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Research article

Dual modeling approach reveals: Need for assisted migration to mitigate loss of forest productivity in Europe

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ABSTRACT

Tree species selection is a critical forest management decision, raising fundamental questions: which species will survive and thrive under future climates, where, and to what extent? To address these questions, we applied a dual-model approach that combines 23 site index models with species distribution models. Drawing on a pan-European dataset of six million individual trees, the models project top height (site index) and climatic suitability (species distribution) for a reference period (1981–2010) and two future periods (2041–2070 and 2071–2100) under RCP4.5 and RCP8.5 scenarios. By integrating site index predictions with low-risk species distribution classifications, we restricted growth projections to climatically suitable ranges derived from Species distribution models (SDMs). Our analysis examined four key aspects: (1) overall changes in forest productivity, (2) regional gains and losses for each species across five major European regions, (3) the most productive species by region, and (4) species with the greatest productivity gains ("winners"). Results reveal contrasting trends: productivity is projected to increase in northern Europe but decline in southern and central regions. Beneficiary species include Douglas-fir, Norway spruce, and European larch in the north, and downy oak and black locust in the south. These findings point to potential management-relevant patterns, suggesting that non-native species may become increasingly suitable in northern regions, while southern forests may require a broader portfolio of adaptation and mitigation strategies to cope with projected productivity declines.

1. Introduction

Forests supply essential ecosystem services, such as carbon storage and wood fiber production. Yet, climate change is increasingly threatening the sustained provision of these benefits (Lecina-Diaz et al., 2024; Hartmann et al., 2022). For instance, prolonged drought in Germany has

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led to more than 300,000 hectares of forest dieback since 2018 (Popkin, 2021). An essential decision in forest management is the selection of tree species adapted to the planting environment, as this choice determines subsequent silvicultural interventions over decades. In practice, however, managers are constrained by the difficulty of anticipating climatic changes at fine spatial scales.

A wide range of models in forestry provide insights into tree species' ecological requirements by analyzing regeneration, survival, disturbances, and disease processes, thereby supporting predictions of species performance in novel forest environments (König et al., 2022; Dyderski et al., 2018; Grünig et al., 2023; Terzi et al., 2019; Repo et al., 2024). Multiple factors influence tree species selection, with key considerations including climate suitability and productivity. When climatic risk is high, incentives for long-term management decline, and management is difficult to justify unless a site offers sufficient growth potential (Hanewinkel et al., 2013; Bolte et al., 2009). Species distribution models (SDMs) are a key tool for assessing climatic risks. They predict distribution patterns by relating species occurrence records to environmental conditions (Elith and Leathwick, 2009). Forest productivity on the other hand, can be modeled using different metrics, such as tree rings, basal area, volume, or biomass (Martinez del Castillo et al., 2022; Vospernik, 2021; Ma et al., 2024). Among the possible approaches is the use of top height, which is defined as the average height of the tallest trees in a stand, typically the 100 highest trees per hectare or sometimes the tallest 20 % of trees (Assmann, 1970; Pretzsch, 2009). Top height offers some advantages over other growth variables: 1) relative insensitivity to management, 2) close correlation with timber yield and above-ground biomass, and 3) simplicity of measurement, facilitating its integration into almost all forest inventories (Wenk et al., 1990; Skovsgaard and Vanclay, 2008). When combined with stand age, top height is therefore widely used to characterize site quality and potential forest productivity, rather than realized growth, which may additionally reflect management history, disturbances, and stand structure. Consequently, site index models (SIMs) provide an estimate of the biophysical growth potential under given environmental conditions, and is commonly used in forest modelling to assess site quality (site index models, SIMs).

To achieve optimal tree species selection in the context of climate change, it is essential to develop models for a wide range of species to establish a comprehensive knowledge base for species-rich forests. Furthermore, modeling non-native tree species holds significance, as they expand the options under shifting climatic conditions. This is particularly relevant in Europe, where the diversity of native tree species is relatively limited (Dimitrova et al., 2022). When non-native tree species are intentionally introduced to geographic regions beyond their natural or current distribution range as a strategy to mitigate the ecological and economic impacts of climate change, this process is termed "assisted migration“ (also known as "assisted gene flow", or "assisted colonization“) (Hewitt et al., 2011; Williams and Dumroese, 2013). This approach is motivated by the observation that many tree species may not be able to naturally migrate or adapt quickly enough to keep pace with shifting climatic conditions, potentially leading to reduced forest productivity, biodiversity loss, or ecosystem dysfunction (Rosenblad et al., 2023). Assisted migration can be categorized into three broad types (Pedlar et al., 2012; Seddon, 2010; Williams and Dumroese, 2013): A) Assisted population migration – movement of populations within a species current range to areas with projected future suitability. B) Assisted range expansion – translocation of species to adjacent regions just beyond their native range. C) Assisted long-distance migration (or "assisted species migration", in special cases "species rescue assisted migration") – introduction of species to entirely new regions where they have no evolutionary history. While these strategies aim to enhance ecosystem resilience and maintain forest services (sometimes referred to as ecosystem services assisted migration), it also carries ecological risks, including invasiveness, disruption of native species interactions, and unintended changes in ecosystem dynamics (Pedlar et al., 2012; Xu and Prescott, 2024).

Ongoing debate over the scale of assisted (population) migration underscores the need to assess climate change impacts on tree productivity within shifting species distributions. Furthermore, a systematic comparison of species productivity responses to climate warming will inform the selection of suitable candidates while minimizing the risk of future productivity losses. Our objective is to answer the following research questions: (RQ1) How does climate change alter forest productivity across Europe? (RQ2) How do projected productivity changes vary among five major European regions? (RQ3) Which tree species are projected to be the most productive and (RQ4) show the greatest productivity gain ('winners')? We hope that our findings will contribute to the broader discussion of adaptive forest management in the face of climate change.

2. Methods

2.1. Data and workflow

We compiled and harmonized presence–absence records and tree growth measurements across Europe (Woehlbrandt et al. in prep.). In order to enhance spatial coverage and completeness, we complemented National forest inventory data (NFI) with additional data sources such as provenance trials or the International Co-operative Programme on Assessment and Monitoring of Air pollution Effects on Forests (ICP Forests) network. The resulting database included 2,734 tree and shrub species with 6.26 million individual records (5.88 million with growth measurements and 0.68 million aggregated datasets) across 860,095 plots in 35 countries. Data density is highest in central and northern Europe and decreases towards eastern and southeastern regions.

