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Rising cost of disturbances for forestry in Europe under climate change

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Climate change has large economic costs for society. An important effect is the disruption of natural resource supply by climate-mediated disturbances such as wildfires, pest outbreaks and storms. Here we show that disturbance-induced losses for Europe's timber-based forestry could increase from the current €115 billion to €247 billion under severe climate change. This would diminish the timber value of Europe's forests by up to 42% and reduce the current gross value added of the forestry sector by up to 15%. Central Europe emerges as a continental hotspot of disturbance costs, with projected future costs of up to €19,885 per hectare. Simultaneous climate-related increases in forest productivity could offset future economic losses from disturbances in Northern and Central Europe but not in Southern Europe. We find high disturbance-related cost of unmitigated warming, highlighting that climate change adaptation in forestry is not only an ecological but also an economic imperative.

Climate change has strong impacts on global ecosystems[1,2]. These impacts are likely to result in high economic costs for society[3]. Recent studies estimated economic losses related to climate impacts on global ecosystems to several trillion dollars[4], with income reductions of 19%[5], several hundred billions of dollars needed to compensate for loss and damage[6], and reductions in the gross domestic product of 1.2% per 1 °C increase in global mean temperature[7]. In particular, the already observed[8] and projected future[9–11] increases in frequency and intensity of extreme events, such as droughts, wildfires and floods, have severe consequences for the global economy[4,12].

Forest ecosystems are particularly prone to climatic extremes because trees are sessile and long lived[13,14]. As forest products are central to a bio-based economy[15–17], changing extreme events pose a major challenge for a wider use of bio-based materials. A major concern in this regard are forest disturbances, that is, large-scale pulses of tree mortality from wildfires, pest outbreaks and storms[18,19]. Forest disturbances have increased in frequency and severity in many parts of the globe in recent decades[20,21] and are expected to further increase under continued climate change[22]. A hotspot of changing forest disturbances is Europe, where disturbance rates doubled in less than 20 years for major disturbance agents[20], and a massive recent pulse of tree mortality was unprecedented in at least 170 years[23]. Societies in Europe are strongly dependent on forests for providing jobs, supporting rural livelihoods, and contributing to environmental and economic well-being[24]. Yet, the continental-scale economic impacts of climate-mediated disturbances remain unclear so far.

Understanding the economic impacts of disturbances is complex, as interactions with other climate-induced changes have to be considered. For instance, climate change affects forest productivity, with decreases projected for water-limited regions[25] but broad-scale increases expected due to CO_2 fertilization[25–27] and an extension of the growing season particularly in boreal and mountain ecosystems[28,29].

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Changing forest productivity interacts with disturbance costs: increasing productivity increases the growing stock, which in turn enhances the timber value of forests. Simultaneously, productivity-related increases in harvest levels lead to higher returns that might partly or completely offset the economic costs of increasing disturbances[30,31]. These interactions require a joint evaluation of the economic consequences of changing disturbance and productivity[30,31].

Here we present an estimate of the current and future economic costs of forest disturbances at continental scale, accounting for climate-mediated changes in both forest productivity and disturbance in Europe. Specifically, we investigated the historical costs of disturbance on the timber-based forest value (under the climate conditions of the reference period 1981–2005) and how they are likely to evolve under scenarios of future climate change (representing the climate conditions expected for the period 2076–2100). We assessed hotspots of economic disturbance impact in Europe and whether increasing forest productivity can offset economic losses from disturbance under climate change.

To address our questions, we coupled three crucial elements, (1) spatially explicit (16 ×16 km) forest growth simulations at the level of individual tree species, (2) >150,000 Monte Carlo simulations of forest disturbances informed by latest remote sensing data and (3) economic models to quantify the costs of changing productivity and disturbance across continental Europe focusing on the commercially most relevant species (a total of 91 million ha, or two-thirds of Europe's forest area). We studied a total of 1,536 scenarios under three different representative concentration pathway (RCP) scenario families and quantified the cost of disturbance by comparing scenario simulations to the counterfactual of simulations without disturbance under the same climate conditions. Economic effects were quantified by converting simulated time series of planned (that is, business-as-usual management) and unplanned (that is, disturbance-related) timber harvests to economic cashflow, which was subsequently discounted and summed to obtain forest value (Extended Data Fig. 1). We translated the present value of total disturbance costs into annual costs by multiplying with a discount rate of 1.5%. Disturbances are discrete events in space and time, and averaging over extended spatiotemporal scales masks their immediate local effects[12]. Hence, we report costs for both the average (mean across all stochastic simulations) and the extreme case (defined as the average of the worst 5% of simulations, conditional value at risk), with the latter being particularly informative for planning under the precautionary principle[32].

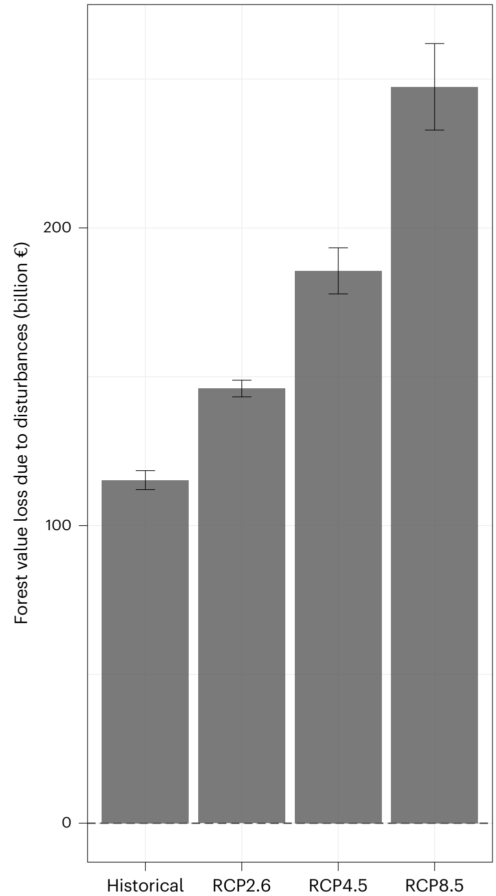

Fig. 1 | The current and future cost of natural disturbances in Europe's forests. Bars show the timber-based forest value losses from disturbances relative to the counterfactual of undisturbed forest development under the same climate scenario. Data denote mean ± s.d. across all simulations (N = 300). 'Historical' assumes climate conditions from 1981–2005, while RCP scenarios are for projected future climate conditions for the period 2076–2100.

Climate change doubles the costs of natural disturbances

Under historical conditions (1981–2005), the economic costs of natural disturbances in Europe (loss of forest values) were €115 ± 3 billion (mean ± s.d., Fig. 1), with an average annual cost of €1,729 ± 48 million yr^{-1} and an average cost per unit area of €1,265 ± 35 ha^{-1}. These costs were the result of on average 74.5 million m^3 of timber disturbed per year (Table 1). Disturbances reduced the total forest value of Europe by 28.6 ± 0.7% compared with the counterfactual of no disturbance. Under climate change, total future timber harvest increased by 17.1%, from 259.6 to 304.1 million m^3 yr^{-1} (for the period 2076–2100) under scenario RCP4.5 (increases of 12.9% and 28.0% under RCP2.6 and RCP8.5, respectively), resulting from both increasing productivity (increasing planned harvest) and increasing disturbance (increasing unplanned harvest; Table 1). Distinct increases in unplanned, that is, disturbance-induced, harvests increased costs of disturbance to €186 ± 8 billion under RCP4.5, and up to €247 ± 15 billion under RCP8.5 (RCP2.6: €146 ± 3 billion). This reduced the potential forest value relative to the counterfactual of no disturbance by up to 42.1 ± 2.5%, and translated to average annual costs of €2,783 ± 116 million yr^{-1} under RCP4.5 (RCP2.6: €2,191 ± 42 million yr^{-1}; RCP8.5: €3,711 ± 218 million yr^{-1}), and average costs per unit area of €2,037 ± 85 ha^{-1} (RCP2.6: €1,603 ± 31 ha^{-1}; RCP8.5: €2,715 ± 160 ha^{-1}). Simulating a moderate shortening of the rotation period by 10 years as a measure to adapt to changing climate and disturbance regimes reduced the cost of disturbance by up to €10 billion under scenario RCP8.5 (Extended Data Fig. 2). All economic results were sensitive to varying discount rates, with higher costs of disturbance at lower discount rates (Extended Data Fig. 3). Different climate model projections within the same RCP family resulted in similar trajectories (Extended Data Fig. 3).

