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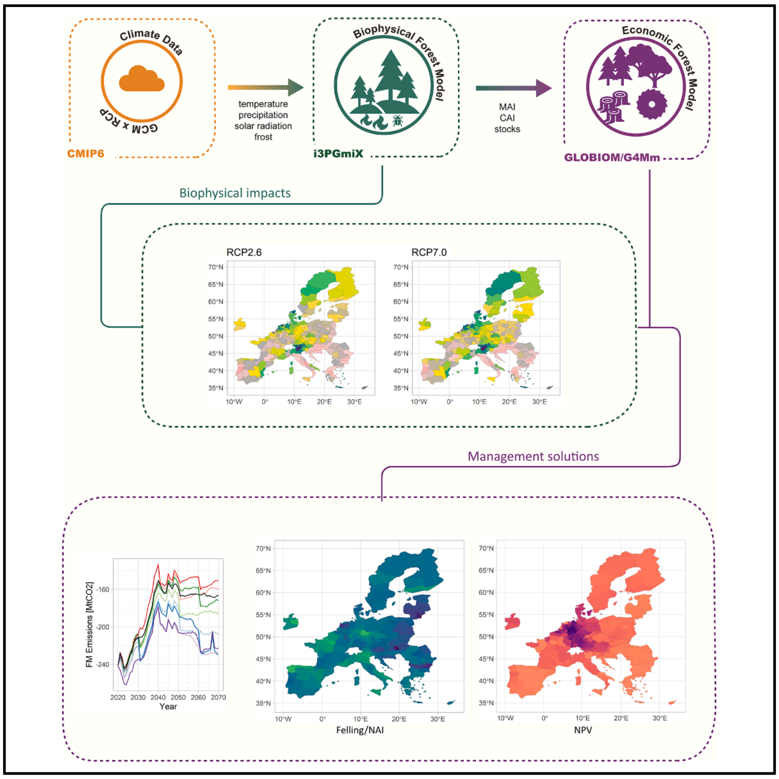
Adapting forest management to climate change impacts and policy targets in the EU: Insights from the coupled GLOBIOM/G4M-i3PGmiX model

Graphical abstract



Highlights

- Climate change may affect the achievement of forest policy targets in the EU
- Changes in forest productivity vary regionally, requiring management adaptation
- The forest sink is expected to decline, with uncertainty across climate scenarios
- Changes in productivity affect wood markets and will change forest profitability

Authors

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In brief

Climate change, the implementation of ambitious climate targets, and the development of the bio-based economy will increase the complexity of forest management in the European Union. This study uses an integrated modeling framework to assess how biophysical impacts on forest productivity and emerging demands may drive timber supply shifts and the need for adaptive management to meet future policy goals.

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Adapting forest management to climate change impacts and policy targets in the EU: Insights from the coupled GLOBIOM/G4M-i3PGmiX model

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SCIENCE FOR SOCIETY Increasing climate change pressures require immediate adaptation of forest management to maintain forests' contribution to sustainability targets, including climate mitigation, biodiversity conservation, and the development of the bio-based economy. In this context, management strategies must consider local conditions and the multifunctional role of forests. This study uses an integrated modeling framework to assess the impacts of climate change on forest management and policy targets in the European Union. The results reveal that changes in forest productivity are not homogeneous, highlighting the need to adapt current management practices to local contexts and regional demands. Management options that maintain forest productivity and health, while ensuring forest resilience to disturbances, will become increasingly important in meeting climate and biodiversity conservation targets.

SUMMARY

Climate change significantly affects forest dynamics in Europe and is projected to intensify further, posing challenges to policy goals and ecosystem integrity. This requires changes in forest management that anticipate impacts and act to minimize negative consequences on forest functioning while maintaining forests' contribution to the bio-based economy and decarbonization targets. However, it is still unclear how alternative forest management strategies can support biodiversity, green growth, and mitigation targets under changing environmental conditions. This study uses an integrated modeling framework to address this issue and assess forest management adaptation in the European Union, considering conservation goals and emerging biomass demands. The results show that climate policies will be a major driver of forest management until mid-century, with climate impacts shaping management decisions thereafter. Productivity changes vary regionally, with temperature-limited ecosystems benefiting and water-limited forests declining in growth. These biophysical impacts may displace harvests from Mediterranean and temperate forests to the boreal zone, requiring changes in management practices. Adaptive forest management will, therefore, be crucial for achieving policy goals in Europe under future climate scenarios.

INTRODUCTION

Forest ecosystems are at the center of current policy pledges to mitigate climate change and safeguard biodiversity, playing a pivotal role in addressing these sustainability challenges.[1] In Europe, forests mitigate around 7% of annual greenhouse-gas emissions and are a key component of the climate change mitigation portfolio of the European Green Deal, with legally binding targets set by the European Union (EU) Climate Law.[2,3] Mitigation actions leveraging forest management and afforestation are essential to mitigate residual emissions from other sectors and achieve climate neutrality by mid-century in the EU. At the same time, forest ecosystems provide essential goods and services to society and contribute to the bio-based economy by supplying biomass for material use and bioenergy, supporting decarbonization targets, and creating green jobs.[4]

However, climate change impacts pose a significant challenge to achieving policy goals and developing the bio-based economy. Changes in temperature, precipitation regimes, solar radiation, and other environmental variables have profound implications for forest dynamics, affecting several vegetation processes and overall forest functioning.[5] For example, alterations in growth rates, tree mortality, and species range shifts have already been observed in Europe.[6] Furthermore, the intensity and frequency of extreme events are expected to increase in the future, leading to losses from wildfires, insect outbreaks, and windstorm damage.[7,8]

Changing environmental conditions will alter forests' capacity to provide multiple ecosystem services, such as carbon sequestration, water regulation, wood production, and the maintenance of habitats for forest taxa.[9] The forest sink in Europe, for example, may be jeopardized by the increase in disturbance activity and the risk related to invasive species.[10,11] Mauri et al.[12] highlight that species range shifts may cause a decrease of 15%–25% in the provision of ecosystem services in the region. It is, therefore, essential to account for climate change impacts on forest dynamics when designing forest management strategies and to adapt silvicultural practices, anticipating changes in forest productivity and forest functioning. In doing so, managers can evaluate and modify silvicultural systems to maintain forest multifunctionality and resilience, seeking to minimize the negative impacts of climate change.[13]

In addition to shifts in forest productive capacity, management decisions must also incorporate plausible changes in the demand for forest products. The contribution of forest ecosystems to the bio-based economy can bring benefits not only to climate change mitigation via the use of biomass for bioenergy and in wood products but may also promote forest resilience due to forest management adaptation.[14] Hurmekoski et al.[15] point out that the bio-based economy is likely to increase the demand for forest products, including shifts in biomass use toward end uses with higher added value, such as wood-based textiles and wood-based chemicals, creating new markets and cascading effects to wood demands.

In this multifaceted decision environment, forest management strategies must reconcile production objectives with other societal demands concerning forest ecosystems. Adaptation and mitigation strategies should guide managers and decision makers to address climate risks and sustain the provision of ecosystem goods and services.[16] This typically involves the assessment of long- and short-term management levers, such as changes in species composition, rotation length, and thinning intensity, and the related effects on ecological and economic indicators of forest management.[17,18] In this context, forward-looking modeling tools can support decision-making and identify efficient management solutions to balance multiple objectives, including biodiversity conservation and climate mitigation goals (e.g., Mazziota et al.[19] and Moor et al.[20]).

Process-based models have been extensively used in Europe to quantify forest responses to climate change impacts (e.g., Reyer et al.[21] and Lindeskog et al.[22]) and have also provided guidance to identify adaptive management solutions for European forests (e.g., Gutsch et al.[23] and Yousefpour et al.[24]). Recent studies have assessed robust management strategies at European level to cope with climate change impacts on forest dynamics[25] and to quantify the implications of climate change for the development of the EU forest sink.[26] Still, regional forest management responses to climate change impacts that are compatible with the development of future forest demands for material use and bioenergy are poorly understood. To address this issue, we deploy an integrated modeling framework, coupling a process-based forest growth model with a forest sector model to unveil regional changes in forest management that address climate change impacts on European forests and the forest sector, integrating future developments of wood markets, biodiversity conservation targets, and additional sustainability criteria. Specifically, we answer the following research questions. (1) How will climate change impacts alter forest dynamics and forest growth in the EU? (2) What are the implications of climate change impacts on the forest sink and changes in forest management practices? (3) What are the economic implications of regional changes in forest growth and forest management?

