



# Mapping megatrends shaping European forests

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## Abstract

European forests are changing rapidly due to environmental pressures and human actions, making it essential to understand the drivers and their potential impacts for informing management and policy. We quantify and map six megatrends affecting European forests: (1) climate change, (2) fire, (3) pests and pathogens, (4) forest cover and felling intensity change, (5) harvesting, and (6) pollution and nutrient enrichment. Our mapping indicates that megatrends act heterogeneously across Europe. Hotspots of negative trends are found in the Nordic and mountainous regions. These correspond to the megatrend combination clusters: (1) the warming North with an intensified felling trend and (2) the bark beetle-affected temperate Europe. The maps show that business as usual is unlikely for most European forests, and the diverse archetypical megatrend combinations highlight the need for region-specific management. Our mapping helps prioritize interventions and tailor adaptation strategies to the combination of pressures.

**Keywords** Horizon scanning · Anthropogenic pressures · Climate change · Scenarios · Forest disturbances · Forestry

## Introduction

Forests cover one-third of the European landmass (FOREST EUROPE 2020) and provide essential ecosystem services, such as air purification, water regulation, erosion control, carbon sequestration, habitat provision, biodiversity, or wood production (Manes et al. 2016; Martínez Pastur et al. 2018; Chen et al. 2020). Above all, forests play a crucial role in mitigating the climate and biodiversity crises (Rizvi et al. 2015), yet they are themselves undergoing rapid change due to processes of climate change, anthropogenic pressures, and management actions. These processes affect the forests' productivity, health and species composition (Maes et al. 2020; Potočić et al. 2021). Most likely, these effects will be heterogeneous across European forests (Reyer et al. 2014; Lindner et al. 2014). Although many studies have analyzed these trends in specific contexts, few studies have addressed

them in an integrated and spatially explicit manner. This article attempts to close this gap.

One way to characterize the changing conditions are megatrends. They are defined as long-term driving forces which are observable today and will likely have transformational potential in the future (Debonne et al. 2022). According to Naisbitt (1982), the intellectual founder of megatrend analysis, the most reliable way to anticipate the future is to understand the present. Therefore, observing current environmental tendencies and projecting them into the future could serve as a major tool in foresight studies. Megatrend analysis emphasizes quantifying drivers rather than their actual impacts (Debonne et al. 2022). This stands in contrast to traditional scenario studies where the causal link between driver and impact is established (e.g., CO<sub>2</sub> emission scenarios), but the future trend is uncertain.

More than 90% of European forests are managed (EEA 2023). As a result, most of the forest is young and lacks the resilience of old forests (Thompson 2009; Barredo et al. 2023). This resilience stems from their high levels of biodiversity and functional redundancy. Moreover, their structural diversity buffers against disturbance spread. Also, their taller and denser canopies create a cooler microclimate that combined with deeper roots makes old forests more resilient to droughts (Barredo et al. 2023). Forest management is commonly categorized along an intensity gradient (Duncker

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et al. 2012). As with old-growth forests, increasing forest diversity across all levels enhances resilience. Natural regeneration after selective fellings is a low-intensity measure achieving this (Keskitalo 2011), while higher-intensity measures include actively increasing tree species diversity. Expanding the share of native broad-leaved species, which are generally more resilient to drought and disturbances, is particularly promising (Bussotti et al. 2015). Adjusting rotation length is another key tool. In the Mediterranean, longer rotations can boost drought resilience (Bussotti et al. 2015), whereas elsewhere, shorter rotations can reduce vulnerability to disturbances like windthrow (Seidl et al. 2011). This underscores the need for regionally differentiated strategies. Increased thinning is also recommended in intensively managed forests, as it limits disturbance-prone timber buildup and reduces water competition (Seidl et al. 2011; Kerhoulas et al. 2013). Although some recommendations in the literature seem contradictory—such as shortening rotations versus promoting old growth forests—they reflect trade-offs between forest characteristics (e.g., young stands are less vulnerable to storms and fires, but also less diverse and drought resilient than older stands) and management objectives (e.g., biodiversity vs. timber). Gregor et al. (2022) balance different forest objectives and determine an optimal management portfolio across Europe. They conclude that 29% of forests should be unmanaged, many coniferous forests should be converted to broad-leaved forests, and coppices should vanish from Southern Europe. Across the literature, the authors agree that forests should increasingly be managed for resilience rather than maximal production (Keskitalo 2011; Bussotti et al. 2015; Barredo et al. 2023).

Forest policy in Europe is shaped by national regulations and overarching EU frameworks. The non-binding EU Green Deal promotes climate neutrality, sustainability, and biodiversity (European Commission 2019; Elomina and Pülzl 2021). It aligns policies with the UN's sustainable development goals (European Commission 2021a) and the convention on biological diversity (CBD) (Wolfslehner et al. 2020). Key components include the EU Biodiversity Strategy (European Commission 2021b) and the EU-forest strategy which promotes closer-to-nature forest management and emphasizes multifunctionality (Scherpenhuijzen et al. 2025). In addition, the binding EU climate law sets the target of climate neutrality by 2050 and relies on the forest's ability to increase its carbon sink (Korosuo et al. 2023). Collectively, these policies reflect the increasing and sometimes competing demands on European forests. Overall, forest management and European policies play a crucial role, indicating the potential impact of targeted responses to megatrends. Therefore, continental-scale insights are valuable, as they offer a spatial overview of trends and enable regional comparisons.

In this article, we consider the following six megatrends: (1) climate change, (2) fire, (3) pests and pathogens, (4) forest

cover and felling intensity change, (5) harvesting, as well as (6) pollution and nutrient enrichment. These have been selected based on a literature review and particularly on Maes et al.'s (2020) list of forest pressure indicators. Most trends are interacting and reinforcing each other, such as climate change and pests (Hlásny et al. 2021). The resulting pressures can add up in non-linear ways and often depend on multivariate thresholds (Maes et al. 2020). Therefore, we analyze the trends jointly.

Individually, several processes affecting forests in Europe have been studied extensively (Nabuurs et al. 2007; de Rigo et al. 2017). However, most of the literature focused either on mapping past trends of disturbances, such as fire, windthrow or bark beetle (e.g., Forzieri et al. 2021; Patacca et al. 2023), or future projections of climate change (e.g., Lindner et al. 2014). Maes et al. (2020) provide one of the few comprehensive studies. They examined the observed trends in drivers of European forest change alongside various forest condition indicators. However, they only focus on past changes, disregarding that future trends might differ. Hence, we complement Maes et al.'s work by projecting into the future rather than just mapping the past. Moreover, new data has become available not considered by Maes et al.

The aim of this paper is to synthesize existing datasets about megatrends in a spatially explicit way and assess how the megatrends jointly affect European forests. Specifically, we address three research questions: (RQ1) how and where will megatrends affect European forests, (RQ2) where will hotspots of pressure emerge, and (RQ3) what are archetypical combinations of megatrends and how are they distributed spatially? Besides producing informative results, we scan the horizon for this relevant topic, identifying gaps and inconsistencies in the literature. This inventory of existing information highlights deficiencies in data availability and quality. The article is structured as follows. In the methods, we present the rationale for selecting the six specific trends and explain how each trend is quantified individually (RQ1), followed by the methods for the two aggregation maps (RQ2 and RQ3). In the results, presents maps for the individual trends and aggregations, contextualized within current literature. In the discussion, we compare the findings of our aggregations with existing literature, include a sensitivity analysis, elaborate on management and policy implications, and address the limitations of our approach.

## Methods

This article examines the drivers, pressures, and ultimately the impacts on forest functions and health of six megatrends (see Table S1). Following the definition in the Millenium Ecosystem Assessment, a driver is any natural or human-induced factor that directly or indirectly

causes a change in an ecosystem, such as the increase in droughts for the climate change megatrend (Nelson 2005). We define the changes in the ecosystem as impacts, while pressures are defined as direct drivers that cause negative impacts. We focus on quantifying and mapping drivers. To make an assessment of the directionality of impacts, we established a directional link between driver and impact. This way, we can map pressures. We refrained from further quantifying the link, because of data availability, non-linearity, and high spatial variations on how a specific driver impacts forests (Lindner et al. 2010, 2014; Bedia et al. 2015; Forzieri et al. 2021; Kortmann et al. 2021; Hlásny et al. 2021).