Based on this database, we developed SIMs for 25 tree species and SDMs for 30 tree species. Using 1981-2010 climate averages as calibration data, we projected species distributions and site index for three time periods (2011-2040, 2041-2070, 2071-2100) and climate scenarios (RCPs 2.6, 4.5, 8.5) at 1×1 km resolution (Woehlbrandt et al. in prep.). RCP2.6, representing strong mitigation, projects a global mean temperature increase of about $\sim 1\ ^{\circ}$C by 2081–2100; RCP4.5, a moderate mitigation/stabilization pathway, projects $\sim 2\ ^{\circ}$C warming; and RCP8.5, a high-emission scenario with continued greenhouse gas growth, projects $\sim 4\ ^{\circ}$C warming by the end of the century relative to 1986-2005 (Pachauri and Mayer, 2015) (Jacob et al., 2014; Karger et al., 2017). As the site index is a common measure of forest productivity, we used top height (m) at age 100 as a proxy for forest productivity in this study (Brandl et al., 2018; Skovsgaard and Vanclay, 2008; Yue et al., 2023). The SDMs were used to assess whether a given tree species will remain climatically suitable for growth at specific sites in the future. Fig. 1 shows the general workflow (the current study focuses on the content in the blue box).

2.2. Tree species selection

For a realistic growth prognosis in Europe, we excluded two species, resulting in a final dataset of 23 species (Fig. 1). Grand fir (*Abies grandis*) was omitted due to limited data, while European ash (*Fraxinus excelsior*) was excluded because of its widespread decline from Ash dieback, a phenomenon not modeled by the SDM (Beck et al., 2016). Despite the ongoing debate about non-native tree species, we included three species—Douglas-fir (*Pseudotsuga menziesii*), red oak (*Quercus rubra*), and black locust (*Robinia pseudoacacia*)—as they could diversify Europe's palette of valuable tree species (see Section 4 for potential risks) (Pötzelsberger et al., 2020b). To address conservation considerations (Pötzelsberger et al. 2020), we also conducted the entire analysis without non-native tree species (Supp. Material).

2.3. Overlaying SIM and SDM predictions

First, we calculated the difference in top height between future

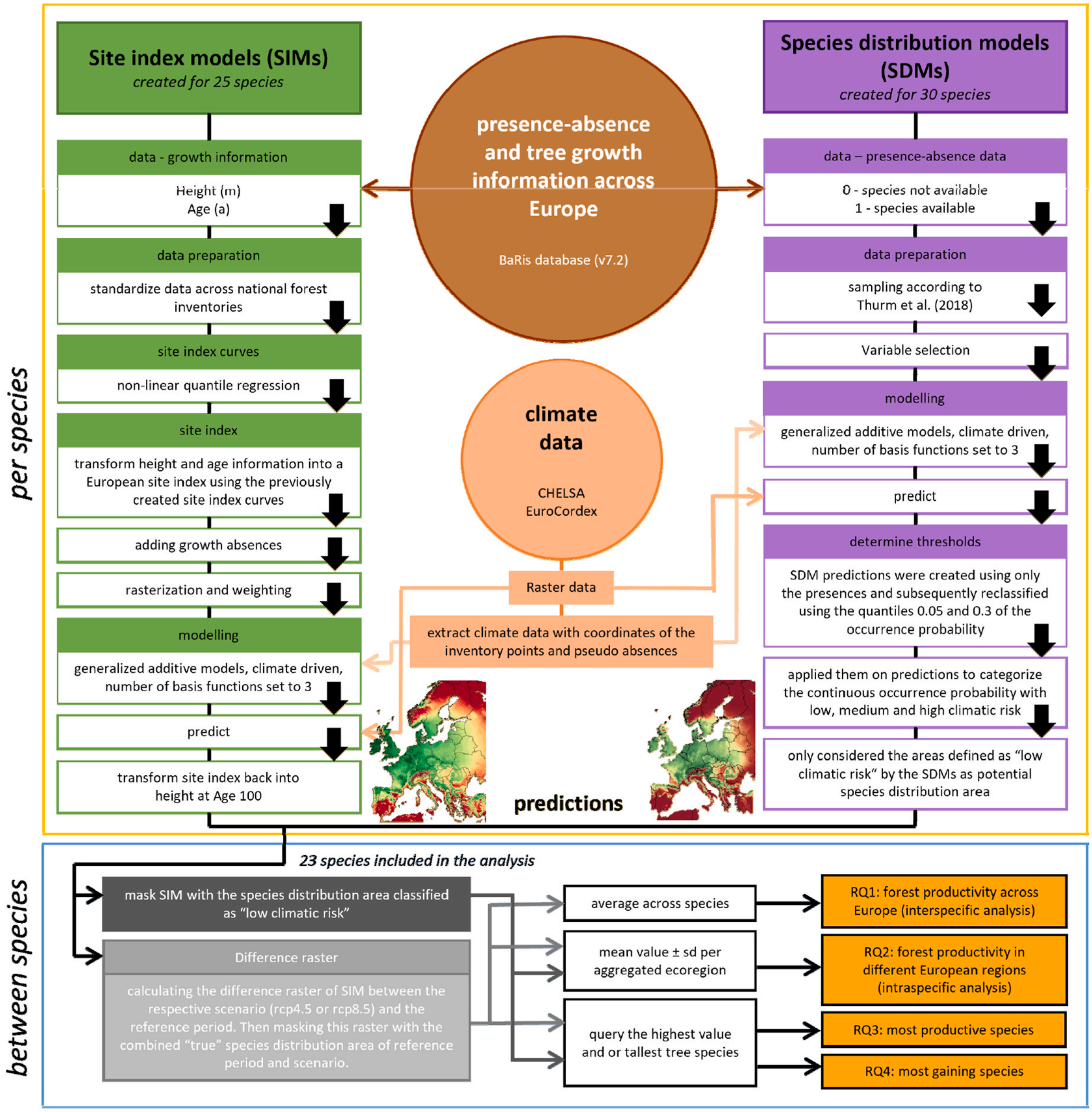

Fig. 1. Overview of the entire workflow. The Site Index Models (SIM) and Species Distribution Models (SDM)—shown in the orange box—are described in the data paper by Wöhlbrandt et al. (in prep.). In this study, we combined SIM and SDM predictions—illustrated in the blue box—to address our research questions (orange boxes, bottom right).

scenarios (RCP4.5 and RCP8.5) and the reference period (1981-2010). These *difference rasters* were masked by the combined current and future suitable ranges—defined as low-risk areas according to the species distribution models (SDMs)—to account for shifting distributions. The approach incorporates changes in species distributions at the time of stand establishment, and reduced growth in already established stands, aligning with the concept of assisted population migration.