Here, we integrate the process-based forest growth model i3PGmiX with the forest management model G4Mm and the economic partial equilibrium model GLOBIOM-EU to analyze forest management decisions in response to climate and economic drivers while preserving compatibility with conservation targets and satisfying future biomass demands in the EU. We deployed this modeling framework under multiple climate scenarios, including representative concentration pathways (RCPs) 2.6 and 7.0, along with a reference scenario without the inclusion of climate change impacts on forest productivity (Table 1). The impacts for each RCP, as modeled by i3PGmiX, were integrated into the GLOBIOM-EU/G4Mm model to account for the effects of shifts in forest productivity in wood and bioenergy markets. The demand for industrial roundwood and bioenergy, as calculated by GLOBIOM-EU, and considering the decarbonization scenario S2 according to the European Commission,[27] was met by the G4Mm model for each scenario, yielding the corresponding changes in forest management and forest sink.

Our results reveal heterogeneous climate change impacts across European forests, with declining growth in water-limited ecosystems and positive responses in temperature-limited regions. These changes in productivity, allied to climate mitigation targets and emerging demands for biomass, required adaptation of forest management regimes. The growing demand for bioenergy and the material use of forest biomass caused an increase in the utilization rates through mid-century. Changes in forest management thereafter were mediated by the climate

Table 1. Scenarios tested

Scenario	GCM	RCP
Reference	Historical	Historical
RCP26_ GFDL-ESM4	GFDL-ESM4	SSP1: RCP2.6
RCP70_ GFDL-ESM4	GFDL-ESM4	SSP3: RCP7.0
RCP26_IPSL-CMA6-LR	IPSL-CMA6-LR	SSP1: RCP2.6
RCP70_IPSL-CMA6-LR	IPSL-CMA6-LR	SSP3: RCP7.0
RCP26_MPI-ESM1-2-HR	MPI-ESM1-2-HR	SSP1: RCP2.6
RCP70_MPI-ESM1-2-HR	MPI-ESM1-2-HR	SSP3: RCP7.0
RCP26_UKESM1-0-LL	UKESM1-0-LL	SSP1: RCP2.6
RCP70_UKESM1-0-LL	UKESM1-0-LL	SSP3: RCP7.0

GCM stands for the general circulation model and RCP for the representative concentration pathway in each climate scenario combination.

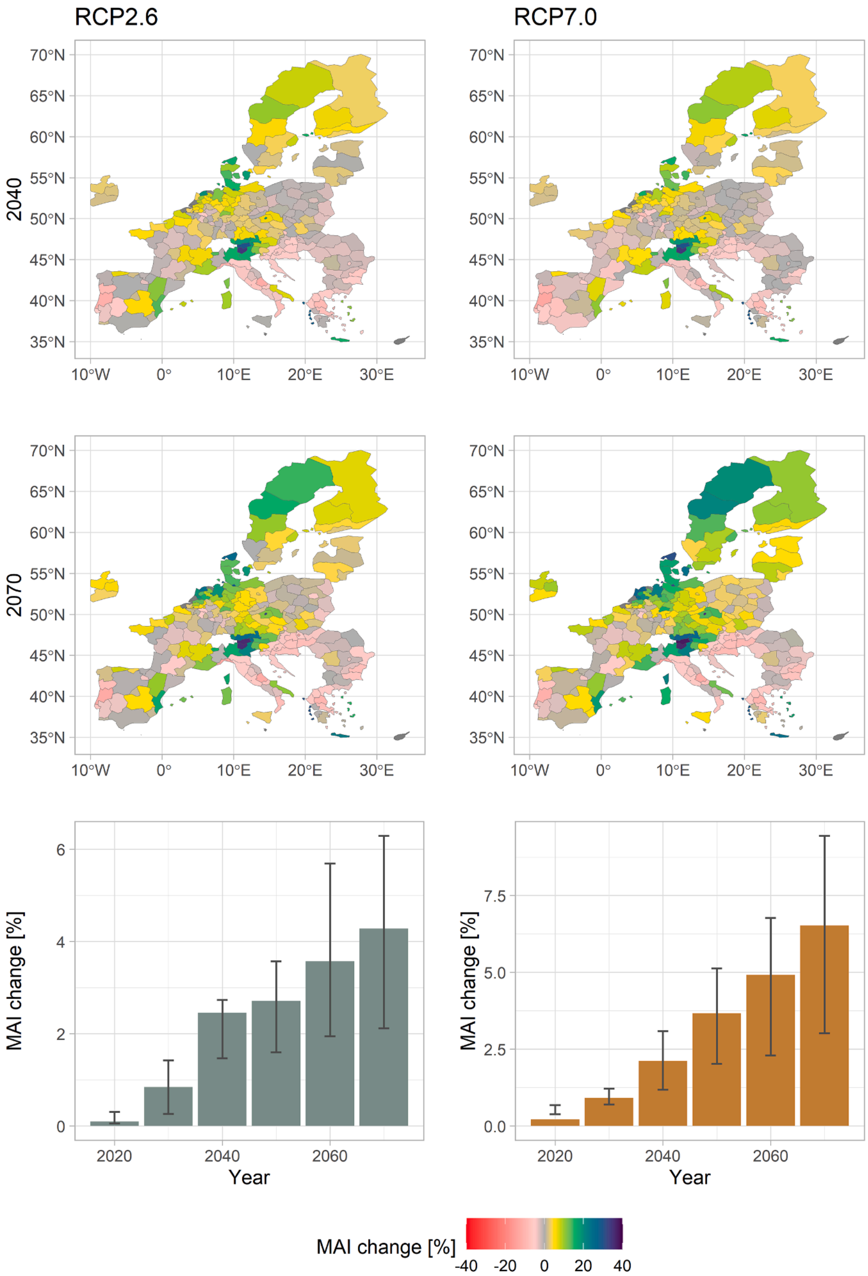

Figure 1. Climate change impacts on forest productivity as impact on the mean annual increment for the EU at the NUTS2 level

The left column displays the results for RCP2.6 averaged across general circulation models (GCMs) by 2040 (first row) and 2070 (second row), while the third row shows the average change over the EU for the simulation period (intervals show the range across GCMs). The right column shows the same outputs for RCP7.0. The mean annual increment (MAI) barplots in the last row display the temporal dynamics of MAI changes until 2070.

scenario considered. These interactions between climate change, forest management practices, and wood markets have not only important implications for the forest sink and policy targets in the EU but also highlight the need for adaptation of the forest sector to these novel conditions, building resilience from forest ecosystems to downstream industrial processing.

RESULTS

Biophysical responses to climate change drivers

Taking into account the reference period (2015–2019), we obtained from the i3PGMix model a gross primary production (GPP) of 1,108 gC/m^2/year and net primary production (NPP) of 475 gC/m^2/year on average for European forests, while the standing stock amounted to 202 m^3/ha. Future climate change scenarios resulted in modest increases in growth rates when aggregated over the whole forest area (disregarding the impacts of natural disturbances and extreme events). Increased growth rates under climate change led to a 3% larger mean annual increment (MAI) by 2040, reaching up to a 6% increase by 2070 for RCP7.0. The growth rates for RCP2.6 remained stable after 2060 (neighboring a 4% increase compared to the current climate) as an average of all general circulation models (GCMs) (Figure 2). The dynamics of forest growth began to diverge for the different RCPs after 2045, with increased productivity for RCP7.0, surpassing 6% by 2070, mainly driven by CO_2 fertilization impacts.

The effects of climate change on forest growth, however, introduced substantial uncertainty depending on the GCM considered, as evidenced by the ranges in Figure 1. The differences across GCMs were larger than the differences between RCPs, where models predicting milder climates in Europe (e.g., GFDL-ESM4) resulted in stronger positive responses of forest growth (NPP and MAI) compared to hotter and drier climates, such as the estimates given by the UKESM1-0-LL. Considering RCP7.0, productivity increases ranged from approximately 2.5% to 10%, depending on the GCM, while the same figures ranged from 2% to 6% for RCP2.6.