### Megatrend selection

To select the megatrends, we conducted a literature review with the help of Google Scholar and Connected Papers (Connected Papers 2025). We reviewed megatrend documents from international organizations (IIASA et al. 2018; OECD 2019; EEA et al. 2020; Wolfslehner et al. 2020; WEF et al. 2024) and research articles about trends on European forests (Schelhaas et al. 2003; La Porta et al. 2008; Fehan et al. 2009; Lindner et al. 2010, 2014; De Vries et al. 2014; Gauthier et al. 2015; Millar and Stephenson 2015; Kniivilä et al. 2018; Maes et al. 2020; Forzieri et al. 2021; Patacca et al. 2023). Many socio-economic megatrends, such as population dynamics, are not explicitly considered as separate megatrends, because they are indirect drivers for forest change. To present stringent driver-impact story lines, we focus on trends based on the most direct drivers. Indirect drivers are not ignored, but rather integrated within the selected trends. For instance, the harvesting trend draws on SSP scenarios, which implicitly reflect various socio-economic factors. The long list of trends resulting from the literature review can be found in S2. Climate change and fire were the most consistently identified trends, appearing in 100% and 92% of the publications, respectively. In contrast, the anthropogenic pressures, forest cover, and felling intensity change as well as harvesting were the least frequently mentioned, occurring in approximately 50% of the publications. Next, we applied a set of criteria for selecting relevant spatial megatrends inspired by Debonne et al. (2022). Megatrends must be (1) credible and relevant for European forest futures, (2) dynamic over multi-decadal timescales, (3) spatially heterogeneous across Europe, and (4) quantifiable with existing data. This resulted in the selection of the following megatrends: (1) climate change, (2) fire, (3) pests and pathogens, (4) forest cover and felling intensity change, (5) harvesting, and (6) pollution and nutrient enrichment.

### Megatrend mapping

To answer RQ1, we produced a series of maps illustrating the observed and projected changes in the drivers for each megatrend. Future projections focus on the 2050–2070 time frame for two reasons. First, forestry is shaping most of Europe's forests and typical rotation lengths range between 40 and 120 years (Kaipainen et al. 2004). While this would argue for a time frame up to 2100, in practice the most common time horizon policymakers and foresters can identify with is about 15 years (Hoogstra and Schanz 2009). Our time frame tries to compromise between the two findings.

Throughout our analysis, we looked at different available RCP and SSP scenarios. For the main analysis, we chose RCP 4.5, RCP 7.0, or SSP2, because they are closest to the current pathway. This is consistent with our definition of megatrends that project current trends into the future. For a sensitivity analysis, maps with different scenarios are provided in S3. We present all findings at the pixel level using the ETRS89/LAEA Europe coordinate reference system. In the maps, sparsely and non-forested areas were masked. We downsampled Copernicus forest cover data (Copernicus Climate Change Service 2019a) and the new larger pixels are forest if at least 25% of the smaller pixels are forest. This ensures that areas with low shares of forest are included in the visualization. The color scheme of the maps uses purple to represent negative effects and green for positive effects on forests. In the following, we present the indicators and the underlying methods of each megatrend separately. For an assessment of indicator adequacy, see S9. Moreover, an overview of the data sources and the rationale behind the model and data choices is provided in S4.

### Climate change

The climate change megatrend was split into three sub-trends: (1) rising temperatures, (2) droughts, and (3) storms. Our indicator for rising temperatures is growing season. It captures two main effects: (1) increased productivity and (2) increased water demand. Growing season days have an average temperature above 5 °C, no snowpack, and a soil water content above 20%. We obtained the data from CHELSA CMIP6 (Karger et al. 2021).

We used mean aridity in the warmest quarter as the indicator for drought. In accordance with the aridity index, aridity is defined as the ratio of potential evaporation to precipitation (Arora 2002). We obtained the data from the Copernicus Climate Change Service (Copernicus Climate Change Service 2021).

For the storm sub-trend, we focused on winter storms because they are responsible for most storm damage (Donat

et al. 2011). Two components were accounted for in the analysis: (1) maximum wind speeds and (2) frozen soils (Gardiner et al. 2013). The corresponding indicators are: (1) relative change in 20-year return periods for annual winter maximum wind speeds at 10 m above ground and (2) ice days (days with a maximum temperature below 0 °C). Maximum 10-m wind speed is an adequate and commonly used variable capturing storm hazard (e.g., Donat et al. 2011). We obtained the wind data from the Rain project (Becker 2016) and the ice days data from the Copernicus Climate Change Service (Copernicus Climate Change Service 2019b). We divided both components into three ordinal categories. This resulted in nine impact categories.

## Fire

There are three main drivers of fire activity: (1) fire weather, (2) fuel load, and (3) ignition (Bedia et al. 2015). We focused on the former two, because ignition is mainly human driven (Ganteaume et al. 2013) and human behavior is difficult to model. We quantified fire weather with the Canadian Fire Weather Index (FWI), widely used in literature (Schelhaas et al. 2010; Varela 2015; De Jong et al. 2015). It combines information about temperature, wind speed, relative humidity, and precipitation (de Rigo et al. 2017). The specific indicator is the annual number of days with moderate fire danger ( $FWI > 15$ ) according to the European Forest Fire Information System (Papagiannaki et al. 2020). We obtained the data from the Copernicus Climate Change Service (Copernicus Climate Change Service 2020).

The fuel load map was derived from Aragoneses et al.'s (2023) fuels data and van der Zanden et al.'s (2017) projections of agricultural abandonment. Aragoneses et al. use land cover and bioclimatic data to classify fuels hierarchically. With a provided table, we cross-walked their fuel types to FBFM fuel loads ranging from low to remarkably high. The fuel load map depicts forest as well as forest-adjacent fuel loads. Aragoneses et al.'s data describe the status quo as of 2020. We used this present estimate, because there are no future projections publicly available. Since in the Mediterranean, agricultural land abandonment is a strong driver of fire activity, we added projections about abandonment in the Mediterranean to the fuel load map (Benayas et al. 2007; van der Zanden et al. 2017). We used the projections for abandonment by 2040 under the provided 'Libertarian Europe'-scenario. Since abandoned lands display high fuel loads, we assigned the maximum fuel load from a moving window ( $3 \times 3$ ) on the fuel data to abandonment pixels. Finally, abandonment fuel loads were added to the map, if they are forest adjacent or at least connected to a forest by other abandonment pixels via 8-connectivity. Finally, we combined the fuel load map and the fire weather map, resulting in nine fire hazard categories.

## Pests and pathogens

Spruce bark beetles (*Ips typographus*) account for over 90% of pest damage in Europe (Forzieri et al. 2023). Thus, Norway spruce (*Picea abies*) distribution is a good indicator for current and future pest damage. Norway spruce distributions were mapped using the product 'relative probability of presence' from the European Atlas of Forest Tree Species (de Rigo et al. 2016). The tree atlas harmonizes many different presence–absence datasets. The second indicator is annual heat sum above 10 °C. Heat sum has a positive effect on infestation risk due to increased water shortage for the host trees and shortened bark beetle life circles (Overbeck and Schmidt 2012). Choosing 10 °C as the threshold for the heat sum is reasonable, because *Ips typographus*' minimum bark temperature for oviposition and larvae development is 11.4 °C (Wermelinger 2004). We used CHELSA CMIP6 data. The map combines both indicators and depicts 9 categories of bark beetle susceptibility.

## Forest cover and felling intensity change

We quantified forest cover change with the land cover dataset provided by Copernicus (Copernicus Climate Change Service 2019a). The dataset is produced by combining multiple high-resolution remote sensing products. We employed the same definition of forest as the authors of the dataset which is in accordance with the IPCC land categories (Defourny 2024).

Viana-Soto and Senf (2025) European forest disturbance atlas provides spatially explicit tree felling data. It shows whether a pixel was subject to felling in a particular year. We aggregated the data spatially to  $25 \text{ km} \times 25 \text{ km}$  pixels and temporarily to three periods of 13 years to best capture larger trends. In the next step, we assigned the values: increasing, decreasing, and mixed trend to each pixel. The trend is increasing if the share of fellings increased between both time steps and decreasing if it declined.