Central Europe as hotspot of future disturbance costs

The economic costs of natural disturbances varied widely across Europe (Fig. 2 and Extended Data Table 1). Hotspots of future disturbance costs were mainly located in Central Europe (especially in parts of Germany, Austria, Switzerland and the Czech Republic; Fig. 2c), where disturbances lowered the economic value of forests on average by €3,233 ha^{-1} under moderate climate change (RCP4.5), and €2,460 ha^{-1} and €4,375 ha^{-1} under mild (RCP2.6) and severe (RCP8.5) climate change, respectively (Fig. 2a). Extreme costs in this region (that is, the average of the economically worst 5% of simulations, conditional value at risk) were €17,067 ha^{-1} under RCP4.5 (€13,932 ha^{-1} and €19,885 ha^{-1} under RCP2.6 and RCP8.5, respectively). In contrast to the high disturbance costs in Central Europe, forests in Northern Europe had 60–65% lower economic costs of disturbance, with average losses of €1,164 ha^{-1} under RCP4.5 (€966 ha^{-1} and €1,523 ha^{-1} under RCP2.6 and

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Table 1 | Planned and unplanned timber harvests under climate change

Climate scenario	Annual timber volume harvested (million m³)			Share of unplanned harvests (%)	Productivity relative to historical (%)
	Total	Planned	Unplanned		
Historical	259.6±9.4	185.1±8.5	74.5±2.7	28.7±1.1	100±7.9
RCP2.6	293.1±9.9	205.1±9.3	88.0±4.2	30.0±1.4	112±7.7
RCP4.5	304.1±15.6	200.3±11.9	103.8±8.5	34.1±2.8	117±3.5
RCP8.5	332.3±24.0	202.7±16.9	129.6±13.2	39.0±4.0	127±2.3

Unplanned harvest is the amount of timber accruing from natural disturbances, while planned harvest is the timber extracted by regular forest management. Values indicate mean±s.d. Productivity refers to potential net primary productivity (compare Supplementary Methods section 'Forest productivity under climate change') in percent of the historical climate scenario. Historical assumes climate conditions from 1981–2005, while RCP scenarios are simulated under the climate conditions expected for the period 2076–2100.

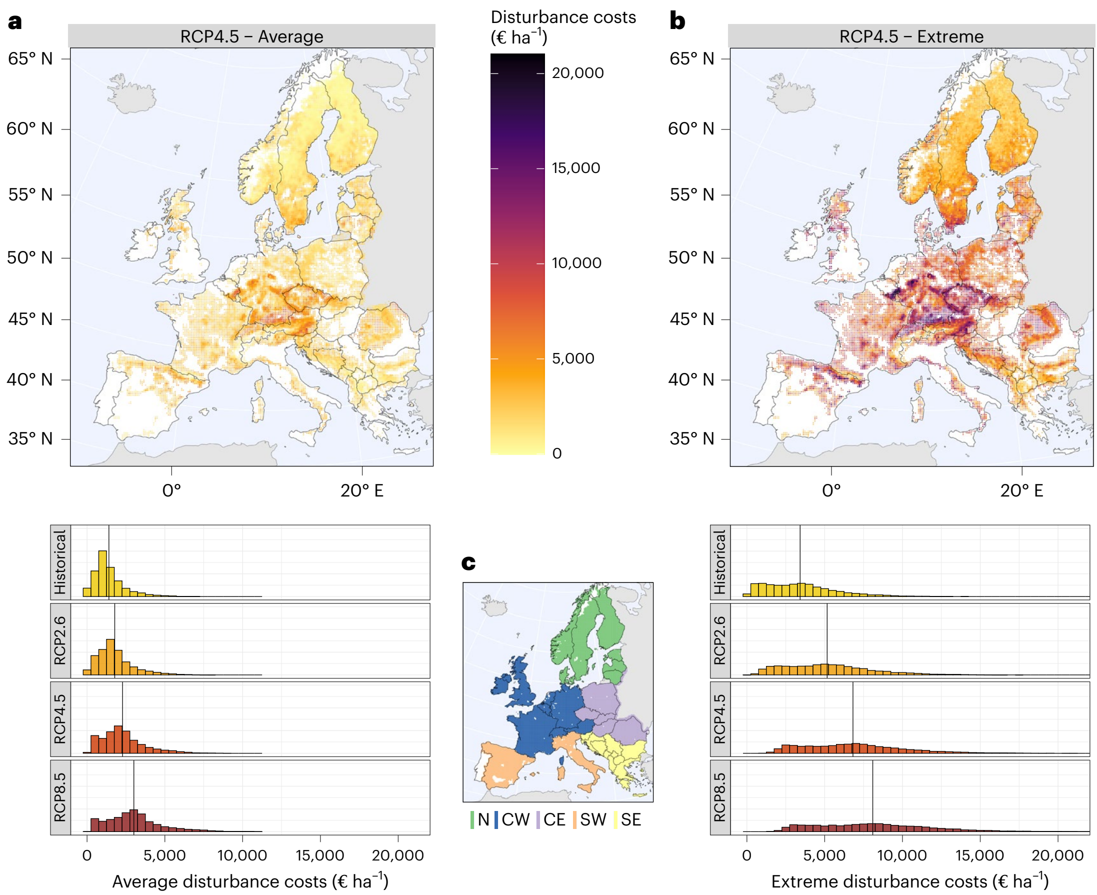

Fig. 2 | Hotspots of future disturbance costs in Europe's forests. The colour of each point represents the cost per hectare of forest within a 16 × 16 km cell, and the size of each point corresponds to the forested area within that cell. **a**, Average disturbance costs across all simulations. **b**, Extreme costs, expressed as the mean over the 5% scenarios with the highest costs. Histograms illustrate the distribution of disturbance costs across all scenarios, with the values for RCP4.5 corresponding to the data shown in the maps. Vertical lines within each histogram indicate average disturbance costs. Only cells with a forest cover of at least 5% are displayed. **c**, Map showing the European regions considered in this study: Northern Europe (N), Central–Western Europe (CW), Central–Eastern Europe (CE), South–Western Europe (SW) and South–Eastern Europe (SE). All maps use the ETRS89-LAEA Europe projection (EPSG:3035). See Extended Data Fig. 4 for maps assuming other climate scenarios. Credit: shape file by Andy South.

RCP8.5, respectively). Nonetheless, local extremes were also high in Northern Europe, exceeding €10,000 ha^{-1} (RCP2.6: €9,747 ha^{-1}, RCP4.5: €12,370 ha^{-1}, RCP8.5: €14,664 ha^{-1}, Extended Data Table 1). Generally, the continental-scale differences in disturbance costs decreased when considering extreme values (Fig. 2). Disturbance costs in Southern Europe (Fig. 2c) were between those in Northern and Central Europe (Extended Data Table 1).

Productivity gains offset disturbance losses

The increase in forest productivity under climate change (Table 1) overcompensated the economic losses from disturbances in Europe overall, but regional variation was high. The productivity-related increase in forest value can be attributed to two effects: higher initial growing stocks and increased sustainable harvest levels from elevated tree growth (Extended Data Fig. 5). These effects were strongest under scenario RCP8.5, yet in this scenario, disturbance-induced losses also increased most strongly (Fig. 3a). The economic effects of productivity and disturbance increased at similar rates across climate scenarios, resulting in little variation in overall forest value with climate change (RCP2.6: €337.9 ± 12.6 billion, RCP4.5: €328.6 ± 20.8 billion, RCP8.5: €340.8 ± 34.9 billion). However, scenario uncertainty was lowest under RCP2.6 and increased considerably with increasing severity of climate change (Fig. 3b). Productivity-related offsets of disturbance losses varied distinctly across Europe. In Northern Europe, economic gains