Despite the modest increases in productivity under future climate change scenarios when aggregated to the whole forest area, impacts varied regionally across European forests. The highest productivity gains were observed in the boreal zone, especially in central Sweden and Finland, displaying forest productivity increases surpassing 10% for RCP7.0. The same behavior was also observed in the montane and alpine forests of central Europe, especially at higher elevations. However, increases in productivity were lower compared to northern Europe. Conversely, forest growth responses in eastern Europe

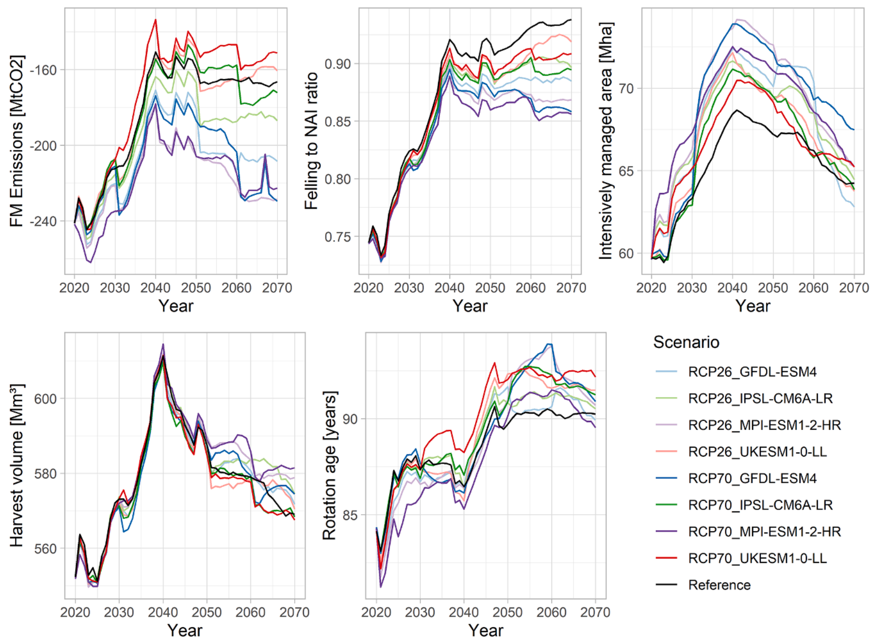

Figure 2. Temporal changes in forest management and implications for the forest management sink in the EU

Shown are the outcomes for each variable across the different climate change scenarios tested as well as the reference scenario. FM refers to forest management, and NAI stands for net annual increment.

and the Mediterranean region displayed large areas with a decrease in forest productivity, as precipitation decreased and temperatures increased, resulting in higher aridity. The same regional growth patterns observed by 2040 for RCP2.6 were maintained under RCP7.0, with an intensification of the increases in productivity for the latter. This behavior was also observed when comparing the changes in productivity between 2040 and 2070, where the same productivity patterns observed by 2040 were amplified toward the end of the century (increasing from 2.5% to 4.3% for RCP2.6 and from 2% to 6.5% for RCP7.0, on average, with most positive impacts in the Nordic countries and montane forests in central Europe).

Changes in forest management and the forest management sink

The impacts of climate change scenarios on forest productivity cascaded to the EU forest management sink and affected forest management decisions (Figure 2). Regardless of the climate scenario, we observed a decrease in the forest sink toward the end of the simulation period. This is a result of the combined effect of the age class dynamics of European forests, which are becoming older (with reduced carbon uptake rates) and the increase in harvesting levels, both driven by a larger share of forests reaching the rotation period and the increase in wood demand for material and bioenergy (growing by 8.5% and 14.7% between 2020 and 2040, respectively). Climate change-induced uncertainty caused the forest sink to range from −230 to −151 $MtCO_2$/year by 2070, depending on the GCM and RCP considered. Following the biophysical impacts, GCMs forecasting more arid climates, e.g., UKESM1-0-LL and IPSL-CM6A-LR, resulted in a lower sink compared to MPI-ESM-1-2-HR and GFDL-ESM4, which project milder climates in the region. Furthermore, for GCMs with hotter climates, RCP2.6 displayed stronger sinks compared to RCP7.0, whereas the opposite occurred for the remaining GCMs, indicating that the CO_2 fertilization effects in more extreme scenarios will not fully counterbalance the harsher growing conditions.

Our results show an increase in the ratio of fellings to net annual increment (NAI) from 2020 until 2040, from 75% to approximately 90%, with subsequent stabilization until 2070. This increase in management intensity has two underlying causes, namely the reduction in growth rates as forests age and the increase in biomass use for bioenergy in the context of EU climate neutrality goals. The demand for bioenergy grows, particularly until 2040, to support the decarbonization of the energy sector. This is also reflected in the total removals in Figure 2, which grow by 12% from 2020 to 2040 (545 million m^3/year to 609 million m^3/year). Thereafter a reduction in removals occurs, and the climate scenarios begin diverging more strongly, with total harvests ranging from 572 to 588 million m^3/year by 2070. In general, total removals after 2040 were larger for more productive climate scenarios, while the felling-to-NAI ratio was lower, as increases in productivity allowed less intensive management to meet biomass demands. The magnitude of the differences in utilization, however, were smaller than changes in biophysical potentials due to demand-side limitations on the former.

The rotation lengths were also dependent on the climate scenario and forest sector developments. The average rotation length increased from approximately 85 years in 2020 to 90 years by 2070. Despite the increase in demands, rotation lengths increased slightly along the simulation period, since the intensively managed area expanded by 12 million ha (on average), and increases in productivity sufficed to satisfy the additional demand. By 2040, the intensively managed area ranged from 70 to 72 million ha across climate scenarios, while the same figure for the reference scenario amounted to 68 million ha. Rotation lengths decreased in scenarios with higher productivity up to 2040, with a reversal of this trend afterward. Less favorable climate scenarios with higher temperatures and lower precipitation (e.g., RCP70_UKESM1-0-LL) displayed rotation lengths longer than in the reference scenario.

Regional changes in forest management and forest profitability

The regionally divergent impacts of climate cascaded to forest management decisions. Breaking down the EU level results to the corresponding regional effects, we observed a higher utilization rate (felling-to-NAI ratio) in central-eastern Europe and northern Europe, while Mediterranean countries displayed lower utilization (Figure 3). For Portugal, however, utilization rates were comparable to those of central European countries, likely due to the high management intensity in Eucalypt plantations in the country. By 2040, climate mitigation targets, along with the growing demand for biomass, became the main drivers of changes in utilization rates, necessitating an increase in management intensity (evidenced by the peak in harvesting until 2040 and subsequent decline in harvesting levels). The utilization patterns observed by 2070 were similar to 2040 for the reference scenario. However, lower subnational differences in utilization rates occurred, with a slight increase in utilization rates for Mediterranean areas, while deintensification was observed in Baltic countries.

Most EU countries displayed a reduction in the felling-to-NAI ratio due to the increases in forest productivity and managed forest area. For RCP2.6, changes in felling-to-NAI ratio ranged from −32% to 27% compared to the reference by 2040. RCP7.0 showed changes in utilization rates ranging from −28% to 46%. For both scenarios, countries in northern and central Europe displayed a stronger decrease in utilization rates, while countries in the Mediterranean and south-eastern Europe displayed similar or increase in utilization rates, reflecting the patterns of biophysical impacts (i.e., increase in utilization rates in areas with a decrease in productivity). By 2040, changes in utilization rates were similar for both RCPs, while by 2070, the higher increase in productivity, due to CO_2 fertilization, led to stronger reductions in utilization rates for RCP7.0 compared to RCP2.6 (with 7.5% lower utilization rates on average).

Rotation ages also responded to climate mitigation policies and climate scenarios, albeit the magnitude of the responses was lower compared to the utilization rates (Figure 4). Rotation ages ranged locally from 44 to 303 years by 2040 and from 43 to 255 years by 2070, with an average value approaching 90 years for both cases. The lowest rotation ages were observed in Portugal and Spain, where short-rotation plantations are more common, with a gradient of increasing rotation toward northern Europe. In Finland and Sweden (75–108 years), as well as montane areas in central Europe (especially eastern Germany and Czechia), rotation lengths exceeded 100 years (ranging from 67 to over 200 years). Slight increases in rotation lengths were observed from 2040 to 2070, with the most pronounced increases in northern France and northern Germany. Exceptions were observed in Czechia and northern Italy, where rotation lengths were shortened by 2070.