Next, we aggregated the *difference rasters* per ecoregion (Metzger et al., 2005), computing arithmetic mean changes and standard deviations per species-region combination (= intraspecific analysis) (RQ2). Some ecoregions were merged for clarity (see Supp. Material for all). By averaging the *difference rasters* across all species, we identified regions where productivity is projected to decline consistently, regardless of species selection (= interspecific analysis) (RQ1). Any calculated difference in the results section, for example 5 ± 2 m, indicates that a species X would have been on average 5 m taller, due to climate warming ± 2 m standard deviation in the observed region, if the tree was planted 100 years ago. Given the spatial dependence of raster-based projections and the scenario-driven nature of the analysis, we focused on effect sizes and variability rather than formal statistical significance testing. Standard tests require independent replicate observations, assumptions not met in scenario-based spatial projections (see section 4.4 for limitations) (Storch and Zwiers 2013).

Third, to identify the most productive species per region, we masked SIM predictions by areas deemed climatically unsuitable based on SDM outputs (mid and high risk zones), ensuring growth projections only included in climatically suitable areas. The species with the highest top height gain per 1-km^2 grid cell was then selected (RQ3). Fourth, to reveal species with increasing growth potential (RQ4), we defined the "winner" species per cell as the one with the largest positive top height changes according to the *difference rasters*.

2.4. Software

The entire analysis was carried out using the open-source statistical software "R" (R Core Team, 2023, version 4.2.3) in combination with the development environment "R Studio" (Posit team 2023, version 2023.3.0.386) and 23 additional packages (Supp. Material).

3. Results

3.1. Regional Productivity Trends

3.1.1. Change in forest productivity

Our models indicate a continental-scale increase in forest top height across Europe, with an average rise of 0.9 ± 3.1 m under the RCP4.5 scenario. Under the more intensive RCP8.5 scenario, the top height at age 100 is projected to increase by 2.3 ± 6.4 m relative to the reference period (1981–2010). The greater standard deviation observed under RCP8.5 highlights the contrasting regional trends—enhanced forest productivity in Northern Europe versus a projected decline in the Mediterranean regions. In the Boreal region (ALN + BOR), for example, the average top height is predicted to be 4.2 ± 2.5 m higher under RCP4.5 and 9.1 ± 3.2 m higher under RCP8.5, respectively (see Fig. 2 for European ecoregions). In contrast, Southern Europe (MDN + MDS + MDM) will lose on average −1.5 ± 2 m under RCP4.5 and −3.6 ± 4.5 m under RCP8.5 in height according to our models. Only a slight change of 0.7 ± 1.1 m is predicted (1.6 ± 2.5 m under RCP8.5, respectively) for the Northern European coasts (NEM + ATN). In the Central region (CON + ATC), especially in France, top heights are predicted to decrease, while in eastern Europe top height remains constant or declines on a regional scale. The average of the Central region is projected to be −0.8 ± 1.4 m for climate scenario RCP4.5. Under RCP8.5, eastern parts of the Central region will be stronger affected by productivity declines (-2.9 ± 3.6 m). In addition, in the Alpine regions (ALS) the models predict a mean increase of 0.9 ± 3.1 m (1.2 ± 7.3 m) in top height, highly dependent on altitude whether top height increases or decreases (Fig. 3 and Supp. Material).

3.1.2. Change in species productivity

While projected forest productivity varies by species and region (Fig. 3), several species consistently emerge as top-performers. According to our model predictions, Douglas-fir is the major winner in the Alpine north and Boreal region with a gain of 6 m ± 2 m top height at age 100 under RCP4.5, while silver fir (*Abies alba*) shows an even greater gain of 14.3 ± 5.4 m under RCP8.5. Field maple (*Acer campestre*) will have the greatest height increase of all species investigated on the Northern European coasts (Nemoral and Atlantic north) with 3 ± 1.7 m (black pine 6.1 ± 2.8 m under RCP8.5, respectively). However, the species with the greatest projected gain is downy oak (*Quercus pubescens*). In the Alpine region, its top height is expected to increase by 2.2 ± 1.8 m under RCP4.5 and by 4.8 ± 3.4 m under RCP8.5. In Continental and Atlantic Central Europe, the projected gains are 1.8 ± 0.9 m and 3.6 ± 1.9 m, respectively, while in the Mediterranean region the expected increase is more modest, at 0.3 ± 1.3 m under RCP4.5 and 1 ± 2.1 m under RCP8.5 (Supp. Material).

