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Climate targets in European timber-producing countries conflict with goals on forest ecosystem services and biodiversity

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The European Union (EU) set clear climate change mitigation targets to reach climate neutrality, accounting for forests and their woody biomass resources. We investigated the consequences of increased harvest demands resulting from EU climate targets. We analysed the impacts on national policy objectives for forest ecosystem services and biodiversity through empirical forest simulation and multi-objective optimization methods. We show that key European timber-producing countries – Finland, Sweden, Germany (Bavaria) – cannot fulfil the increased harvest demands linked to the ambitious 1.5°C target. Potentials for harvest increase only exists in the studied region Norway. However, focusing on EU climate targets conflicts with several national policies and causes adverse effects on multiple ecosystem services and biodiversity. We argue that the role of forests and their timber resources in achieving climate targets and societal decarbonization should not be overstated. Our study provides insight for other European countries challenged by conflicting policies and supports policymakers.

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The global warming level of 1.5°C will be beyond reach in the next decades unless there are immediate and large-scale reductions in greenhouse gas (GHG) emissions[1]. To mitigate climate change, several European countries have committed to reduce 55% of GHG emissions by 2030 compared to 1990 values, and to become climate neutral by 2050[2,3].

Forests provide an important contribution in achieving GHG reduction targets due to their potential to be a natural carbon sink and provide timber for material and bioenergy resources[4–6]. From the policy side, the LULUCF regulation poses the basis for accounting the mitigation efforts of forests[7]. Dampening climate change thus can be impacted by the way how forest resources are utilized[8–12]. However, the question arises if acknowledging timber resources to meet mitigation targets, also driven by bioeconomy policies[13], leads to further increased harvesting in forests. Recent scientific evidence suggests that such an increase in harvest has already happened in Fennoscandian forests[14,15], supported also by forest statistics showing an increase in roundwood production[16].

Increased forest resource demands escalate pressures on forest ecosystem services and biodiversity[17–20]. The climate change mitigation policies may thus interact with goals from other policy domains, such as the EU Biodiversity Strategy[21] or the EU Forest Strategy[22], both emphasizing the importance of forest conservation and the multifunctional role of forests. Those policy domains are usually operationalized nationally reflecting the countries' priorities placed on forests[23]. However, conflicts among policy strategies related to wood harvest and mobilization are usually not openly addressed[24,25].

Therefore, it is uncertain whether targets from different policy domains are aligned, and to which extent forests can actually fulfil multiple forest ecosystem services and biodiversity (FESB) demands under the climate change mitigation targets. A comprehensive assessment of the pressures on forest multifunctionality caused by climate change mitigation targets and its related timber demands is still missing[4,22]. This lack of information poses challenges in the public debate but also for sustainable forest management that aims to balance multiple and divergent policy objectives and to find climate-smart-forestry approaches[26,27].

We investigated the following research questions: (i) How will EU climate change mitigation targets impact future harvests to satisfy timber demands? (ii) How consistent are EU mitigation targets with national policies guiding demands for FESB? (iii) Which are the optimal forest management programs achieving the divergent policy objectives? (iv) What is the impact on FESB if EU mitigation targets must be achieved?

Our study comprised Fennoscandia and the temperate region of Germany (Bavaria) (Fig. 1), important timber production regions together contributing 29% of the European roundwood production[16]. First, we used empirical models to simulated forest dynamics and management under climate change and to gain information on the future provision of FESB. Second, we modeled the future harvest demands related to EU mitigation targets using the global forest sector model GLOBIOM. Third, we elaborated the demands for FESB of three national policy domains. Fourth, we resolved the optimal forest management programs for national and EU policy targets by using the method of multi-objective optimization: in a bottom-up approach we optimized for FESB demands of national policy domains, and in a top-down approach we prioritize harvest demands of EU mitigation targets above national policy demands during the optimization. Finally, we quantified the coherence between national- and EU-level policies by comparing the outcomes of the two optimization approaches in terms of: (i) their capacity to reach harvest demands related to EU mitigation targets, (ii) change in the composition of optimal management programs (a combination of management regimes), and (iii) change in the provision of FESB.

Results

Harvest demands for climate change mitigation targets. The EU policy targets for climate mitigation were represented as future expected domestic harvests for each study region representing the Nationally Determined Contribution (NDC) scenario aiming for 40% GHG reduction by 2030, and a scenario aiming for climate neutrality by 2050 and limiting temperature change to 1.5 °C (1p5). The highest harvest demands were forecasted under the 1p5 scenario following the current climate trajectory (representative concentration pathways RCP1.9). It suggests increases in harvests ranging from 38% in Sweden, to 85% in Norway by the end of the century (Fig. 2a). Under the NDC scenario, following the RCP4.5 trajectory, increases in demands were more modest, ranging from 22% in Sweden to 37% in Bavaria.

The highest overall demands were forecasted for Sweden and Finland, with levels more than twice as high as Bavaria and Norway. However, for Bavaria harvest demands per hectare were threefold higher than for Finland and Sweden and even fourfold higher than for Norway (Fig. 2b). Concerning assortments, sawlogs were mainly demanded from the temperate region, and medium-sized assortments of pulp- and fuelwood from the boreal regions (Supplementary Fig. 1).

Management for national policy demands (Bottom-up). In the case of Finland, Sweden, and Bavaria, harvest demands representing the mitigation target 1p5 were not met when optimizing for FESB demands of national policies (Fig. 3a). While the mismatch was strongest for the biodiversity strategies (BDS), even the scenarios for the national forest strategy (NFS) and the bioeconomy strategy (BES) failed to achieve all demands. In Norway, all of the demanded timber assortments required at the 1p5 target were delivered under the NFS (Fig. 3a). Under the NDC mitigation target, the national policy scenarios neared harvest demands in Finland and Bavaria and met demands under the BES in Sweden and under the NFS and BDS in Norway. In contrast to the other study regions, the BES scenarios of Norway provided the lowest harvest (Fig. 3b).

Gaps between demand and potential supply existed for the assortments pulp- & fuelwood and residues in Finland, as well as pulp- & fuelwood and sawlogs in Bavaria. In Finland, the overproduction of sawlogs could be used to alleviate the gaps. In Sweden, the NFS and BDS provided too low sawlog volumes to meet the NDC mitigation target. Under the 1p5 scenario, only residues and pulp- & fuelwood were sufficiently provided by the NFS and BES, respectively. The BDS did not provide sufficient volumes of any assortment under the 1p5 scenario (Fig. 3a).

In Finland and Bavaria, the harvests were mainly provided by intensified rotation forestry and continuous cover forestry achieving their largest share of the total harvest under the BDS scenario (Fig. 3b). In Sweden and Norway, the harvested timber was mainly provided by variants of rotation forestry, strongly dominated by the intensified version. Continuous cover forestry played a minor role in the optimal management. The extensified version of rotation forestry was thereby more prominent in Norway and the intensified version in Sweden. In Bavaria under the NFS scenario and in Finland under the BDS and BES scenarios, also the climate adaption regime contributed to timber provisioning.