## Harvesting

Roundwood production quantifies the harvesting trend. For the observed trend, we calculated the annual %-change on the country level from 2000 to 2020 based on FAO statistics (FAO 2024). The future projections are based on GLOBIOM, a partial equilibrium model (Havlík et al. 2018; Frank et al. 2024). This model calibrates demand and supply for the wood sector with FAO harvesting data. As the available model results only include EU countries, we filled in the gaps with data of countries that we regard as the most resembling, namely Sweden and Finland for Norway, Austria for Switzerland, Ireland and the low countries for the UK, Croatia for the Balkan countries, and Greece for North

Macedonia. To supplement the country-level harvesting trends with finer spatial insights into harvesting intensity, we provide Scherpenhuijzen et al.'s (2025) more detailed forest management map. The map is a product of a rule-based decision tree that takes disturbance data and forest characteristics as inputs.

### Pollution and nutrient enrichment

Many forest pollutants have been either declining rapidly [e.g., sulfur deposition (EEA 2014)] or do not have a significant impact on forests at their current and projected levels [e.g., ozone (Etzold et al. 2020)]. This is not the case for nitrogen. Therefore, we mapped its observed %-change between 1990–1992 and 2020–2022 with data from EMEP (The Norwegian Meteorological Institute 2023). Their modeling is based on an extensive network of ground measurements (Tørseth et al. 2012). For mapping the projected change, we used outputs from GAINS, an integrated assessment model (Amann et al. 2011). We chose a baseline scenario that assumes current legislation to continue in the future. To mask changes in depositions that do not have much of an ecological effect, we marked areas that exhibit uncritical loads. The conservative thresholds are 500 mg/m<sup>2</sup> for coniferous/mixed forests and 1000 mg/m<sup>2</sup> for broad-leaved forests (Bobbink et al. 2011).

### Aggregation maps

To highlight hot and cold spots of megatrends (RQ2), we produced a map of the sum of substantial negative trends. For each sub-trend (9 in total), the 25% of forest pixels that are subject to the most negative changes were labeled as pixels experiencing substantial negative change. For the trend-specific definitions of negative change, see the right column in S5. As a result, we have a binary map for each trend with 25% of the forest area denoted as substantial negative change. The provided map is the sum of these binary maps.

We performed a k-prototypes clustering to identify archetypes of megatrend driver combinations (RQ3). K-prototypes clustering is a hybrid algorithm that combines k-means and k-modes to cluster datasets with mixed continuous and categorical variables (Sangam and Om 2018). As inputs, we fed all our 12 indicators and the parameter defining the number of clusters. With the help of the elbow method, a commonly used practice (Humaira and Rasyidah 2020), we determined six as the optimal number of clusters (for the elbow plot, see S6). To account for the influence of the initial center values, we ran the clustering 20 times and selected the output with the lowest sum of all within cluster distances.

## Results

For each megatrend, we present the data and place the results in the context of the current literature (RQ1).

### Climate change

Figure 1 (map a) shows that growing season length is expected to increase in most of Europe. There is a North–South gradient with large increases in the North and significant decreases in the South. This is due to rising temperatures. We observe larger increases at higher altitudes (e.g., in the Pyrenees). Regions experiencing a decline in growing season length are affected by increasing water limitations. This trend is particularly pronounced in the Western Mediterranean. Longer growing seasons contribute to higher forest productivity and shifts in habitat suitability to the North and to higher elevations (Lindner et al. 2014). On the contrary, increased heat stress limits forest productivity and might make certain regions unsuitable for particular forest types (Lindner et al. 2014).

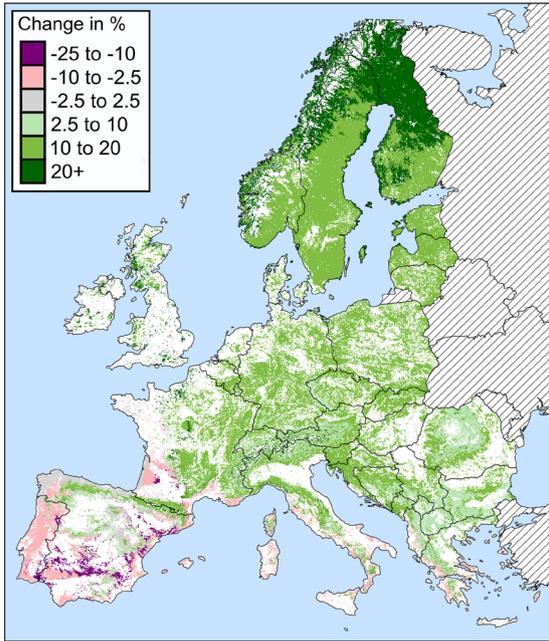
Our mapping in Fig. 1 (Plot b) projects the drought indicator, aridity in the warmest quarter, to increase across most of Europe. Exceptions include many regions in Fennoscandia and areas along coastlines. Significant increases, exceeding 50%, are projected in inland Spain, eastern France, and the Balkans. An increase in aridity will likely result in lower biomass productions and degraded forest health (Lindner et al. 2014).

Winter storm impact is projected to increase across most of Europe (Fig. 1, Plot c). The highest increase takes place in the mountainous areas of Eastern and Central Europe, in parts of the Baltics and Southern Scandinavia. This will lead to higher biomass losses resulting in lower carbon stocks, habitat loss, and inflexible harvesting of lower-quality wood (Hamilton and Bardon 2011). These projected trends coincide with observed trends that show an increase in wind damage (Gardiner et al. 2010; Groenemeijer et al. 2016; Senf and Seidl 2021). However, the reasons are contested. Groenemeijer et al. argue more frequent and severe storms are responsible, whereas Schelhaas et al. (2003) contribute it to species composition and higher forest biomass levels. In general, projecting wind damage is difficult, because it has many stochastic components (Lindner et al. 2014). Nevertheless, Donat et al. (2011) predict an increase in Central Europe due to the combination of stronger winds, less frozen soils, and wetter winters.

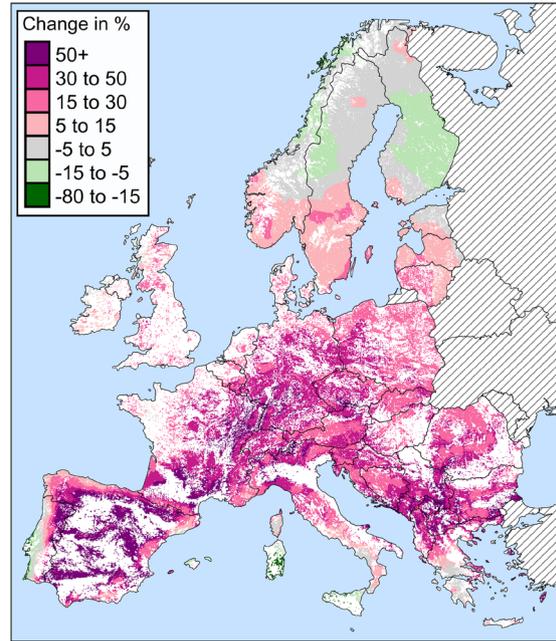
### Fire

Figure 2 (Plot a) shows that high fuel loads are predominantly found in the Mediterranean, the British Isles and parts of Fennoscandia. Remarkably high fuel loads are

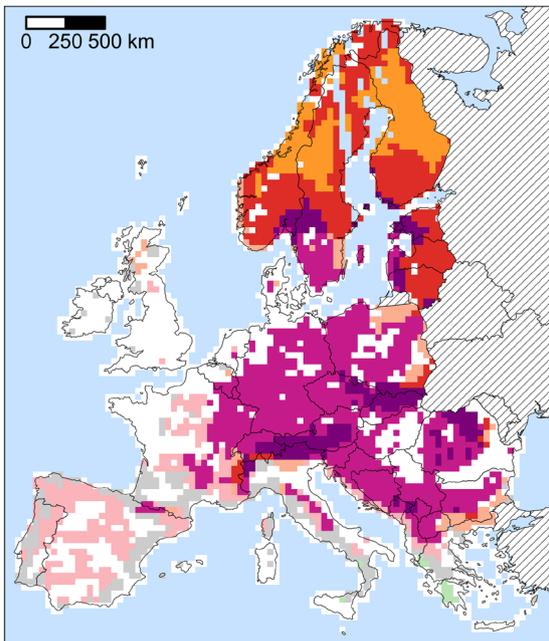
**A. Projected Change in Growing Season Length**