3.2. Most productive species

In Northern Europe, the species predicted to be most productive

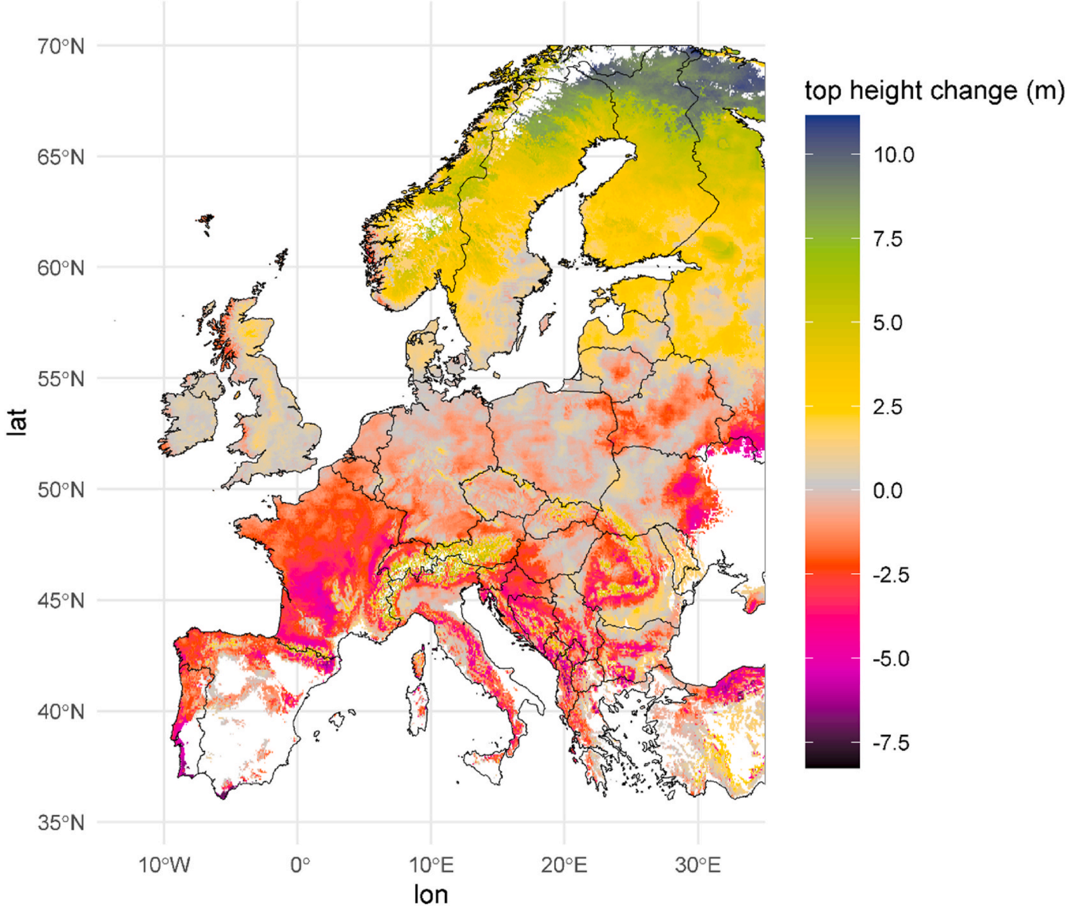

Fig. 2. Change in forest productivity. Mean difference (in meters at age 100) in top height between climate scenario RCP4.5 (2071-2100) and reference period (1981-2010) for 23 tree species. Differences of top heights (m) were calculated for each species between the scenario and the reference period inside the combined species distribution of the reference period and scenario. Calculations are purely climate driven and do not consider numerous other important growth factors, such as soil conditions, extreme events, or pathogens.

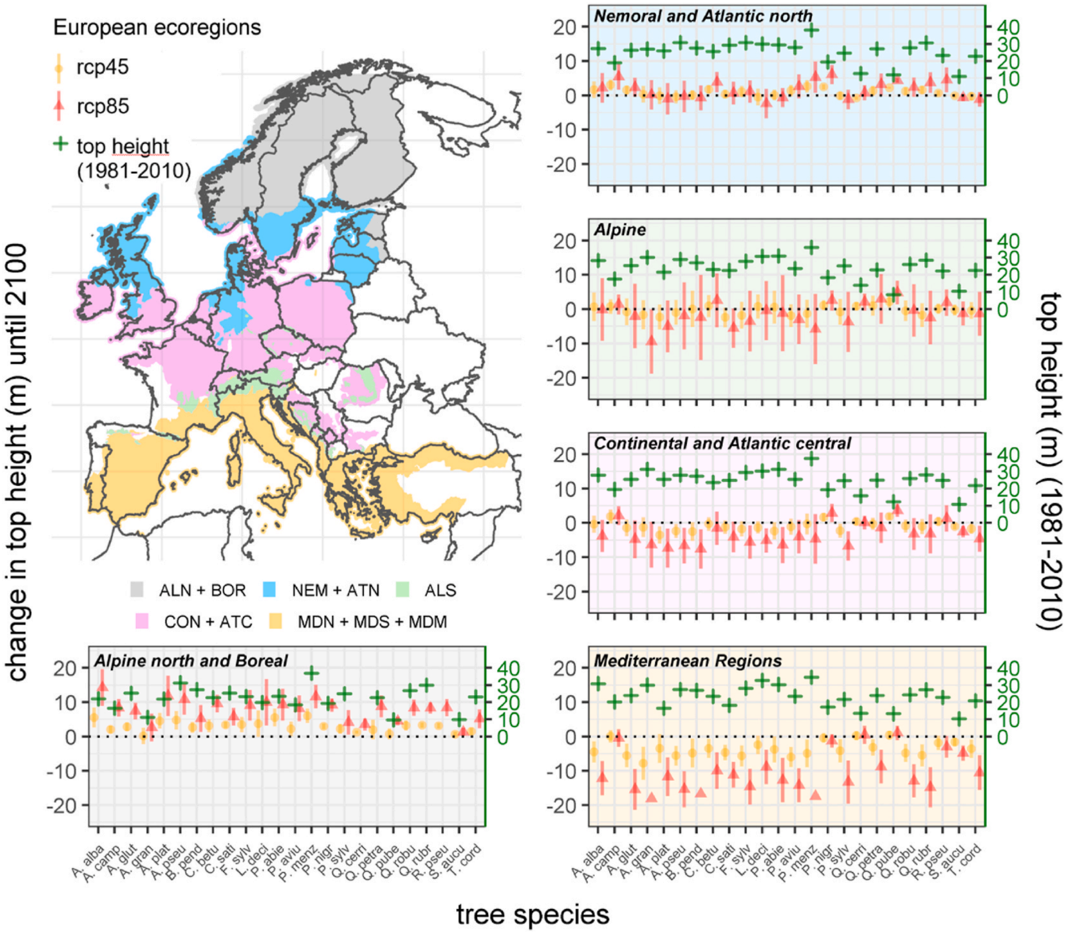

Fig. 3. Change in species productivity. Mean difference [m] ± standard deviation between the predicted top height of scenario RCP4.5 (2071-2100, orange), RCP8.5 (2071-2100, red), respectively, and the reference period (1981 to 2010) per region and tree species. A positive difference indicates a gain of tree height (m at age 100), negative values show a loss of a tree species in the future. The predicted tree height (m) of the reference period is displayed on the right Y-axis for comparison and was computed as the mean height in the species distribution area and region. Differences and standard deviation were calculated within the combined species distribution area of reference period and scenario. Calculations are purely climate driven and do not consider numerous other important growth factors, such as soil conditions, extreme events or pathogens. Aggregated European ecoregions (ALN + BOR = Alpine north and boreal, NEM + ATN = Nemoral and Atlantic north, ALS = Alpine, CON + ATC = Continental and Atlantic central, MDN + MDS + MDM = Mediterranean Regions) (Metzger et al., 2005).