The forest area set aside for protection, was for all study regions highest under the BDS scenarios with 56% in Finland, 17% in Sweden, 19% in Norway, and 36% in Bavaria. The lowest share of protection was achieved under the NFS scenario in

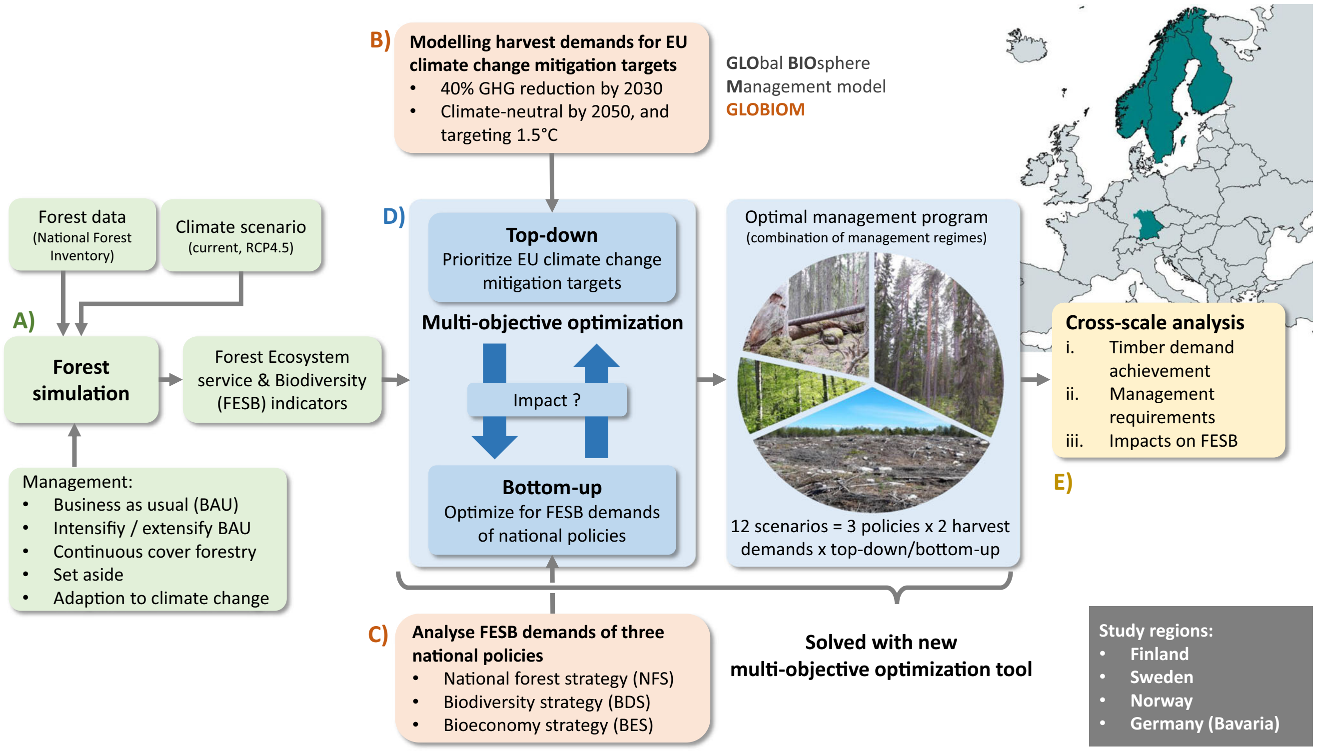

Fig. 1 Data and workflow of the study identically implemented in four European study regions. This included: A) empirical forest dynamics and management simulations to obtain future potentials of forest ecosystem services and biodiversity (FESB) indicators under alternative climate pathways, B) modeling future harvest demand scenarios for EU climate change mitigation policies, C) analyzing national policies for FESB demands, D) optimizing forest management for FESB demands representing national forest policy domains (bottom-up approach), and by prioritizing harvest demands representing EU mitigation targets above national policy domains during the multi-objective optimization (top-down approach), and E) a cross-scale analysis between the EU-level perspective versus the national-level perspective based on the optimized forest management outcomes and its consequences for FESB.

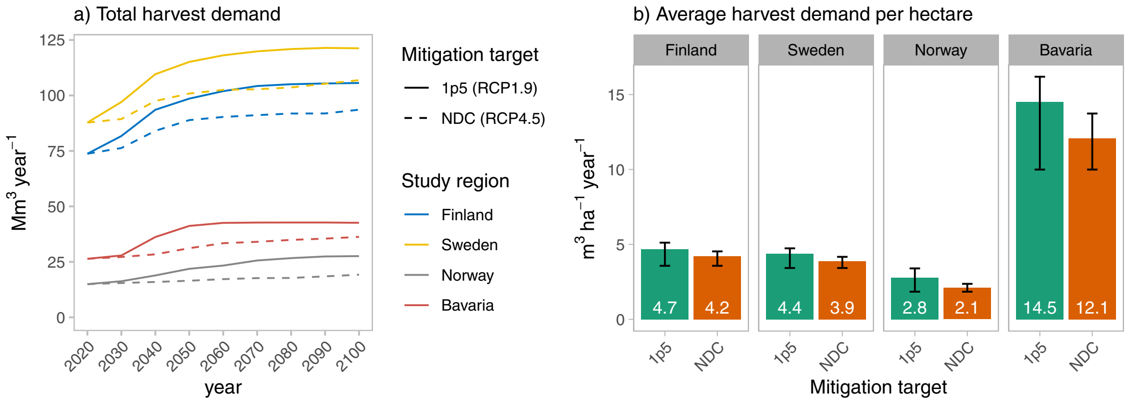

Fig. 2 Expected future harvest demands representing EU policy targets for climate change mitigation. Scenario 1.5°C (1p5) is following the representative concentration pathways RCP1.9, and scenario Nationally Determined Contribution (NDC) is following RCP4.5. **a** shows the total demands over time by study region, and **b** the corresponding average demands per hectare with error bars representing the minimum and maximum value over time (strictly protected areas without management were excluded from per hectare values).

Finland (30%), Sweden (13%), and Norway (5%), and under the BES scenario in Bavaria (~0%) (see Supplementary Figs. 2–5).

Management for EU mitigation targets (Top-down). Harvest demands from the 1p5 mitigation targets could only be achieved in Norway under NFS and BDS, when the EU climate change mitigation targets were prioritized above the FESB demands of national policies (Fig. 4a). Under the lower mitigation target NDC, both Norway and Sweden met the demands for all assortments, when the mitigation target was prioritized. Finland exceeded the demands for sawlog and Bavaria for residues, under both mitigation scenarios. For Finland, this over-production in harvested Sawlogs could be used for filling up gaps of pulp- & fuelwood and residues. For Bavaria, a compensation of the pulp- & fuelwood gaps was not possible (residues cannot be used for its replacement).