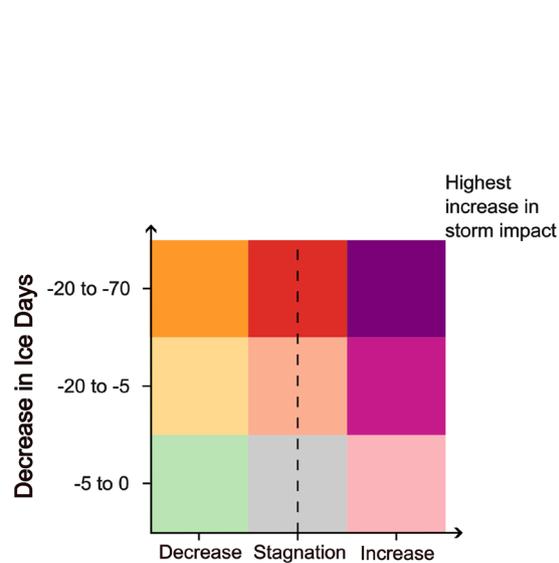
**B. Projected Change in Aridity**



**C. Projected Change in Winter Storm Impact**



**D. Legend of C**

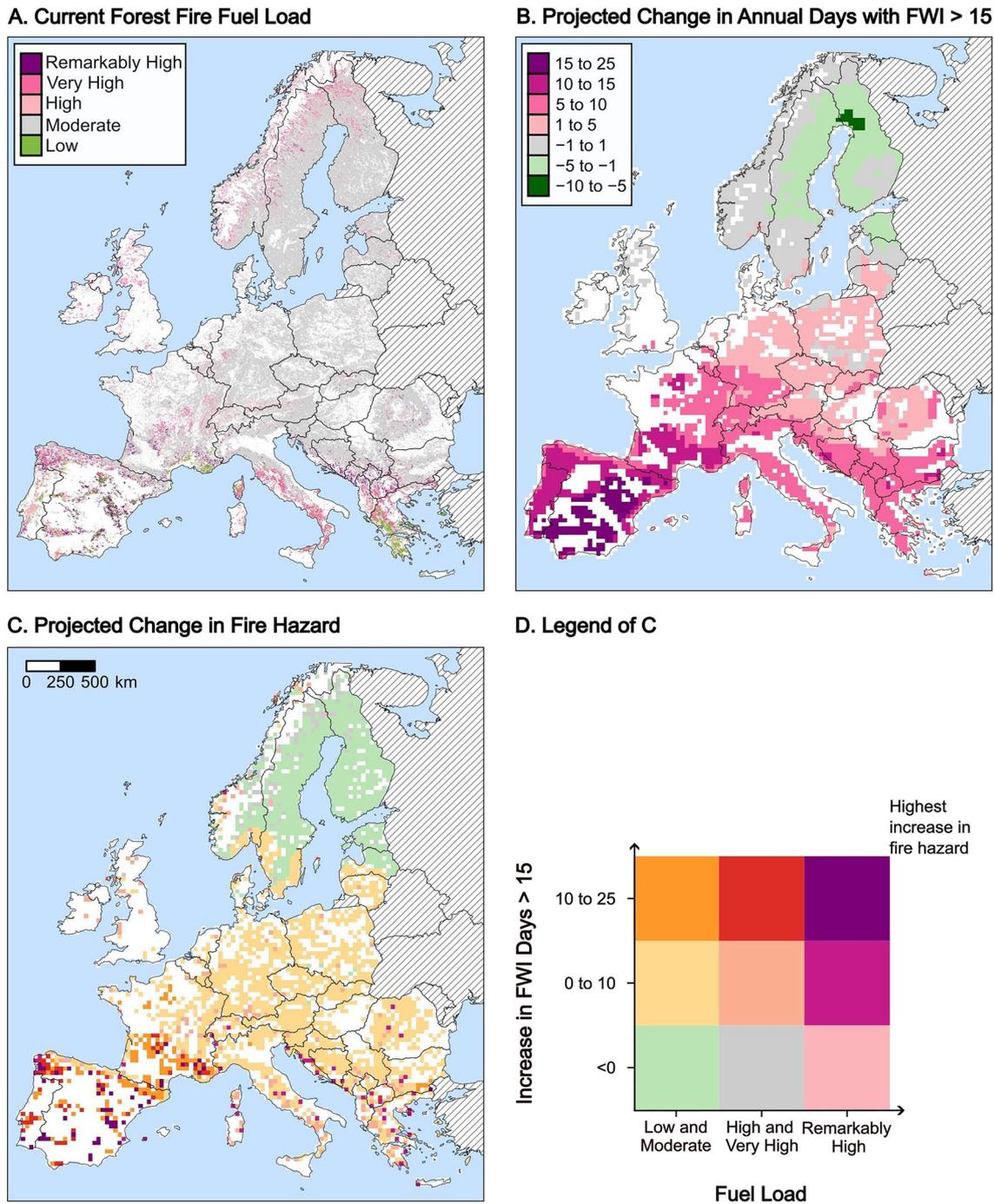


**Fig. 1** Megatrend maps for climate change: **a** projected change in growing season length from 1980–2010 to 2041–2070 according to RCP 7.0 Data: CHELSA. **b** Projected change in aridity of the warmest quarter from 1990–2009 to 2050–2069 according to RCP 4.5 Data: Copernicus Climate Change Service. **c** Projected change in

winter storm impact from 1970–2000 to 2070–2100 according to RCP 4.5. In the legend, storm impact change increases from bottom to top and from left to right. Data: Pan-European datasets of wind-storm probability of occurrence in present and future climate (RAIN Project); Copernicus Climate Change Service

almost exclusively found in the Western Mediterranean and the Balkans. The corresponding areas are open woodlands with shrubs in the understory. Locally, abandoned agricultural lands also contribute (see S7). The number

of days with moderate fire danger is expected to increase everywhere but Fennoscandia, Estonia, and Latvia (Fig. 2, Plot b). The main reasons for this increase are higher temperatures and less precipitation. There is an increasing



**Fig. 2** Megatrend maps for fire: **a** current forest fire fuel load: FBFM fuel loads are shown. Data: Aragonese et al. (2023) and van der Zanden et al. (2017). **b** Projected change in annual days with moderate fire danger (FWI > 15) from 2001–2020 to 2051–2070 for RCP

4.5. Data: Copernicus Climate Change Service. **c** Projected change in fire hazard from 2001–2020 to 2051–2070 for RCP 4.5. In the legend, hazard change increases from bottom to top and from left to right. Data: see A and B

gradient from the northeast to the southwest. Projected fire hazard combines both factors (Fig. 2, Plot c). As a result, the Western Mediterranean and the Balkans display the highest increase.

The temporal trend of fire damage was positive until the 1990s (Patacca et al. 2023). Since then, it is stagnating. 83% of the damage occurred in the Mediterranean where ecosystems are adapted to fire. However, a changing

frequency and severity of fires could lead to a shift in competitive advantages between species and ultimately lead to different species compositions and forest productivities (Vallejo et al. 2012). Moreover, we expect frequent fires in forest types in the temperate and boreal zones that are not adapted to fires (Grünig et al. 2023). The ecological effects on these forests are very heterogeneous and context specific (e.g., Adámek et al. 2016; Gustafsson et al. 2019).

