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Reconciling the EU forest, biodiversity, and climate strategies

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Abstract

Forests provide important ecosystem services (ESs), including climate change mitigation, local climate regulation, habitat for biodiversity, wood and non-wood products, energy, and recreation. Simultaneously, forests are increasingly affected by climate change and need to be adapted to future environmental conditions. Current legislation, including the European Union (EU) Biodiversity Strategy, EU Forest Strategy, and national laws, aims to protect forest landscapes, enhance ESs, adapt forests to climate change, and leverage forest products for climate change mitigation and the bioeconomy. However, reconciling all these competing demands poses a tremendous task for policymakers, forest managers, conservation agencies, and other stakeholders, especially given the uncertainty associated with future climate impacts. Here, we used process-based ecosystem modeling and robust multi-criteria optimization to develop forest management portfolios that provide multiple ESs across a wide range of climate scenarios. We included constraints to strictly protect 10% of Europe's land area and to provide stable harvest levels under every climate scenario. The optimization showed only limited options to improve ES provision within these constraints. Consequently, management portfolios suffered from low diversity, which contradicts the goal of multi-functionality and exposes regions to significant risk due to a lack of risk diversification. Additionally, certain regions, especially those in the north, would need to prioritize timber provision to compensate for reduced harvests elsewhere. This conflicts with EU LULUCF targets for increased forest carbon sinks in all member states and prevents an equal distribution of strictly protected areas, introducing a bias as to which forest ecosystems are more protected than others. Thus, coordinated strategies at the European level are imperative to address these challenges effectively. We suggest that the implementation of the EU Biodiversity Strategy, EU Forest Strategy, and targets for forest carbon sinks require complementary measures to alleviate the conflicting demands on forests.

KEYWORDS
carbon sink, climate change mitigation, ecosystem services, Europe, forest management, management portfolios, robust optimization, substitution effects

1 | INTRODUCTION

Climate change and biodiversity loss are among humanity's most pressing issues (IPBES, 2019; IPCC, 2023a). The progress in climate change mitigation has been slow and has fallen short of targets set by the Paris Agreement (United Nations, 2023). Nevertheless, there is a growing trend worldwide to enact legislation addressing climate change (Eskander & Fankhauser, 2020). Likewise, biodiversity loss is continuing at an alarming rate. But despite international policy efforts, it often receives less attention than climate change (Barbier et al., 2018), sometimes overshadowing the intricate relationship between the two issues (Pörtner et al., 2023; Sage, 2020). On the one hand, a significant portion of biodiversity loss is linked to rising temperatures. Thus, limiting global warming is crucial for preserving biodiversity (Ohashi et al., 2019; Warren et al., 2018). On the other hand, future land use changes stemming from mitigation policies can be detrimental to biodiversity (Hof et al., 2018; Ohashi et al., 2019). Hence, there is a clear need for more concrete actions and legislative measures to support biodiversity conservation, especially in Europe, where over 80% of the land surface have been transformed over the past millennia (EEA, 2023; Ellis et al., 2021).

To combat biodiversity loss, the European Union (EU) created the *EU Biodiversity Strategy for 2030* (European Commission, 2020). Key objectives include the protection of 30% of its land area by 2030, with 10% strictly protected, the planting of 3 billion trees, and the establishment of ecological corridors. “Protection” refers to responsible management and the prevention of deterioration. Protected forests can be managed for timber, but harvest levels are typically subject to restrictions (Verkerk, Zanchi, & Lindner, 2014). “Strict protection” means maintaining ecosystems in an unmanaged state, with interventions limited to those sustaining natural processes (e.g., wildlife population control, European Commission, 2022). At present, 26% of the EU's land area is legally protected, and 3% strictly protected (European Commission, 2020; Forest Europe, 2020). Since 35% of Europe is covered with forests and most other land covers are more intensively used than forests, a substantial portion of newly protected areas will lie in forests (Forest Europe, 2020; Hengl et al., 2018). In addition, the *New EU Forest Strategy for 2030* was proposed, promoting broad-leaved species, forest multi-functionality, carbon sequestration, long-lived wood products, synergies between wood production and conservation, and forest adaptation to climate change (European Commission, 2021). Such forward-looking objectives are also often subsumed under the term “climate-smart forestry” (Nabuurs et al., 2018). Furthermore, both strategies demand the strict protection of Europe's remaining old-growth and primary forests. Non-EU states have similar strategies in place (e.g., FOEN, 2012; House of Lords, 2023).