The top-down approach led to a harmonization of total harvest levels and management programs among policy scenarios, since targeting the steadily increasing harvest demands were strongly driving the optimizations (Fig. 4b). An exception was Sweden, where the BES, in contrast to the NFS and BDS scenarios, also included intensified regimes with fertilization and exotic tree

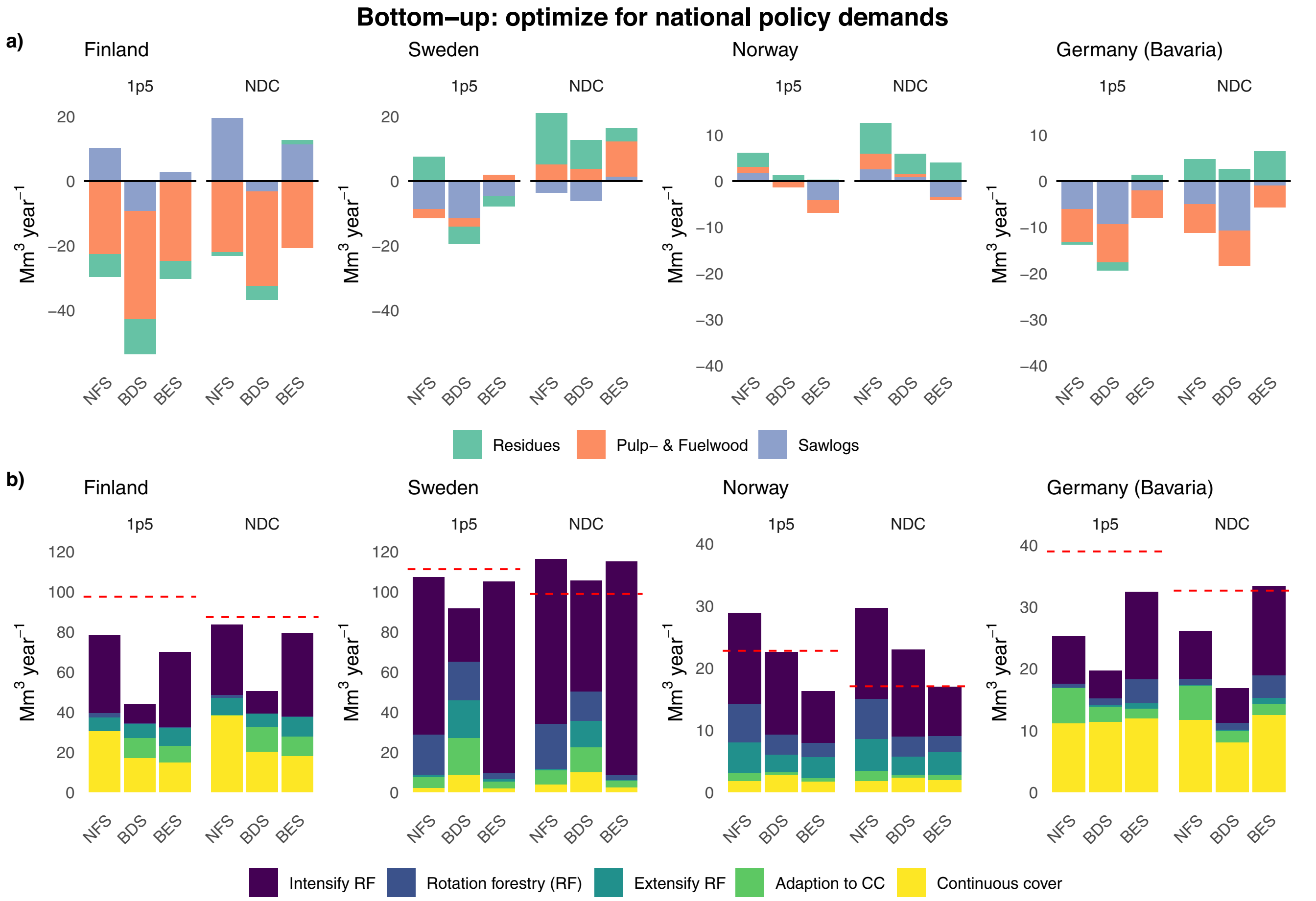

Fig. 3 Bottom-up optimization outcomes for national policy demands of forest ecosystem services and biodiversity. a Difference between harvest demands for EU climate change mitigation targets (1p5 and NDC, see Fig. 2) and forecasted harvests under national policy scenarios by assortments. Bars below the black line indicate that the demand for that assortment is not met (an exceed of sawlogs could be used to alleviate an under-production of pulp- & fuelwood and residues, e.g., Finland). **b** Forecasted harvests by management classes. The bars in both plots, **a** and **b** represent mean values over the planning horizon. The red dashed line in **b** represents the average harvest demand of each mitigation target, NFS stands for national forest strategy, BDS for biodiversity strategy, BES for bioeconomy strategy. Note variable scaling of *y*-axis.

species and therefore delivered almost the entire harvest (Fig. 4b). For Finland and Bavaria, the required harvest demands were mainly provided by continuous cover forestry and intensified rotation forestry. For Sweden and Norway, the main management classes contributing to the harvests were based on rotation forestry practices. Management for climate change adaptation contributed little to the harvests, except for NFS and BDS in Sweden, and NFS in Norway.

The share of set-asides decreased compared to the bottom-up approach and was between 28% and 38% among all scenarios in Finland, between 4% and 17% in Sweden, and 11% and 21% in Norway. In Bavaria, no set-asides were assigned for any scenario under the top-down approach (see Supplementary Figs. 6–9).

Effects on forest ecosystem services and biodiversity (FESB). The provisioning of FESB was overall lower when EU climate change mitigation targets were prioritized over national forest policy demands (Fig. 5). The impact was most negative for ecosystem services not related to timber production and for biodiversity, and vice versa, most positive for the ecosystem services wood and bioenergy. The strong changes were however limited to mostly Finland and Bavaria, while Sweden and Norway were less affected. There were clear exceptions to this general pattern, which are discussed below. Top-down effects on individual indicators used to evaluate FESB are presented in Supplementary Figs. 10–13.

In Finland, the attainment of FESB under the NFS scenario was less affected by EU mitigation targets, as compared to the BDS and BES scenarios (Fig. 5). Timber production targets for the NFS were set very high (Supplementary Table 1) and thus more in line with EU mitigation targets. This led to rather minor losses for biodiversity and non-timber ecosystem services, particularly for water regulation. The BDS scenario showed very strong gains for wood and bioenergy and strong losses across all non-timber services and biodiversity. The BES scenario showed contradictory effects on wood and bioenergy, since prioritizing EU mitigation targets caused an increased roundwood harvest and decreased harvests for bioenergy when compared with bottom-up (Supplementary Fig. 10). The FESB of the BES were less severely affected under the mitigation scenario NDC due its lower harvest demand targets (Fig. 2).

In Sweden, the effect of prioritizing EU mitigation targets was strongest for bioenergy under the NFS scenario, showing a loss. Prioritizing the 1p5 target over demands of the BDS scenario increased the delivery of wood and bioenergy. No other ecosystem services increased beyond marginal changes when aiming for EU mitigation targets. Across all policies and mitigation scenarios, climate and water were most stable. The prioritization of the NDC target over demands of the BES