Changes in rotation length at the country level due to climate impacts ranged from −6.4% to 6.9% by 2040 and from −7.9% to 24.9% by 2070. By 2040, the responses across RCP scenarios remained similar, mirroring the patterns observed for utilization rates. Biomass demand driven by climate goals influenced both management intensity and rotation length, leading to a decrease in rotation length between 2030 and 2040, followed by an increase toward 2070. Wood and bioenergy demand by 2040 were mostly fulfilled by adjusting utilization rates rather than rotation length. By 2070, climate change impacts asserted a stronger influence on the rotation age. For most countries, an increase in rotation length was observed, especially in the montane forests of central Europe. Nevertheless, countries with stronger positive impacts on forest productivity showed a reduction in rotation length, particularly Finland, Sweden, and Ireland, where it decreased by 2%, 3%, and 7%, respectively. Moreover, divergent responses to the RCP considered occurred for eastern European countries (e.g., Slovakia, Poland, and Romania), where more intense climate change in RCP7.0 led to a decrease in rotation length, while the opposite trend occurred under RCP2.6.

The adaptation of forest management and changes in forest productivity influenced the economic output of forest management. Figure 5 displays the net present value (NPV) for the period 2030–2070. The average NPV in managed forest areas for the reference scenario amounted to €4,479/ha, while climate change scenarios induced a reduction in NPV for managed forests, which ranged from €4,068/ha to €4,461/ha on average at the EU level. In general, scenarios with sharper increases in forest productivity showed stronger NPV losses due to a decrease in local wood prices. Moreover, similar profitability patterns were observed between RCP2.6 and RCP7.0, where the latter scenario displayed marginally lower average profitability (€4,251/ha compared to €4,261/ha for RCP2.6).

When examining the regional differences in changes in forest profitability under climate change, most countries experienced a decrease in NPV. Despite the increase in productivity in Finland and Sweden, the feedback with wood markets caused a reduction in wood prices. For Sweden, the baseline NPV amounted to €3,076/ha and ranged between €2,675/ha and €2,998/ha, depending on the climate trajectory, while in Finland it ranged between €2,349/ha and €2,606/ha, compared to €2,573/ha at the baseline. Similar patterns were observed in the Baltic region (e.g., Estonia and Latvia), although lower reductions in wood prices occurred in these areas. In the Mediterranean region, e.g., Spain and Croatia, moderate increases in profitability occurred, mainly driven by the increase in wood prices in the region in the face of increasing demand and decreasing harvesting levels. In these areas, however, the baseline NPV was lower than the EU average. For example, the baseline scenario in Spain displayed an NPV of €722/ha, whereas it ranged between €679/ha and €823/ha when climate change scenarios were considered.

DISCUSSION

We have deployed an integrated modeling framework to compute climate change impacts on forest management decisions in Europe, considering feedback to wood markets. Our results show that climate impacts will have heterogeneous implications for forest productivity, requiring tailored management solutions to satisfy future biomass demands for material use and for bioenergy.

Climate change impacts

The productivity estimates for the reference period, with a GPP of 1,108 gC/m^2/year and NPP of 475 gC/m^2/year, align with existing literature values. GPP estimates range from 899 to 1,199 gC/m^2/year, while NPP estimates range from 439 to 574 gC/m^2/year.[28] Our results show a modest increase in forest productivity and harvesting rates in future climate scenarios; however, this trend was negated when the effects of CO_2 fertilization were excluded. These results are in line with previous studies analyzing climate change impacts on European forests. Reyer et al.[21] used the process-based model 4C to evaluate changes

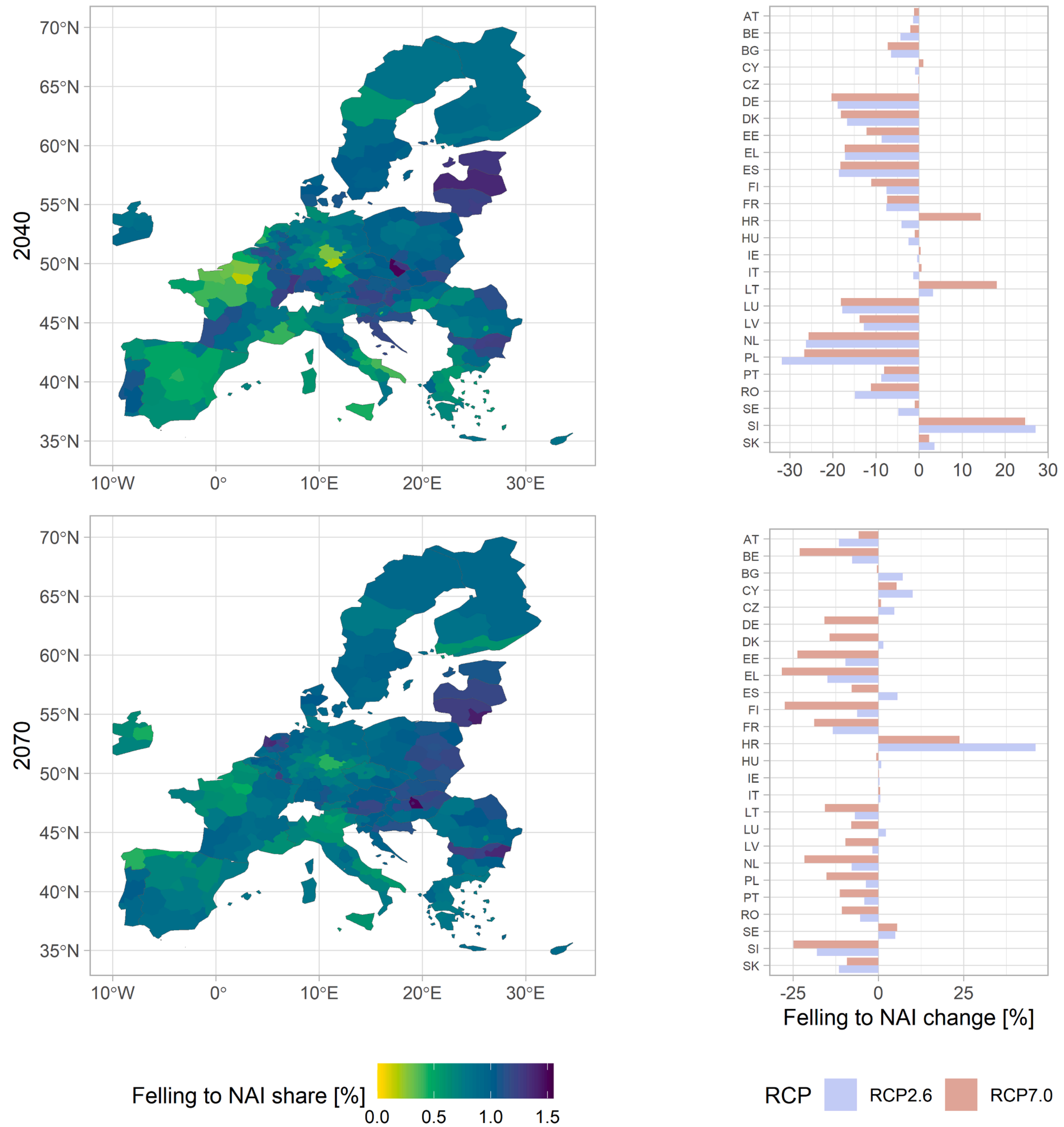

Figure 3. Regional changes in utilization rates, expressed as the felling-to-NAI ratio

The left plots show the spatial patterns of utilization rates for the EU countries in 2040 and 2070, and the right barplots show the corresponding relative changes compared to the reference scenario, according to the climate scenario. NAI, net annual increment.

in forest NPP in a series of climate change scenarios and reported increases of 0.6 to 1.2 tC/ha/year, depending on the region. In contrast, when assuming acclimation to atmospheric CO_2 concentration, the estimated changes ranged from −0.3 to 0.3 tC/ha/year. Gregor et al.[25] also reported similar patterns with carbon stock gains along the 21st century and an increase in NPP, especially in the boreal zone. We observed a gradient of changes in forest productivity under future climate from north to south, where boreal forests displayed increases in productivity in future climate, and Mediterranean forests displayed the opposite trend. Bussotti et al.[29] highlighted the same effects of climate change in European forests, with increasing productivity in the boreal zone and a decrease in productivity in southern Europe.

