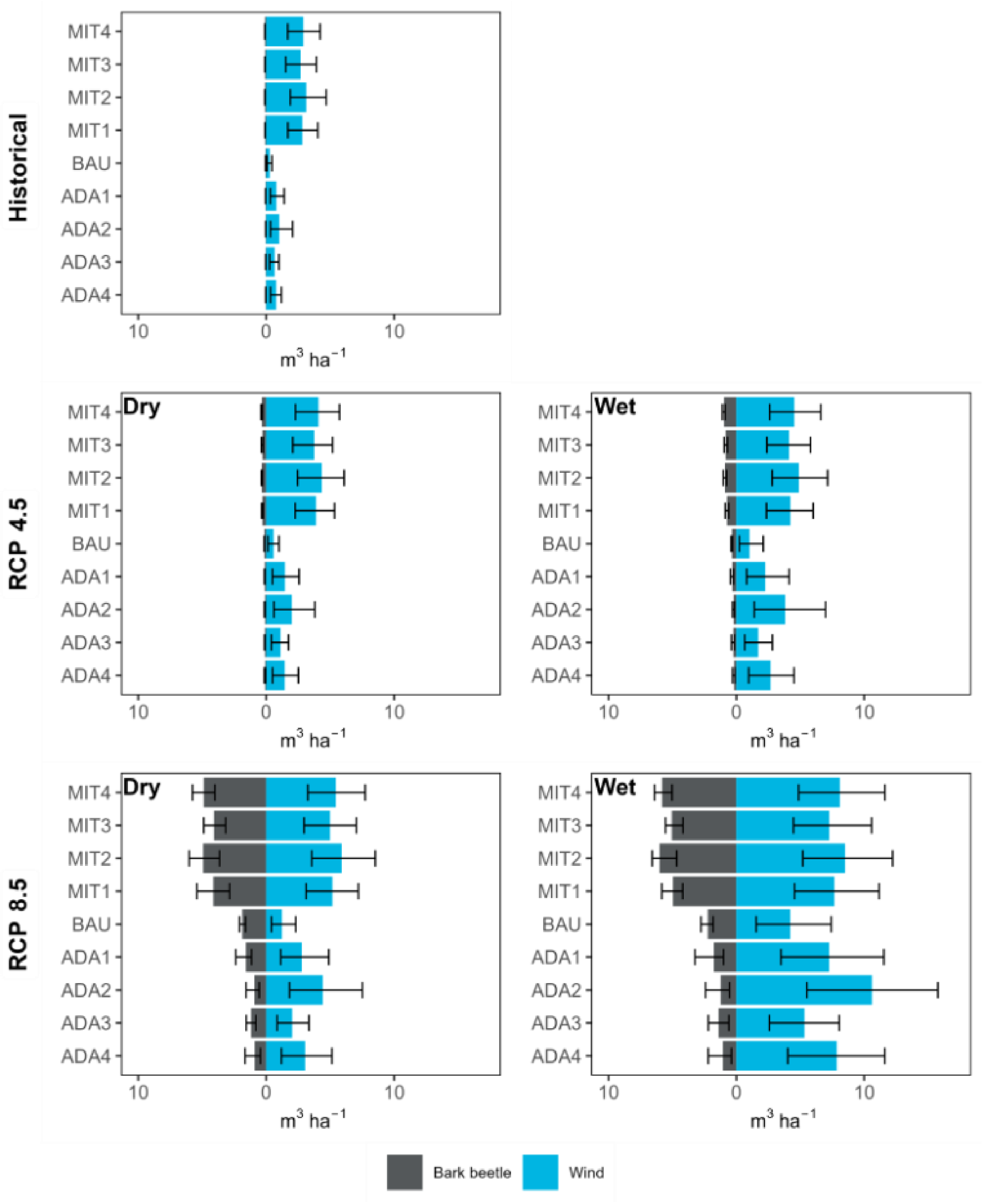


Figure 12. Accumulated disturbed volumes by bark beetles and wind in 80 years of simulation in different management and climate scenarios in Äänekoski. Climate scenarios are: RCP 4.5, dry=MPI, RCP 4.5, wet=NCC, RCP 8.5, wet=IPSL, RCP 8.5=ICHEC. Bars show the mean of 10 replicates and whiskers show the maximum and minimum among replicates. For abbreviations of management scenarios see Table 2.

4.2.2. Trade-offs between disturbance risk prevention and climate change mitigation potential of forests

Forest management options focused on climate change mitigation generally increased total carbon stocks both in the short- and long-term but increased disturbed volumes and resulted in lower harvests compared to BAU (Table 5, Table 6). The trends were similar in both regions. However, it is worth noting that the increase in disturbed volumes did not outweigh the gained carbon benefits obtained with combinations of forest protection and prolonging rotation length. In mitigation regimes, the total average carbon stocks calculated over the full simulation period were larger than in ADA or BAU options, even when losses due to disturbances were accounted for. The trade-off of mitigation options was a significant reduction in harvested volumes. Adaptive management to reduce risks generally reduced the disturbed volumes compared to mitigation options but not always compared to BAU (Table 5, Table 6) For example, under the ADA2 regime, disturbed volumes were larger than in the business-as-usual regime towards the end of the century due to the intensive substitution of spruce for broadleaves. Despite shortened rotations, there was an increase in wind disturbance due to the faster early height growth of birches.

Table 5. Management effects on total carbon stocks, harvested and disturbed timber as difference to BAU management in different climate scenarios in short term (average over first 30 years) and long-term (average over last 30 years) for the Urjala landscape. Light background colours (green/orange) signify a difference to BAU under that climate larger than one standard deviation, dark background colours signify a difference larger than 2 standard deviations.