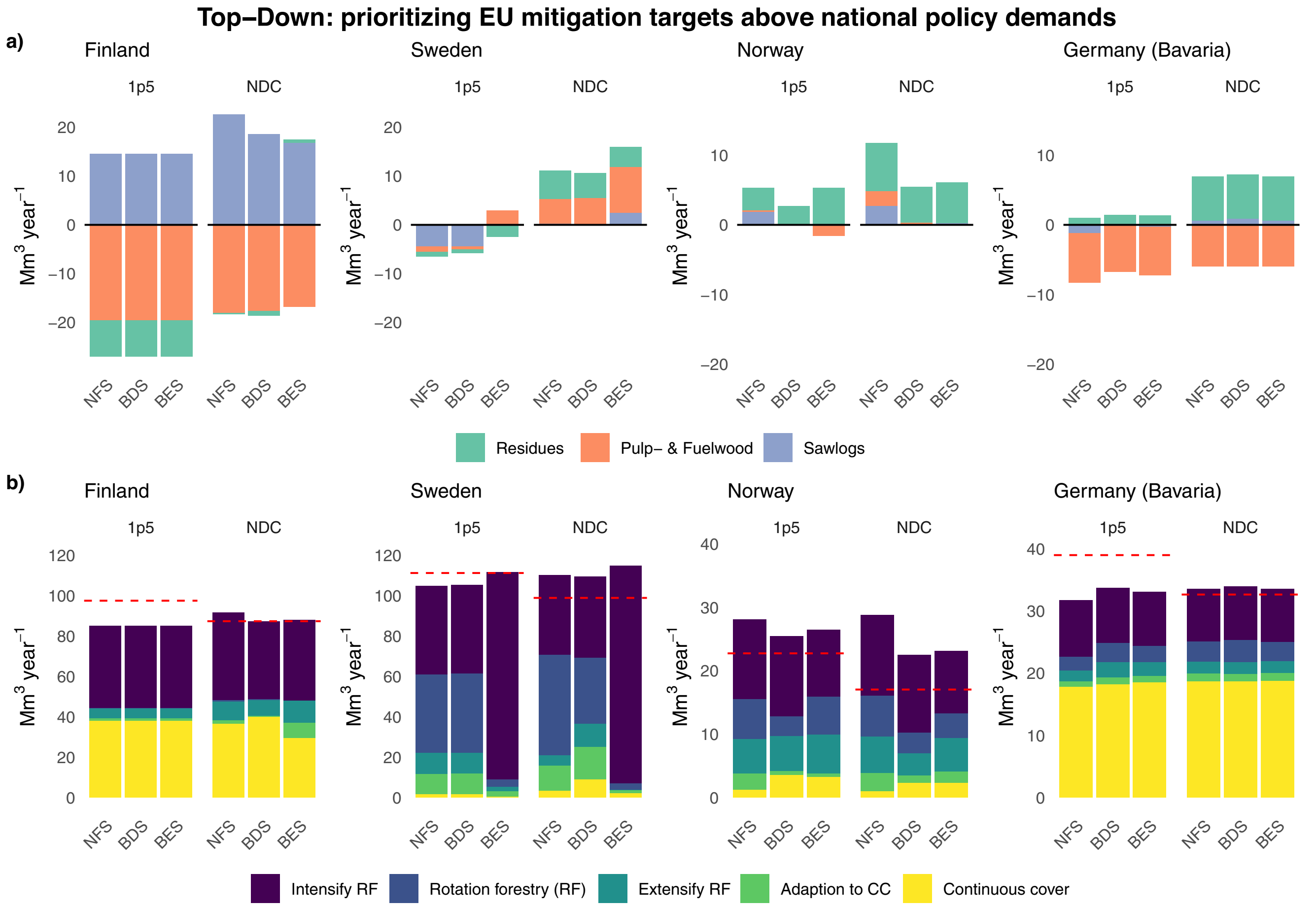

Fig. 4 Top-down optimization outcomes prioritizing harvest demands for EU climate change mitigation targets above national policy demands. **a** Difference between harvest demands for EU mitigation targets (1p5 and NDC, see Fig. 2) and forecasted harvests under optimization scenarios by assortment. Bars below the black line indicate that the demand for that assortment is not met. **b** Forecasted harvests by management classes. The bars in both plots, **a** and **b** represent mean values over the planning horizon. The red dashed line in **b** represents the average timber demand of each mitigation target, NFS stands for national forest strategy, BDS for biodiversity strategy, and BES for bioeconomy strategy. Note variable scaling of *y*-axis.

scenario was the only case not affecting any ecosystem service (Fig. 5 and Supplementary Fig. 11). Thus, the bioeconomy policy was most coherent with EU mitigation targets.

In Norway, the prioritization of EU mitigation targets showed almost no effects on FESB under the NFS scenario, and small effects on non-timber ecosystem services under the scenarios BDS. This resulted from the relatively low harvest demand targets (Fig. 2), which were already reached under optimizations prioritizing national policy FESB demands (Fig. 3). Prioritizing EU mitigation targets even led to slight losses for wood due to decreased harvest net incomes under the BDS scenario compared to bottom up (Supplementary Fig. 12). For the BES scenario, harvests were in turn increased, leading to gains for ecosystem service wood and bioenergy, but also for water, whereas biodiversity and climate were negatively affected.

In Bavaria, FESB were strongly affected when prioritizing harvest demands for EU mitigation targets (Fig. 5). The increased harvests, particularly under the NFS and BDS scenarios, resulted in losses for non-timber services and biodiversity in both scenarios, with BDS being the most sensitive scenario due to its lack of policy targets for timber provisioning (Supplementary Table 2). FESB of the BES scenario were less affected, as the scenario was strongly oriented towards timber production with harvest closest to the EU mitigation targets. Thus, the bioeconomy policy was most coherent with EU mitigation targets. Top-down optimization reduced harvesting pressures for pulp- & fuelwood (Supplementary Fig. 13), which lead at the same time to gains for all other services.

Discussion

Our study provides a comprehensive analysis on the potential consequences of future harvest demands required for achieving EU climate change mitigation targets. For the first time, forests are assessed to determine if multifunctional benefits can be provided while transitioning to a climate-neutral economy; an open research question that was also highlighted by the new EU Forest Strategy[22]. This was achieved by comparing the effects of bottom-up (aiming for FESB demands stated by national policies) vs the effects of top-down optimization (addressing first the mitigation targets). Previous studies following a similar approach analyzed policies just from the national point of view[28,29].

The results of our cross-scale (EU vs. national) policy coherence analysis are novel and can help to coordinate policy processes: the integration between EU and the member states (vertical integration) and of separate sectoral policy objectives (horizontal integration), as it demonstrates the potential contribution of forests to climate change mitigation. The major challenge for forest policymaking is that forestry-related decisions are linked to several policy domains and policy scales (EU vs national), which require new modes of cooperative forest governance and processes to foster policy integration[30–32]. Our