## Pest and pathogens

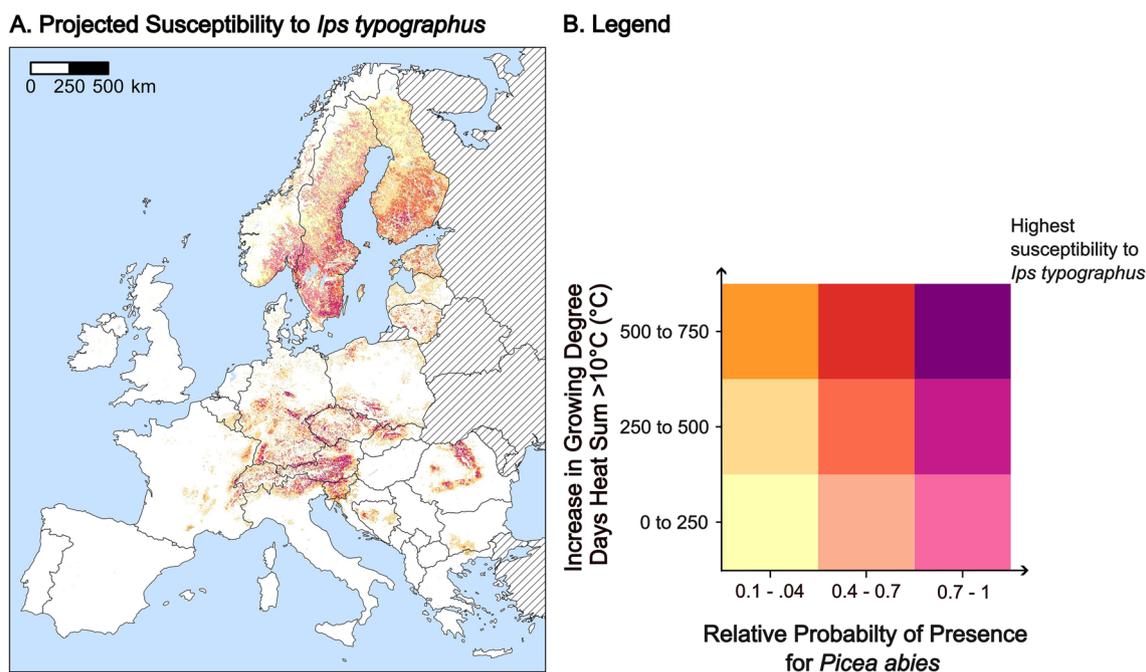
Susceptibility to *Ips typographus* is highest in Fennoscandia, the Baltics, and the mountainous areas of Central and Eastern Europe (Fig. 3, Plot a). Susceptibility is quantified by the distribution of spruce and the increase in growing degree days heat sum (for a mapping of both factors see S3.4). Since the increase in growing degree days heat sum is larger in lower latitudes, susceptibility especially increases in Southern Fennoscandia as well as Central and Eastern Europe. However, in Central and Eastern Europe, the areas of high increase are scattered and co-exist with areas of low increase. The underlying reason lies in the spruce distribution, as spruce is mostly found in low mountain ranges and subalpine areas (de Rigo et al. 2016).

Pests and pathogens often result in timber and habitat destruction (Singh et al. 2024). They are responsible for 17% of disturbance damage in the last 70 years (Patacca

et al. 2023). Bark beetles damage trees primarily through their feeding activities in the inner bark tissue and by the introduction of fungal pathogens (Paine et al. 1997). Infestation is more likely in forests that are already in poor health after experiencing other disturbances, such as droughts (Allen et al. 2010) or storms (Gohli et al. 2024). The spruce forests of Central Europe are most affected (Forzieri et al. 2023). In the last 20 years, the beetle's share in total disturbance damage doubled (Patacca et al. 2023). This indicates further increases in the future.

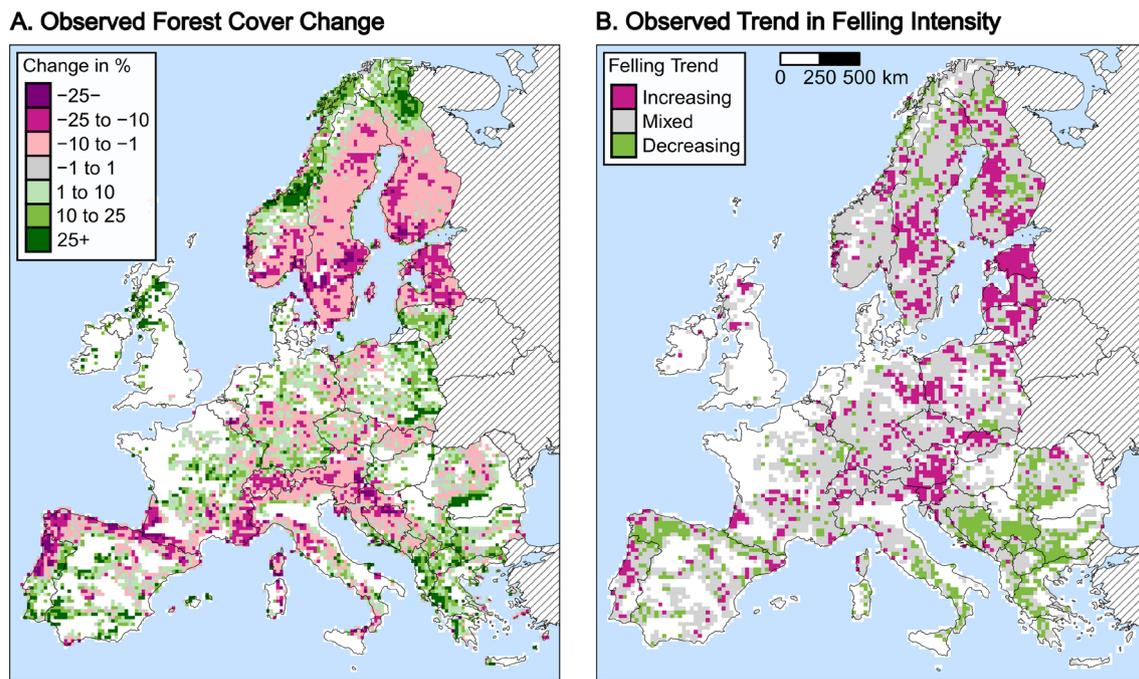
## Forest cover and felling intensity change

In the last 30 years, forest cover gains and losses are heterogeneous (Fig. 4, Plot a). Gains are pronounced in remote northern areas, Eastern Europe, and many parts of the Mediterranean. For the latter two, agricultural abandonment is an important driver (Palmero-Iniesta et al. 2021). For Eastern Europe, abandonment is mainly due to the decline in cropland after the collapse of socialism (Kuemmerle et al. 2016). Forest loss took predominantly place in Southern Fennoscandia, Estonia, Latvia, the Alps, Northern Spain, Northern Portugal, parts of Southern France, and the Northern Balkans. One common feature of all these regions except for the Northern Balkans is their high management intensity (see Fig. 5, Plot a). Overall, our data quantifies a net forest loss of 1.2% from 1992 to 2022. This is contradictory to official



**Fig. 3** Megatrend maps for pests and pathogens: projected susceptibility to *Ips typographus*: in the legend, susceptibility change increases from bottom to top and from left to right. Growing degree

days heat sum projections are based on RCP 7.0. Data: European Atlas of Forest Tree Species; CHELSA



**Fig. 4** Megatrend maps for forest cover and felling intensity change: **a** observed forest cover change between 1992 and 2022. Data: Copernicus Climate Change Service. **b** Observed trend in felling intensity

between 1985 and 2023: felling per area is used to quantify felling intensity. Data: Viana-Soto and Senf (2025)

statistics from Eurostat that report a net gain of 5.3% in the EU from 2000 to 2021 (Eurostat 2023a). The reason for this difference might be that our data relies on remote sensing products, whereas Eurostat uses reporting from the member states. Remote sensing methods have problems identifying post-harvesting recovery from non-forest to forest (Guindon et al. 2018). In particular, this applies to areas with clearcutting harvesting regimes which can be found predominantly in Fennoscandia. This can lead to underestimating forest cover and in our case overestimating forest cover loss.

Figure 4 (Plot b) also shows that the observed trend in felling intensity is heterogeneous across Europe. It decreased in most parts of the Mediterranean and Southeast Europe. In the Western and Central Mediterranean, a plausible reason is a climate-driven decline in forest productivity (Pretzsch et al. 2023). An increase in intensity took place in Central, Northern, and Northeast Europe. These regions correspond to areas where climate change increases forest productivity (Pretzsch et al. 2023). Moreover, rising demand for wood products (Eurostat 2024) drove the intensification of forests. The intensification has negative effects on ecosystem services, like biodiversity, carbon sequestration or water regulation (Paillet et al. 2010; Sing et al. 2018). Management intensities changed tremendously after WW2. Especially in Fennoscandia and Germany, forestry moved away from selective fellings to clearcutting of even-aged patches (Vilén

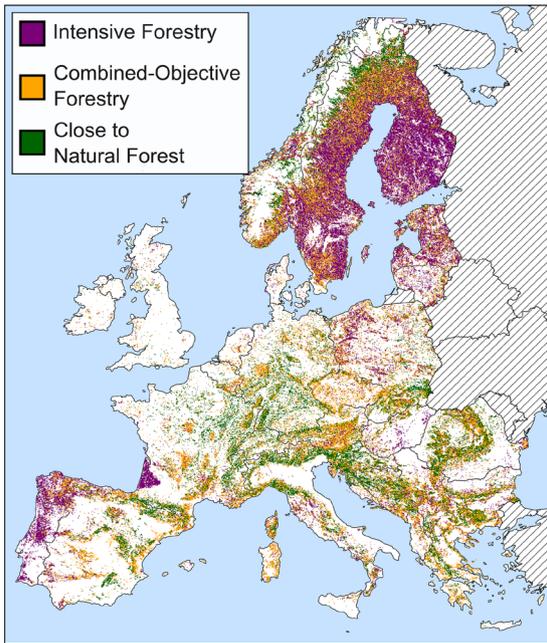
et al. 2012). As a result old-growth forest declined and the average age of trees dropped by up to 39 years.