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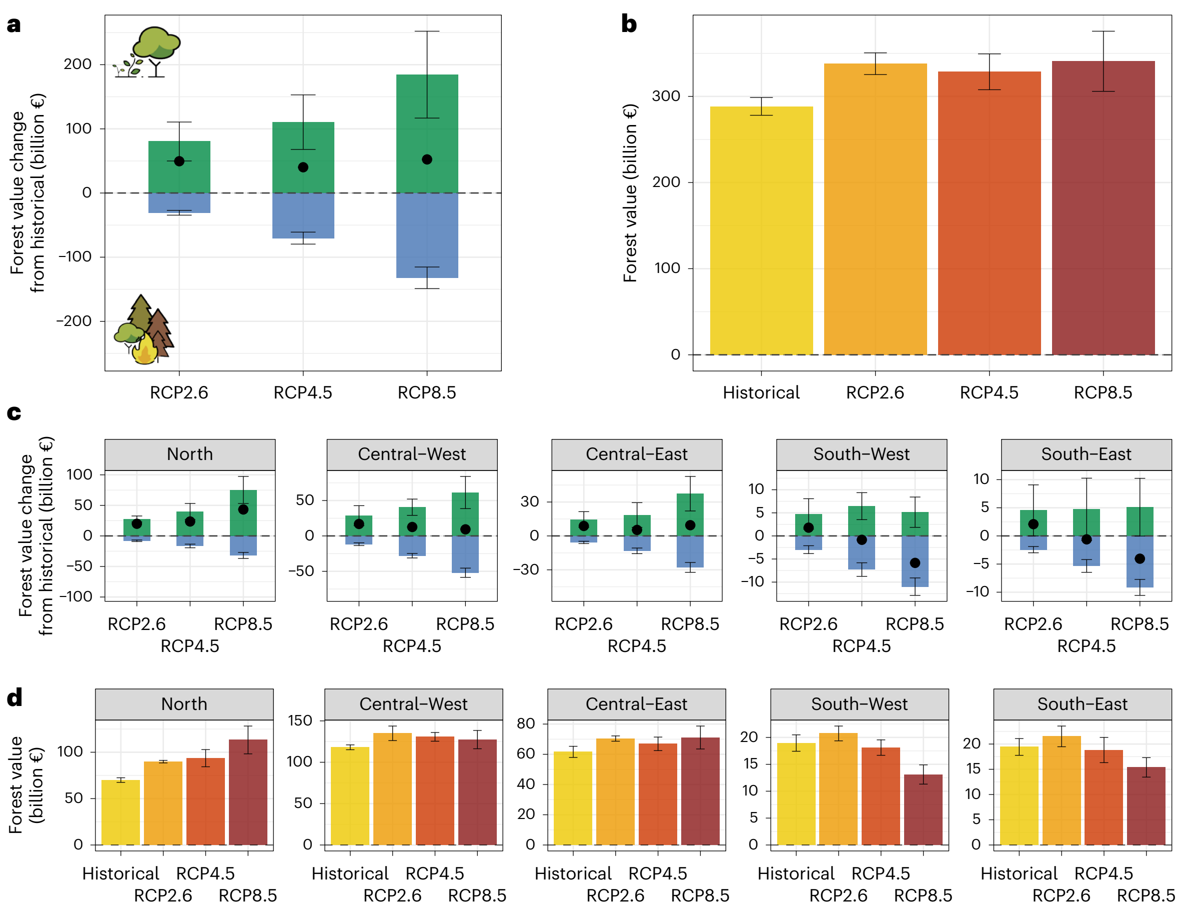

Fig. 3 | Effects of changing forest productivity and disturbance on forest value in Europe. a,**c**, Changes in forest value at the continental (**a**) and regional (**c**) scale under future climate compared to historical values. Historical assumes climate conditions from 1981–2005, while RCP scenarios are simulated under the climate conditions projected for the period 2076–2100. Blue bars represent losses due to increasing disturbances, green bars show gains from increasing productivity. Dots indicate the net change in forest value compared to historical values. **b**,**d**, Continental (**b**) and regional (**d**) forest values under different climate scenarios. In all panels, data show the mean ± s.d. across all simulations in the respective stratum. Regions were defined as in Fig. 2c. Icons in **a** adapted from OpenMoji (https://openmoji.org/) under a CC-BY-SA 4.0 licence.

from increasing productivity clearly outweighed disturbance-mediated losses under climate change (Fig. 3c,d). In contrast, productivity stagnated or declined in Southern Europe while disturbances increased, resulting in decreasing net forest values under climate change. In Central Europe, productivity was projected to increase, albeit at a lower rate than in Northern Europe. Here, economic losses from disturbances are compensated by gains in productivity, yet the offset capacity decreases with increasing severity of climate change (Fig. 3c,d). Only under the mild climate scenario RCP2.6 was the forest value of all European regions (and 92% of all European countries, Extended Data Fig. 6) projected to increase relative to historical levels, when considering the net effects of both changing productivity and disturbance.

Discussion and conclusions

Here we provide a continental-scale estimate of forest disturbance costs for Europe. Our findings suggest that disturbance costs could more than double under climate change. Under severe climate change, the annual losses estimated here correspond to up to 15% of the current gross value added of the forestry sector in Europe[24]. We furthermore highlight considerable differences in the economic costs of forest disturbances throughout Europe, identifying particular hotspots in Central Europe. Local-scale studies from this region show that disturbance costs could be even higher than estimated here, when only considering disturbance impacts on the economically most valuable tree species[32]. Nonetheless, our results of disturbance-based losses on the timber-based forest value of up to €19,885 ha^{-1} suggest that disturbances could posit major economic challenges for timber-based forestry in the future. Our results also indicate that simultaneous increases in forest productivity under climate change could offset economic losses from increasing disturbances. The finding that Northern Europe is the main beneficiary of climate change, with increasing forest values in Europe's boreal zone, is in agreement with previous studies on the economic effects of climate change[33]. In contrast, the timber-based forest value in Southern Europe is already considerably lower than in other parts of the continent[24] and will decrease further under climate change. The negative impacts of climate change on Southern Europe identified here correspond well with previous assessments[9,25,33,34].

Important limitations need to be considered when interpreting our results. First, our estimates of the cost of disturbances are likely conservative, because we only focused on timber-related forest values. Although timber remains the main marketable good from forests throughout Europe, disturbances have broad impacts beyond timber[35], and the societal costs of disturbance impacts on non-marketable ecosystem services were not considered here. Similarly, we focused on the economically most important tree species and did not study the effect of tree species change in response to changing climatic conditions. More broadly, the consideration of alternative silvicultural strategies was beyond the scope of our analysis. Rather, we assumed even-aged management as the most widely used silvicultural strategy across the continent[24,36,37] and considered local differences in productivity and their effect on rotation periods. While this approach is not able to capture the full variability of forest management regimes applied in Europe[24,36], it approximates the dominant management of the simulated tree species well[36,38], and provides a robust and consistent baseline for quantifying continental-scale disturbance costs. We also omitted income from thinning, likely underestimating Europe's forest value. However, previous studies showed that considering thinnings does not substantially reduce disturbance costs[32]. The increasing volatility resulting from disturbances may also drive risk-averse forest owners to exit the market[39], which can have considerable economic effects beyond the ones considered here. Moreover, we only incorporated the three most important forest disturbance agents in Europe, namely, wildfires, windstorms and bark beetle outbreaks. The advent of novel disturbances such as invasive alien pests and pathogens could considerably alter future disturbance regimes at the continental scale[40] and further increase economic costs of disturbance. Another important assumption in our analysis is that some of the disturbed timber is salvage harvested and thus enters the timber market. This is the current default management response to disturbances in Europe[41,42], yet the practice is increasingly criticized for its ecological impacts[43,44]. Lower salvage rates would likely further increase the economic costs of forest disturbances[32,43].

While our quantification of disturbance costs is likely conservative, the estimate of the compensatory effect of increasing productivity might be optimistic. Productivity gains offset disturbance losses because they simultaneously increase initial forest values and periodic returns in our analysis (Extended Data Fig. 5), yet the assumptions with regard to initial values are uncertain (that is, similar forest age structure at higher productivity levels). Furthermore, effects of reduced water use efficiency[45] or acclimation effects in response to elevated CO_2[46] were not considered here. In fact, recent studies already indicate declining forest growth even in some areas of Northern Europe[47]. While we here used best available modelling approaches at continental scale, these uncertainties call for further research on economic effects of both changing productivity and disturbance[34,48].

The high economic costs of disturbance identified here have important implications for forest policy and management. First, losses from disturbances need to be considered more explicitly in forest planning and the economic valuation of different forest management strategies. While even-aged coniferous forests were propagated throughout Europe on the basis of economic grounds in the past, these considerations ignored the substantial disturbance risk of these silvicultural systems[13,49], and hence also the associated costs. As disturbances are likely to increase further under climate change, future considerations of forest planning and management need to explicitly account for their impacts[50]. Second, we show that considerable adaptation efforts are needed to reduce disturbance impacts in Europe's forests. While these efforts (including measures such as planting less disturbance-prone tree species and managing for structured and mixed forests[49,51]) require resources, they will also reduce disturbance risk[49,51] and thus disturbance-related costs. This highlights that there is not only an ecological but also an economical imperative to climate change adaptation in forestry. We show that moderately reducing rotation lengths might reduce disturbance costs, illustrating the potential of climate change adaptation measures in silviculture. However, such measures could also have unintended consequences on other ecosystem services such as forest carbon storage and habitat value[36,52], and should thus only be applied after careful consideration of local trade-offs. Efforts should particularly focus on hotspots of disturbance impacts in Central and Southern Europe, where the expected rise in disturbance-related costs could become increasingly prohibitive for regular forest management in the absence of adaptive measures. Lastly, our results underline the importance of climate change mitigation. Only when climate change was limited to mild levels (scenario RCP2.6) did net positive economic effects of changing productivity and disturbance emerge throughout the European continent. In contrast, largely unmitigated climate change (scenario RCP8.5) could lead to severe economic losses from disturbances, particularly in Southern and Central Europe. We thus conclude that mitigating climate change can avoid substantial disturbance-related costs in the forestry sector.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-025-02408-9.