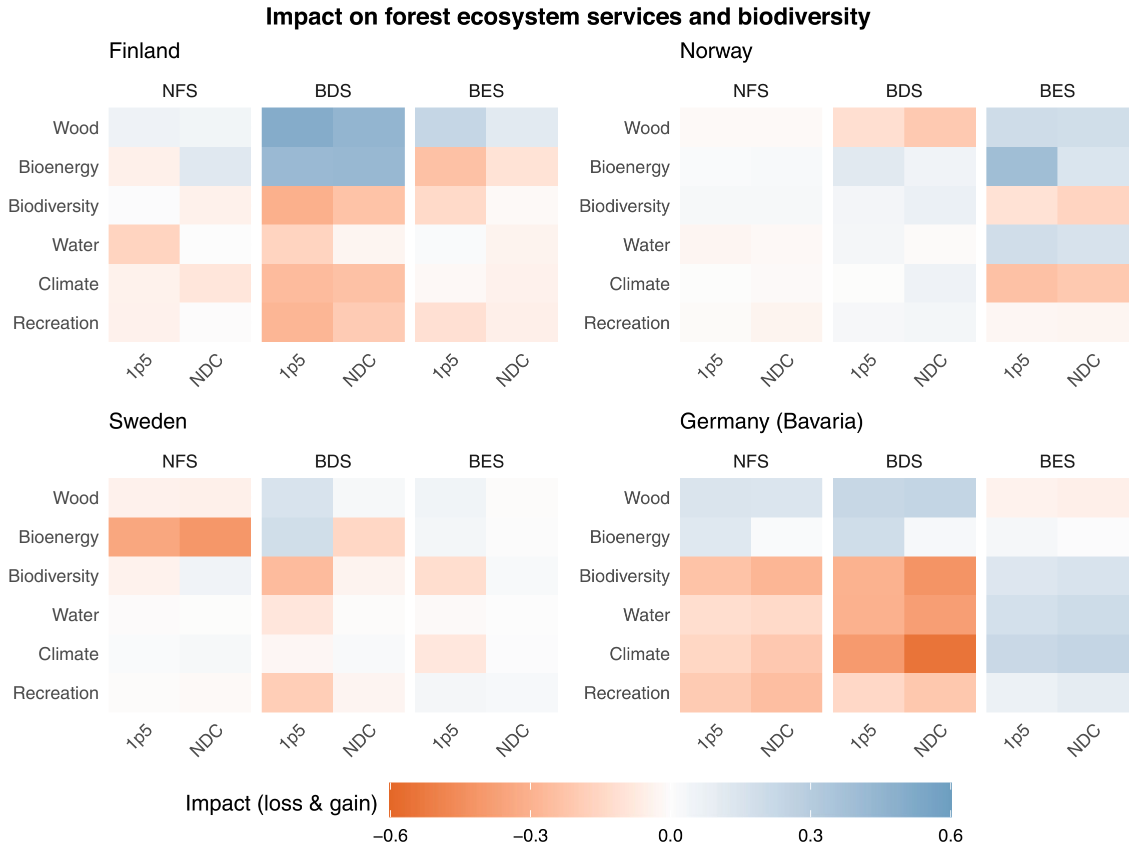

Fig. 5 Impact on the provided forest ecosystem services and biodiversity (FESB) when prioritizing EU climate change mitigation targets. Presented are the differences in normalized indicator values of top-down minus bottom-up, which were further averaged by FESB if a service is represented by more than one indicator. Blue means EU mitigation targets induced a gain in FESB, and red means a loss, NFS stands for national forest strategy, BDS for biodiversity strategy, BES for bioeconomy strategy. The top-down effect on individual indicators used to evaluate FESB are presented in Supplementary Figs. 10–13.

results can also provide insights for other European countries facing similar challenges of balancing conflicting policies.

EU climate mitigation targets vs national FESB demands. Our results highlighted the incoherence between EU climate change mitigation policies and national sectoral policies addressing FESB, particularly with national strategies for biodiversity. Three major timber production regions (Sweden, Finland, and Germany)[16] were not able to mobilize enough resources for the climate change mitigation targets set by the EU while meeting national policy demands for FESB. Covering the demands for the 1p5 mitigation targets would require a large harvest increase by 2100 from the current level (Fig. 2), with negative impacts for non-timber ecosystem services and biodiversity.

The potential negative consequences for FESB would conflict with strategic targets of the new EU Forest Strategy, which aims to improve forest multifunctionality and reverse biodiversity loss, while increasing forest resilience at the same time[22]. Our results show that the targets for achieving high harvest demands for climate change mitigation are in conflict with targets for boosting multifunctionality and biodiversity. Societal decarbonization requires strong efforts in changing our whole socio-economic system, driven by policies that support change by consistent action[33]. Thus, we conclude that the contribution of forest ecosystems and especially its timber resources, like currently discussed under the umbrella of bioeconomy[25,34,35], should not be overestimated to reach the EU mitigation targets.

Harvest demands representing EU mitigation targets were more easily reached for lower mitigation targets linked to RCP4.5, where less wood resources will be required. Climate change is expected to strongly influence forest ecosystems in Europe, leading to increased forest productivity, particularly in northern latitudes[36–38], a contributing reason why demand targets were more easily reached. However, climate change also leads to suboptimal conditions for certain tree species in temperate regions[39,40], and higher disturbance rates in the future (e.g., by wind, drought, and bark beetles)[41–43]. Those effects were not considered in the current study and might cancel out climate change induced productivity gains[44]. This would in turn pose additional challenges to achieve the required harvest demands for EU mitigation targets and further increase the incoherence in policy objectives. Disturbances related to climate change should be included in future policy coherence analyses.

GHG removal by forest resources plays a crucial role in reaching a climate-neutral future, according to the EU Forest Strategy[22]. To meet the target, the European Commission has suggested increasing harvest and making more wood available for carbon storage in wood products and for substitution of fossil resources[45]. To overcome a potential reduction of net forest sinks, it has been suggested that forest productivity (increment) should be increased through forest management practices and new forest area[45]. In Finland and Sweden, intensive rotation forestry has led to a constant increase in harvests and increment during the last decades, currently being at its highest level ever[46,47] (Supplementary Table 5). At the same time, several important forest habitat types have become threatened due to reduced deadwood, old-growth forests and trees, and reduced share of deciduous trees[48]. A further harvest increase to meet the ambitious climate targets will result in several conflicts with other FESB, particularly with biodiversity conservation (Fig. 5). In Norway, there is potential for higher harvests for mitigation efforts, but their projected average demands per hectare were also 40–50% lower compared to the other boreal study regions (Fig. 2b). In Bavaria, an increase of timber harvest was hampered by the current high proportion of mature forests (ready for harvest) caused by historical management legacies (i.e., major replanting after WWII, Supplementary Table 5), being also the main reason for the future demand gaps of pulp- and fuelwood assortments (Fig. 4a).

Management for multiple demands. Our results highlight the need to use a diversity of managements for the efficient provisioning of multiple FESB. The optimal management differs from the current situation, particularly in the boreal study regions, where rotation forestry is still the dominant practice leading to even-aged forests with lack of mature and old-growth forest characteristics[49,50]. However, there is increasing scientific evidence that diverse silvicultural management practices, and uneven-aged, mixed forests increase resilience against climate change and promote FESB provision compared to even-aged forests[51–53].

Our optimized management for policy objectives (bottom-up) also highlighted the importance of conservation-oriented management regimes for all study regions, including extensified rotation forestry (longer rotation time, reduced thinning and harvesting, green tree retention), continuous cover forestry and protected areas (set asides). This converges with the EU Biodiversity Strategy and the EU Forest Strategy[21,22]. Both aim at protecting at least 30% of the EU land area by conservation-oriented management regimes, including 10% of strictly protected land areas.

Our results suggest that between 10-30% strictly protected areas could be achieved for the most multifunctional national policy scenario in each study region (Finland and Bavaria = NFS; Sweden = BDS, Norway = BES; Supplementary Note 1). Considering extensified rotation forestry and continuous cover forestry as conservation-oriented management regimes, the overall protection targets for those scenarios were suggested to be at minimum 41% in Sweden, 46% in Norway, 52% in Bavaria, and 69% in Finland (Fig. 3b and Supplementary Figs. 2–5). In Finland and Bavaria, the major share of the optimal management was allocated to continuous cover forestry, while it was mainly extensified rotation forestry in Sweden and Norway. Continuous cover forestry enables creating resilient and multifunctional forests that also contribute to biodiversity conservation[53–55]. However, in contrast to rotation forestry, this type of management currently plays a minor role in Fennoscandia[49]. Obstacles that hinder a wider application are; a lack of knowledge among forest owners and professionals in applying continuous cover forestry and transforming forests toward a higher structural diversity, lack of subsidy instruments favoring such management regimes, and a forest industry sector geared to processing medium-sized logs stemming from rotation forestry[49]. Consequently, also the forest industry (particularly in northern latitudes) needs to adapt to larger log dimension usually growing under continuous cover forestry.