URJALA		Difference to BAU							
Total carbon (tC ha^{-1}) (short-term)	**BAU**	**MIT1**	**MIT2**	**MIT3**	**MIT4**	**ADA1**	**ADA2**	**ADA3**	**ADA4**
Historical	152.9	+3.0	+9.32	+8.1	+14.3	-2.27	-2.81	-6.48	-7.04
RCP 4.5 Dry (MPI)	157.3	+3.4	+10.3	+9.0	+15.9	-2.34	-2.85	-7.41	-8.04
RCP 4.5 Wet (NCC)	156.2	+3.8	+10.3	+9.1	+15.6	-2.14	-2.57	-6.48	-6.96
RCP 8.5 Dry (ICHEC)	159.4	+3.5	+10.5	+9.2	+16.4	-2.26	-2.67	-6.54	-7.08
RCP 8.5 Wet (IPSL)	158.7	+3.1	+9.6	+8.5	+15.0	-2.35	-2.80	-6.74	-7.35
Total carbon (tC ha^{-1}) (long-term)									
Historical	174.8	+15.0	+24.9	+17.9	+26.1	-0.8	-3.0	-13.2	-15.2
RCP 4.5 Dry (MPI)	183.4	+17.6	+30.2	+21.6	+32.3	-1.6	-4.8	-13.9	-16.3
RCP 4.5 Wet (NCC)	184.2	+16.9	+28.4	+20.3	+30.1	-1.7	-4.7	-13.8	-16.1
RCP 8.5 Dry (ICHEC)	200.9	+17.4	+30.3	+21.9	+32.5	-5.1	-11.3	-17.6	-21.7
RCP 8.5 Wet (IPSL)	193.4	+16.4	+27.8	+20.8	+29.7	-4.4	-10.8	-17.6	-20.6
Harvested (m^3 ha^{-1}) (short-term)	**BAU**	**MIT1**	**MIT2**	**MIT3**	**MIT4**	**ADA1**	**ADA2**	**ADA3**	**ADA4**
Historical	5.62	-1.05	-2.51	-2.09	-3.47	+0.43	+0.41	+1.14	+1.08
RCP 4.5 Dry (MPI)	6.24	-1.27	-2.82	-2.38	-3.83	+0.31	+0.27	+1.02	+0.96
RCP 4.5 Wet (NCC)	6.26	-1.34	-2.87	-2.44	-3.88	+0.29	+0.22	+0.97	+0.88
RCP 8.5 Dry (ICHEC)	6.45	-1.30	-2.87	-2.41	-3.89	+0.29	+0.26	+0.98	+0.90
RCP 8.5 Wet (IPSL)	6.34	-1.14	-2.71	-2.30	-3.78	+0.45	+0.39	+1.23	+1.12
Harvested (m^3 ha^{-1}) (long-term)									
Historical	5.28	-1.37	-2.01	-1.63	-1.98	+0.33	-0.14	+1.37	+0.80
RCP 4.5 Dry (MPI)	6.70	-1.74	-2.57	-2.01	-2.51	-0.12	-0.60	+0.90	+0.26
RCP 4.5 Wet (NCC)	6.99	-1.84	-2.72	-2.08	-2.65	+0.01	-0.35	+1.02	+0.46
RCP 8.5 Dry (ICHEC)	9.41	-2.30	-3.47	-2.48	-3.26	-0.89	-1.64	+0.10	-0.97
RCP 8.5 Wet (IPSL)	10.30	-2.51	-3.83	-2.64	-3.59	-0.73	-1.33	+0.20	-0.77
Disturbed (m^3 ha^{-1}) (short-term)	**BAU**	**MIT1**	**MIT2**	**MIT3**	**MIT4**	**ADA1**	**ADA2**	**ADA3**	**ADA4**
Historical	0.051	+0.040	+0.063	+0.046	+0.064	+0.001	+0.000	+0.001	-0.000
RCP 4.5 Dry (MPI)	0.061	+0.044	+0.072	+0.054	+0.078	+0.000	-0.001	-0.002	-0.003
RCP 4.5 Wet (NCC)	0.098	+0.070	+0.123	+0.090	+0.143	+0.005	+0.004	-0.002	-0.002
RCP 8.5 Dry (ICHEC)	0.106	+0.064	+0.125	+0.091	+0.150	+0.000	-0.003	-0.009	-0.010
RCP 8.5 Wet (IPSL)	0.111	+0.078	+0.151	+0.106	+0.176	+0.001	+0.000	-0.007	-0.010
Disturbed (m^3 ha^{-1}) (long-term)									
Historical	0.047	+0.177	+0.272	+0.180	+0.282	+0.093	+0.281	+0.033	+0.100
RCP 4.5 Dry (MPI)	0.174	+0.260	+0.392	+0.259	+0.405	+0.160	+0.463	-0.002	+0.110
RCP 4.5 Wet (NCC)	0.466	+0.400	+0.655	+0.386	+0.637	+0.229	+0.649	-0.072	+0.078
RCP 8.5 Dry (ICHEC)	1.120	+1.000	+1.840	+1.100	+1.910	+0.151	+0.550	-0.281	-0.148
RCP 8.5 Wet (IPSL)	1.690	+1.130	+2.180	+1.180	+2.210	+0.288	+0.801	-0.410	-0.191

Table 6: Management effects on total carbon stocks, harvested and disturbed timber as difference to BAU management in different climate scenarios in short term (average over first 30 years) and long-term (average over last 30 years) for the Äänekoski landscape. Light background colours (green/orange) signify a difference to BAU under that climate larger than one standard deviation, dark background colours signify a difference larger than 2 standard deviations.

ÄÄNEKOSKI		**Difference to BAU**							
Total carbon (tC ha^{-1}) (short-term)	**BAU**	**MIT1**	**MIT2**	**MIT3**	**MIT4**	**ADA1**	**ADA2**	**ADA3**	**ADA4**
Historical	122.4	+6.2	+7.7	+8.1	+8.3	-2.3	-2.8	-6.5	-7.0
RCP 4.5 Dry (MPI)	123.3	+6.6	+8.3	+8.7	+9.0	-2.3	-2.9	-7.4	-8.0
RCP 4.5 Wet (NCC)	120.2	+6.1	+7.6	+7.9	+8.1	-2.1	-2.8	-6.5	-7.0
RCP 8.5 Dry (ICHEC)	122.4	+6.4	+8.1	+8.5	+8.8	-2.3	-2.7	-6.5	-7.1
RCP 8.5 Wet (IPSL)	124.7	+6.3	+7.9	+8.3	+8.5	-2.3	-2.8	-6.7	-7.3
Total carbon (tC ha^{-1}) (long-term)									
Historical	145.0	+5.5	+11.4	+11.3	+17.3	+1.6	+0.1	-3.3	-4.8
RCP 4.5 Dry (MPI)	144.7	+6.6	+13.5	+13.5	+20.5	+1.8	+0.5	-3.0	-4.3
RCP 4.5 Wet (NCC)	141.7	+4.8	+10.9	+10.8	+17.2	+2.5	+1.9	-2.1	-2.7
RCP 8.5 Dry (ICHEC)	159.7	+5.9	+12.8	+12.8	+20.2	+0.0	-2.1	-5.8	-7.6
RCP 8.5 Wet (IPSL)	151.9	+6.4	+14.2	+13.9	+22.2	+2.6	+1.5	-3.4	-4.2
Harvested (m^3 ha^{-1}) (short-term)	**BAU**	**MIT1**	**MIT2**	**MIT3**	**MIT4**	**ADA1**	**ADA2**	**ADA3**	**ADA4**
Historical	2.55	-1.35	-1.85	-2.03	-2.14	+0.27	+0.28	+0.87	+0.87
RCP 4.5 Dry (MPI)	2.75	-1.42	-1.95	-2.17	-2.29	+0.26	+0.26	+0.94	+0.95
RCP 4.5 Wet (NCC)	2.57	-1.36	-1.86	-2.04	-2.14	+0.30	+0.29	+0.95	+0.96
RCP 8.5 Dry (ICHEC)	2.62	-1.34	-1.86	-2.07	-2.18	+0.28	+0.28	+0.88	+0.90
RCP 8.5 Wet (IPSL)	2.75	-1.44	-1.95	-2.17	-2.29	+0.31	+0.30	+0.96	+0.97
Harvested (m^3 ha^{-1}) (long-term)									
Historical	2.93	-0.14	-0.58	+0.11	-0.45	-0.08	-0.20	+0.62	+0.43
RCP 4.5 Dry (MPI)	3.50	-0.24	-0.74	+0.06	-0.61	-0.21	-0.33	+0.55	+0.34
RCP 4.5 Wet (NCC)	3.33	-0.18	-0.67	+0.11	-0.53	-0.14	-0.17	+0.74	+0.66
RCP 8.5 Dry (ICHEC)	4.5	-0.38	-1.01	-0.15	-0.97	-0.43	-0.68	+0.37	+0.01
RCP 8.5 Wet (IPSL)	4.78	-0.43	-1.15	-0.18	-1.05	-0.27	-0.38	+0.68	+0.50
Disturbed (m^3 ha^{-1}) (short-term)	**BAU**	**MIT1**	**MIT2**	**MIT3**	**MIT4**	**ADA1**	**ADA2**	**ADA3**	**ADA4**
Historical	0.003	+0.001	+0.008	+0.008	+0.008	+0.001	+0.001	+0.002	+0.001
RCP 4.5 Dry (MPI)	0.004	+0.002	+0.012	+0.011	+0.010	+0.001	+0.001	+0.002	+0.002
RCP 4.5 Wet (NCC)	0.006	+0.001	+0.013	+0.016	+0.015	+0.001	+0.002	+0.001	+0.001
RCP 8.5 Dry (ICHEC)	0.005	+0.001	+0.010	+0.010	+0.010	+0.001	+0.001	+0.001	+0.001
RCP 8.5 Wet (IPSL)	0.006	+0.001	+0.013	+0.014	+0.014	+0.002	+0.001	+0.002	+0.001
Disturbed (m^3 ha^{-1}) (long-term)									
Historical	0.006	+0.052	+0.060	+0.050	+0.054	+0.014	+0.020	+0.009	+0.012
RCP 4.5 Dry (MPI)	0.016	+0.072	+0.086	+0.070	+0.060	+0.024	+0.041	+0.013	+0.022
RCP 4.5 Wet (NCC)	0.036	+0.070	+0.090	+0.070	+0.082	+0.035	+0.082	+0.015	+0.044
RCP 8.5 Dry (ICHEC)	0.090	+0.154	+0.199	+0.149	+0.185	+0.038	+0.069	+0.001	+0.025
RCP 8.5 Wet (IPSL)	0.193	+0.132	+0.184	+0.117	+0.159	+0.077	+0.168	+0.004	+0.076