## Harvesting

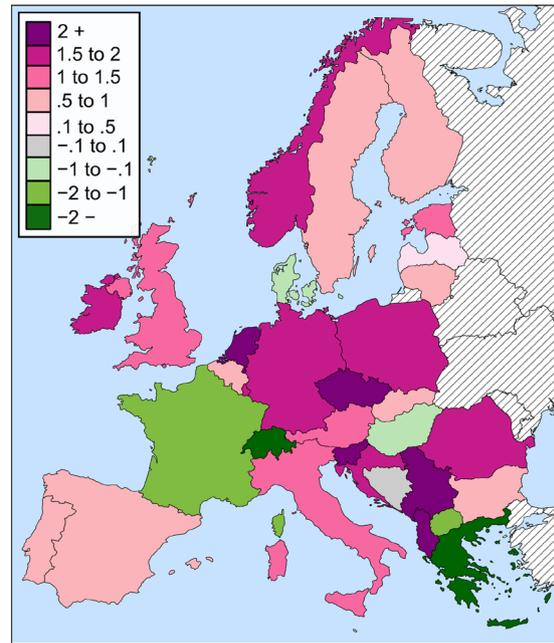
Figure 5 (Plot a) displays the heterogeneous distribution of forest management types in Europe. The exception is intensive forestry which mainly takes place in non-alpine Sweden, Finland, the Baltics and the Atlantic regions of Portugal, Spain, and Southern France. The former are mainly Norway spruce or Scots pine (*Pinus sylvestris*) plantations, whereas the latter are mostly eucalyptus or pine plantations (de Rigo et al. 2016).

Observed harvesting is mostly increasing (Fig. 5, Plot b; Eurostat 2024). Notable exceptions of decreasing harvests are Switzerland, Greece, France and North Macedonia. The reason for the increases in the Eastern countries can likely be attributed to the introduction of free markets (Moskalik et al. 2017) and the expansion of forest area after the collapse of socialism (Palmero-Iniesta et al. 2021). Harvesting under SSP2 is projected to increase or at least stagnate in all countries except for Ireland (Fig. 5, Plot c). High production regions like Germany or Fennoscandia are projected to stagnate. Under SSP3, harvesting is projected to increase less than under SSP2 (Fig. 5, Plot d). This stems from lower population growth in Europe, reduced forest cover due to higher agricultural land demand, and the lesser

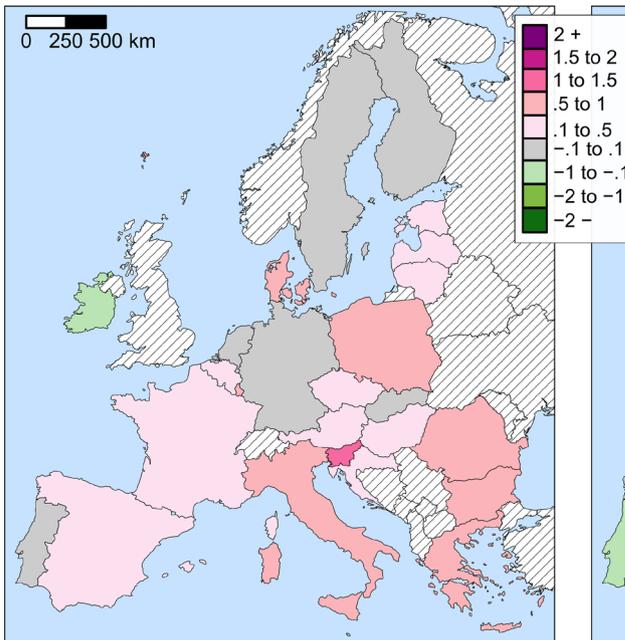
### A. Current Forest Management Type



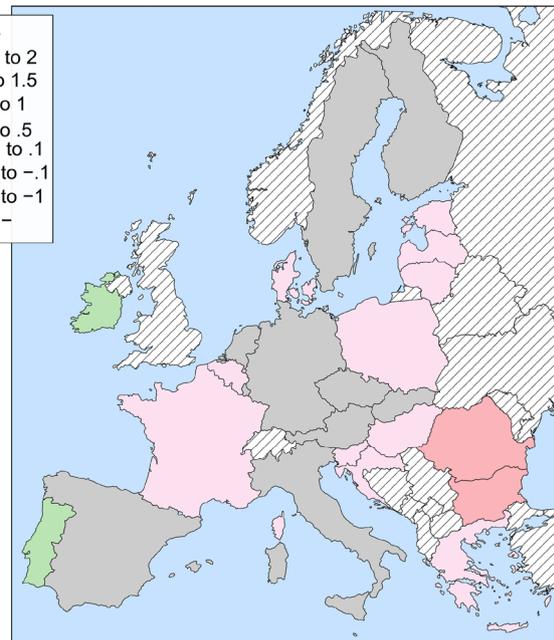
### B. Observed Annual %-Change in Harvesting



### C. Projected Annual %-Change in Harvesting According to SSP2



### D. Projected Annual %-Change in Harvesting According to SSP3



**Fig. 5** Megatrend maps for harvesting: **a** current forest management map. Data: Scherpenhuijzen et al. (2025). **b** Observed annual %-change in harvesting between 2000 and 2020: harvesting of roundwood is shown. Data: FAO. **c** Projected annual %-change in harvest-

ing between 2020 and 2060 under SSP 2. The model GLOBIOM is used to obtain roundwood harvesting statistics. Data: Frank et al. (2024). **d** Projected annual %-change in harvesting between 2020 and 2060 under SSP 3. Data: Frank et al. (2024)

role of biofuels from forests in climate mitigation (Hu et al. 2018; Smith et al. 2019).

The fine granularity of the forest management type map in combination with the harvesting maps can help us make

predictions for the harvesting trend at the local level. Given that a country increases its harvest, this additional harvest can come from three sources: (1) from converting close to natural forest into managed forests (green areas in Map a),

(2) intensifying harvesting (orange or pink areas in Map a), or (3) from forest cover gains. In conclusion, increases in harvesting either result in intensification or forest expansion. As mentioned above, intensification further limits the ability of forests to provide additional ecosystem services and biodiversity (Paillet et al. 2010; Sing et al. 2018).

### Pollution and nutrient enrichment

Our mapping in Fig. 6 shows almost without exceptions that nitrogen deposition is decreasing, and under the assumption of current legislation it is projected to decrease further until 2050. Thus, areas with uncritical levels of N deposition are spreading. By 2050, almost all of Fennoscandia and half of the Baltics are expected to exhibit uncritical levels. Despite declining trends, the high density of intensive farming and industrial activities prevent Western, Central, and Central-Eastern Europe from reaching levels below the critical threshold (EEA 2024).