Forest ecosystem modeling and optimization. Using the approach of combining forest ecosystem modeling and multi-objective optimization[17,18,53], we developed optimal management programs matching with the different policy demand levels. The usage of regional empirical forest simulators had the advantage that it allowed to address best the national diversity of policy objectives and provide decision support[56]. Tree growth and mortality algorithms of all four applied forest simulator are based on statistical growth and yield models[57–60], that were modified to describe the increase of tree growth due to climatic variables (like temperature, precipitation, and CO_2 concentration; see Supplementary Note 4). We acknowledge that applying process based or hybrid models might usually be preferred for addressing climate change aspects in long-term forest ecosystem simulations[61], and future work addressing similar research questions would benefit from using such models. However, previous studies that applied process or hybrid models also found that the future supply of FESB will be more strongly determined by management than by climate[19,62–64]. A benefit of our regional forest simulators is further that the models cover best the variety of regional forest management practices; e.g., in Finland and Germany the management class of continuous cover forestry included also production oriented regimes for monospecific stands, which lead to their larger contribution in the optimized management programs. Thus, our simulation set up is particularly designed to develop optimal management programs matching different national policy demands, since the focus of the work was not on the pure effects of climate on forestry, but instead how forest management can satisfy multiple and conflicting policy demands. For addressing a larger European area, a common forest modeling approach among countries would however be beneficial[65,66].

The correlation between forest dynamic simulations and FESB was achieved via a set of indicators that assess the changes in forest stand structures under alternative forest management. Forest structural attributes have been proven to be good predictors of several ecosystem services and forest biodiversity, as well as predictors of synergies and trade-offs[67]. The advantage of using forest structural attributes is that they are directly derivable from model outputs, allow to scale up stand results (to national scales) and are sensitive to forest management practices[68,69]. A shortcoming lies in the fact that indicators used to measure the FESB partly differed among study regions and modeling approaches. This was taken into account to represent a wide spectrum of policy demands for FESB categories instead of only a minimum common set of addressed categories. Policy demands for FESB were elaborated following a methodological framework for analysis of policy documents[23]. However, linking the policy demand to our indicators and translating demands into an optimization problem required inherent simplifications, also representing the opinions and knowledge of the authors of this study. Acknowledging this shortcoming allowed to set holistic targets for the most important policy demands within each region, and to address the multifunctional role of forest ecosystems.

The use of the multi-objective optimization tool applied to generate scenarios of forest development has both advantages and disadvantages. The key advantage is the flexibility in constructing the objective function. The flexibility is only limited by the ability to predict specific FESB indicators. The tool allows decision makers to set hard requirements (through the epsilon constraint), while allowing prioritization between objectives (through the achievement scalarization function). Additionally, the tool is not connected to a specific simulator, and can flexibly link to a range of outputs from different forest simulators. A key limitation of the approach is the lack of uncertainty assessment, quantification, or optimization. Approaches exist that link the achievement scalarization functions (ASF) with stochastic programming[70]. However, this approach requires integration of uncertainty to the forest simulator and increases the computational demands tremendously. Alternative approaches to mitigate risk would be the robust optimization approach of Knoke et al. [71], recently also implemented as open source tool[72]. A challenge would however be to link the robust optimization method[73] with the method of ASF[74].

Global forest sector model. Climate change mitigation targets were expressed as timber harvest demands and modeled with the global spatially explicit forest sector model (GLOBIOM). The ability to capture and explain market developments with such models is essential since it provides foresight analysis on future resource demands relevant to society and policy makers[75]. When simulating GHG mitigations under the interplay of different land-uses and sectors, carbon storages in forests and the contribution of using forest biomass for bioenergy is accounted for[76]. However, the assessment did not consider carbon storages in long-living timber products, which offer important GHG mitigation potentials[77,78]. Thus, the full contribution of our simulated resources for GHG mitigations, particularly of sawlogs and pulpwood, might be underestimated.

Nevertheless, the applied forest sector model has great importance for studying policy effects and interlinkages among policies, as well as its market impacts. GLOBIOM has the advantage that it allows to consider market impacts caused by EU climate mitigation policies that boost/constrain harvest; like for example increased timber prices that lead to leakage effects, meaning a harvest shift from one EU country to another (or outside EU) and increase in turn national imports (cf. Supplementary Fig. 1). Those international market effects are thus reflected in the targeted harvest demands addressed in our top-down optimization[79]. International market effects were, however, not considered under our bottom-up approach, where particularly national biodiversity policy demands might restrict the harvest potential within a specific country[28,29]. To incorporate these market effects, a feedback loop between the bottom-up results and GLOBIOM would have been required. But still, the comparison of outcomes under the bottom-up and top-down approach allowed us to study the coherence of national forest policy and EU level climate mitigation policy frameworks.

The consideration of two distinct RCPs, represented in the EU forest sector model GLOBIOM by alternative developments of biomass demands from society and climate mitigation targets, captured some of the socioeconomic uncertainties in the long run for the forest sector. However, a larger set of forest sector outcomes remain possible when considering the full range of SSPs-RCPs[80]. Result uncertainties could be disclosed when considering different parametrization of the EU model, such as the different assumptions for demand elasticities and/or trade constrains. Some of the uncertainty in our results is also due to the current EU forest sector model structure, as it can be observed in a recent model intercomparison[81]. We further acknowledge that the forest sector model (GLOBIOM) did not include potential impacts of climate change on forest mitigation potentials. These impacts could increase forest mitigation potential in some of the considered countries, compared to our results, as shown in recent studies[82]. At the same time, the climate change driven increase of natural disturbances and extreme events could counteract positive effects and decrease the mitigation potentials[41]. However, previous analyses that have jointly evaluated socioeconomic and climate impacts under a similar modeling framework found that socioeconomic drivers tend to have a greater influence on large scale forest sector models outcomes, compared to climate impacts[81,83].

Methods

Study regions and forest data. We studied the four regions Finland, Sweden, Norway, and Bavaria in Germany, which represent two main forest ecosystems in Europe (boreal and temperate, Supplementary Table 5). The representation of the forest situation (Fig. 1) was obtained by a systematic sample of the forest area in each country, respectively region (Bavaria). Specifically, we utilized the measurements of the national forest inventory (NFI) for Sweden (2008-2012), Norway (NFI11, 2015-2019) and Bavaria (NFI3, 2012) as input data. In Finland, the inventory scheme of the NFI11 was used to sample public forest data (2015/2016) and to systematically represent the national forest area. The total number of inventory plots in the four study regions were 56221 in Finland, 29892 in Sweden, 9371 in Norway and 7456 in Bavaria. We also recorded if NFI plots were located in statutory protected areas, where management activities are not allowed. For further details, see Supplementary Note 3.