4.2.3. Effects of adaptation and mitigation management on biodiversity and ecosystem services

The combined effects of management and climate change resulted in trade-offs and synergies with biodiversity and ecosystem service indicators (Figure 13, Figure 14). Mitigation options were found to increase carbon stocks, large trees, and scenic beauty index compared to BAU in both regions in the short- and long-term. The effects on deadwood were slightly positive or negative in the short-term but positive in the long-term. The magnitude of the positive effects was impacted by the severity of climate change. For instance, in mitigation options, the number of large trees increased by up to 50%. However, the positive trend was reduced due to the severity of climate change. Overall, the scenic beauty index was minimally affected by climate change or management options.

Adaptive options resulted in more mixed positive and negative effects on the chosen indicators. In the short-term, adaptive management led to an increase in timber harvested, had a small positive or negligible effect on deadwood and bilberry yields while it also reduced carbon stocks and the number of large trees compared to BAU. Over the long term, adaptive management increased or decreased harvests, reduced carbon stocks, increased bilberry yields, increased deadwood, and had mixed effects on the number of large trees. When in adaptive management rotation was shorted by 10% (ADA1 and ADA2), the number of large trees increased compared to BAU in the long-term (largely due to the effect of added set-aside areas). However, also in this case, the severity of climate change reduced the effect.

The share of set-aside areas had an impact on ecosystem service indicators, increasing particularly biodiversity relevant variables such as deadwood and large trees. In the case of adaptive management, set-aside areas partially contributed to offsetting the negative impacts of shortened rotations on these variables on the landscape level, particularly in the long-term.

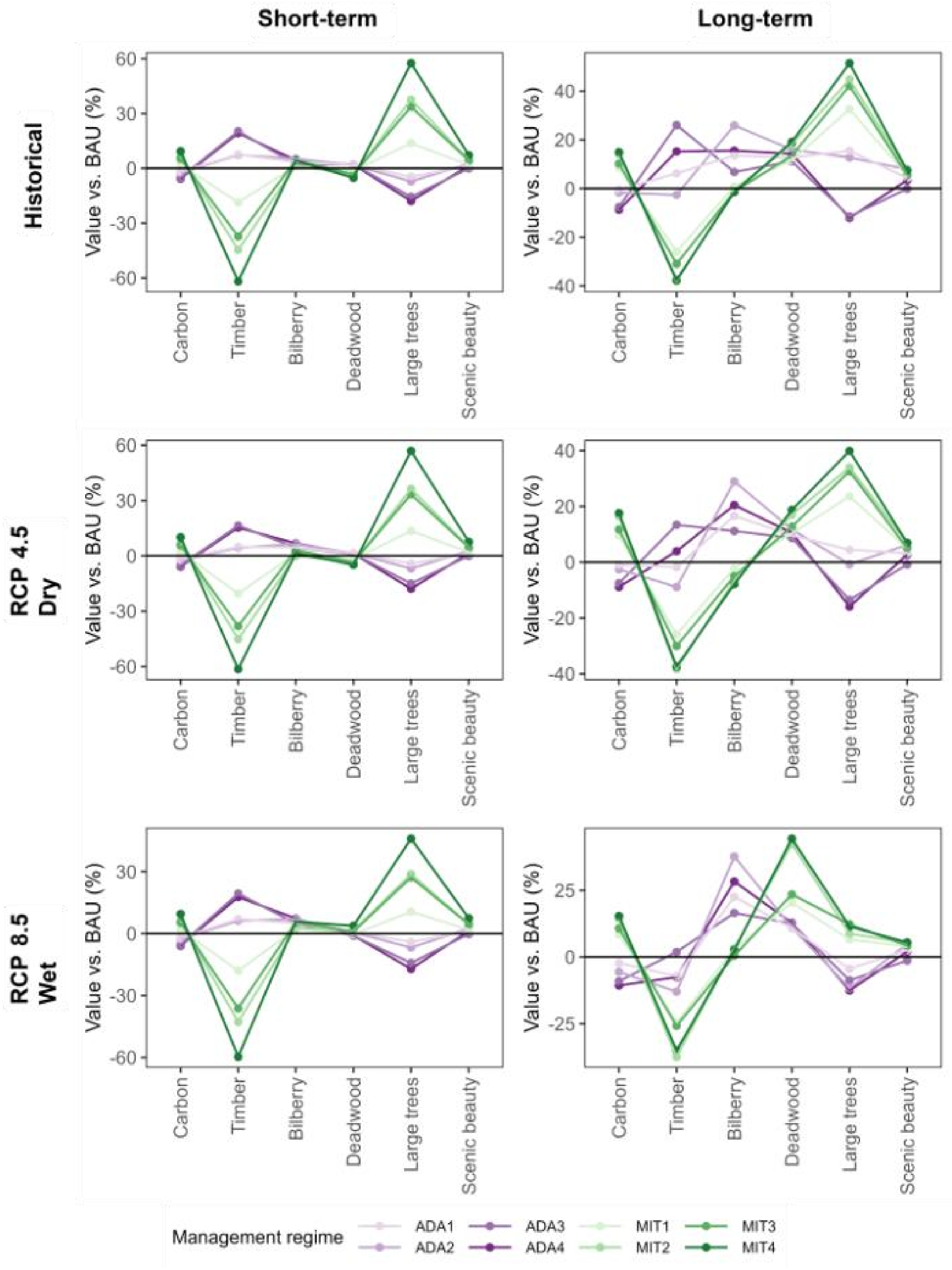


Figure 13. The effects of different management regimes on biodiversity and ecosystem service indicators compared to business-as-usual management in selected climate scenarios in Urjala. The values present average differences over 10 simulation runs. Only historical climate and most high-end climate scenarios are presented. Note different x-axis scales.