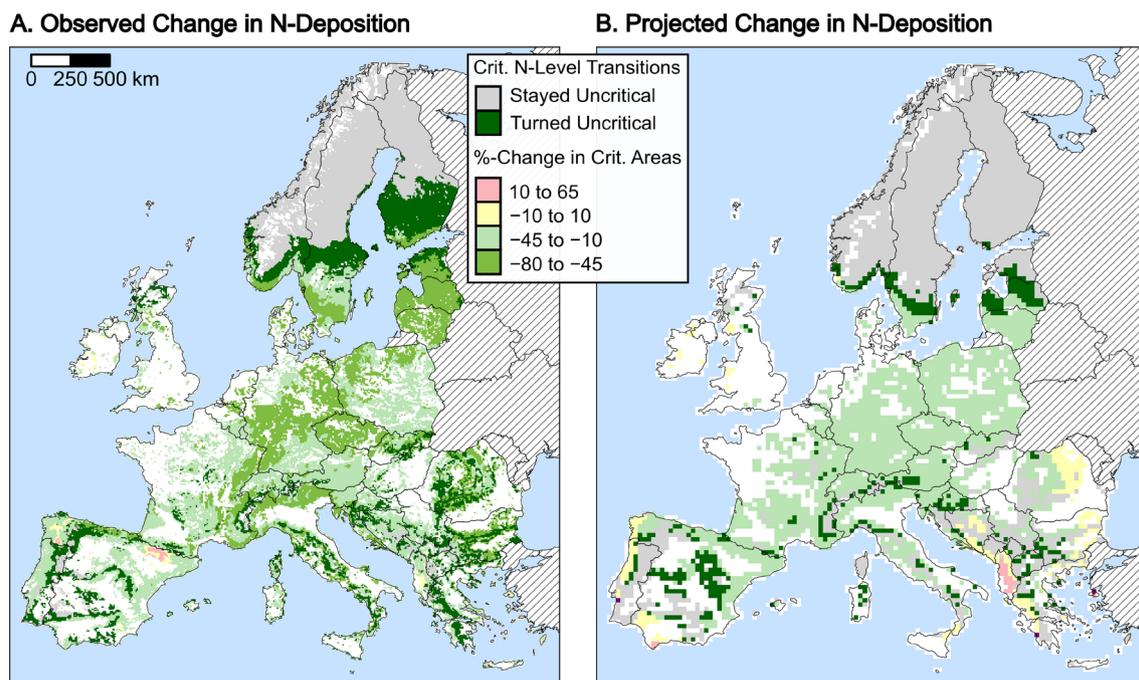
The negative effects of N deposition are acidification of soils and eutrophication (De Vries et al. 2014). In contrast, N deposition also acts as a fertilizer, increasing plant productivity. Regarding the overall effect on forest productivity, the scientific community is divided and impacts are likely context dependent. Schmitz et al. (2019) observe a negligible effect, whereas Etzold et al. (2020)

detect a considerable positive one. Finally, N deposition can lead to a reduction of forest biodiversity by creating a nutrient-rich environment that favors only a few dominant species (Schmitz et al. 2019).

### Aggregation maps

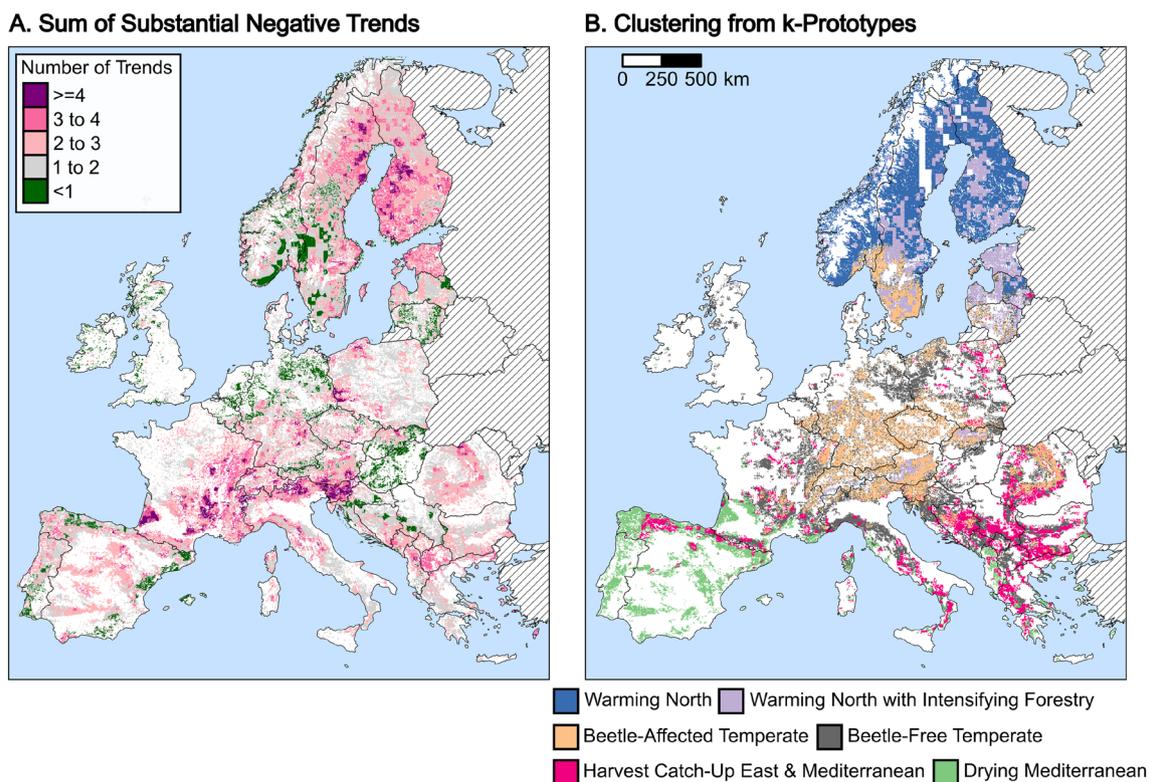
Figure 7 (Plot a) displays hotspots of negative change in Northern Scandinavia, Western Poland, the Southern Alps, as well as Southern and Eastern France. Except for Western Poland and South-Western France, all these regions are either Nordic or mountainous. Cold spots are the British Isles, most of the flat temperate areas, coastal regions of the Iberian Peninsula, parts of Southern Sweden, and Southern Norway. Most of these regions are coastal or low in elevation.

The clustering in Fig. 7 (Plot b) displays six distinct clusters (for the cluster centers, see S8). The warming North is mainly characterized by climatic trends, i.e., warming and moistening patterns accompanied by reduced storm activity. The warming North with intensifying forestry has very similar cluster centers, except for felling intensity which is increasing. The beetle-affected temperate Europe cluster is primarily defined by a strong increase in the beetle driver, an increase in storms and a decrease in N deposition. As the name suggests, the beetle-free temperate Europe



**Fig. 6** Megatrend maps for pollution and nutrient enrichment. The thresholds for uncritical levels of nitrogen are 500 mg/m<sup>2</sup> for coniferous/mixed forests and 1000 mg/m<sup>2</sup> for broad-leaved forests. Forest types are derived from Copernicus land cover maps. **a** Observed

change in N deposition from 1990–1992 to 2020–2022. Data: EMEP. **b** Projected change in N deposition between 2020 and 2050: N deposition is obtained from the GAINS model under the current legislation scenario. Data: IIASA



**Fig. 7** Aggregation maps: **a** sum of substantial negative trends. The sum is calculated across the 9 sub-trends. A pixel is considered to undergo substantial negative change if it falls within the upper quartile of the trend. **b** Clusters of megatrends

cluster is very similar to the beetle-affected temperate Europe except for the beetle driver and the trend for more harvesting. The harvesting catch-up cluster is characterized by a decreasing observed trend in felling intensity, but an increasing projected trend in harvesting. At last, the drying Mediterranean is mainly defined by warming and drying conditions as well as a below-average decrease in N deposition. Overall, the warming North with intensifying forestry is most affected by negative changes, with 40% of its pixels exhibiting three or more substantial negative trends. This is more than double the average percentage of 19%. The second most impacted cluster is beetle-affected temperate Europe with 25%, while the harvesting catch-up cluster is the least affected with 10%.

## Discussion

Our mapping of six megatrends shows that most European forests are affected by multiple megatrends and that current pressures are likely to exacerbate in the future. At the same time, we see strong spatial variation in the trends, leading to different impacts in different regions. Primary hotspots of likely negative impacts are found in Northern Europe and mountainous regions, namely North-Eastern Sweden,

North Ostrobothnia in Finland, the Southern Alps, mountain regions of Eastern France, South-Eastern Poland and as an exception the flat, non-Nordic region Landes de Gascogne in Southern France.