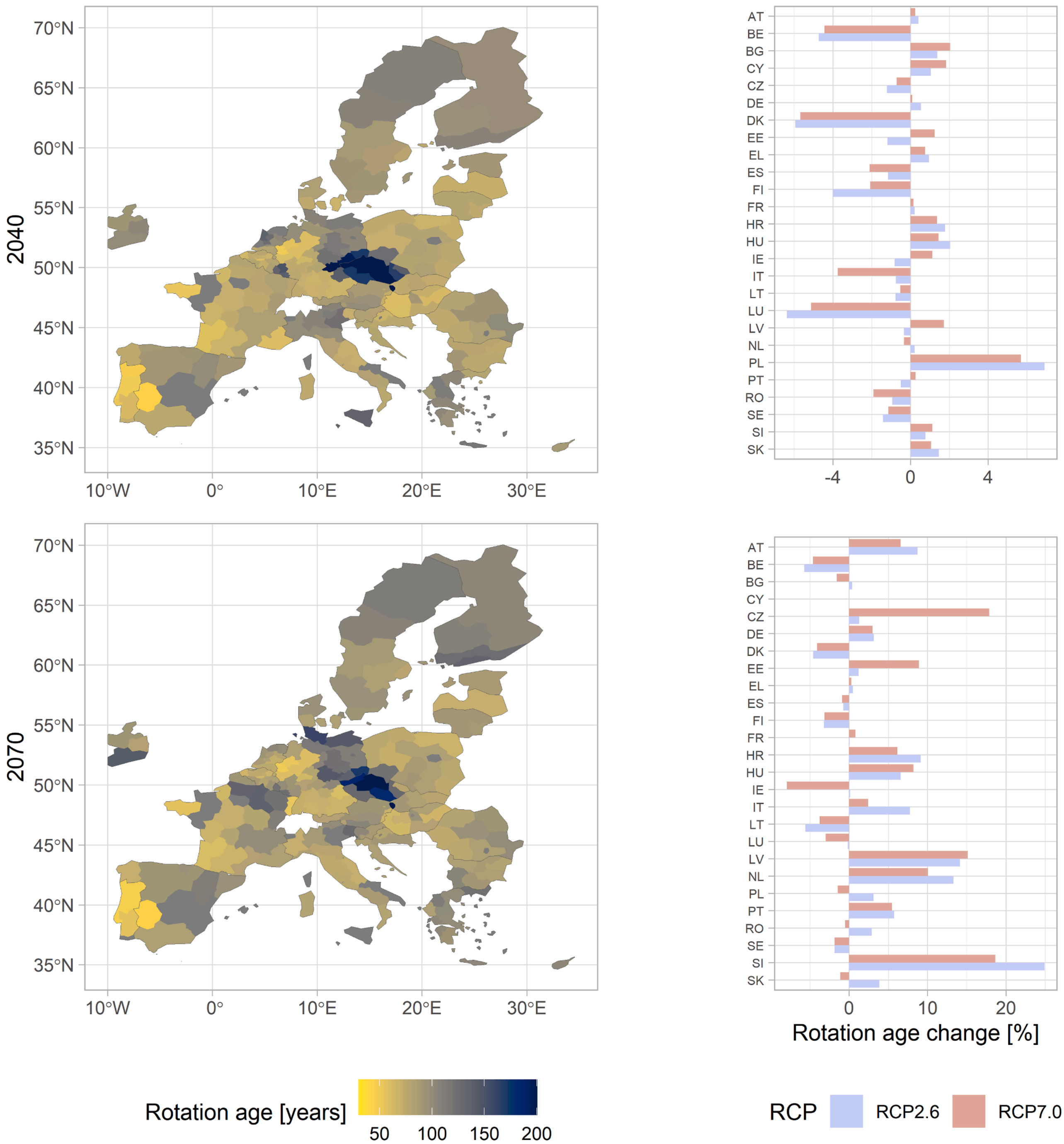

Figure 4. Regional changes in rotation age

The left plots show the spatial patterns of rotation age for the EU countries in 2040 and 2070, and the right barplots show the corresponding relative changes compared to the reference scenario, according to the climate scenario.

Kalliokoski et al.[30] also reported a predicted increase in forest productivity in Finland due to climate change. Additionally, the authors point out a GPP increase of up to 30% by the end of the century in more intense climate change scenarios due to CO_2 fertilization. Maroscheck et al.[31] observed increases in increments and growing stocks in mountain forests in central Europe due to climate change effects. The authors point out, however, that disturbances (bark beetles) are also expected to increase substantially with higher warming. These patterns are also corroborated by Dobor et al.,[32] who analyzed the recovery of disturbed landscapes under climate change in a forest landscape in Slovakia. The deterioration of growing conditions for Mediterranean forests is also well documented. For example, Peñuelas et al.[33] reported a decrease in carbon stocks in these

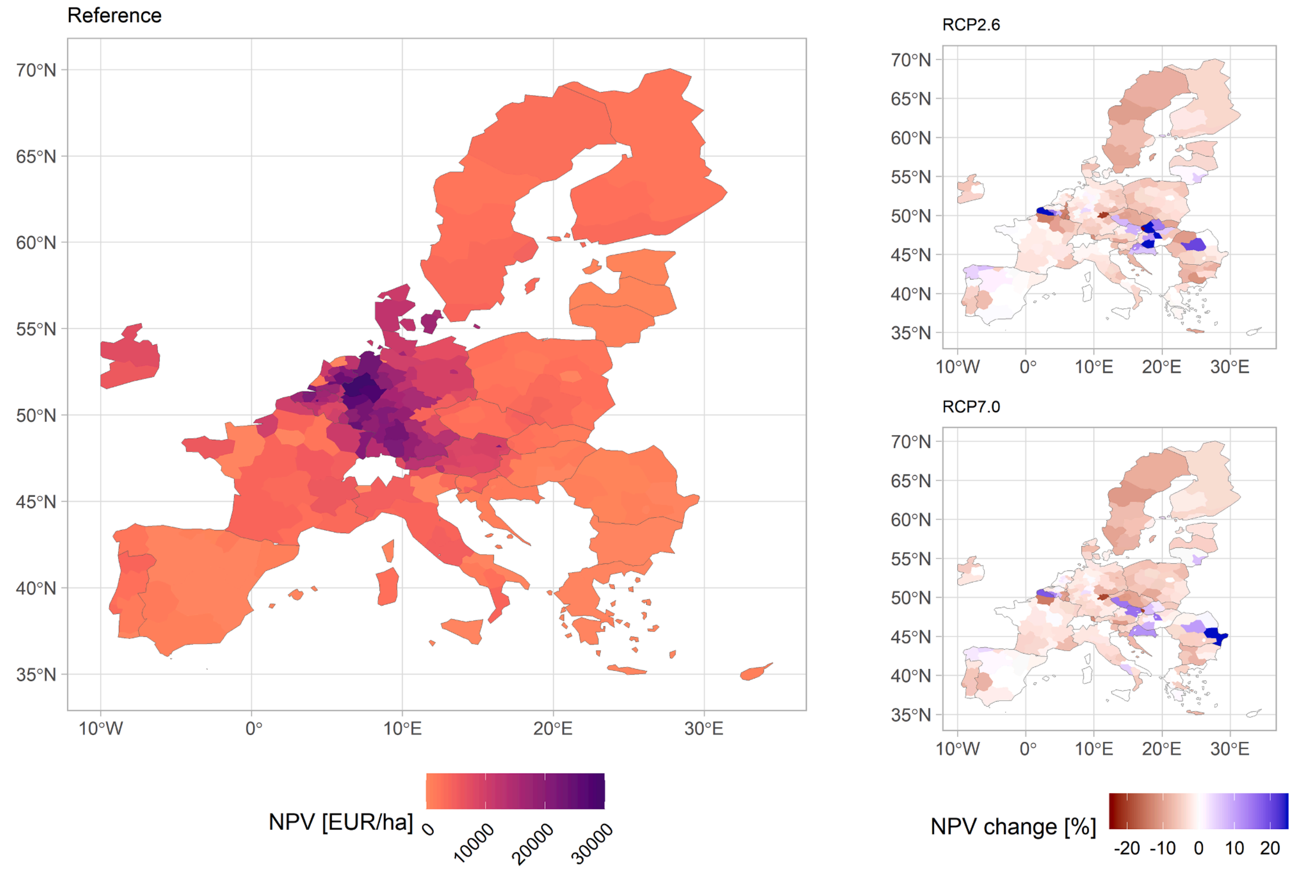

Figure 5. Regional changes in economic output of forest management, in terms of the net present value

The left plot shows the spatial patterns of net present value (NPV) for the EU countries, and the right plots show the corresponding relative changes compared to the reference scenario, according to the climate scenario.

areas despite an increase in GPP due to CO_2 fertilization under climate change, resulting from increases in maintenance respiration rates.