under RCP4.5 scenario include Norway spruce (*Picea abies*) (27.5 ± 4.1 m), silver birch (*Betula pendula*) (27.8 ± 1.1 m) and larch (*Larix decidua*) (28.6 ± 6.2 m) (Fig. 3). Douglas-fir (38.7 ± 3.6 m) and European beech (*Fagus sylvatica*, 27.9 ± 1.4 m) are projected to reach the greatest heights along the northern European coasts. In Central Europe, northern red oak (26.5 ± 2.1 m), black locust (25.7 ± 2.3 m), and sessile oak (*Quercus petraea*, 22.6 ± 0.8 m) are expected to grow tallest. To the west, the most productive tree species is predicted to be pedunculated oak (*Quercus robur*) (21 ± 0.8 m), wild cherry (*Prunus avium*) (26.5 ± 2 m), black alder (*Alnus glutinosa*) (24.8 ± 2.5 m), chestnut (*Castanea sativa*) (17 ± 3 m) and downy oak (15.6 ± 2.9 m), respectively. The southeast of Europe is projected to be dominated by Turkey oak (*Quercus cerris*) (19.5 ± 4 m) and black pine (*Pinus nigra*) (16.4 ± 3.9 m). Under RCP8.5, Douglas fir remains the species with the greatest height potential (37.9 ± 3.6 m) on the northern European coasts and higher altitudes. In large parts of Central and Eastern Europe (12.2 mil. km2), however, black locust is predicted to be the most productive species (27.2 ± 3 m). Turkey oak (18.5 ± 3.3 m), small-leaved linden (*Tilia cordata*) (22 ± 0.9 m) and Norway maple (*Acer platanoides*) (26.9 ± 1.6 m) are predicted as top performers in smaller areas in eastern Europe. Spruce (30 m ± 2.9 m), larch (30.4 ± 4.1 m) and birch (28.1 ± 1.1 m) will be the most productive species in the North, while downy oak (16.2 ± 2.2 m), black pine (18 ± 3.1 m), chestnut (17.1 ± 3.5 m) and field maple (22.5 ± 0.7 m) will have the highest top height in the south. In contrast, wild cherry (26 ± 1.7 m) and sessile oak (22.7 ± 0.8 m) are projected to shift their most productive sites to south of Britain and northern Bavaria (Germany), respectively (Fig. 4).

3.3. *Highest gaining tree species*

The tree species that are predicted to experience the greatest growth gains and losses, and the magnitude of these changes, vary strongly by region and climate scenario. Under an RCP 4.5 scenario, species projected to show growth gains by 2100 are Norway spruce (6.5 ± 2.4 m), larch (5.8 ± 3.1 m), and sycamore (*Acer pseudoplatanus*) (5.7 ± 2.6 m) in the boreal region (Fig. 5). In the Nemoral and Atlantic north region, we expect silver fir (5.8 ± 2 m), beech (2.7 ± 1.0 m) and Douglas fir (3.4 ± 1.4 m) to benefit the most (RCP4.5). Southward, in the Central area, field maple (3.1 ± 1.2 m) and downy oak (1.4 ± 1.3 m), as well as black pine (1.7 ± 1.4 m) show the highest increase in top height. Black alder (2.1 ± 1.7 m), Norway maple (4.3 ± 2.5 m), small-leaved linden (-1.2 ± 1.3 m), sessile oak (2.7 ± 2 m) and hornbeam (*Carpinus betulus*) (2.5 ± 1.7 m), respectively, are predicted to gain the most in eastern and southern Europe. In the Balkans and Turkey, the highest top height increase will have black locust (2.4 ± 1.1 m) and Turkey oak (1.5 ± 0.8 m). Areas with no expected height gain of any observed species are located in the Northwest of France and Spain, at the Portuguese coast, parts of southern Italy, as well as southern Russia and parts of Ukraine.

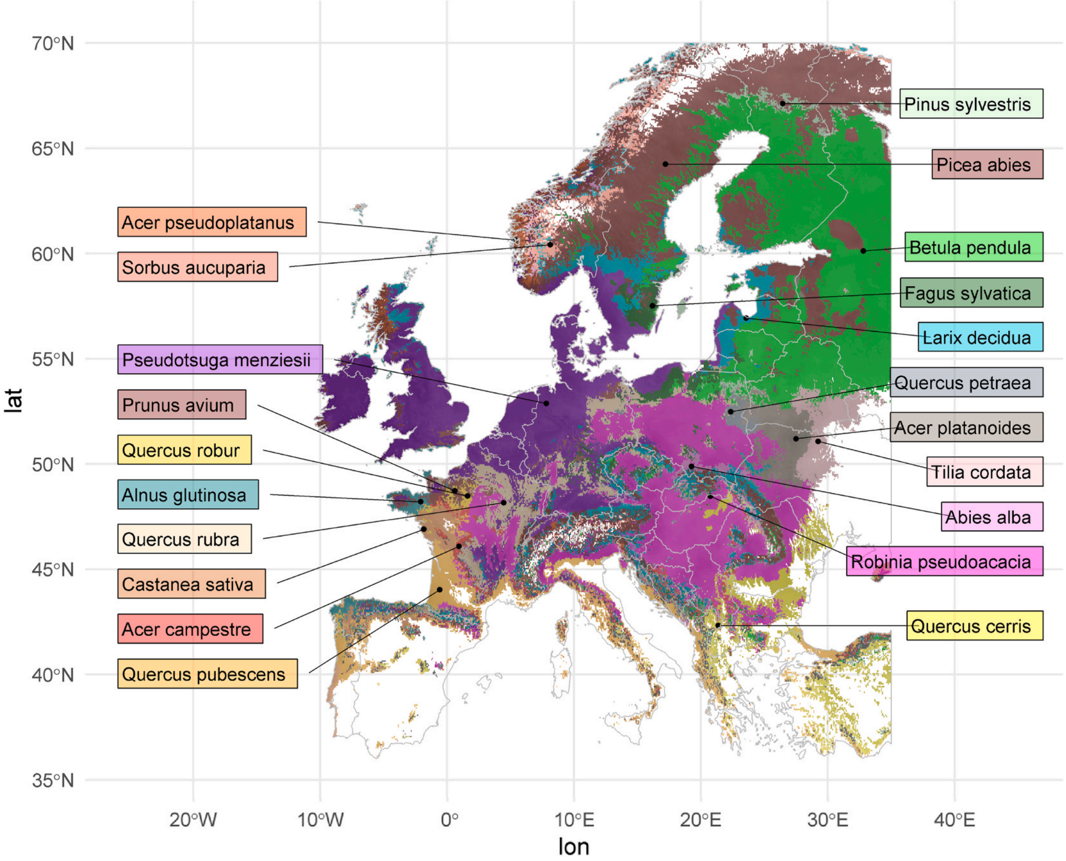

Fig. 4. Most productive tree species—highest absolute projected productivity as calculated by the site index at age 100—under climate scenario RCP4.5 (2071-2100). For each species, the prediction of the site index model was masked by the respective species distribution area. Only tree species were labeled which had a contiguous area of 2500 km^2 or more. Calculations are purely climate driven and do not consider numerous other important growth factors, such as soil conditions, extreme events or pathogens.