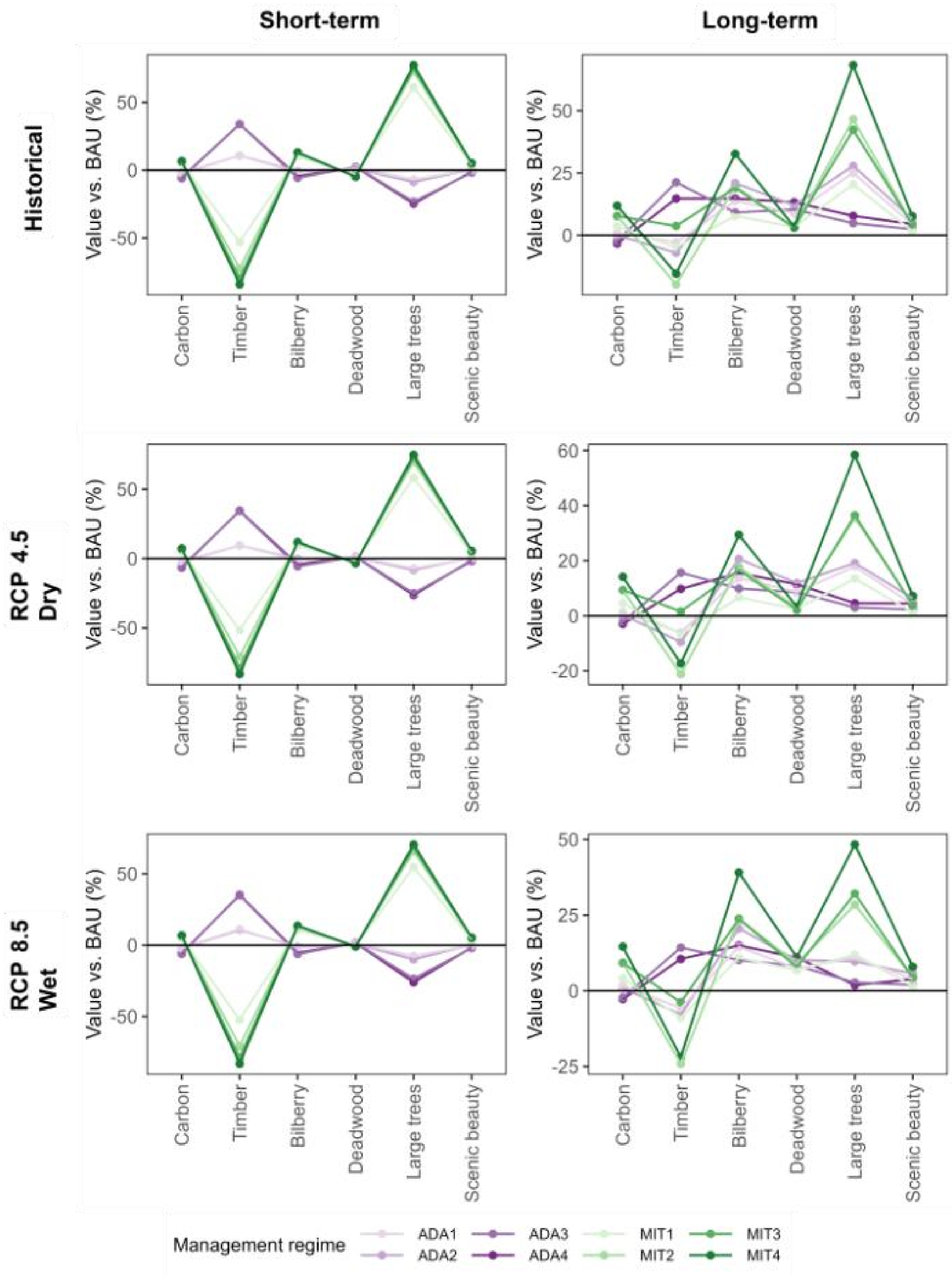


Figure 14. The effects of different management regimes on biodiversity and ecosystem service indicators compared to business-as-usual management in selected climate scenarios in Äänekoski. The values present average differences over 10 simulation runs. Only historical climate and most high-end climate scenarios are presented. Note different x-axis scales.

4.3. Regional results (Motti)

4.3.1. Results of the large study-regions

In terms of total area and forest structure, the large study-regions (Regions 1 and 2) were quite homogeneous, which means that the results – especially the comparisons between scenarios – follow a similar pattern.

The rotation lengths and the share of set-aside areas had the largest impacts on the development of the study-area forests and on the differences between scenarios. The small proportion of the stands, where management was changed from even-aged management to continues-cover management had only minor impacts on the overall results. Changing management from spruce to birch in regeneration had impacts, which cannot be seen properly during a 30-year study-period. Further, the impacts of the different selection methods of set-aside areas (MIT vs. ADA) can only be seen in some results.

4.3.2. Development of the growing stock and carbon storage

At the onset, the growing stock was 307 and 329 million m^3 (168 m^3 ha^{-1} and 148 m^3 ha^{-1}) in Region 1 and Region 2, respectively. At the end of the 30-year study-period, total growing stock was notably higher (30–70%) in MIT scenarios with extended rotations when compared to BAU (Figure 15). Correspondingly, shorter rotations clearly decreased the total stand volumes in ADA scenarios. They were lower than BAU in the first 10-year period (due to large harvests in forests, which had already met or exceeded the shortened rotation target at the beginning of the simulation), and barely returned to the BAU-level in 30 years (+/− 5% compared to BAU, and the scenarios with final harvests scheduled 30% earlier staying below BAU for the whole study-period). Further, the larger the area of set-aside stands, the higher the growing stock, i.e., including productive-, protected-, and set-aside forests (MIT2 and MIT4 compared to MIT1 and MIT3). A minor increase in volumes was obtained as more birch was planted instead of spruce, which is due to the rapid growth of young birches (e.g., ADA2 vs. ADA1).

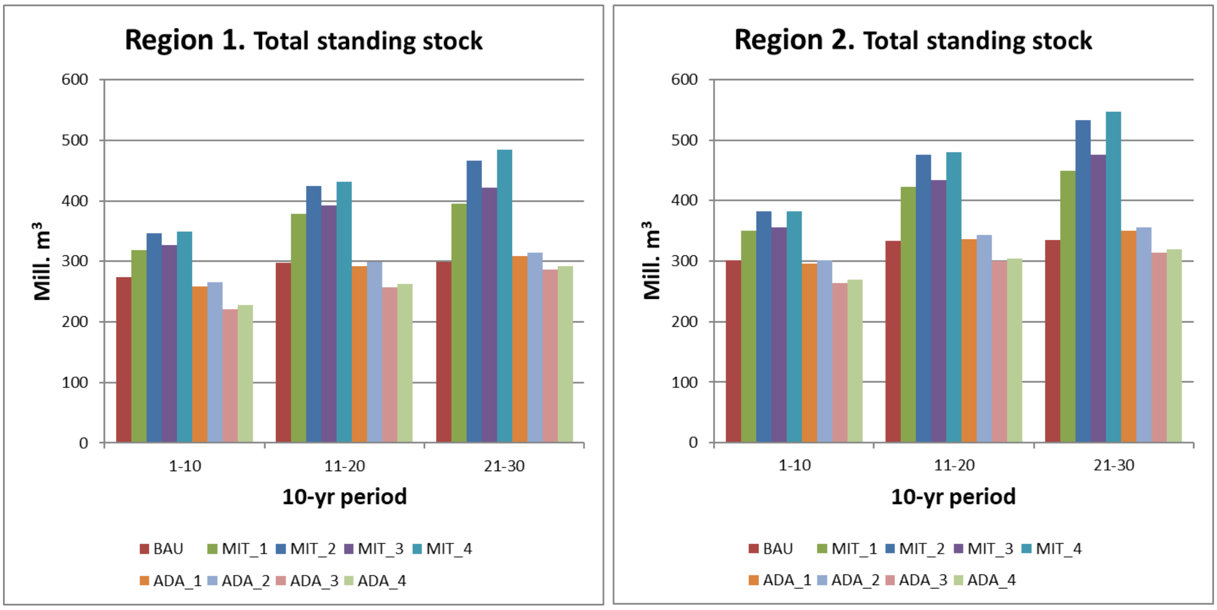


Figure 15. Development of total growing stock (volume) during the first 30 years in different management scenarios (periods: 10-year average).

Carbon storage, here calculated from biomasses to tCO₂eq (including all living parts of the trees both above and below ground) followed the same pattern as the total volume, driven by changes the scheduling of final cuttings and the share of set-aside areas. At the end of the study-period, carbon storages were substantially higher in MIT with extended rotations and at the same level in ADA with shortened rotations when compared to BAU (Figure 16). Over the 30 years, storages increased continuously in BAU and MIT (with a stronger relative increase in MIT scenarios), whereas in ADA there was first a drop due to the increased cuttings based on shorter rotations and then a slower increase (compare also the pattern of harvested wood in Figure 17). Set-aside areas, where no wood was removed through management, increased carbon storage, similar to volume. This was evident particularly from the differences between the MIT scenarios, where those with a higher share of set-aside area (MIT2, MIT4) had higher carbon stocks. Although both total volume and carbon storage were slightly higher in Region 1 than in Region 2, the averages per hectare were lower in Region 2 due to the larger proportion of poorer peatland sites and pine dominated stands (Table 3). The pattern between the scenarios remains the same in Region 2.