In this context, additional adaptive management alternatives may become increasingly important, especially regarding the implementation of resilience-oriented forest stewardship in the face of increasing disturbance activity. The promotion of mixed forest stands, conversion toward species adapted to future climate, and expansion of continuous cover forestry have been proposed to cope with climate change impacts in Europe.[16] Thus, these management strategies deserve further investigation, particularly considering the costs of admixing or replanting forest stands, thereby highlighting priority areas for investments in forest conversion with the highest possible benefits to climate, biodiversity, and bio-based economy.

Impacts on the forest sink

Our results show a decrease in the magnitude of the forest management sink in Europe toward 2070, reducing from −225 $MtCO_2eq$/year to a range of −231 to −155 $MtCO_2eq$/year by the end of the simulation period. Pilli et al.[26] reported similar patterns, with a decrease in the total European forest sink from −300 $MtCO_2eq$/year in 2020 to −80 $MtCO_2eq$/year by 2100, whereas the sink by 2070 ranged between −300 and −100 $MtCO_2eq$/year due to climate change impacts. The authors highlighted that the loss in the forest sink is mainly driven by the age class dynamics of European forests as well as the effect of forest management. Nabuurs et al.[34] also reported a decrease in increment rates in European forests, attributed to the age class development and the increasing share of mature forests in the region. The maturing of European forests also implies that a larger share of the forest area is reaching the rotation age, and the continuation of current management practices is further increasing removals. A recent increase in harvesting has been observed in the past years in Europe (e.g., Ceccherini et al.[35]), which, combined with the occurrence of natural disturbances, can further contribute to the loss in the forest management sink.

Although CO_2 fertilization may partly counterbalance the loss in the sink for more favorable climate scenarios in the future, the achievement of the forest mitigation targets will require the reversal of the current trend of the EU forest sink.[3] Some levers were proposed in the literature to counterbalance the decrease in carbon sequestration rates in the region. Specifically, the increase in the forest areas through afforestation and restoration, e.g., in abandoned agricultural lands, may contribute to the maintenance of the forest sink in the future. Korosuo et al.[3] emphasized that improved forest management, with better genetic material, fast-growing species, and adequate thinning interventions while observing resilience, can contribute to the enhancement of the forest sink and the achievement of climate targets in the EU. Moreover, the authors point out that a shift in wood use toward more durable products (e.g., increasing wood in the construction sector) and promoting circularity can support the contribution of the forest sector toward climate neutrality in the region. Chakraborty et al.[36] also stressed that assisted tree migration using provenances adapted to future climatic conditions can maintain or even increase the European forest sink in the future.

Changes in forest management and profitability

Our results highlight the need to adapt forest management due to climate change impacts and bio-based economy demands. Areas with increased forest growth displayed a reduction in utilization rates and an increase in rotation length, whereas the opposite trend was observed for regions with a reduction in productivity. Furthermore, in the short term to midterm, the implementation of climate mitigation policies may dominate management decisions to cope with the increasing demand for bioenergy and material wood use, whereas toward the end of the century, climate impacts may become prevalent. In line with our results, Korosuo et al.[3] also suggest that changes in rotation length and utilization rates may play an important role in maintaining the contribution of European forests to climate neutrality.

These management changes, however, must take local conditions into account and consider future risks posed by increased disturbance activity under climate change scenarios, as well as additional adaptation measures. Our results indicate that forests in the Mediterranean generally maintain lower utilization rates, reflecting a focus on a more diversified portfolio of forest values in the region,[37] particularly under the growing pressures of climate change. In this context, the maintenance of ecosystem services provision and biodiversity conservation emerge as key components of management goals.[38] The maintenance of multifunctionality and adaptation in these ecosystems will require management diversification, promoting site-adapted (drought-resistant) species mixtures and applying fire-prevention measures[39,40] in addition to changes in silvicultural regimes. In regions highly vulnerable to disturbances, such as spruce-dominated forests in central Europe particularly susceptible to windstorms and bark beetle damage, more stable species mixtures and modified rotation ages may be necessary to reduce forest exposure under future climate conditions.[41,42] Expanding continuous cover forestry and promoting uneven-aged forests are also seen as important strategies for reducing disturbance damage in these areas.[42,43] In the boreal zone, climate change impacts may increase forest productivity, but adaptive management actions also need to consider the mitigation of risk due to disturbances and maintenance of forest health in the future.[44] Adaptation measures might include adjustments to rotation lengths and utilization rates, expanding continuous cover forestry, fertilization, retention forestry practices, and promotion of mixed forests.[45,46] In addition to local-level actions, landscape-level approaches will be essential. These approaches should include a combination of intensification and extensification areas, based on productivity changes, disturbance risks, and wood demand, to maintain forest multifunctionality.[47]

The increase in disturbance activity and frequency[7] is likely to become a key factor in management decisions in the future. Disturbances can change the assortment structure of wood removals, since salvaged wood typically displays a lower wood quality and produces assortments better suited to energy, pulp, or panel production. Asada et al.[48] show that natural disturbances and the related supply shocks caused a reduction in pulpwood prices and may increase sawlog prices due to shortages of high-quality wood. The increase in long-lasting products to enhance the mitigation potential of the forest sector may need to be accompanied by adaptation not only of forest management but also within the industry to accommodate these lower-quality assortments. For example, the increase in the use of engineered products, such as cross-laminated timber, can make use of lower-quality feedstocks to produce long-lasting products, contributing to the climate mitigation potential of forests. Additionally, the increase in price for higher-quality products can counteract the loss in NPV due to decreased average wood prices.

The NPV of forest management ranged from €313/ha to €20,247/ha at the country level, with an average of €4,479/ha in our results. Forest profitability was highest in central-western Europe and lowest in the Mediterranean and eastern Europe. This is in line with profitability estimates reported in the literature. For example, Pukkala[49] obtained NPVs in Finland ranging from €1,177/ha to €7105/ha. Hanewinkel et al.[50] reported land expectation value for different species groups in Europe ranging from €78/ha to €8,485/ha, depending on the species groups and climate scenario, where broadleaved species groups (birch and oaks) showed the lowest profitability and Norway spruce the highest. Yousefpour et al.[24] and Augustynczik and Yousefpour[51] obtained NPV values ranging from €1,000/ha to €15,000/ha in Europe, depending on the climate scenario considered. The authors also point to higher profitability in central Europe compared to Mediterranean and eastern European countries. This is a result of the low wood prices in the latter region, combined with higher interest rates and lower growth rates.

Concerning the changes in forest profitability, our results show a negative influence of future climate scenarios on forest NPV. This is in line with results obtained by Hanewinkel et al.,[50] who reported a loss in European forestland value, especially due to species range shifts and the expansion of oaks in central Europe. Conversely, studies show that increases in productivity due to climate impacts may increase forest profitability (e.g., Routa et al.[52]). Considering only changes in productivity, however, can mask interactions with wood markets. In our results, the reduction in wood prices due to productivity shocks dominated the NPV response to climate change effects, leading to a reduction in profitability, even in scenarios with increased productivity. Favero et al.[53] pointed to the same patterns in analyzing climate change impacts on global wood markets. The authors highlight that increases in productivity lowered wood prices, leading to increases in welfare for consumers but reducing that of forest owners.

Limitations of the study

One important aspect of the future impacts of climate change not analyzed here refers to changes in species range shifts (e.g., Mauri et al.[12] and Hanewinkel et al.[50]). Dyderski et al.[54] highlight that most late successional species are likely to benefit, in contrast to pioneer species (e.g., spruce and pine) that are predicted to lose habitats. This may have important implications for wood markets, which are currently highly specialized in conifer wood processing and will thus have to adapt to future species mixes. Hence, the results obtained here might be affected by the inclusion of these dynamics, such as a decrease in the conifer forest area and a corresponding decrease in conifer wood availability. This could lead, for example, to an increase in wood prices and forest profitability in Fennoscandia. Moreover, the role of additional adaptive options, such as changes in species composition and expansion of continuous cover forestry, has been suggested as an important adaptation lever and also deserves investigation. It should also be noted that in the long run, with an increase in the share of broadleaved species in the harvesting pool in Europe, the wood price of conifers may increase and counterbalance the profitability patterns obtained. Nevertheless, these effects do not take place at a significant scale within the time frame investigated here, since changes in species composition will be reflected in harvestings when stands are mature.