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Methods

We modelled forest development explicitly for 16 × 16 km grid cells across Europe at 10-year time steps using a matrix model (Extended Data Fig. 1). In each grid cell, we considered the forested area of the four economically most important tree species in Europe[38], namely, European beech (*Fagus sylvatica* L.), Norway spruce (*Picea abies* (L.) H. Karst), Scots pine (*Pinus sylvestris* L.) and deciduous oaks (*Quercus robur* L. and *Quercus petraea* Matt. Liebl.). Together, these species account for more than 95% of the European timber market[53] and two-thirds of Europe's forest area (91 million hectares). Stand age distributions were extracted from an analysis based on remote sensing[54], and tree species shares for each 10-year age-class bin were considered proportional to the species composition at grid-cell level. For each 16 × 16 km grid cell, the forest area was thus distributed to 104 classes (4 tree species × 26 age classes).

For the sake of parsimony and to consistently compare the effects of disturbance and productivity change across Europe, we assumed a single silvicultural system for all simulated forests. As the clear-cut system is still the dominant silvicultural system in Europe for the tree species considered here[24,36,37], we simulated even-aged stand development followed by clear cutting and planting. We accounted for local variation in management intensity across Europe by deriving rotation lengths at the cell level. Specifically, we calculated economically optimal rotation lengths (that is, the age of final cutting that maximizes forest value) contingent on tree species and local site productivity for each cell (see Supplementary Table 1 and section 'Calculation of the economically optimal rotation age' in Supplementary Methods for more details). For the calculation of optimal rotation lengths, we assumed timber production to start from bare ground and we disregarded disturbances.

Forest managers are actively adapting their management to the emerging changes in environmental conditions. While a comprehensive assessment of the economic effects of climate change adaptation measures is beyond the scope of our analysis, we considered two elements of climate change adaptation in our simulations: First, we simulated an adaptation of optimal rotation periods to the emerging changes in productivity under climate change. This was implemented by deriving optimal rotation periods separately for each climate scenario and grid cell (see section 'Climate data' in Supplementary Methods for more details). Thus, rotation periods are effectively shortened in locations where productivity increases, and rotation periods are extended in areas where productivity decreases, simulating dynamic adaptation of managers to changing environmental conditions. Second, we tested the effect of adapting the rotation length from its local economic optimum value in a sensitivity analysis, varying rotation period length by up to ±20 years from the economic optimum (Extended Data Fig. 2). In Europe, reducing rotation period length is a measure that is frequently discussed in the context of dampening the impacts of disturbances[52,55], while extending rotation periods can increase forest carbon storage and habitat value[36]. Thinnings were disregarded in our simulations[32], and we simulated no tree species change, that is, species were replanted in their current proportions after final harvesting or disturbance (but see refs. 53,56).

We assessed the effect of climate change by considering two time slices, one representing historical climate (1981–2005) and one future climate (2076–2100). For each time slice, we simulated 500 years of forest development starting from current forest conditions, with climate conditions averaged for each time slice. We chose this approach over transient scenario simulations as it better quantifies the long-term economic consequences of changing climate and disturbance regimes, given that discounting in economic analyses strongly reduces the weight of future changes in transient analyses. We chose a simulation period of 500 years, as it contains multiple rotations, and aggregated cash flows beyond this period have little influence on the forest value because of discounting. Additional to the time slice representing historical climate, we considered 3 climate scenarios (representing different radiative forcing levels, that is, RCP2.6, RCP4.5 and RCP8.5 from CMIP5) each derived from 3 different climate models, downscaled to our 16 × 16 km grid cells (for details see section 'Climate data' in Supplementary Methods). This resulted in 12 different climate scenarios considered in the analyses. Climate affected both productivity and disturbance in the simulations, as described in the following paragraphs.

Forest productivity and its response to climate change was quantified by dynamically simulating the potential net primary productivity (NPP) per grid cell and species. Potential NPP was defined as the NPP of a fully stocked pure stand of a species under a given climate, during the stand development stage in which tree growth culminates. Potential NPP for each grid cell and scenario was estimated using a deep neural network trained on data generated by the process-based simulation model iLand[57,58]. To derive training data for the deep neural network, we used iLand to simulate NPP values of the four tree species across the full climate and soil gradients of Europe and under the 12 different climate scenarios considered. In iLand, NPP increases with temperature (as long as temperatures are below optimal temperatures for photosynthesis) and atmospheric CO_2 concentration, while water availability (in the atmosphere and soil) and plant-available nitrogen limit the carbon uptake of trees (a detailed description of iLand and the mechanisms used to calculate NPP can be found in refs. 57,58 and on the model website https://iland-model.org). We ran simulations on the basis of daily climate data for each climate scenario (see section 'Climate data' in Supplementary Methods) and extracted the resulting annual NPP values. We developed a feedforward convolutional deep neural network with 13 layers and 189,000 trainable parameters. We subsequently trained the deep neural network on 14 million datapoints derived from iLand to predict annual potential NPP values for the four tree species under study, contingent on the soil and climate conditions prevailing at a grid cell (see section 'Forest productivity under climate change' in Supplementary Methods). The deep neural network was well able to learn the responses of the underlying process-based model and generalized well between climate change scenarios. Predicted potential NPP values for current climate conditions were evaluated against independent observations from satellite data (see section 'Forest productivity under climate change' in Supplementary Methods). To derive merchantable timber volume in our matrix model simulations, we used species-specific yield table estimates (see section 'Yield tables' in Supplementary Methods for more details), dynamically calculating the respective yield class from potential NPP values per cell. Specifically, we used a quadratic link function to capture the nonlinear relationship between NPP and yield class (see section 'Mapping of NPP values to yield tables' in Supplementary Methods), assuming correspondence between the range of potential NPP values predicted in simulations under historical climate and the range of yield class values covered in yield tables. In this way, we combined the robust estimates of merchantable timber volume from yield tables with dynamically simulated productivity changes under climate change, resulting in realistic projections of future timber production at cell level.

To comprehensively assess the impact of natural disturbances, we considered two types of disturbances in the simulation: first, climate-sensitive 'background' disturbances were derived on the basis of statistical survival probabilities estimated on the basis of continental-scale forest inventory data[59] (see section 'Background disturbances' in Supplementary Methods). This disturbance type represents small- to medium-scale events that happen regularly (for example, small-scale mortality from drought or insect infestations, small-scale windthrow), but do not lead to larger-scale economic implications such as market crashes. They were sensitive to changing mean annual temperature, maximum temperature of the warmest month, minimum temperature of the coldest month, annual precipitation sum and precipitation sum of the warmest quarter in our simulations[59]. For each grid cell and tree species, we simulated these disturbances within each time step by resetting a proportion of the cell's area to age class zero and replanting the area, with the proportion affected by disturbance derived from a climate-sensitive hazard probability function[59]. Second, to account for economic risks from rare but large disturbance events, we simulated stochastic, landscape-scale extreme events, such as severe fires, windstorms and bark beetle outbreaks, using biome-specific remote sensing data[60–62]. Extreme events were defined for each scenario as those affecting more than twice the area disturbed in an average year of the scenario. To estimate the occurrence of such extreme disturbance events, we first calculated historical biome-specific average disturbance rates (1986–2005). We subsequently developed scenarios of potential future changes in average disturbance rates based on expected increases in drought intensity and frequency in Europe[2], as well as on other best available estimates for future disturbance change[20,22] and the already observed responses to recent climate change (Supplementary Table 2). On the basis of these analyses, we assumed mean disturbance increases by a factor of 2, 4 and 6, respectively, for RCP2.6, RCP4.5 and RCP8.5, and investigated the sensitivity of our results to a wide range of different potential future disturbance changes (Supplementary Figs. 7 and 8). Subsequently, the specific frequencies and magnitudes of extreme events were derived using Taylor's power law equations fit to remote sensing data[63] (Supplementary Fig. 1), estimating the temporal variance of disturbance rates per agent and biome under historical and increased future mean disturbance rates. The occurrence of extreme events in a simulated time step was determined at the level of biomes by drawing from Poisson distributions. The affected area in each biome was calculated by multiplying the number of extreme events in each time step by their magnitude. Affected cells were then drawn randomly until the estimated disturbed area was reached. In disturbed cells, depending on the disturbance agent (see section 'Extreme disturbances' in Supplementary Methods), all or most of the forest area was reset to age class zero.