According to our cluster analysis, the main reason for these hotspots are climatic drivers. This aligns with existing research indicating that climate change progresses more rapidly in these areas (IPCC 2013; Pepin et al. 2015). Of particular concern are mountainous forests, since they are very sensitive to climatic changes (Michelsen et al. 2011; Thakur et al. 2021). The two clusters that are affected most negatively by future trends are the warming North with intensifying forestry and the beetle-affected temperate Europe. This points to strong challenges for the European timber sector, as parts of the top three roundwood producers—Germany, Sweden, and Finland—belong to these clusters (Eurostat 2023b). Our study aligns with that of Maes et al. (2020) in concluding that all European forests face negative trends. However, there is disagreement regarding the specific hotspots of negative change. Hotspots coincide in the Southern Alps and the Landes de Gascogne. In contrast, only Maes et al. identify non-alpine Northern Italy and Central Portugal as regional hotspots, whereas our study exclusively identifies Northern Scandinavia and Western

Poland. Moreover, Maes et al.'s results have a general tendency for more negative trends in the South than in the North. One reason for this discrepancy is that 4 out of 14 of their indicators are precipitation related, whereas for us it is only 1 out of 9. Since wetter conditions are not pressures, their emphasis on precipitation results in a North–South gradient, showing fewer pressures in the moistening North. Maes et al. identify Central Eastern Europe and Southern Sweden as areas where many forest indicators are improving. This aligns with our cold spots. However, our cold spot in Central Europe spans further West across the flat Central European plain. Our cold spot in the coastal areas on the Iberian Peninsula can also be observed in Maes et al.'s map, but not as pronounced. Forzieri et al.'s (2021) study the vulnerability of forests to wind, fire, and insects. They support our findings that Scandinavia and the Alps are disproportionately at risk. In addition, they identify the interior of the Iberian Peninsula as vulnerable. Patacca et al. (2023) compiled 70 years of country-level data on wind, fire, and bark beetle damage. Disturbance hotspots include Portugal, the Alpine countries, Czech Republic, Slovakia, and Romania. Except for Portugal, all these regions coincide with our beetle-affected temperate Europe cluster. The hotspot Portugal, in turn, corresponds to one of Maes et al.'s hotspots. Overall, all three studies agree with our findings that the Alps face disproportionately high pressure and that Central Europe mountainous regions face more pressures than flat areas. However, they differ on other hotspots: some highlight the far North, others the interior of the Iberian Peninsula.

### Sensitivity analysis

To assess the sensitivity of our results to different climate change scenarios, we additionally mapped all climatic variables for RCP 2.6 and 8.5 (see results in S3). The maps reveal mostly consistent spatial patterns across scenarios, with the magnitude of change increasing as expected with higher RCPs. In addition, we mapped the change in nitrogen deposition according to different policy and socio-economic scenarios (see results in S3.6). The spatial patterns are largely consistent, but the magnitude of change differs considerably across scenarios. This is expected, because some scenarios are extremely optimistic, diverting from our business-as-usual assumption. The biggest driver of deposition is livestock numbers (EEA 2024). Overall, the sensitivity analysis demonstrates that our results are robust across a wide range of scenarios.

### Management and policy implications

Adaptation of forest management is vital to counter the negative effects of megatrends on forests (Keskitalo 2011). For the warming North with intensifying forestry, our most-affected cluster, intensive management measures are seen as the viable option, because this is in line with current practices (Keskitalo et al. 2016). Measures include: (1) shortened rotations to increase harvesting and limit damaged timber due to disturbances, (2) increased thinning, (3) continuous harvesting to foster biodiversity, (4) genetic adaptation to booster climate change resilience, and (5) increase in the share of broad-leaved trees to diminish the impact of bark beetles (Jönsson et al. 2015; Keskitalo et al. 2016). To reinforce the latter, Keskitalo et al. stress the importance of replacing spruce monocultures, because they are very vulnerable to bark beetle, droughts, and storms. The same recommendation can be made for the beetle-affected temperate Europe cluster in which virtually all spruce forests will have a high risk of infestation (Hlásny et al. 2021). In a study on Austrian forests, Seidl et al. (2011) evaluate management options based on their effects on timber and C-stocks, biodiversity, disturbance damage and economic costs. They conclude that mixed species stands, silvicultural techniques fostering complexity (e.g., natural regeneration), and increased management intensity (e.g., shortened rotations) are measures that can reduce the forest's vulnerability to climate change by 50 percentage points. For such studies, it is important to note that the selection of evaluated objectives and their weighting influence the results heavily (Keenan 2015).

The EU-forest strategy emphasizes resilient and multi-functional forests (Lier et al. 2022), but balancing climate goals with biodiversity conservation remains challenging (Wolicka-Posiadala and Kaliszewski 2024). The former relies on a thriving bioeconomy and hence on productive, wood-producing forests, whereas the latter benefits from low-intensity management. Given the mounting pressures from the mapped megatrends, increasing the forests' contribution to both objectives, as the EU climate law and the European biodiversity strategy demand, is difficult. Recent findings show that the European forest carbon sink is declining (Korosuo et al. 2023), indicating that current policies and management are insufficient. This is particularly evident in northern countries, such as Finland, which has already become a net carbon source (OSF 2024). Since the EU-forest strategy is non-binding, its implementation into enforceable law remains uncertain. Effective policy should include financial incentives for forest owners to reward ecosystem service provision, such as subsidies and taxation (Larsen et al. 2022). One initiative is the EU's carbon removals certification framework which paves the way for financial compensation based on carbon credits (European Council 2024).

## Limitations

Our study brings together a lot of data on European forests, while also revealing that consistent data at the European scale is often missing. One example of missing data is harvesting data on the regional level. To improve our understanding of the dynamics of European forests, spatially explicit time series data consistent across time and space are critical. In addition, for certain trends like fire or drought, climatic extremes and not averages should be used for the analysis (Lindner et al. 2014). Many data sources, such as CHELSA climate data (Karger et al. 2021), only provide multi-decadal or monthly averages. In contrast to our goal of using future trends, most of our non-climate data reflect past trends (e.g., forest cover loss) or current conditions (e.g., fire fuel load). One exception is harvesting with scenarios based on SSPs which are widely accepted throughout academia (Mitter et al. 2020). Nevertheless, they have been criticized for (1) ignoring external shocks, (2) relying on linear relationships, and (3) the uncertainty induced by complex model chains and long-term socio-economic projections (Buhaug and Vestby 2019; EDHEC Climate Institute 2024). Note that these projections are not forecasts, but explorations about the future. Thus, sensitivity analyses across different SSPs are important.

Megatrend analysis relies on simplifying complex processes into a clear communication tool, supporting policy and management decisions and identifying key areas for future research. While our study moved beyond other megatrend analyses in addressing spatial variations, we had to make several simplifications on the megatrend and indicator level that limit the accuracy, completeness and generalizability of the results. First, we do not take into account all sub-trends of each megatrend. For example, we neglect sulfur deposition for pollution. Second, it is nearly impossible for indicators to capture the entire complexity of the driver. To give an example, our drought indicator ‘aridity of the warmest quarter’ ignores droughts in other seasons, such as spring. In our defense, we aimed at selecting the most ecologically relevant indicators, such as length of the growing season for the warming trend. For an evaluation of all indicators, see S9. Third, we simplify the data for the sum of negative trends map by only considering whether pixels fall within the top quartile of each trend. This choice was made to avoid the strong assumptions required for scaling all indicators on the same ratio scale.

We focused on quantifying the drivers of forest megatrends rather than the impacts for several reasons. First, for many cases, credible data sources are missing. For example, we are not aware of any comprehensive, spatial–temporal dataset of bark beetle damage. Second, impacts of megatrends are often context-specific, depending

on the particular forest constitution. The impact of droughts, for example, depends on species composition and topographic factors (Rita et al. 2020). Finally, there is a huge diversity of potential impacts of the considered megatrends on forests, making it challenging to achieve a complete picture. To illustrate how an impact-oriented analysis could look like, S10 provides maps of the sum of substantial trends that have a negative impact on biomass and biodiversity.

## Conclusion

This article offers the first spatial megatrend analysis on European forests. Our findings show that pressures are intensifying due to multiple drivers that vary across the continent. For nearly every forested area in Europe, business as usual is very unlikely, with mounting pressures threatening ecosystem service provision. Policymakers often underestimate these threats, as evidenced by the incompatibility between the goals of the EU climate law and the EU Biodiversity Strategy under current management. To overcome this challenge, the scientific community should focus on closing persistent data gaps and evaluating sustainable forest management practices in local contexts. Our hotspot mapping of pressures identifies two priority regions for such efforts: (1) mountainous forests and (2) the boreal forests of the North.

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**Data availability** All data supporting the findings of this study and the final maps can be found on dataverse.nl: <https://doi.org/10.34894/FFGZEF>.

## Declarations

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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