Managed forests are critical for the European economy, providing income, jobs, and essential resources (Forest Europe, 2020). The demand for wood products has recently been growing (FAO, 2022a, 2022b; Nabuurs et al., 2007) and further increases are likely, also driven by the transition to a bioeconomy (Hurmekoski et al., 2022). Forests also contribute to climate change mitigation through the forest and product carbon sink, and by substituting carbon-intensive non-wood products (e.g., Grassi et al., 2021). Additionally, woody bioenergy plays a key role in Europe's energy transition (European Commission, 2021). Furthermore, forests offer numerous important ecosystem services (ESs), including biodiversity preservation, local climate regulation, water cycling, and recreation.

The corresponding complex demands placed on forests result in intricate trade-offs. Particularly, the relationships among biodiversity protection, timber production, mitigation, and adaptation have been extensively discussed in the scientific literature. Most studies indicate a conflict between biodiversity protection and timber production (Başkent & Kašpar, 2023; Felton et al., 2016; Gutsch et al., 2018; Verkerk, Mavsar, et al., 2014), although some suggest synergies (Biber et al., 2020). Additionally, there is an ongoing debate regarding the mitigation potential of intensively managed, extensively managed, and unmanaged forests (Dugan et al., 2018; Gregor et al., 2024; Gustavsson et al., 2021; Peng et al., 2023; Petersson et al., 2022; Roebroek et al., 2023; Schulte et al., 2022; Soimakallio et al., 2021).

One potential strategy to address these trade-offs is regional specialization, focusing on wood production in highly productive regions (e.g., Lessa Derci Augustynczik & Yousefpour, 2021). This *land-sparing* approach allows for increased production in one region while setting aside land for conservation elsewhere (Balmford, 2021). In Europe, however, *land sharing* typically prevails, where both production and protection objectives are pursued on the same land (Betts et al., 2021), but this could interfere with *strict* protection goals.

Developing forward-looking forest management strategies is a challenging task. One approach is to use management portfolios, as demonstrated by Luyssaert et al. (2018), who optimized portfolios for single objectives, such as maximizing carbon sequestration. Assessing multi-functionality, that is, the provision of multiple ESs, has been explored by Diaz-Balteiro et al. (2017), who selected optimal forest management types for various climate scenarios to find the single best management option in a case study in Spain. Here, we combine the two approaches by developing portfolios for multi-functionality under climate change.

The task is further complicated by the vulnerability of forests to different degrees of climate change and associated disturbances (IPCC, 2014; Senf & Seidl, 2021a, 2021b; Spinoni et al., 2018). Consequently, it is necessary to assess various forest functions under a range of climate scenarios to develop strategies for climate-adapted, multi-functional forests today. Robust multi-criteria optimization offers a valuable tool for this purpose (Ben-Tal & Nemirovski, 2002; Groetzner & Werner, 2022; Ishizaka & Nemery, 2013; Knoke et al., 2016; Uhde et al., 2017). Gregor et al. (2022) employed this approach to compute forest management portfolios for Europe, ensuring the provision of various ESs across a wide range of climate scenarios. They found that significant portions of unmanaged forests and a gradual transition to more broad-leaved species are beneficial for multi-functional forest landscapes in the face of climate change. However, this would also lead to strong reductions in wood harvests, conflicting with rising wood demands and the objective of leveraging wood products for climate change mitigation.