Revenues from timber-based forest management were calculated from tree diameter- and species-dependent timber prices and establishment costs[53] (Extended Data Table 2). Revenues were discounted and summed over the whole simulation period to quantify forest value[32,53] (default discount rate of 1.5%, but see Extended Data Fig. 3 for a sensitivity analysis of different discount rates). Simulated increases in productivity under climate change influenced forest value via increased timber harvests, which positively affected forest value. Simulated disturbances had a range of nuanced economic impacts in the simulation (Extended Data Table 3). For climate-sensitive background disturbances, we assumed that the impacted timber is sold with a 50% decrease in net revenue due to a loss of timber quality and increased harvesting costs (see section 'Prices' in Supplementary Methods). For extreme disturbance events, revenues from disturbed timber were set to zero for the affected grid cell, assuming a collapse of the timber market in the region as a result of large quantities of disturbed timber flooding the market[32]. For extreme events, planting costs for the next cohort of trees were assumed to increase by a factor of two, to reflect higher post-disturbance expenses from planting large areas and to account for typical shortages in nurseries after large disturbance events. To assess the sensitivity of our results to additional market effects of disturbances (that is, price drops from extreme disturbance events radiating out to larger areas), we conducted an auxiliary analysis in which we reduced the timber prices of regular harvests in cells adjacent to those affected by extreme disturbance events (see section 'Prices' in Supplementary Methods and Supplementary Fig. 7).

To account for the stochastic nature of disturbances, we used Monte Carlo simulations[32] to consider a wide range of potential future disturbance impacts. This method involved running multiple simulations for each studied scenario. Within each simulation, different random disturbance events were generated to capture a wide range of disturbance sequences and their corresponding economic outcomes. This allowed us to quantify the variability of the economic impacts of disturbances. Monte Carlo approaches have been widely used in economics and ecology[64–67], and are particularly suited to capture the impacts of highly variable events[32]. Specifically, we ran 100 Monte Carlo simulations for each scenario and cell with different random numbers used for (1) drawing extreme disturbance events in each time step and (2) choosing which cells are affected by these events. To assess the economic impact of disturbances, we calculated losses as the average difference in economic value between simulations with and without disturbances across all simulations. In other words, simulations without disturbances in the respective climate scenarios served as the counterfactual to quantify the economic impacts of disturbance. Since disturbances, particularly extreme events, disproportionately impact the fat tail of skewed economic damage distributions (Supplementary Fig. 2), and mean comparisons cannot fully capture the effects of increasing frequencies of rare events[12], we also analysed extreme values from our Monte Carlo simulations. Specifically, for each scenario and simulated cell, we calculated the average of the worst 5% of economic losses across all Monte Carlo runs (conditional value at risk). To transform losses in net present value into annual costs, we calculated an annuity by multiplying the losses by the assumed discount rate of the simulation (1.5%). Regional analyses were conducted for European regions as suggested in the Forest Europe report[24] (Fig. 3c). Within each region, hotspot areas were defined as cells above the 99th percentile of all values in that region (Extended Data Table 1). To estimate economic costs per unit forest area, the total costs were divided by the forested area for each cell.

We successfully evaluated our simulation approach against independent data for several key metrics. The simulated standing timber volume and annual timber extraction rates under historical climate matched observed values well (Supplementary Figs. 5 and 6). The model estimated that 28.7% of the annual timber harvest was due to natural disturbances under historical climate, which amounted to 74.5 million m^3 timber yr^{-1} (Table 1). These values are well within the range of empirical data from recent decades, reporting 42.6–78.5 million m^3 of timber disturbed annually and 12%–32% of unplanned canopy openings from disturbances relative to the total harvested timber volume for the period 1986–2005[20,68]. These results highlight the robustness of our simulations; full details of the evaluations conducted are provided in Supplementary Methods (see sections 'Standing timber volume' and 'Amount of extracted timber'). We used TensorFlow[69] in combination with Keras API[70] in Python for implementing the deep neural network. All other simulations and analyses were done using the R programming environment[71] in R Studio[72] v.2023.12.1.402.

Data availability

The simulated data are available via Zenodo at https://doi.org/10.5281/zenodo.15878694 (ref. 73).

Code availability

The code for reproduction of all analyses is available via Zenodo at https://doi.org/10.5281/zenodo.15878694 (ref. 73).

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Author contributions

J.M. conceptualized the project, conducted formal analysis and investigation, designed the methodology and software, performed visualization, wrote the original draft, and reviewed and edited the manuscript. F.B. conceptualized the project, conducted investigation, designed the methodology, wrote the original draft, and reviewed and edited the manuscript. M.G. designed the methodology, procured resources, and reviewed and edited the manuscript. D.T. designed the methodology, and reviewed and edited the manuscript. W.R. designed the methodology and software, and reviewed and edited the manuscript. T.K. conceptualized the project, acquired funding, designed the methodology, supervised the project, and reviewed and edited the manuscript. C.S. procured resources, and reviewed and edited the manuscript. R.S. conceptualized the project, acquired funding, designed the methodology, administered and supervised the project, and reviewed and edited the manuscript.

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Competing interests

The authors declare no competing interests.

Additional information

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Extended Data Table 1 | Average and extreme costs of disturbance for each European region and RCP scenarios

Region	RCP scenario	Regional average		Local hotspots	
		Average costs (€ ha^{-1})	Extreme costs (€ ha^{-1})	Average costs (€ ha^{-1})	Extreme costs (€ ha^{-1})
North	Historical	782.5	1,186.0	3,730.1	6,568.4
	RCP2.6	966.2	2,426.8	4,308.1	9,746.8
	RCP4.5	1,163.7	3,893.3	4,745.4	12,370.1
	RCP8.5	1,523.9	4,940.5	6,005.2	14,664.4
Central-West	Historical	1,906.4	4,831.1	5,108.4	10,936.0
	RCP2.6	2,460.1	7,105.1	5,920.5	13,931.6
	RCP4.5	3,233.1	9,097.0	7,114.6	17,066.5
	RCP8.5	4,375.4	10,959.7	8,876.3	19,885.1
Central-East	Historical	1,737.6	4,181.6	5,203.1	9,502.4
	RCP2.6	2,150.9	6,115.1	5,775.3	12,195.7
	RCP4.5	2,688.7	7,955.1	6,509.2	14,507.7
	RCP8.5	3,742.7	10,037.2	7,986.7	16,709.5
South-West	Historical	1,522.7	4,885.9	3,623.6	11,362.0
	RCP2.6	2,085.4	6,731.1	4,423.1	13,949.6
	RCP4.5	2,902.4	8,397.5	5,941.3	16,438.1
	RCP8.5	3,603.3	8,837.1	7,550.8	17,183.2
South-East	Historical	1,190.7	3,009.0	2,853.2	7,453.8
	RCP2.6	1,509.0	4,381.2	3,452.3	9,329.0
	RCP4.5	1,886.2	5,501.1	4,250.0	10,949.3
	RCP8.5	2,383.4	6,022.1	5,270.1	12,008.4

The table shows both the average value of the whole region (Region average) and the costs of hotspots within the regions (Local hotspots), that is the 99th percentile of all cell values in the region. All values are shown as cost in € per hectare.

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Extended Data Table 2 | Prices and costs

Species	Timber prices (net after harvesting costs) (€/m³) for diameters of						Establishment costs (€/ha)
	5-15 cm	15-25 cm	25-35 cm	35-45 cm	45-55 cm	>55 cm	
Beech	0	5	10	25	40	50	500
Oak	0	5	15	25	40	60	500
Pine	0	5	20	35	40	45	1,500
Spruce	0	5	25	40	45	45	2,000

Assumed timber prices (net prices after harvesting costs) (€/m³) for each species and diameter class and planting costs (€/ha) derived from 53.