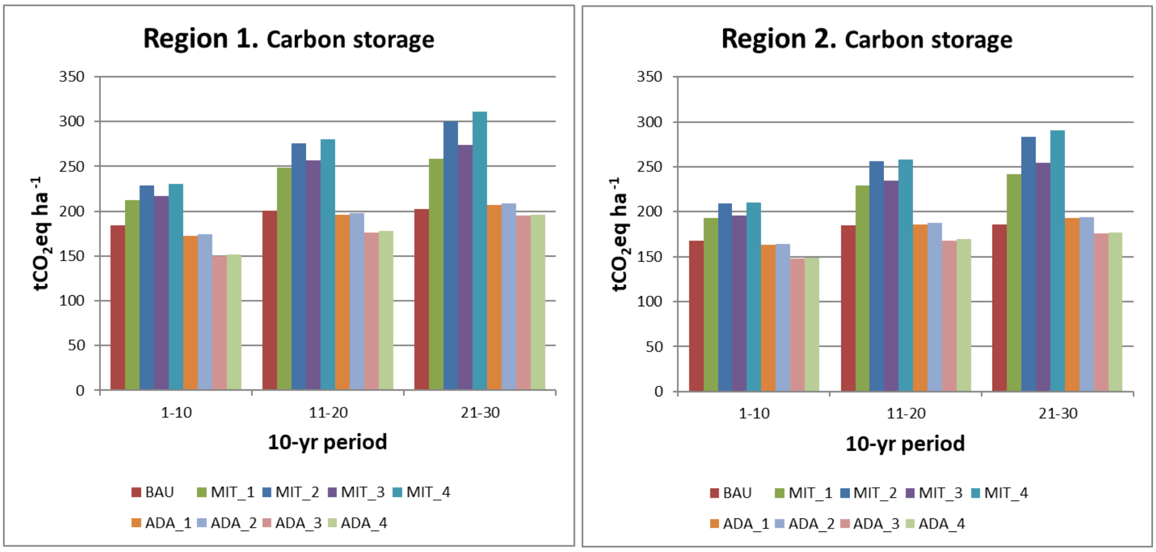


Figure 16. Development of carbon storage of living trees during the first 30 years in different management scenarios (periods: 10-year average).

4.3.3. Cuttings

Different rotation lengths caused notable differences in cuttings, especially at the beginning of the study period (Figure 17). In BAU the stands mature for final cutting were harvested to the extent that beforehand-set level of annual cutting volumes (including both thinning and final-cutting removals) was reached. In the other scenarios no restrictions were set to the cutting volumes, but the final cuttings were either postponed (MIT) or executed earlier (ADA). This led to very different temporal patterns in the cuttings, with the bulk of removals in ADA happening in the first 10 years and lower than BAU removals for the remaining 20 years. Cuttings under MIT increased towards the end of the simulation, as more stands reached the extended rotation prescriptions.

The total removals over 30 years were 190 and 188 mill. m^3, in Region 1 and 2, respectively. During the 30-year study-period, almost the same removal was cut in BAU and ADA, whereas 20–60% less in MIT. However, the structure of the removals varied between scenarios. In BAU, 55% of removals were sawlogs, whereas the share of sawlogs was 40–55% and 55–60% in MIT and ADA, respectively (Figure 17).

Due to the fact that higher volume and older stands were prioritized when selecting set-aside areas in MIT scenarios, the total removals and especially the sawlog removals in MIT2 and MIT3 were almost half of those in MIT1 and MIT2 (Figure 17). The impacts of increased use of birch in regeneration under ADA scenarios began to appear in removals only at the end of the study-period. It resulted in slightly higher removals (due to the earlier thinnings), but at the same time the proportion of sawlogs decreased.

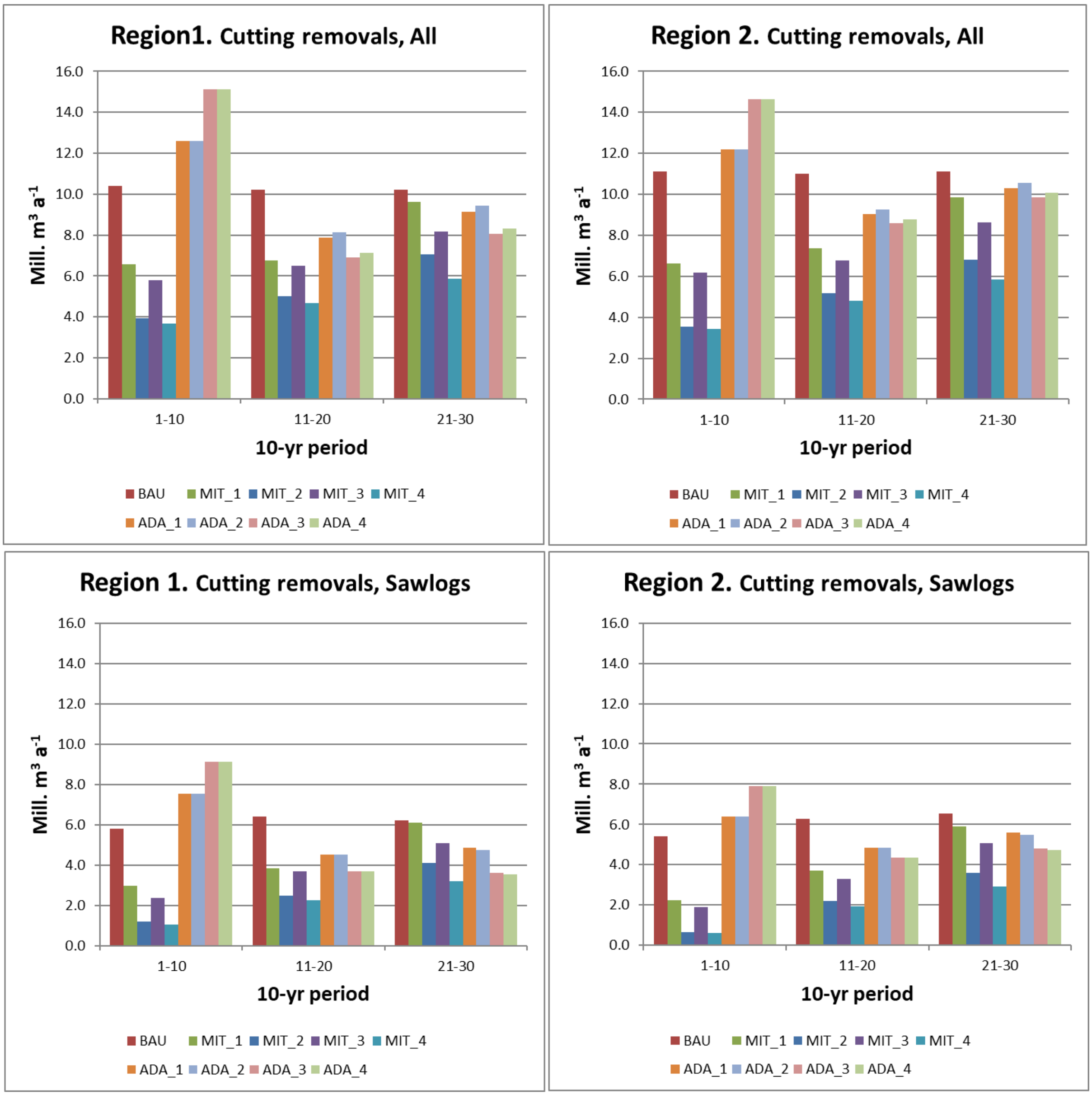


Figure 17. Annual cutting removals (total and sawlogs) in different management scenarios for 30 years of simulation (periods: 10-year average).