We assumed that salvage logging from disturbances fully displaced planned harvesting when satisfying country-level wood demands and that damaged areas were fully replanted immediately. In reality, however, harvesting capacity is limited, and the residues and debris after disturbances may delay forest regeneration. Hence, the disturbance impacts simulated here are likely underestimated. Accounting for disturbance feedback may offset productivity gains due to carbon fertilization and transient climate change, which could cascade to forest management decisions, e.g., requiring management intensification to meet the same demands. At the same time, disturbances can have significant impacts on the forest sink and change the contribution of the forest sector to climate neutrality pathways. Furthermore, climate impacts on forest productivity were decoupled from disturbances. Nevertheless, disturbances may alter forest productivity, and these effects deserve closer analysis in future studies.

METHODS

Modeling framework

To address our research questions, we coupled the process-based model i3PGmiX and the GLOBIOM-EU/G4Mm model (https://globiom.org/documentation.html; Kindermann et al.[55]), using a similar approach to that used by Pilli et al.[26] We began by computing changes in forest productivity with i3PGmiX under different climate change scenarios. For each scenario, changes in forest growth and carbon stocks were assessed in comparison with a baseline scenario, considering historical climate. These changes in forest productivity, which act as supply shocks, were then integrated into GLOBIOM-EU/G4Mm by shifting internal forest growth functions and stocks (represented in these models by the MAI) and computing the corresponding changes in optimal forest management and wood markets (Figure 6).

i3PGmiX

The IIASA-3PGmix-X (i3PGmiX) model is a further development of the 3PGmix model (Forrester and Tang[56] and Trotsiuk et al.[57]), which implements enhancements to several forest processes to improve the climate sensitivity and the representation of the carbon and nitrogen balance in vegetation and soil (Table 1).

i3PGmiX is a reduced-complexity process-based model that simulates stand productivity based on the absorbed photosynthetically active radiation (APAR) and canopy quantum efficiency. The APAR is defined based on the incoming radiation, the stand canopy architecture, and the stand leaf area index (LAI), applying the Beer-Lambert law. The model employs the light interception module from 3PGmix, which allows for the simulation of mixed forest stands and more complex forest structures, such as multilayered canopies. LAI is determined based on the specific leaf area of each species and the corresponding foliage biomass, where the LAI varies with stand age. The canopy quantum efficiency is constrained by several environmental conditions, including water availability, stand age, and soil fertility (Almeida et al.[58]).

The GPP is calculated based on the optimality-based Farquhar-von Caemmerer-Berry (FvBC) models of photosynthesis P-model[59] or Phydro-model.[60] The P-model computes optimal leaf internal to ambient CO_2 ratios to balance the costs of maintaining carboxylation and transpiration, while the Phydro model is a further development of the P-model framework, integrating a complete coupling of plant and soil water demands to compute optimal assimilation rates. The NPP is then obtained by deducting maintenance and growth respiration from GPP. Growth respiration is calculated as a fixed fraction of the assimilation, and maintenance respiration is a function of fine roots and sapwood biomass, the nitrogen content of the different tissues, and temperature (air temperature for sapwood and soil temperature for fine roots), following Collalti et al.[61] After the computation of the NPP, the carbon allocation routine follows, partitioning carbon to root, foliage, and stem biomass. The partitioning routine prioritizes the allocation to roots, which is controlled by the local growing conditions, where less favorable sites induce more allocation to roots. The allocation to foliage and stems follows, maintaining the balance between the growth of the compartments.

i3PGmiX includes a competition-driven mortality submodel following the −1.5 self-thinning law (as in 3PGmix) and alternative algorithms to compute stress mortality, namely: (1) the survival probability curves developed by Brandl et al.[62] that yield the mortality probability depending on the species group and species-specific climatic parameters; (2) the growth efficiency approach developed in the LPJ-GUESS model (Smith et al.[63] and Hickler et al.[64]), where the mortality probability is computed based on the ratio between NPP and LAI; and (3) the approach used in the iLand model (Seidl et al.[65]), based on a stress index given by the ratio between NPP and turnover from foliage and fine roots. Further losses are triggered by management interventions (thinning and final harvesting operations) and natural disturbances from wind, based on the ForestGALES-TMC model (Gardiner et al.[66] and Hale et al.[67]) and bark beetle, based on the LandClim model (Temperli et al.[68]).

The model also includes a soil-water balance submodel, describing the water availability based on the initial soil water, monthly precipitation, evaporation, transpiration snowfall, and snowmelt. Transpiration is calculated based on the Penman-Monteith equation; the evaporation accounts for the water interception by the canopy.[69]

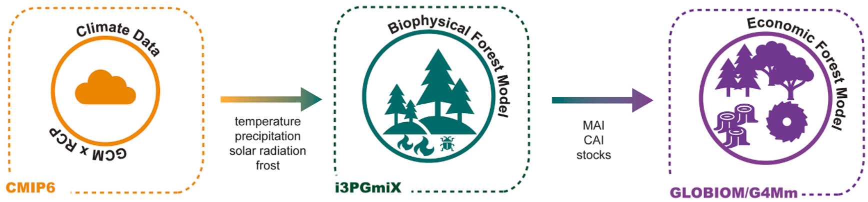

Figure 6. GLOBIOM-EU/G4Mm-i3PGmiX modeling framework

The schematic shows the workflow to account for climate impacts on the forest sector. Initially, climate forcing data are used to drive the simulations of the biophysical mode i3PGmiX. Changes in forest productivity and stocks are converted to growth shifters and applied in GLOBIOM/G4Mm to derive the impacts on wood markets and forest management decisions.

Soil carbon and nitrogen dynamics are modeled through coupling with the ICBM/2N and Yasso20[70] soil models. Following Xenakis et al.,[71] the ICBM/2N soil module takes as input litter and coarse wood debris (CWD) from i3PGmiX, resulting from mortality, litter turnover, and harvesting residues. The plant available N resulting from the soil model can also be employed to limit forest productivity, based on the unstressed N demand given by the increments of different compartments (foliage, roots, stems, and branches) and their N concentration. The coupling with Yasso20 follows a similar rationale, with the inputs to the model given by the litter and CWD, but with differentiation between branches and stems for the CWD pool and the partitioning of these inputs into the Yasso20 pools (sugars, celluloses, wax-like compounds, and lignin-like compounds). This allows the computation of C and N dynamics as well as the net ecosystem exchange (NEE) in the model. A summary of the main model developments implemented in i3PGmiX is provided in Table 2, and a detailed description is given in the supplemental information.

GLOBIOM-EU/G4Mm

GLOBIOM-EU/G4Mm consists of two iteratively linked models, GLOBIOM-EU and G4Mm. The Global Biosphere Management Model (GLOBIOM) is a global recursive dynamic partial equilibrium model of the forest and agricultural sectors. The model is based on a bottom-up approach whereby the supply side of the model is built up from the bottom (land cover, land-use, and management systems) to the top (production/markets). The GLOBIOM-EU model is directly derived from the GLOBIOM model, containing more data and details that facilitate a more refined simulation of European land-use, with a main focus on the estimation of LULUCF emissions and removals.

The model has a detailed supply-side representation, built around simulation units—aggregates of 5–30 arcminute pixels that share similar altitude, slope, and soil characteristics, aligned with country borders. For EU countries (except Croatia, Cyprus, and Malta), the spatial representation begins at 1 $\times$ 1-km pixels, which are aggregated to the NUTS2 level in the model implementation. For crops, livestock, and forest products, spatially explicit Leontief production functions are parameterized using biophysical models such as the Environmental Policy Integrated Climate Model (EPIC) and the Global Forest Model (G4M). Demand and international trade occur at the regional level (58 regions), covering all 27 EU member states and 31 regions in the rest of the world. Agricultural and forest biomass demand for non-energy use is exogenously determined by population and GDP growth over time and endogenously by price responses. Bioenergy demand is exogenously introduced into the model. For the agricultural sector, income elasticities are calibrated to mimic anticipated Food and Agricultural Organization (FAO) projections of diets.[72] Income elasticities for the forest sector are taken from Buongiorno et al.[73] and Buongiorno.[74] Price elasticities for agricultural commodities are taken from a global database from the US Department of Agriculture[75] and for the forest sector from Buongiorno et al.[73] and Buongiorno.[74]

The model computes a market equilibrium for agricultural and forest products by allocating land-use among production activities to maximize the sum of producer and consumer surplus, subject to resource, technological, demand, and policy constraints. The level of production in a given area is determined by the agricultural or forestry productivity in that area (depending on suitability and management), by market prices (reflecting the level of demand), and by the conditions and costs associated with land conversion, to expansion of the production and, if relevant, to international market access. Trade is modeled following the spatial equilibrium approach,[76] which means that the trade flows are balanced out between different specific geographical regions. Trade is based on cost competitiveness, and goods are assumed to be homogeneous. This approach allows the tracing of bilateral trade flows between individual regions.