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Extended Data Table 3 | Disturbance effects on the timber-based economy

Disturbance type	Affected variable	Effect	Implemented as
Background disturbance	Net revenue	Net timber price drop resulting from lower quality and increased harvest costs	Reducing the price of disturbed timber by 50%
Extreme disturbances	Net revenue	Timber price drops as markets crash due to a pulse of disturbed timber flooding the market	Reducing the price of disturbed timber by 100%
	Salvage costs	Additional costs to salvage harvest disturbed timber	Additional costs of €10 per m^3 disturbed timber
	Establishment costs	Increased establishment costs, as local availability of machinery, manpower, and planting material is limited	Increasing establishment costs by 100% relative to establishment costs following regular harvests
Both	Harvest age	Disturbances lead to earlier harvests than the economically optimal rotation age	Harvesting timber when disturbance occurs

Consequences of disturbances on the timber-based value of forests by disturbance type, and notes on their implementation in our analysis.

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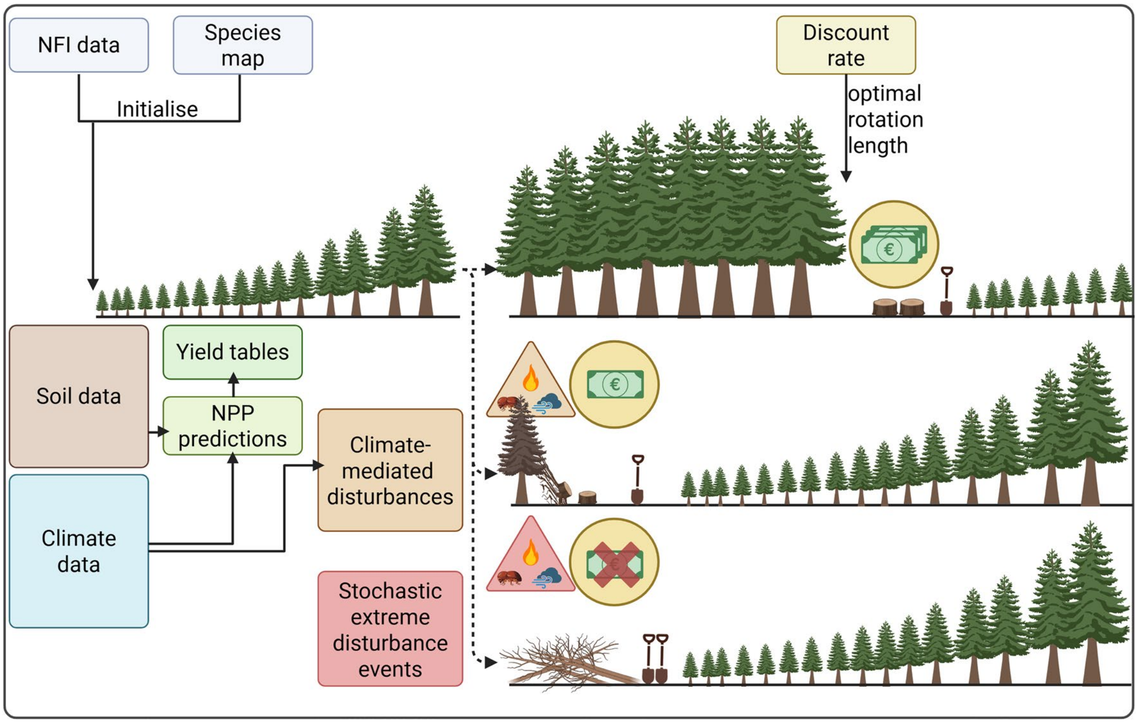

Extended Data Fig. 1 | Graphical overview of the analysis approach. We initialized the simulated forests (16 ×16 km grid cells) using recent species distribution maps[38] and age class information extrapolated from NFI data for continental Europe[54]. Forest growth was simulated based on soil- and climate-sensitive NPP estimates for each tree species, derived from a deep neural network trained on simulations of a process-based forest growth model. NPP values were mapped to yield tables to obtain information on merchantable timber volume and mean tree diameter. We simulated an even-aged clear-cut system (pictograms in top row), with the rotation length varying between cells. To calculate optimal rotation length per cell, we converted extracted timber volumes into economic cashflow and computed the net present value for each possible rotation length (from 0 to 260 years in 10-year intervals), assuming a discount rate of 1.5%. The optimal rotation length was defined as the one that maximizes net present value. After final harvest, we assumed the area was regenerated with the same tree species. To quantify the effect of disturbances, we explicitly simulated two types of disturbances: First, climate-sensitive, background disturbances derived from empirically parameterized hazard probabilities[59] (center row), and second, stochastic extreme disturbance events informed by observations from remote sensing[61] and scaled to future scenarios using Taylor's power law equations[63] (bottom row). In the event of a disturbance, the revenues from timber were reduced for background disturbances, and set to zero for extreme disturbances, representing the combined effects of market price responses, wood devaluation, and increased harvesting costs in the wake of disturbances[32]. Figure created with BioRender.com.

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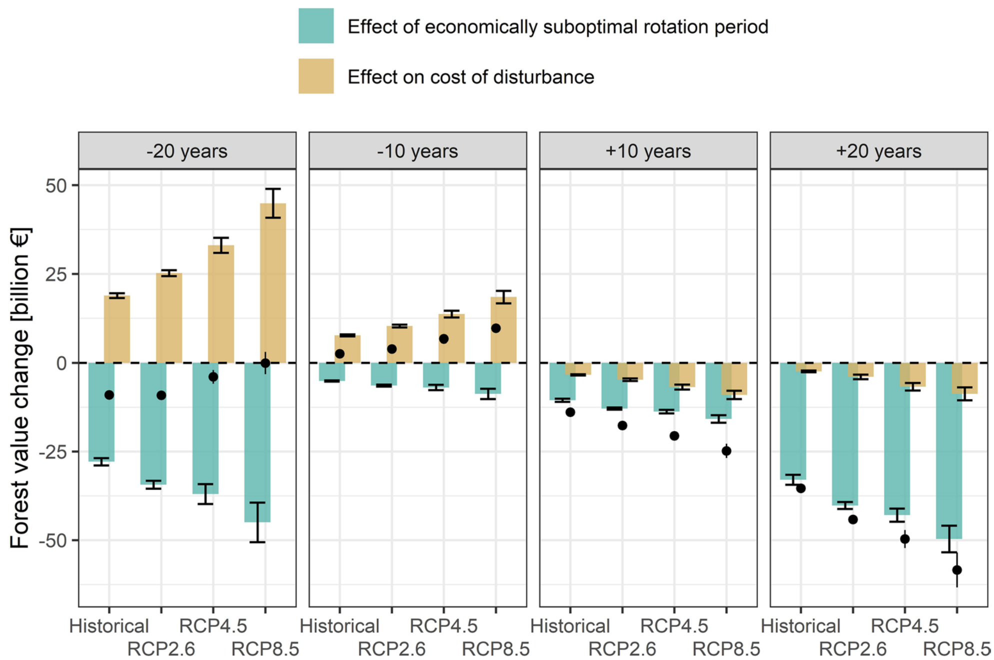

Extended Data Fig. 2 | Economic effects of adjusted rotation lengths. Changing rotation periods from their economic optimal values can be used in silviculture to reduce disturbance risks, and to improve other forest functions such as forest carbon storage and habitat value. Changes in the rotation period have two effects: (1) they result in economic losses because the rotation period is no longer at its economically optimal value (blue bars), and (2) they affect the economic costs of disturbance (orange bars). Bars indicate average values, whileE error bars indicate the standard deviation (N = 300), and points are the net effect and its standard deviation of both economic implications. A positive net effect means an overall increase in forest values compared to default rotation lengths.