Here, we investigate to which extent reconciling targets for forest protection, wood production, mitigation, and the provision of ESs is feasible. We enhanced the methodology of Gregor et al. (2022) by incorporating Europe-wide constraints on harvest levels and forest protection that must be met under all climate scenarios. Specifically, we explored whether strategies for multi-functional forests can align with stable wood production and the EU's legal aims for strict forest protection and carbon sequestration. Furthermore, we examined the resulting impacts of these constraints on other ESs and the diversity of management strategies. We considered how the burden imposed by these constraints can be equitably distributed among regions, in line with the directive that all member states should contribute their "fair share of the effort" (European Commission, 2020).

2 | METHODS

In this study, building upon simulations with a dynamic vegetation model, we computed forest management portfolios that provide multiple ESs in an optimally balanced way, while considering the uncertainty of future climate. In previous work, this optimization was carried out independently for each grid cell (Gregor et al., 2022), providing one management portfolio suitable for all emission scenarios (Figure S1). Here, we substantially extended this methodology by introducing Europe-wide hard constraints on ES provisioning that had to be met under all emission scenarios. This implied that grid cells were no longer independent entities. They were not required to meet all constraints individually, provided they were compensated for by other grid cells.

2.1 | Forest management simulations

2.1.1 | Dynamic vegetation model

We employed the dynamic vegetation model LPJ-GUESS for the forest simulations. LPJ-GUESS simulates various ecological processes, including photosynthesis, water uptake, carbon allocation, soil and litter dynamics, the nitrogen cycle, as well as the growth, competition, management, mortality, and establishment of plant functional types (Haxeltine & Prentice, 1996; Lindeskog et al., 2021; Sitch et al., 2003; Smith et al., 2001, 2014). We used the parametrization of European tree species, which are characterized by various parameters such as phenology, growth form, bioclimatic limits, and shade-tolerance (Hickler et al., 2012). See Smith et al. (2014) for a detailed description of the model and Lindeskog et al. (2021) for details on the forest management module. LPJ-GUESS was designed to assess the impacts of climate change on terrestrial vegetation and has been thoroughly benchmarked against numerous independent regional and global estimates of carbon fluxes, harvests, biomass, CO_2 fertilization, and other datasets (Chang et al., 2017; Friedlingstein et al., 2022; Haverd et al., 2020; Ito et al., 2017; Lindeskog et al., 2021). Simulations were conducted in "cohort-mode", with age classes represented by a number of individuals sharing the same characteristics. We used 25 replicate patches to represent random samples of the same stand.

2.1.2 | Simulation protocol

The modeled region of interest was Europe, excluding Georgia, Iceland, Cyprus, and Russia (except for the Kaliningrad region), simulated at 0.5°×0.5° resolution. LPJ-GUESS was forced with monthly temperature, radiation, and precipitation data (including number of wet days) from CMIP5 simulations (Taylor et al., 2012) of the general circulation model IPSL-CM5A-MR (Dufresne et al., 2013), as well as nitrogen deposition (Lamarque et al., 2011) and CO_2 concentrations (Meinshausen et al., 2011), all for the representative concentration pathways (RCPs) 2.6, 4.5, 6.0, and 8.5. The climate input was bias-corrected against CRU-NCEP and interpolated bi-linearly from a spatial resolution of 2.5°×1.25° to 0.5°×0.5° (Ahlström et al., 2012). To bring soil pools into equilibrium, a 1200-year spinup period was conducted using cycled, detrended 1850–1879 climate data. Afterward, the time period 1900–2130 was simulated using transient climate. The species map of Brus et al. (2012) was combined with the forest age map of Poulter et al. (2018) to prescribe clear-cuts and plantings in the historical simulation period. This ensured a realistic representation of European forests in 2010 in terms of species, age distribution, and total forest cover per grid cell (Figure S2). We focused on forests that are currently available for wood supply. To map these areas, we defined the oldest age class of the age dataset (older than 140 years in 2010) as forests that are not available for wood supply, keeping this area stable for the simulation runs. This simple indicator resulted in a good approximation of country-reported areas of forests available for wood supply (Figure S3).