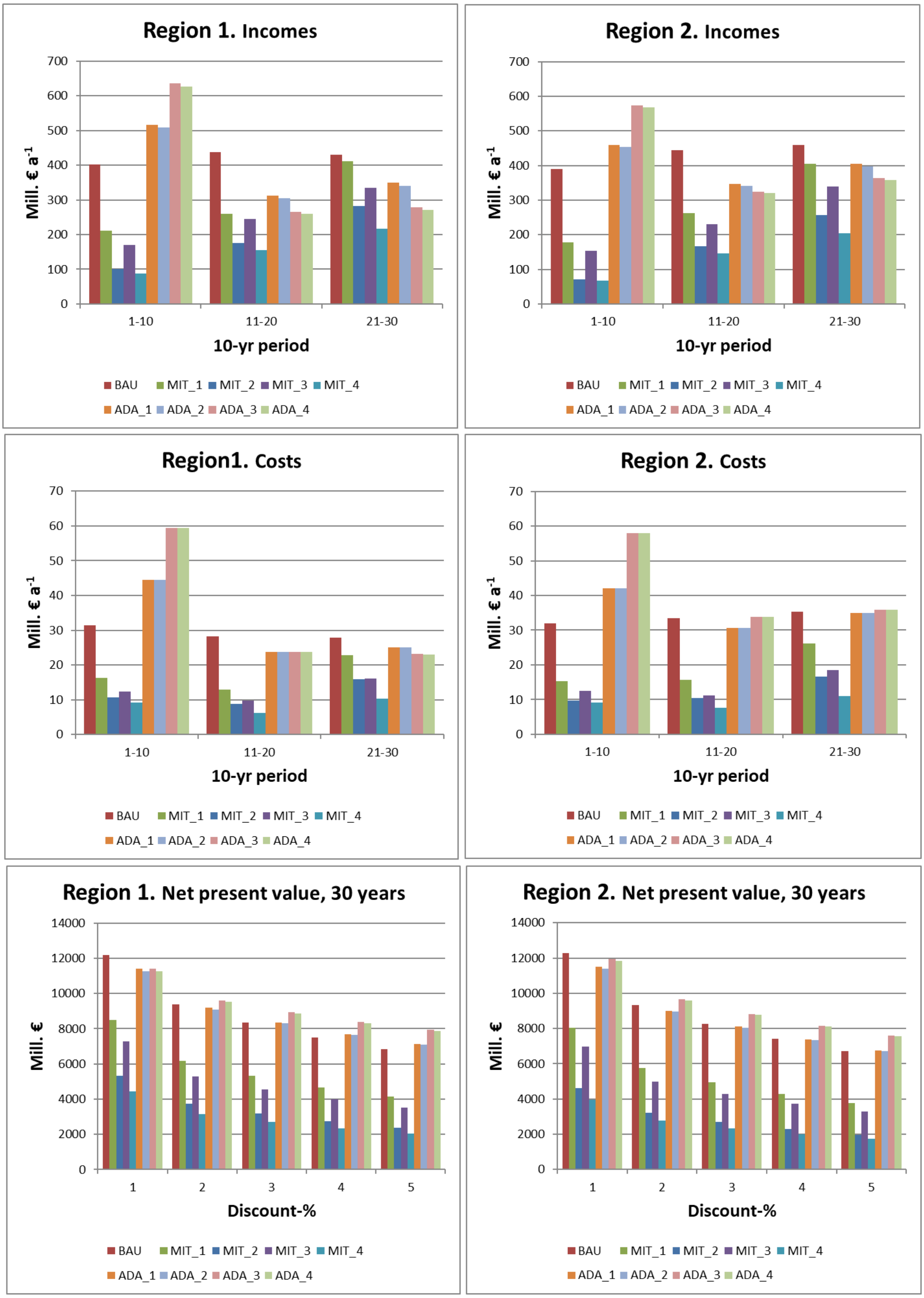


Figure 18. Annual harvesting incomes, costs of silvicultural treatments, and net present values (NPV) in different management scenarios for 30 years of simulation. NPVs were discounted by differ-ent interest rates (1–5%) for the first 30 years (periods: 10-year average).

4.3.4. Economics

Different rotation lengths caused the largest differences between incomes – lower in MIT and larger in ADA (especially in the first 10-years), when compared to BAU (Figure 18). Set-aside areas reduced both cutting incomes and silvicultural costs in overall results. Differences in costs between scenarios arose primarily from differences in cutting areas, which directly affect the areas of forest regeneration and juvenile stand management, the main causes of silvicultural costs. Other silvicultural treatments, like fertilization and ditch network maintenance, had only small impacts on and between scenarios.

Since a lot of final cuttings were carried out in the first 10-year period in BAU, and even more in ADA, the discounted net present values (NPV) were clearly higher in those scenarios than in MIT. In general, the higher the interest rate the larger NPV of ADA in relation to other scenarios (e.g., ADA1 and ADA2 bypass BAU with 4% interest rate) (Figure 18). The set-aside areas, having neither incomes nor costs, decreased NPVs proportionally to the area they covered. That was also the reason why removals and NPVs of ADA didn’t bypass BAU.

Here, the NPVs were calculated only for a 30-year study-period. However, many activities carried out in these scenarios will have their impacts only beyond the simulated period. To get an idea of that, we calculated the value of the growing stock at the end of the 30-year study-period. In this calculation, we excluded protected- and set-aside areas so that value includes only the stands available for wood production. At the end of the 30-year period, the value of growing stock was on average 20% higher in MIT1 and MIT3 (extended and 15% set-asides), −5% lower in MIT2 and MIT4 (extended and 30% set-asides), and −35% lower in ADA (short rotations and 15% set-asides), when compared to BAU.

4.3.5. Biodiversity

Differences between scenarios associated with biodiversity were not as clear as differences associated with cuttings and economics. The changes in management affect the biodiversity indicators only slowly and clearer differences would show up only in the longer term. For example, in these scenarios **total volume of broadleaved trees** will increase when older and higher-stocking stands were set aside, and broadleaved trees avoided cuttings (especially MIT2 and MIT3) (Figure 19). Increased planting of birch increases broadleaved trees volumes little by little after regeneration, but its real volume-impact would be seen beyond the 30-years study-period, when these stands mature.

Similarly, the **amount of deadwood** was mainly driven by the share of set-aside areas. The rotation lengths were a secondary driver. Although the earlier cuttings inhibited deadwood production in productive stands, ADA had more deadwood than BAU due to the set-aside areas (Figure 20). In all scenarios, including BAU, deadwood volume grew over the full 30 years simulation, but its growth was much stronger in the alternative management scenarios. **The diversity-index**, based on the number of tree species, decaying stage of deadwood, and mirroring the deadwood volumes, were slightly better in MIT-scenario, and correspondingly lower in ADA, when compared to BAU (Figure 21).