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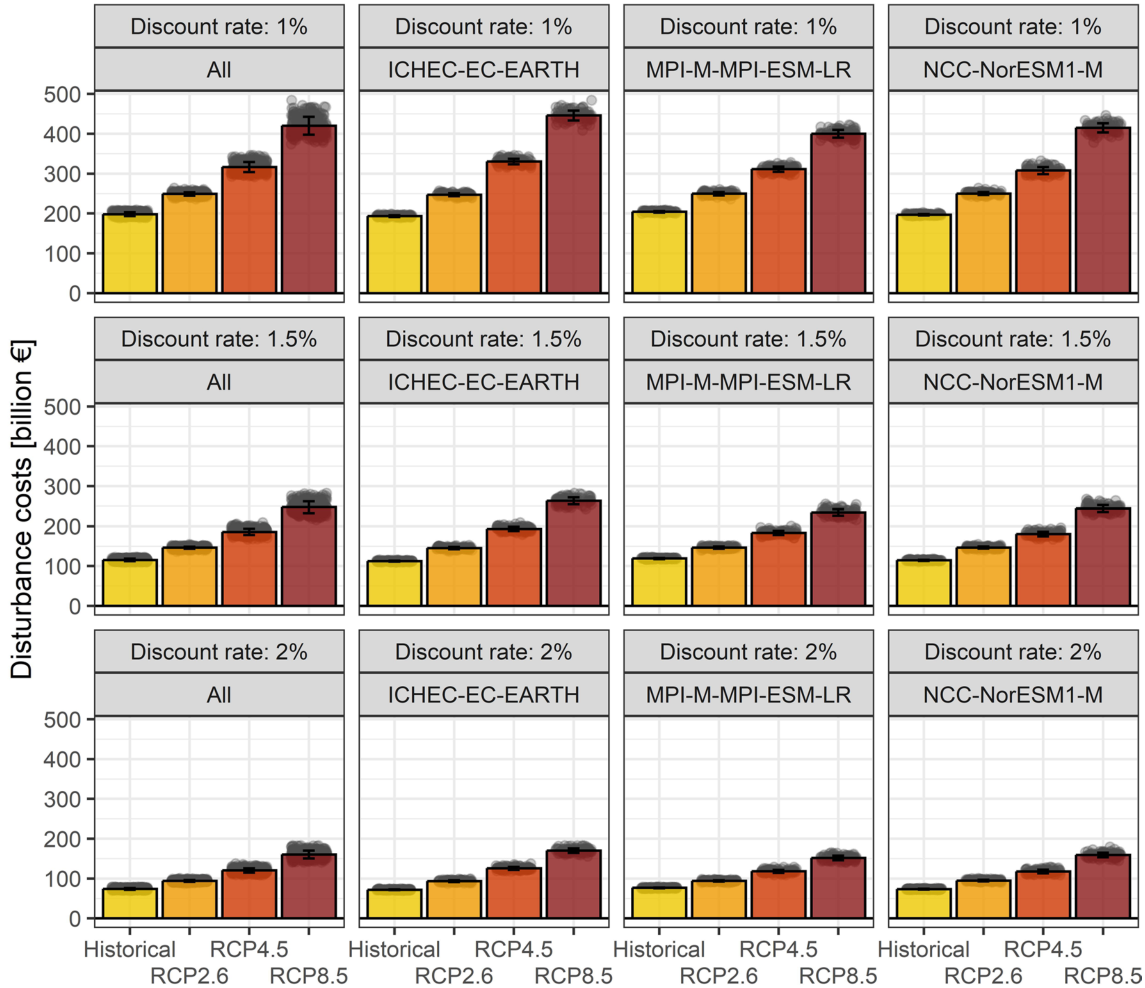

Extended Data Fig. 3 | The impact of varying discount rates and choice of climate model on the costs of disturbances. Lower discount rates decrease forest value due to higher costs of disturbance. The overall effect of climate change on the costs of disturbance is apparent for all evaluated discount rates and climate models used. Each bar indicates the average disturbance costs (N = 300 for panel 'All', N = 100 for each climate model), while the error bars show the average costs ± the standard deviation of simulated costs. The 'All' panels include results of all simulated climate models. Raw data is shown as points.

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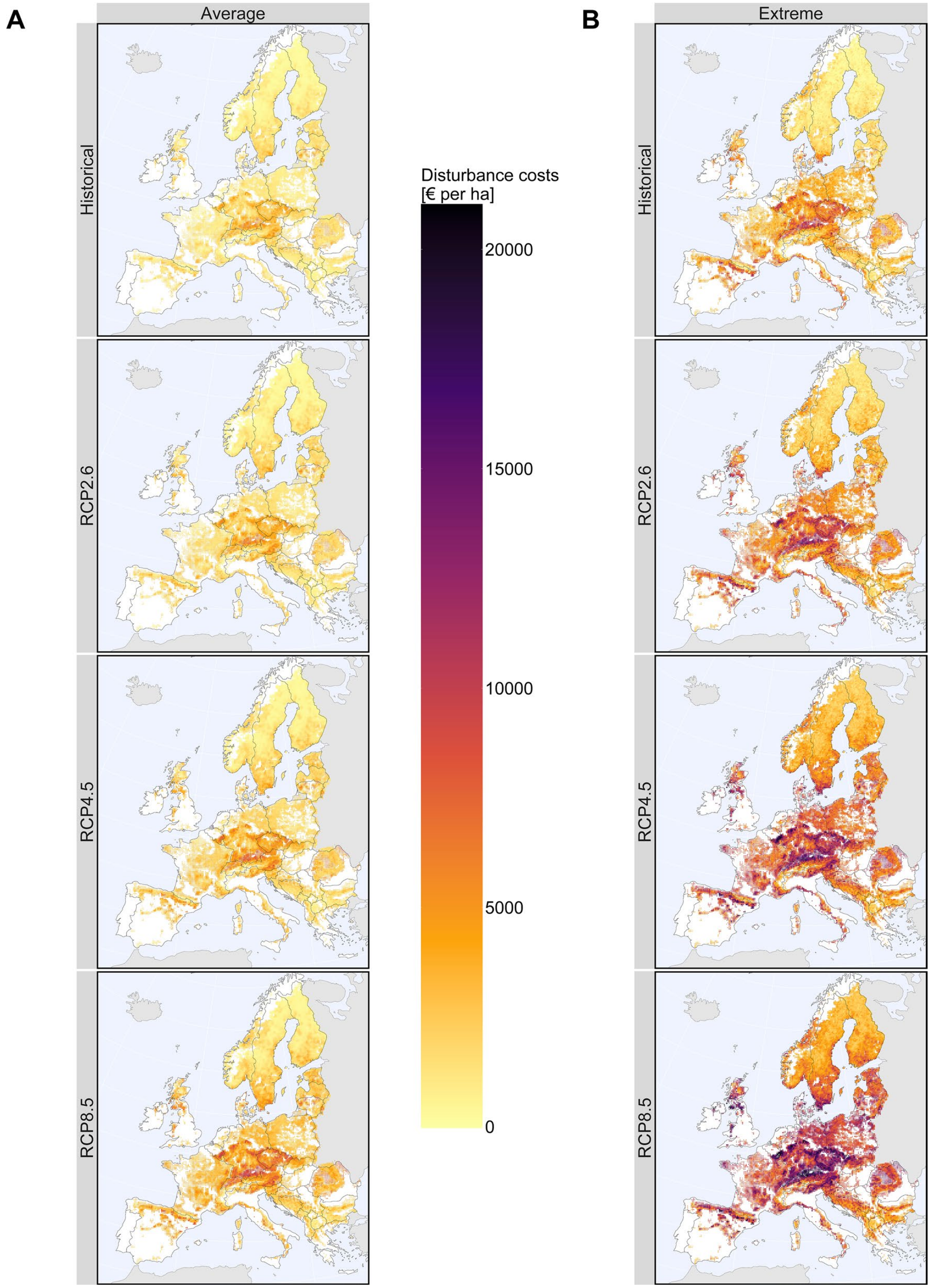

Extended Data Fig. 4 | Hotspots of future disturbance costs in Europe for different climate scenarios. The color of each point represents the cost per hectare of forest within a 16 by 16 km cell, and the size of each point corresponds to the forested area within that cell. Panel (**a**) shows average disturbance costs across all simulations, while panel (**b**) indicates extreme values, expressed as the mean over the 5% highest costs. For visibility, only cells with a forest cover of at least 5 % are displayed. For comparability with Fig. 3, we kept the color scale the same as in Fig. 3. We note, however, that 0.1% of the extreme disturbance costs under RCP8.5 are beyond the color scale used. The map uses the ETRS89-LAEA Europe projection (EPSG:3035). Credit: shape file by Andy South.