While predictions under an RCP8.5 scenario share some similarities with RCP4.5 simulations, they also show notable shifts in species rankings, performance, and the extent of regions with no predicted gains. For example, under RCP8.5, spruce (14.8 ± 2.3 m), silver fir (17 ± 3.2 m), and Norway maple (18.2 ± 3.5 m) benefit in the north of Europe. At higher altitudes of the Scandes, the highest productivity gains are predicted for larch (15.8 ± 5.3 m) and sycamore (13.9 ± 3.2 m). In the Nemoral and Atlantic north region, we expect Douglas-fir (9.7 ± 4.1 m), birch (6.8 ± 5.2 m) and field maple (3.9 ± 2.6 m) to show the highest top height increase under a strong climate change scenario. Considering the extent of their projected range gains, the leading species are downy oak in the south (mean height gain 3 ± 2.7 m), black pine in the east (6.6 ± 3.3 m), and black locust in the southeast of Europe (6.8 ± 2.3 m). Turkey oak (2.8 ± 2.2 m), sycamore (13.9 ± 3.2 m) and sessile oak (11.1 ± 2.7 m) are predicted to gain the most productivity in the southeast and east, respectively. In the south of Great Britain and northwest France, parts of Spain and Italy, the predictions show no increase in productivity under RCP8.5 for any tree species (Fig. 5 and Supp. Material).

4. Discussion

4.1. Regional Productivity Trends

Our models suggest that climate change will have heterogeneous impacts on forest productivity across Europe. An increase in productivity is projected in Northern regions, whereas a decline is anticipated in Central areas, with a notable decrease in France (Fig. 2 and Supp. Material). Similar trends and projections of European forest growth under climate change are documented in other studies (Pretzsch et al., 2023; Martinez del Castillo et al., 2022; Lindner et al., 2010; Brandl et al., 2018). For example, the Swedish forest inventory recorded height increases without changes in basal area, suggesting that the site index reflects ecosystem “carrying capacity” rather than volume growth (Mensah et al., 2023). The “carrying capacity” describes how much an ecosystem can sustain under a given set of environmental conditions (Monte-Luna et al., 2004). Volume increment however, is also strongly influenced by factors such as tree density, masting years or soil fertility (Skovsgaard and Vanclay, 2008; Pretzsch, 2009; Hacket-Pain et al., 2015). Thus, a rise in site index represents a heightened potential for forest productivity under certain environmental conditions that does not invariably correspond to an increase in tree diameter. While an increasing site index may promote aboveground biomass carbon sequestration, higher top heights do not necessarily imply greater carbon storage, since declining wood density or changes in soil carbon dynamics can reduce the overall carbon storage capacity of future forests (Pretzsch et al., 2018; Lal, 2005).

In addition, future productivity gains in Northern Europe attributed to extended growing seasons and rising temperatures could be constrained by intensifying biotic and abiotic disturbances (Senf and Seidl, 2021). In southern Europe, human interventions such as irrigation and altered forest management may be able to offset some of the expected negative climatic effects (Barichivich et al., 2013; Ruiz-Peinado et al., 2017). More frequent and intense drought events, compounding rising temperatures, may result in trees reducing leaf area to mitigate water loss through evaporation (Chaves et al., 2003). Under more optimal climatic conditions, however, trees tend to expand their leaf area to optimize photosynthetic capacity, which can result in delayed partial