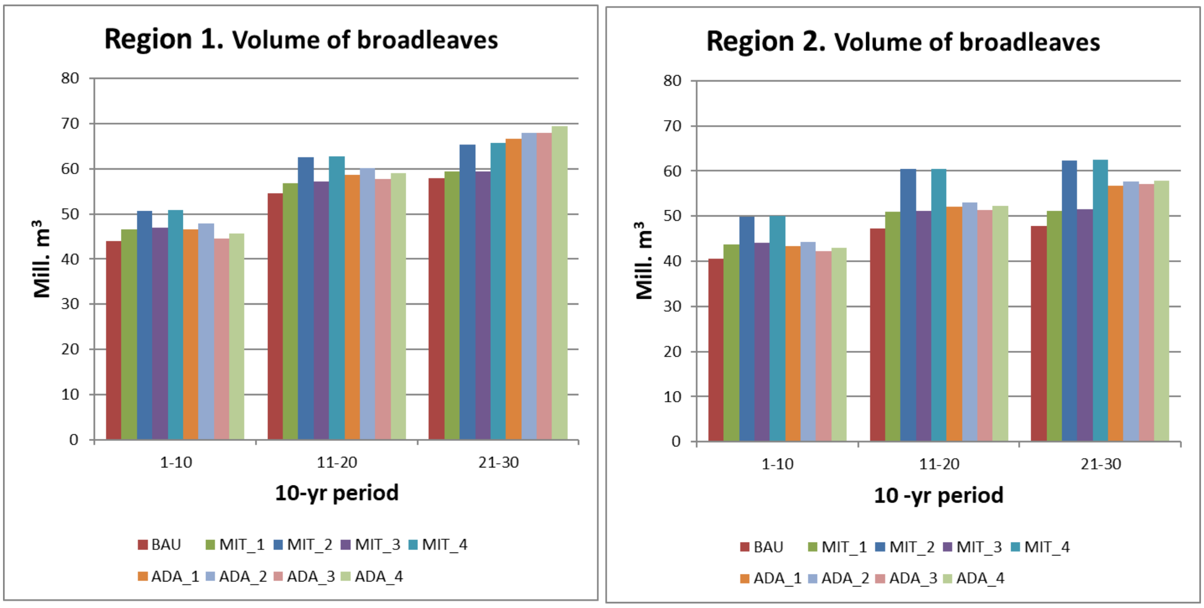


Figure 19. Stem volume of broadleaves in different management scenarios for 30 simulated years (periods: 10-year average).

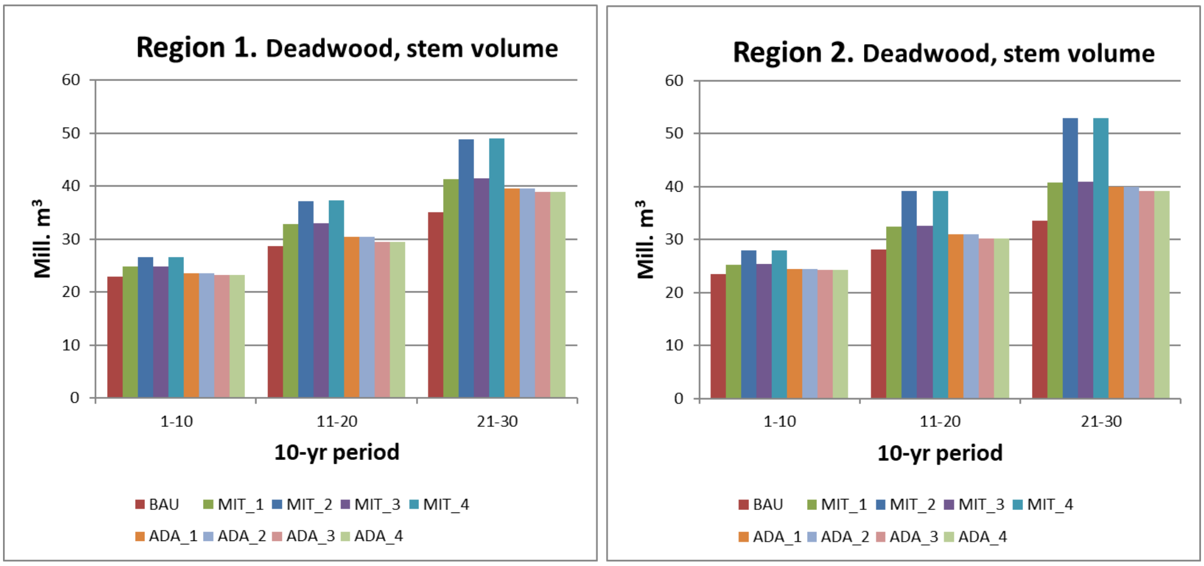


Figure 20. Stem volume of deadwood in different management scenarios for 30 simulated years (periods: 10-year average).

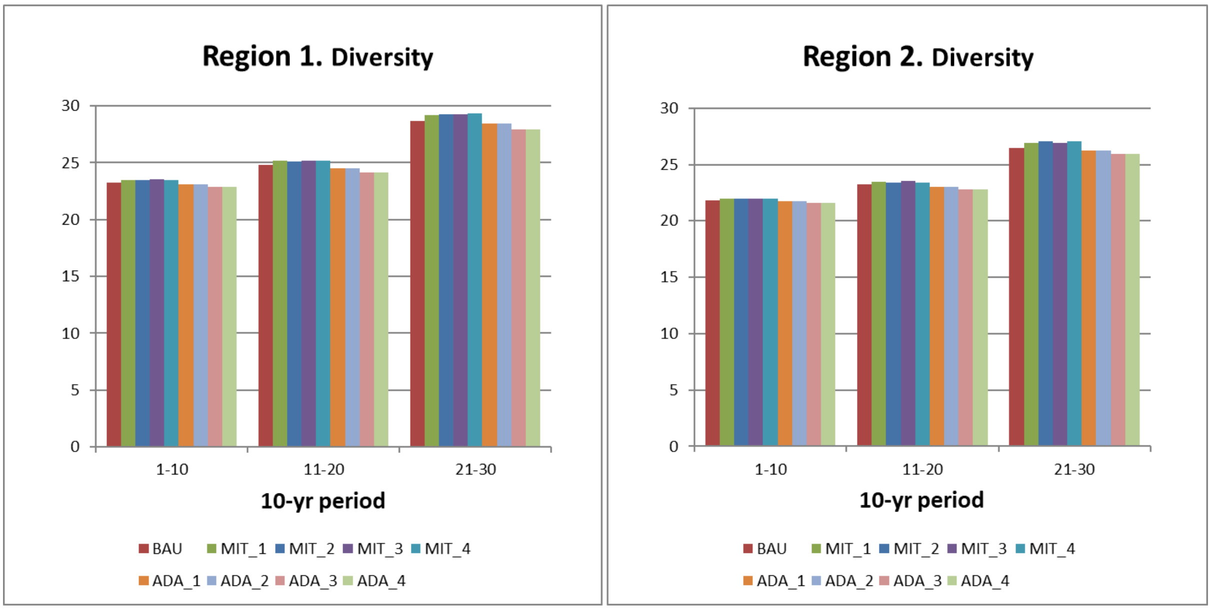


Figure 21: Deadwood diversity in different management scenarios for 30 simulated years (periods: 10-year average).

4.3.6. Summary and comparison to iLand-results

Two large-scale study-areas based on NFI-data gave us a representative and up-to-date basis for the scenarios. The management alternatives defined for the scenarios were somewhat ambitious, and the aims were not fully met in simulations (i.e., the rotation lengths). Also, the 30-year study period was too short to show all the impacts of the treatments (like birch planting in ADA scenarios).

However, the result showed the general trends caused by the alternative forest management scenarios. As the birch planting impacts were not seen yet in the study period and the effects of CCF management remained marginal due to the small areas, the main factors causing differences between scenarios were the changes in rotation lengths and the proportion of set-aside areas.

Two study-regions (Region 1 and 2) were very similar, so the comparisons between scenarios resulted in similar results.

- **Carbon storage** increased by extending rotations and by increasing the share of set-aside areas. Both ensured that more trees grow longer in the forests.
- In short perspective, **cutting removals, incomes, and NPVs** increased by shortening rotations, but if cutting volumes were not kept at the same level (as was done in BAU scenario) changes between annual or periodical cuttings can be remarkable. Early cuttings also decreased the growing stock in the beginning of the scenarios, which decreased both volume and value of the growing stock in the end of the study-period. Extended rotations had contrary effects. The share of the set-aside areas decreased the cutting possibilities and further the incomes and NPVs, because in this analysis cuttings were not directed to the other areas.
- **Biodiversity** impacts were poorly seen in this analysis due to the slow changes in the forests and a short study. Extending rotations slowly increased both broadleaved trees and deadwood volumes, shorter rotations having contrary effects. Favoring old and

high-stocking stands in the selection of set-aside areas was beneficial for both. It is also worth noting that all structural characteristics for forest biodiversity were not available in NFI-data. Thus, only development of the general characteristics can be assessed with these scenarios.