Forest dynamics and management simulators. Forest dynamics and management were simulated individually in each study region using empirical simulators. This allowed to cover the site-specific forest conditions and dynamics (tree growth, mortality, and regeneration) in a good manner, while at the same time cope with the diversity of regional forest management practices and policy objectives. The forest simulators used were SIMO for Finland[57], Heureka for Sweden[58], SiTree for Norway[59,84], and SILVA for Bavaria[60,85]. Each simulator used the NFI based data as input for the projections describing the initial forest structural characteristics. We simulated forest dynamics and management under two climate trajectories; current climate and representative concentration pathways RCP4.5. Further, all simulators provided a set of FESB indicators, including harvested timber assortments that could be used to meet the expected harvest demands for EU climate change mitigation targets calculated by GLOBIOM (see below). For details about each simulators see Supplementary Note 4.

Forest management regimes. The simulated forest management regimes represent the current most common and potentially possible management practices in each study region (assuming no new forest management constraints in future). Despite the heterogeneity in simulated regimes, stemming from the different regional practices, management regimes could be grouped into six common classes among all study regions.

The management class rotation forestry (RF) represented regimes based on even-aged forest management with intermediate thinnings and final clearcut with planting after the final harvest. The intensified RF category described those regimes with shortened rotation times of forest stands. In the boreal study regions, it could further include the effects of fertilization, whereas in Bavaria and Sweden it also included the promotion of productive foreign tree species. In Sweden, these additional intensified RF regimes were only allowed under the BES scenario. The category extensify RF described mainly regimes with prolonged rotation times and decreased thinning intensity (in all regions) and regimes that could also leave a larger number of retention trees after final harvest (Finland, Sweden). The continuous cover forestry category described regimes that aim towards continuous wood production and forest stands that are permanently covered with trees and have a diverse forest structure and natural regeneration. It also included regimes that are production oriented for monospecific stands of Norway spruce or Scots pine (Finland, Bavaria). The category adaption to climate change represented a management that aimed at promoting species diversity to increase resilience and stability against climate change and climate-induced disturbances. It followed either the concept of even-aged rotation forestry (boreal regions) or the continuous cover concept for mixed stands (Bavaria). Additionally, a setting aside regime was simulated without any management activities (e.g., NFI plots falling into statutory protected areas were only simulated with set aside). The actual number of regimes representing each management class differed, depending on the applied simulator and region (except for set aside). For details, see Supplementary Note 4.

Forest ecosystem service and biodiversity indicators. Each forest simulator projected a set of FESB indicators developed for the specific regional context, which formed the basis for the optimization aiming to meet the demands of the national forest policies. The simulated forest characteristics (e.g., tree species, tree height and diameter (in 1.3 m above ground), deadwood amounts, harvest volumes) were used to calculate indicators for FESB assessments. In total, we defined six common services according to international classification schemes[86,87] and following an analysis framework for European policy documents:[23] wood production and bioenergy (provisioning services), water protection and climate regulation (regulating services), recreation (cultural service) and biodiversity conservation.

Each study region aimed to link at least one indicator to each ecosystem service and biodiversity. FESB indicators were selected if the corresponding national policy directly mentioned a demand for an FESB, and if indicators could be calculated from available data. The aim was to address a wide spectrum of FESB instead of having only a common minimum set of indicators. Thus, indicators can differ among study regions, e.g., for water and biodiversity. However, all indicators were based on established approaches able to address the forest situation and the policy requirements appropriately. Comparison among study regions did however not take place at the level of indicators but at the level of FESB categories, as well as management classes and harvest timber assortments. These were used in the optimization to address the timber demands representing EU climate mitigation targets. The selected indicators used to measure FESB in each study regions and the rationale behind are described in Supplementary Note 1 and Supplementary Tables 1–4.

National policy demands for ecosystem services and biodiversity. We created three policy scenarios for each study region, based on national sectoral policy documents or suggested strategies (white papers) setting objectives for either forest use in general, biodiversity or developing the bioeconomy. The studied countries differ in their institutional structures and forest use histories, which is reflected in variation among policy targets and legal requirements for forests. For each country, we analyzed the available policy documents regarding six common services following the methodological policy analysis framework of Primmer et al.[23]; which FESB were addressed, what was the stated demand for FESB in each document, and what is the importance of individual services in relation to others.

In Finland, there are parliamentary prepared strategies that clearly represent each policy scenario[88–90]. However, the associated policy documents differ in coverage of FESB, detail, and quantitative objectives, with the NFS providing widest coverage and most quantitative targets[28]. In Bavaria, the evaluation of three policy sectors were achieved by elaborating the objectives of the federal NFS[91], BDS[92] and BES[93] on the state level. The German multifunctional tradition was reflected in the NFS, although with little emphasis on non-wood services. In Norway, the evaluations of the national BDS[94] and BES[95] were complemented with analysis of the parliament white paper on forest policy[96]. The Norwegian policies were the least explicit in setting targets, but most specific in pointing out certain FESB. In Sweden, the researchers in consent with key stakeholders considered the official strategies unfit to represent the explicit policy strategies and constructed the scenarios based on specific reports advising policy implementation, e.g., on increasing growth of wood, addressing biodiversity deficit or expanding bioeconomy[97–99]. The variation in policy scenarios among countries thus also reflects national differences in policy cultures and level of national policy dissensus or consensus related to FESB governance.

The outcome of the policy analyses was used to define three multi-objective optimization scenarios in each study region (e.g., Blattert et al.[28] and Vergarechea et al.[29]). Therefore, the stated policy demands for FESB were related to the simulated FESB indicators by individual objective functions and constraints, assuming that current demands remain unchanged in future. For details on the policy documents considered in each region see Supplementary Note 1, and for the defined optimization scenarios see Supplementary Tables 1–4.

Domestic harvest demands for climate mitigation targets. Demands were computed according to two alternative climate change mitigation targets of EU policies by the Global Biosphere Management Model (GLOBIOM), which is a global land use model that spatially explicitly covers the agricultural, forest, and bio-energy sectors[100,101]. In this study, we used a version of the model called GLOBIOM-forest, where the representation of the agricultural sector is simplified, but where forestry, the forest industry and the forest bio-energy sectors are modeled in detail[102]. A more detailed overview on the model framework and the underlying assumptions (e.g., international trade and timber prices) is provided in Supplementary Note 5.

Two scenarios were developed to reflect future domestic harvest demands for energy, transport and buildings sectors under climate change mitigation ambition of the EU. Each scenario was developed utilizing the SSP2 (Socio-Economic Pathway “Middle of the Road”[103]) assumptions for global socio-economic developments (e.g., GDP and population growth), as a baseline for projecting future harvest demands. Afterward, the demands for timber in GLOBIOM were further detailed according to the RCP related mitigation demand projections of the MESSAGE energy system model[76]. Specifically, the two scenarios were:

NDC scenario: The scenario accounted for the targets as set out in the 2016 Nationally Determined Contribution (NDC) by the European Commission and included a 40% reduction of GHG emissions by 2030 as compared to 1990 levels and follows the RCP4.5 pathway.

1.5°C scenario: The scenario assumed that the EU overall achieves net zero GHG emission by 2050 and further accounted for the Paris Agreement’s temperature objectives of pursuing efforts to limit to 1.5°C temperature change by the end of the century and follows the RCP1.9 pathway.