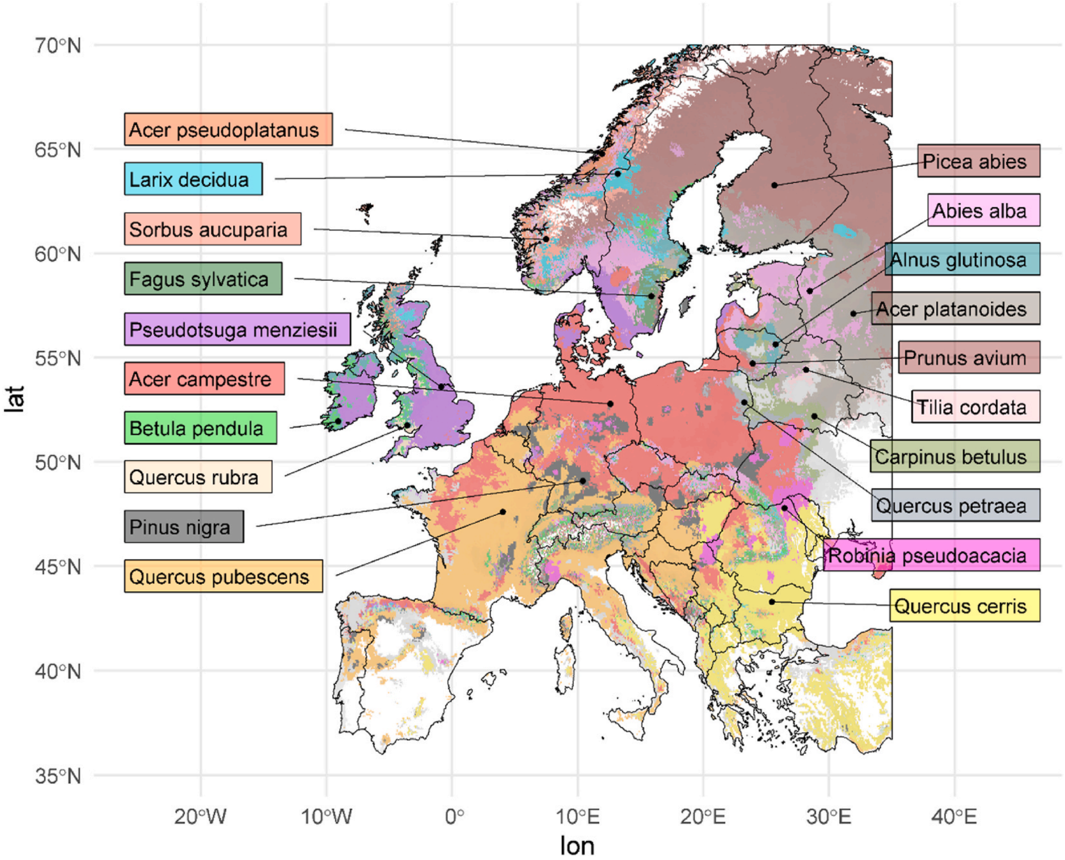

Fig. 5. "Winning species"—defined as species with the strongest relative height gains compared to current conditions—up to 2071-2100 (climate scenario RCP4.5). Differences of tree heights (m) were calculated for each species between the scenario and the reference period (1981-2010) within the combined species distribution of the reference period and scenario. Areas where the maximum gain of all species was below zero meters (at age 100) (= all species losing) were removed and replaced by light grey color. Only tree species that had a contiguous area of 2500 km^2 or more were labeled. Calculations are purely climate driven and do not consider numerous other important growth factors, such as soil conditions, extreme events or pathogens.

dieback. This phenomenon, known as "structural overshoot," may increase tree mortality during or after drought events (Jump et al., 2017). Accordingly, Fig. 2 highlights regions where the risk of altered canopy structure and heightened susceptibility of branches, trees, or entire stands to mortality is projected to increase.

Areas projected to see declines in productivity would require substantial investment in identifying climatically and edaphically suitable species and provenances capable of coping with future climates (Ruiz-Peinado et al., 2017; Chakraborty et al., 2024). In Northern Europe, however, the existing species pool could potentially be enriched, and the species diversity broadened by incorporating more southerly, eventually more productive, species and provenances. Yet, tree species selection in Northern regions remains strongly constrained by frost and cold (Sakai and Larcher, 1987), creating a bottleneck in species diversity that is expected to persist until the end of the century (Wesseley et al. 2024). While our models do not account for numerous factors (see Section 4.4), they assume the implementation of climatically adapted tree species, whether already planted or to be introduced, and predict productivity declines in southern Europe.

Consequently, maintaining or enhancing Europe's forest productivity, assuming our models project accurately, would necessitate the widespread adoption of assisted (population) migration, including species not explicitly examined in this study. However, widespread clear-cutting and reforestation with the most productive tree species does not constitute a comprehensive solution for mitigating effects of climate change on European forests. Risk factors such as introduction of pests, frosts, invasiveness, or changes in ecosystem dynamics must be considered in planning interactions (Pedlar et al., 2012; Xu and Prescott, 2024). A more practical approach may be leveraging clear-cuts or disturbance events as opportunities, incorporating non-native tree species where appropriate and feasible. From a broader perspective, it is important to consider that introducing alternative tree species is also strongly shaped by socio-economic factors, such as planting costs (resulting from seed availability, nursery capacities, regulatory costs, workforce, local demand, etc.), wood demand (e.g., hardwood or softwood, thickness, etc.), the uptake of forest adaptation strategies including assisted migration (i.e., the opinions of local forest managers regarding which measures are feasible or acceptable), and supranational and regional forest management policies (Hoeben et al., 2025; Sousa-Silva et al., 2016; Permadi et al., 2018).

4.2. *Most productive tree species*

Figs. 3 and 4 present an overview of potentially fitting tree species. They identify regionally productive species, aligning with previous studies. Douglas fir dominates Central Europe under both reference and RCP4.5 scenarios (Figs. 3 and 4, Supp. Material), consistent with its documented climate change adaptation potential (Vitali et al., 2017). Southern regions show black locust as most productive, reflecting its invasive potential and drought tolerance (<550 mm annual precipitation; Klisz et al., 2021; Nicolescu et al., 2020). Birch prevails in north-eastern Europe (Finland, Russia, Belarus, Baltic States) due to its climatic adaptability (Dubois et al., 2020), while spruce remains prominent in the north despite projected drought- and pest-related mortality (Barichivich et al., 2013). Discrepancies emerge when comparing productivity (Fig. 4) with dominance maps (Brus et al., 2012). Although, it is important to note that maps illustrating productivity and those depicting dominance are not entirely equivalent, as productive species may be outcompeted by shade-tolerant counterparts. However, this comparison with literature still appears to be the most straightforward. For instance, while Scots pine dominates continental parts of East Germany in Brus et al. (2012), our models predict higher productivity for beech, birch, and red oak there. This divergence reflects: red oak's non-native tree species classification limiting historical presence (Nagel, 2018), and beech's drought sensitivity on sandy soils (Leuschner et al., 2023). Both factors remain unmodeled. These cases highlight Fig. 4's utility for identifying growth potential while underscoring its limitations (Section 5.4). Furthermore, high productivity of a species does not necessarily translate into long-term dominance in mixed or unmanaged forests, particularly beyond a single generation (Shan et al., 2025). Species interactions, including competition and facilitation, strongly influence outcomes (Ammer, 2019; Jactel et al., 2018). Fast-growing species that perform well in monocultures may not maintain dominance in mixtures, and high productivity alone does not guarantee ecological resilience or long-term success (Morin et al., 2011; Tatsumi, 2020). Lastly, it should be noted that other tree species not considered in this study could exhibit higher productivity on some sites (e.g., *Quercus ilex, Pinus pinea*). .

4.3. Highest gaining tree species

Predictions of future top height gain suggest surprising changes to future forest communities (Figs. 3 and 5). For example, field maple shows the greatest gains in the Nemoral/Atlantic north region, likely benefiting from warming at its northern range edge (Zecchin et al., 2016), though its medium size limits its relevance. Not investigated species in this study (e.g., *Cedrus libani*) may show even greater potential (Messinger et al., 2015). Douglas-fir and silver fir exhibit maximum gains in Great Britain, Ireland, and southern Scandinavia under RCP4.5 (Fig. 5). While cultivated in the British Isles, their absence in Scandinavia reflects both non-native status and winter temperature limitations (Gazol et al., 2015; Malmqvist et al., 2018; Mauri et al., 2016). Downy oak shows particular promise in France and Italy, where it is already established. The RCP8.5 scenario reveals northward shifts of winners, with southern regions increasingly dominated by downy oak and Turkey oak - species tolerant to both warming and reduced precipitation (Pasta et al., 2016; Supp. Material). In addition to a broad climatic evaluation via climate-growth relationships, validating this map based on existing literature has proven to be challenging. As a result, assessments of growth improvements are primarily confined to individual case studies; comparative analyses across different species therefore hardly possible.