Generally, the regional simulations under historical climate (*Motti* scenarios) revealed similar patterns as the landscape level simulations (*iLand* scenarios) for the effects of alternative management strategies. It is however important to consider the differences in input data (*Motti*: NFI data, *iLand:* stand data), length of simulations (30 for *Motti*, 80 for *iLand*), and model architecture (*Motti*: empirical model, includes peatlands, no climate change or disturbances, *iLand*: process-based model, no peatlands included, includes climate sensitivity and disturbances).

According to the datasets, there were also differences in forests they were representing (e.g., distributions of site types, dominant tree species). *iLand* study-areas consisted of mineral soil stands only, whereas in *Motti* study-areas there were also peatlands included (20% and 26% of the total area in region 1 and 2, respectively) (Table 3). When mineral-soil sites were compared, the proportion of better sites (herb rich and mesic) is higher in *iLand* study-area 1 (Urjala) than in *Motti* study-area 1, whereas in study-area 2 the proportion of better sites (especially herb rich) is higher in *Motti* data. The proportion of pine-dominated stands is clearly larger in *Motti* study-areas than in *iLand* study-areas (Table 2 and 3).

Some general comparisons are, however, possible. Both models showed a strong impact of changing the management strategy. Even when simulating different climate-change scenarios with *iLand*, the difference between management scenarios was much larger than between climate change scenarios. Both the change in rotation lengths and the share of protected areas in the landscape substantially influenced the results in both *iLand* and *Motti*.

There are some interesting considerations regarding how disturbances affect the results, taking into account also some differences in indicator definition, e.g.,:

- while a direct comparison between carbon values in *iLand* and *Motti* was not possible due to the difference in the carbon pools that are included, it can be noticed that especially the relative increases under mitigation strategies was much less pronounced in *iLand* even under historical climate (Table 5, 6), which was likely an effect of disturbances (and of including the soil carbon pool which is a large, slow-responding pool and reduces variability overall).
- For the harvested wood, *Motti* allowed us to distinguish between pulp and sawn wood and showed for example that not only do MIT scenarios had lower harvests (particularly in early parts of the simulation), but they also had a higher share of pulpwood, overall causing a substantial reduction in income. While only a small amount of wood removals in *iLand* were salvage harvest compared to regular harvest, these would also impact the quality of removed wood, increasing the share of pulp wood.
- In relation to biodiversity, the effects were only partially seen within the 30-year simulation period used in *Motti* scenarios but became clearer over the longer duration of *iLand* simulations. In both *Motti* and *iLand*, the share of set-aside area was a major driver in relation with biodiversity, with all alternative scenarios eventually having higher deadwood amounts than BAU due to deadwood being left behind in protected areas. The disturbances included in *iLand* further contributed to this as an additional deadwood generating process, as protected areas are not salvage-logged.

5. Conclusions

Finnish forests are facing changing climate, disturbance regimes and societal demands in the future. They will have to provide multiple ecosystem services while potentially being impacted by more extreme climate and increasing disturbances. Alternative management approaches are needed but different demands are difficult to reconcile within forest management. The FOSTER project aimed to provide better understand of future development of multifunctional forests, gaining a better understanding of potential disturbance agents and climate impacts and exploring a wide range of alternative management strategies, both from climate change mitigation and adaptation angles.

When adapting forests to future challenges, forest regeneration plays a crucial role, particularly when aiming for mixed species stands by increasing the share of broadleaves. Ungulate browsers have considerable impacts on forest regeneration in Finland. In FOSTER, we focused on gaining better understanding of the relatively less researched but potentially impactful small browsing agents, white-tailed deer and roe deer. For both these species, our review found that young trees make up a substantial part of their diet (particularly in winter) and based on movement analysis, young forest stands are an important habitat for them (broadleaved stands in summer, coniferous stands in winter). On the national level, moose however remains the most impactful browser. Assumed combined food consumption of roe and white-tailed deer (based on their daily consumption and populations estimates) still represent only about 10 % of moose consumption nationally. However, especially white-tailed deer can locally have a considerable impact in high population density areas.

Climate change is one of the main drivers of forest change, both directly and indirectly (through disturbances and demands for forests to act as carbon sinks). Mean temperature in Finland is rising considerably faster than the global average, particularly in winter. Along with a rise in temperature, increasing precipitation is also forecast. Due to the uncertainty associated to future climate, we aimed to cover a range of climate scenarios in our simulations. We therefore assembled a set of four future scenarios, ranging from a relatively weak climate change signal to strong changes, covering both increases in precipitation but also a dry and hot scenario. While our main simulations of climate change impacts on forests use the conventional approach utilizing macro-climate data, including micro-climatic effects is an important next step in simulation modelling. Local variation in topography, vegetation, and soil creates large microclimatic variability in e.g. temperature and moisture. Micro-climatic effects in forest microclimates can play an important role in buffering climate extremes (e.g. heat, drought). However, forest models rarely consider such microclimate data and instead generally utilize coarse-scale climate data. The representation of processes such as regeneration, deadwood dynamics and the lifecycle of disturbances such as bark beetle could be further improved by including micro-climatic effects. In FOSTER, we explored the possibility of integrating a process-based micro-climate modelling approach and a forest simulator, laying the groundwork for an improved inclusion of micro-climate in forest simulation.

To explore the effects of a portfolio of alternative management scenarios (combining various levels of rotation length increase/reduction, tree species change and setting aside areas from management) we used two simulation models, *iLand* and *Motti*. With iLand we simulated two forest landscapes investigating the management strategy portfolio under climate change and disturbances from wind and bark beetles. Scenarios aiming to mitigate climate change through increased carbon storage succeeded in raising carbon stocks in the landscape while scenarios aiming to adapt to future disturbance risks reduced carbon storage relative to business-as-usual. Overall the chosen management scenarios affected carbon storage more than climate change. Disturbances increased considerably under climate change, particularly bark beetle disturbances, but significant increases are expected only in the latter half of the century. Disturbances increased considerably under mitigation scenarios, particularly in set-aside stands which had high volume at risk. However, losses due to disturbances did not offset the gain in carbon storage in mitigation scenarios. Mitigation scenarios were overall more successful in fulfilling multiple ecosystem services (carbon stocks, deadwood, large trees, scenic beauty index) but had a strong trade-off in the form of considerably reduced harvests due to lengthening rotations and setting aside large shares of the most productive forests from harvest. Regional simulations with Motti were in line with the iLand simulations yet adding that economic differences between scenarios were primarily driven by rotation lengths because of their effects in decreasing/increasing harvested area. Increased cuttings under adaptive management increased Net Present Value but larger shares of set-aside area reduced it.

The key messages from the FOSTER project are;

1. **Increasing carbon storages in forests is possible with controlled risks.** Even though the risks are increasing in the future, using forests to mitigate climate change is possible in Finland in the coming decades. Climate change mitigation is also crucial to control future disturbance risks.
2. **Adaptation to climate change.** Different adaptive measures of forests management, such as mixed species stands and shorther rotations, are needed in the future and they have the potential to mitigate also the disturbance risks. Increasing rotation lengths is climate-smart forestry to mitigate climate change, but at the time of regenerating a stand, adaptation measures should be considered carefully.
3. **Management choices provide synergies and tradeoffs between ecosystem services.** FOSTER results remind well that forest management choices with single main aim (mitigation vs. adaptation) impact still all the different ecosystem services in different ways.

The FOSTER project provided insights on the future of multifunctional forests in Finland, investigating the main drivers impacting them and exploring potential effects of changing management regimes. We integrated multiple suggested changes to forest management (rotation length and species shifts, setting aside large shares of forest) which interacted in complex and even surprising ways. This highlights that changing forest management to adapt forests to future challenges requires clear setting of priorities and deep understanding of the complex interactions between climate, disturbance agents, and forest management. Further research is needed to better understand the future disturbance regime in Finland and to integrate these effects more fully into simulation modelling approaches.

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