Woody biomass production costs in GLOBIOM cover both harvest and transportation costs. Harvest costs for forests are based on the G4Mm model using spatially explicit constant unit costs that include planting, logging, and chipping in the case of logging residues. Harvest costs also vary depending on geographical considerations such as the region and the steepness of terrain. Markets for seven semi-final forestry products (chemical pulp, mechanical pulp, sawnwood, plywood, fiberboard, other industrial roundwood, and household fuelwood) are represented in the model. Demand for the various products is modeled using regional-level constant elasticity demand functions. Forest industrial products (chemical pulp, mechanical pulp, sawnwood, plywood, and fiberboard) are produced by Leontief production technologies, whose input-output coefficients are based on the engineering literature (e.g., FAO[77]). By-products of these technologies (bark, black liquor, sawdust, and woodchips) can be used for energy production or as raw materials for pulp and fiberboard. Initial production capacities for forest industry final products are based on production quantities from FAOSTAT (2000–2010–2020). After the base period, the capacities evolve according to investment dynamics, which depend on depreciation rate and investment costs.

G4Mm is spatially explicit and runs on a 0.5° $\times$ 0.5° resolution. It estimates the impact of forestry activities (forest management, biomass harvest, afforestation, and deforestation) on carbon stocks. By comparing the net present value of managed forests (revenues from selling wood and storing carbon in forests) with income from alternative land-use in the same place, a decision on afforestation or deforestation is made. Deforestation does

Table 2. Summary of the main improvements implemented in the i3PGmiX model

Processes	Model variable	Description of model enhancements
Photosynthesis	GPP	coupling with Farquhar-von Caemmerer-Berry models of photosynthesis (P-model and Phydro-model)
Autotrophic respiration	NPP	explicit computation of maintenance and growth respiration, with climate-sensitive respiration rates for each compartment (foliage, fine roots, and sapwood)
Soil processes	soil carbon and soil nitrogen stocks and fluxes	coupling with the ICBM/2N model and the Yasso20 soil models
Water balance	ASW	inclusion of the snow water storage and snowmelt processes, and derivation of the soil matrix potential for coupling with the Phydro-model
Forest management	management mortality	forest management routines were extended to include the computation of thinning targets based on the basal area or volume of the stands. Additionally, routines for computing crop tree parameters and automated final harvesting and regeneration were included
Mortality	natural mortality	inclusion of three alternative climate-sensitive routines for natural mortality computation
Forest disturbances	disturbance mortality	coupling with the wind disturbance and impact model ForestGales-TMC and a bark beetle module based on the LandClim model

not take place in areas under some form of protection, such as Natura2000 sites, primary forests, or old-growth forests. The model simulates wood production to meet exogenous wood demand at the country scale. The model incorporates empirical forest growth functions for major tree species groups, which are calculated for different levels of MAI. Since the model does not represent either forest markets or other economic sectors, it relies on information from other sources (GLOBIOM or other databases) for the development of wood prices, land rents, urban sprawl, and other land-use drivers. Similarly, information about natural disturbances is exogenously input to the model. As outputs, G4Mm produces estimates of forest-area change, carbon sequestration and emissions in forests, impacts of carbon incentives (e.g., avoided deforestation), supply of biomass for bioenergy and timber, and the corresponding management regimes.

GLOBIOM-EU and G4Mm are run sequentially. As a first step, G4M provides data on harvest potentials, productivity, and costs for the forest sector, which are used in GLOBIOM-EU to parameterize the model. Building on this information, GLOBIOM-EU is then solved for a specific scenario until the year 2070. The market solution determines the amount of harvested wood as a result of the interplay between demand and supply. The derived harvest from GLOBIOM-EU is subsequently communicated to G4Mm, which uses the harvests as an exogenous constraint that needs to be fulfilled. Furthermore, GLOBIOM-EU provides data on agricultural and wood prices to G4Mm. Based on these parameters, G4Mm simulates forest management decisions, afforestation, and deforestation activities and estimates the respective emissions and impacts on the forest structure.

Simulation setup

Climate data

To capture the uncertainty in future climatic conditions, we ran our simulations under a set of different climate change scenarios (Table 1). We employed bias-corrected climate data from ISIMIP (https://protocol.isimip.org/), based on CMIP6 climate data. In our design were monthly projections of temperature (minimum, maximum, and average), precipitation, and solar radiation, and we derived the number of frost days based on the minimum temperature (using a 0°C threshold) and the corresponding atmospheric CO_2 concentration for RCPs 2.6 and 7.0, representing a low-emission scenario and a reference medium- to high-emission scenario, respectively. We employed the results from four GCMs, namely GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, and UKESM1-0-LL. The choice of GCMs was conducted to cover the range of variation of GCMs in the available climate data and following the ISIMIP protocol, where UKESM and IPSL represent hotter models, whereas GFDL and MPI project milder climate for Europe.

Socioeconomic data and bioenergy demand

The socioeconomic conditions and forest sector development until 2070 for each scenario were quantified based on the GLOBIOM-EU model. These socioeconomic developments are based on inputs from the Aging Report 2021 for GDP growth and Eurostat's population projections. Biomass demand from the energy sector follows the decarbonization scenario S2 in EC.[27]

Forest management decisions

Forest management decisions were assessed in the G4Mm model according to the procedure described by Gusti.[78] For each grid cell, the model adjusts the rotation length and the stocking degree (thinning intensity) across age classes. Management decisions are driven by the wood demand at the country level, wood prices, and CO_2 prices, and implicitly by profitability of alternative land uses (agriculture), which determine land-use change decisions (afforestation or deforestation). G4Mm adjusts the forest management to match the country-level wood demand, prioritizing harvesting in the initialized locations and in areas with higher productivity, larger forest area, and closer to consumption hubs in an iterative manner, based on the NPV for each grid cell. The spatial allocation of wood production is initialized to the map by Verkerk et al.[79] A forest management decision in every cell is adopted if it brings country wood production closer to the demand and the new forest management does not lead to a significant loss of NPV. The NPV is compared to the NPV under previous forest management or maximal NPV in the case of carbon sequestration policy. In the case of active carbon sequestration policies, G4Mm finds optimal rotation that maximizes NPV under given wood and CO_2 prices. The dynamics of wood demands and wood prices, used for the NPV computation, are informed by GLOBIOM-EU.

Here, we investigate changes in the main complementary management parameters adapted in the model, namely the rotation age and the felling to net annual increment ratio. The former parameter indicates strategic responses of forest management in the mid to long term, while the latter is the main lever in the short term, also acting as a key sustainability indicator of forest management.[80]

Natural disturbances

Natural disturbances were included in the G4Mm model to assess their impacts on the forest age class distribution and harvesting rates. To this end, we have combined the results from Seidl et al.[10] and Patacca et al.[8] on the disturbance rates for wind, bark beetles, and wildfires in Europe with the vulnerability maps from Forzieri et al.[81] to allocate the different disturbance agents spatially. The total disturbance volume computed for each grid cell was then removed from the standing stock in G4Mm, mimicked by final harvestings. A share of this disturbed volume was salvaged (the shares depending on the disturbance agent and country) and displaced planned harvestings when fulfilling country-level wood demands. Protection targets were also implemented in G4Mm, where 10% of the forest area was set aside by 2030, with further restrictions on the expansion of the managed forests applied to 20% of the area, resulting in 30% of the forest area under some level of protection. The expansion of protected areas was prioritized in old-growth forests and primary forests identified by Sabatini et al.[82]

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Andrey Lessa Derci Augustynczik (augustynczik@iiasa.ac.at).

Materials availability

Additional information can be found in supplemental methods.

Data and code availability

The code for the i3PGmiX model is available at: https://github.com/iiasa/i3PGmiX. Climate and initial vegetation data used in this study are publicly available from the references.

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AUTHOR CONTRIBUTIONS

Conceptualization and methodology, A.L.D.A., M.G., and A.D.; investigation and writing – review & editing, A.L.D.A., M.G., A.D., M.N., F.J., F.d.F., and P.H.

DECLARATION OF INTERESTS

The authors declare no conflicts of interest.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work the authors used generative AI to perform a language revision on the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

SUPPLEMENTAL INFORMATION

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