Disturbances were modeled as patch-destroying events with return intervals dependent on the forest type, namely 1000 years for broad-leaved deciduous species, 500 years for broad-leaved evergreen species, and 300 years for needle-leaved species (Pugh et al., 2019). An annual 1% increase in disturbance probabilities, starting in 2010, was assumed based on trends derived from satellite observations (Senf & Seidl, 2021a).

2.1.3 | Forest management, wood usage, and substitution effects

In the model, forest management is implemented through thinning and final harvest. Commercial thinnings are based on Reineke's self-thinning rule, while the rotation period depends on the forest type and target densities (Lindeskog et al., 2021; Reineke, 1933). This led to the model harvesting the total net annual increment (NAI) and thus constant carbon stocks. In reality, only roughly three-fourths of NAI are harvested each year, but with higher shares in productive countries like Finland (Forest Europe, 2020). We accounted for this by refraining from thinning on 20% of patches, which led to harvest levels close to observations (Figure S4). Simple coppice management was implemented, allowing broad-leaved species to resprout from the stumps after cutting (Gregor et al., 2022). Wood usage was implemented depending on the species type (Eurostat, 2023a). Specifically, 23% (2.5%) of the stem mass of conifers (non-conifers) was allocated to the long-lived product pool, and 9.4% (11.9%) to the medium product pool. 12% (49%) was used as fuel wood, while the remaining portion was returned to the atmosphere within 1 year. Forty percent of twigs and their leaves were harvested as fuel wood, and the remainder was left to decay on site together with the coarse roots (see Lindeskog et al., 2021). Each of the product pools had its own decay function, which accounted for the age of each product (Figure S5).

Substitution effects, which refer to avoided emissions due to the replacement of carbon-intensive products with wood products, were incorporated into the model based on Knauf et al. (2015): Present-day displacement factors of 1.5 tC/tC for materials and 0.67 tC/tC for fuels (denoting avoided emissions per ton carbon in the final product) were applied. The 1.5 tC/tC does not contain end-of-life handling. For this, we assumed 23% of materials to be land-filled at the end of their lifetime (Eurostat, 2023c), leading to a reduction in the displacement factor to 1.1 tC/tC to account for landfill emissions (Sathre & O'Connor, 2010). The other 77% were assumed to be used to generate energy. The displacement factors were discounted over time according to the RCPs, reflecting the projected decrease in carbon intensity of non-wood products over time (Brunet-Navarro et al., 2021; Gregor et al., 2022).

2.1.4 | Management options and management change

Six simplified management options were implemented (Figure 1). At the time of the final harvest, one of the options was chosen: replanting the same species composition (*base*), converting to needle-leaved evergreen, broad-leaved deciduous, broad-leaved evergreen, or coppice forests (*toNe*, *toBd*, *toBe*, and *toCoppice*), respectively, or refraining from the final harvest and leaving the forest untouched from this point in time (*unmanaged*). For the conversion to coppice, broad-leaved trees were cut down and allowed to regrow from the stumps, while needle-leaved trees were cut down, replaced with broad-leaved species, and managed as coppice from then on.

2.1.5 | Ecosystem services and indicators

We considered the ESs climate change mitigation, provisioning of habitat for biodiversity, local climate regulation, water availability, and wood production. They were quantified as in Gregor et al. (2022) and are briefly outlined in Table 1. Adaptation was covered implicitly by only including forest management options in the portfolios that ensured tree cover in 2100–2130 under all RCPs (see Section 2.2.1).