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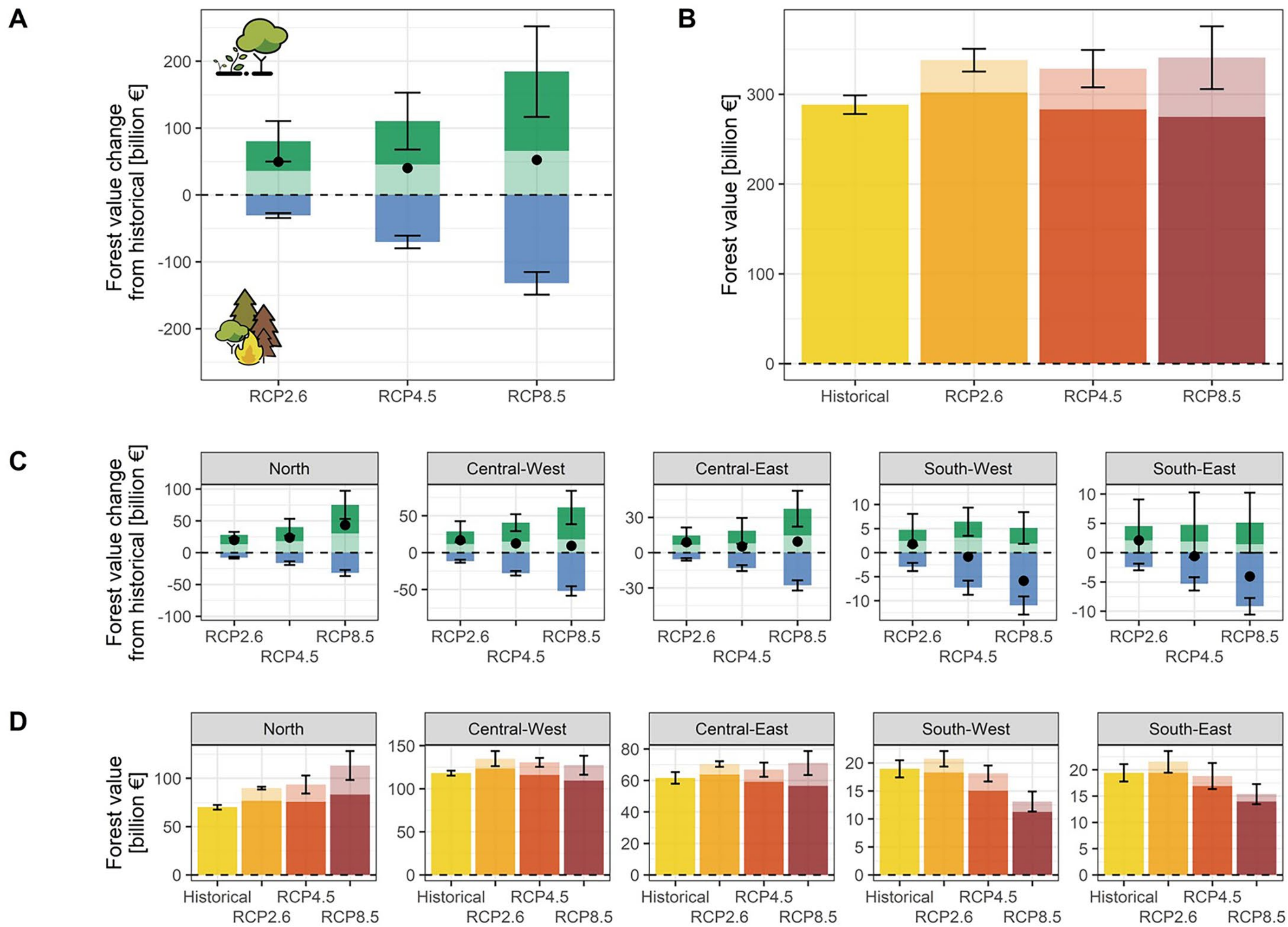

Extended Data Fig. 5 | Effects of productivity-related increases in initial growing stock on gains in forest value. Changes in forest value at the continental (**a**) and regional (**c**) scale under future climate compared to historical values as in Fig. 3. Blue bars represent losses due to increasing disturbances, green bars show gains from increasing productivity. Productivity-related gains are attributed to effects on initial growing stock (derived relative to growing stock levels under historical productivity) – indicated by the transparent portions of the bars – and effects related to increased sustainable harvest levels over the simulation period (solid portion of the bars). Dots indicate the net change in forest value compared to historical values. Dots within the transparent area of the bars indicate high uncertainty of net positive economic effects, as economic effects would turn negative in these cases if initial forest values were to remain constant with increasing productivity. Continental (**b**) and regional (**d**) forest values under different climate scenarios as in Fig. 3. Gains due to a productivity-related increase in initial forest value are indicated as the transparent portion of the bars. In all panels, data show the mean ± s.d. across all simulations (N = 300) in the respective stratum. Regions were defined as in Fig. 2c. Icons in **a** adapted from OpenMoji (https://openmoji.org/) under a CC-BY-SA 4.0 licence.

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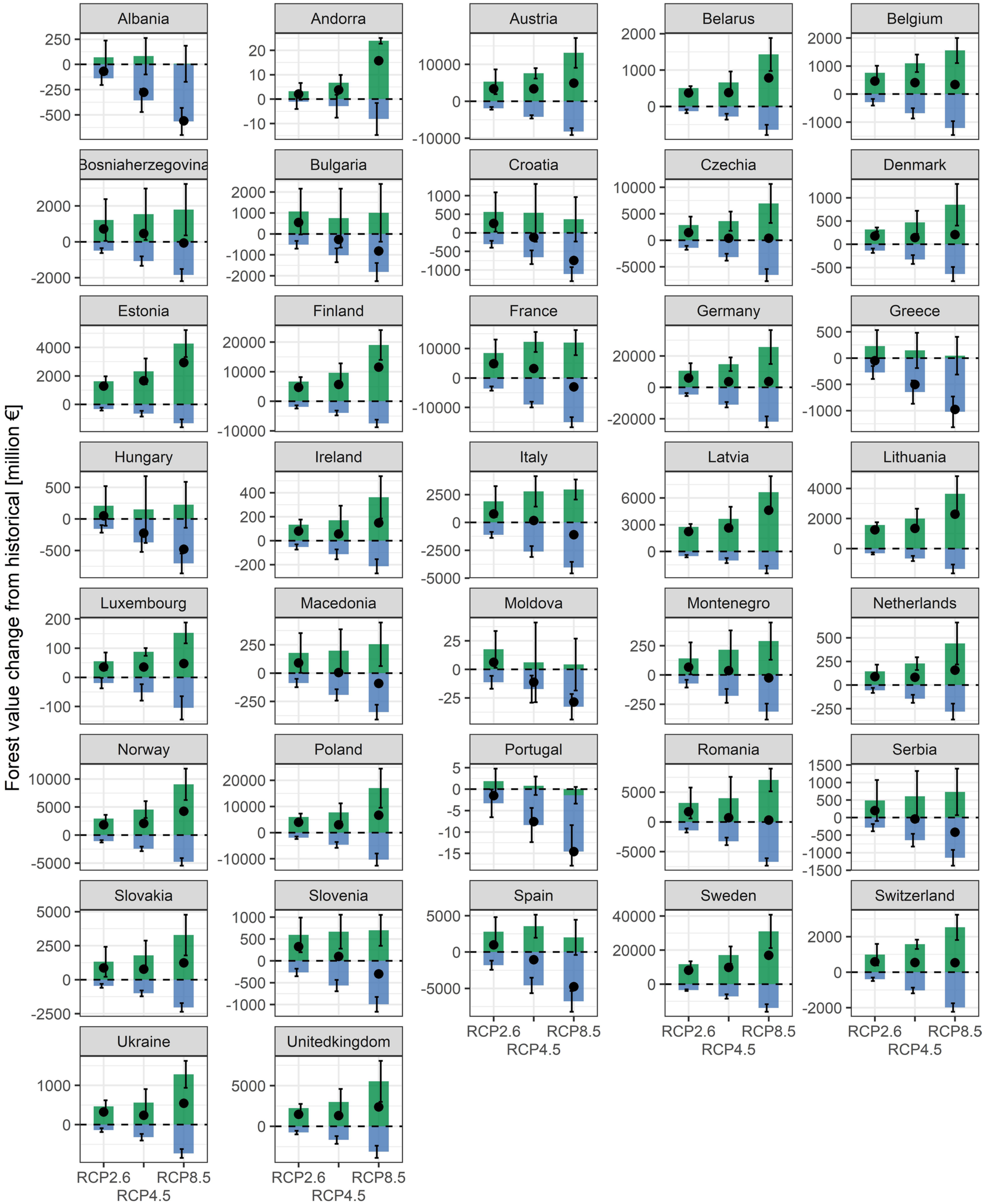

Extended Data Fig. 6 | Effects of changing forest disturbance and productivity on forest value in Europe. Changes in forest value for each country under future climate compared to historical values. Blue bars represent average losses due to increasing disturbances, green bars show average gains due to increasing productivity. Dots indicate the net change in forest value compared to historical values, error bars represent the standard deviation across all simulations (N = 300) in the respective country.