4.4. Limitations and potential for improvement

Statistical modeling, and in particular SDMs and SIMs, provide a valuable tool for exploring how climate and edaphic factors shape forests across Europe. Such models allow complex ecological relationships to be summarized in a tractable way, facilitate comparisons across large spatial scales, and support scenario analyses of future climate impacts. At the same time, it is important to recognize the inherent limitations of these approaches, such as i) resolution constraints (1 × 1 km grids) obscuring stand-level variability from genetics, microtopography, and management history (Pretzsch and Schütze, 2016; van der Maaten et al., 2017), as well as ii) the exclusion of extreme events affecting growth and mortality (DeSoto et al., 2020). Moreover, the models are iii) influenced by anthropogenically biased species distributions and planting biases (Sallmannshofer et al., 2021; Pötzelsberger et al., 2020a; Vadell et al., 2016). That said the models are not intended to accurately predict tree-wise, not even stand-wise growth dynamics. Overall, they only allow a prediction of the respective regional growth potential (SIM) or of the climate suitability (SDM) given certain climatic conditions. Additionally, future climate projections based on global climate models are subject to multiple sources of uncertainty, including scenario uncertainty related to future emissions pathways, model structural uncertainty arising from differing representations of key physical processes, and internal climate variability reflecting natural climate fluctuations (Nowack and Watson-Parris, 2025, Deser et al., 2012).

A further point to consider is that the explanatory power of the SIMs is comparatively weaker than models developed for regional applications (Seynave et al., 2005; Yue et al., 2016; Socha et al., 2020; Wöhlbrandt et al. in prep.). This limitation can be attributed to several factors: the reliance on i) a large ecological dataset from diverse sources and ii) the omission of soil variables, despite their significance for top height growth. However, the available data is rather coarsely resolved on European scale, and it might be preferable to build a climate-driven model without soil, than using potentially unreliable soil information (Panagos et al., 2012). Moreover, the SIMs do not account for iii) differences in management regimes, due to a lack of relevant data. Moreover, iv) the use of static-SIMs (space-for-time substitution approach) is questioned, as recent studies indicate that static models fail to accurately reflect dynamic local growth patterns influenced by climate change and shifts in nitrogen deposition (Yue et al., 2023; Schick et al., 2023). While forest inventories have long existed, inconsistent methodologies and limited repeated measurements hinder the potentially more precise state-space applications at the European scale, necessitating assumptions of static-site indices (Tomppo et al., 2010; Brandl et al., 2018). Despite these limitations, the SIMs and SDMs used here are fitted to a large European dataset, thus cover a large geographic gradient and show results consistent with literature (Brandl et al., 2018; Thurm et al., 2018; Caudullo et al., 2017; Wessely et al., 2024; Pretzsch et al., 2023). Furthermore, the use of absences (named ‘growth absences’ in Wöhlbrandt et al. in prep.) is a novel approach in SIM, enforcing the extrapolative power and biological meaningfulness of the stand-alone SIM predictions under climate change.

4.5. Conclusion and outlook

Provided that the models capture large-scale growth patterns accurately, our results indicate pronounced regional differences in future forest productivity across Europe. Northern and parts of Central Europe are projected to maintain or increase productivity, whereas southern regions face a substantially higher risk of productivity declines under climate change. These patterns suggest that maintaining European forest productivity will require region-specific strategies and a differentiation between potential productivity and its realization under increasing disturbance pressure. The analysis covers a wide range of tree species and indicates that projected northward shifts in climatic suitability may lead to a progressive loss of suitable habitat for several species in southern Europe. This highlights the need for further research on the adaptive and genetic potential of drought-tolerant species and the integration of such information into large-scale modelling frameworks. In northern regions, projected productivity gains may be supported by species or provenances with high growth potential under future climates. In Central Europe, where our results indicate slight productivity declines, increasing disturbance frequency suggests a growing need for stabilizing management strategies, including the enrichment of stands with drought-resistant species and the promotion of structural diversity to enhance resilience. In southern Europe, declining productivity and shrinking climatic suitability ranges imply that adaptation options may become increasingly constrained. Assisted migration and assisted gene flow may therefore gain relevance in some contexts, alongside early interventions such as density regulation and other silvicultural measures aimed at reducing climate-related stress. These approaches should be considered within broader ecological, social, and governance frameworks. Overall, this study provides a continental-scale, comparative assessment of future forest productivity that can inform strategic planning, species selection, and future research, while recognising that local management decisions must account for site-specific conditions, uncertainties, and multiple forest objectives.

CRediT authorship contribution statement

Anna Wöhlbrandt: Writing – original draft, Visualization, Validation, Formal analysis, Data curation, Conceptualization. **Anabel Onay:** Writing – review & editing, Validation, Formal analysis, Data curation. **Ute Bachmann-Gigl:** Writing – review & editing, Validation, Project administration, Data curation. **Wolfgang Falk:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Christian Temperli:** Writing – review & editing, Resources. **Samuel Aspalter:** Writing – review & editing, Validation, Data curation. **Debojyoti Chakraborty:** Writing – review & editing, Resources, Funding acquisition. **Silvio Schüler:** Writing – review & editing, Resources, Funding acquisition. **Johannes Breidenbach:** Writing – review & editing, Resources. **Jonas Fridman:** Writing – review & editing, Resources. **Miriam Isaac-Renton:** Writing – review & editing, Resources. **Vladimír Šebeň:** Writing – review & editing, Resources. **Mitja Skudnik:** Writing – review & editing, Resources. **Tzvetan Zlatanov:** Writing – review & editing, Resources. **Dominik Thom:** Writing – review & editing. **Eric A. Thurm:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT-5 (https://chatgpt.com/), DeepSeek-V3 (https://chat.deepseek.com/), and PaperDigest – TextRewriter (https://www.paperdigest.org/rewriter/) in order to improve the readability and language of the manuscript. After using these services, the authors reviewed and edited the content as needed and took full responsibility for the content of the published article.

Declaration of Competing 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.129142.

Data availability

The authors do not have permission to share data.

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