It should be noted that these scenarios do not account for the AFOLU (agriculture, forestry and other land use) specific targets of the EU ‘Fit for 55’ proposal[104], aiming for climate neutrality of this sector by 2035. Further, no forest product innovations were considered within the energy, transport or building sector. However, products recycling efficiency considered in the model is assumed to increase over time towards their respective theoretical maximum.

For each scenario, projected harvest demands for material and bioenergy use until 2100 were specified at the national (Finland, Sweden, Norway) and regional level (Bavaria) for different timber assortments: sawlogs, pulpwood and other industrial roundwood, fuelwood, and logging residues. Harvest demands were grouped into three classes (sawlog, pulp- and fuelwood, residues) to match them with the simulated harvests of forest simulators in the multi-objective optimization. Forest simulator outcomes under the current climate trajectory were assumed to relate to GLOBIOM scenario 1.5°C, and outcomes under RCP4.5 corresponded to NDC scenario. Details about the scenario assumptions are provided in Supplementary Note 5.

Multi-objective optimization. The FESB demands of the national policies and harvest demands representing EU climate change mitigation targets were addressed within a new multi-objective optimization framework that was specifically developed for this policy analysis. The framework was used to identify optimal forest management programs that best fulfill the different demands and balances among divergent policy objectives. Therefore, the optimization aimed to seek an efficient management solution for each individual forest entities derived from NFI plots. As input, we used the future trajectories (5-year steps) of FESB indicators under alternative management regimes and climate scenarios on each NFI plot.

The aim of the optimization was to find a single solution for each optimization scenario – 12 for each study region: 3 national policy domains, 2 harvest demand scenarios, bottom-up and top-down. Each solution was found through the formulation of unique multi-objective optimization problems[105]:

$$\begin{aligned} &\underset{x}{\text{minimize}}\left\{f_1(x),\ \ldots\ ,f_n(x)\right\} \\ &\text{subject } x \in S \end{aligned} \tag{1}$$

where $f_i(x)$, $i = 1,\ldots,n$ denote the different objective functions addressing demands, x the vector of available management regimes, and S is the feasible set of management regimes determined by a set of constraints. By convention, maximization objectives are reformulated as minimization objectives inside the optimization software.

The optimization framework was applied in each study region and tailored to the specific national policy demands based on a set of pre-defined function types, each addressing a simulated FESB indicator. The function types differ in 3 key ways: (1) How the simulation time is considered, (2) if the objective should be minimized or maximized, and (3) limitations to the set of management regimes allowed and NFI plots considered (see Supplementary Equations 1–11). Depending on the scenario definitions in each region, the individual functions were combined to a logically consistent multi-objective optimization problem (see Supplementary Note 1). Therefore, each set of functions can be interpreted as targets for a specific policy. Technically this was done by implementing two approaches: the methods of achievement scalarizing functions[74] (for maximizing objectives), and the method of epsilon-constraints[105]. Achievement scalarizing functions measure the preferability of the solution, based on specified reference points. The reference points can be feasible or infeasible, as the method will find a solution that is the closest point on the Pareto frontier (the set of solutions where none of the demand levels can be further improved without impairing another demand solution). Epsilon-constraints define instead strict upper/lower targets that need to be achieved. The joint usage of these approaches guaranteed Pareto optimal solutions[105]. Details on the multi-objective optimization are provided in Supplementary Note 6. The codes to run the optimization in each study region can be retrieved together with example data on forest simulations to run the optimization from https://doi.org/10.5281/zenodo.6631109.

Combining demand levels. The joint optimization for FESB demands of national policies and EU climate change mitigation target was done following two approaches: a bottom-up and a top-down approach (Fig. 1). In the bottom-up approach, we optimized for the FESB demands of national policies along the steps indicated in the national policy scenarios (Supplementary Tables 1–4), using a lexicographic approach[105]. The optimization steps represented the priority that was put on the different FESB categories by the national policies (starting with the most important one), or represented a general logic of a policy, e.g., in Finland the BES scenario maximized harvest under the premise that biodiversity should not decline.

In the top-down approach, the achievement of harvest demands for EU climate change mitigation targets were optimized first, before optimizing for FESB demands of national policies. The optimization steps of national demands were again done using the lexicographic approach. The harvest demand optimization aimed to maximize the minimum difference between possible harvest and targeted demands (Supplementary Equation 9 in Supplementary Note 5), individually for all three timber assortments (sawlogs, pulp- & fuelwood, residues). The optimization allowed to complement demand gaps of residues and pulp- & fuelwood by the next higher quality timber assortment class, if the higher quality assortment harvest exceeded its required demand level (i.e., sawlogs can be used to fill up demand gaps of pulp- & fuelwood and residues, but the opposite direction is impossible). This was implemented by a routine minimizing the sum of transferred assortments between classes over the planning horizon.

Cross-scale analysis. The effects of bottom-up and top-down optimization were analyzed in respect to: i) the achievement of harvest demands representing EU climate change mitigation targets, ii) the optimized management requirements contributing to the demand achievement, and iii) the impacts of increased harvest demands on the FESB achieved under national policy scenarios.

For analysis (i), the total harvest arising under the optimized management were averaged over the investigated time horizon (2020–2100) and compared with the average harvest demand levels by assortments provided by GLOBIOM. Further, we analyzed (ii) under which management classes the harvests were provided. Each analysis was done for the bottom-up and top-down approach.

For analysis (iii), we calculated the arising gain or a loss in landscape FESB when aiming for EU climate change mitigation targets. Therefore, the FESB benefits under the national policy scenarios (bottom-up) were compared to the FESB benefits under the top-down approach, setting the forest ecosystem as system boundary (i.e., carbon storages in wood products targeted in national policy scenarios were not included, see Supplementary Tables 3 and 4). First, the landscape averages per FESB indicator were calculated arising under the optimized managements for each period of our planning horizon (5-year steps until 2100).

Second, landscape averages were normalized between 0 (minimum) and 1 (maximum) to allow for better comparison among indicators within a study region:

$$f(x_{i,j,k,l,m}) = \frac{x_{i,j,k,l.m} - \min_i}{\max_i - \min_i} \quad (2)$$

where $f(x_{i,j,k,l,m})$ is the normalized landscape average of indicator (i), at simulation period (j), under national policy scenario (k), under climate change scenario (l), and top-down or bottom-up optimization approach (m). The normalized values represent a utility or social benefit of an indicator[69,106,107]. Third, the differences between normalized values of top-down and bottom-up were calculated and averaged over the planning horizon (mean over time). An exception was done for indicators addressing regime shares (e.g., Supplementary Tables 1 and 2), for which the difference was calculated based on the timely constant regime shares. Finally, those outcomes were averaged for each FESB category if a service was represented by more than one indicator assuming thereby equally weights for indicators (Supplementary Figs. 10–13).

Reporting summary. Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability
The data supporting the findings of this study can be retrieved from https://doi.org/10.5281/zenodo.7751296, together with the country-specific raw forest simulation data used as input for the multi-objective optimizations and the raw optimization outputs.

Code availability
The codes to run the national optimization can be retrieved together with example data of forest simulations to run the optimizations from https://doi.org/10.5281/zenodo.6631109. The code used to analyze the data and produce the figures is available from https://doi.org/10.5281/zenodo.7751296.

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Author contributions
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Competing interests
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Additional information

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