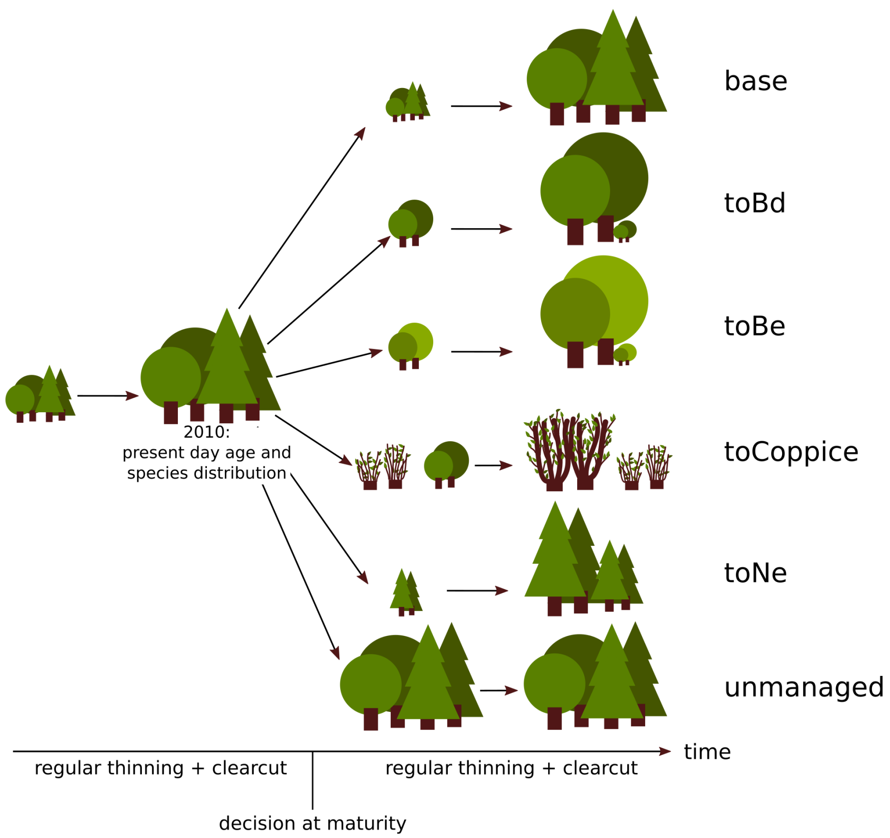

FIGURE 1 Six simplified management options, described in Section 2.1.4. A management decision was made for each stand after 2010 as soon as it reached maturity (i.e., a target density). The conversion was implemented by planting the most common species of each forest type for that grid cell.

TABLE 1 Ecosystem service indicators used in this study.

Variable name	Ecosystem service indicator	Explanation
Harvests	Total harvests	Total wood provision (including firewood, pulp, etc.)
HLP	Harvests for long-lived products	Wood provision for furniture, construction, etc.
Mitigation	Carbon sink plus material and energy substitution effects	Total carbon in vegetation, soil, litter, and products, plus avoided emissions from substitution with wood products
z_0	Surface roughness	Indicator for atmospheric conductance, influencing heat fluxes. Higher roughness results in higher fluxes
ET	Total evapotranspiration	Indicator for latent heat fluxes. More ET means more local cooling
Ψ_{soil}	Soil water potential	Yearly minimum of monthly values, indicator of water availability and drought stress
Bio	RCP-normalized mean combining the amount of coarse woody debris, Shannon entropy of 5 cm DBH classes, and number of trees with DBH >50 cm	Coarse woody debris, large trees, and an abundance of various tree sizes provide high numbers of habitats and resources (Cordonnier et al., 2014)

Abbreviation: DBH: diameter at breast height.

2.2 | Optimization

2.2.1 | Optimization for climate-smart forestry under uncertainty

We used robust multi-criteria optimization to develop forest management portfolios that provide all ESs in an optimally balanced way across a range of climate scenarios, leading to one portfolio per grid cell, viable for all RCPs (Gregor et al., 2022). This approach deals with the so-called "deep uncertainty" of climate change which avoids assigning probabilities to specific scenarios because it suggests a false sense of certainty (Lawrence et al., 2020). The inclusion of a wide range of emission scenarios is also endorsed by the IPCC (2023b). For each grid cell independently, ESs were measured via their respective indicators (*esi*) and for each RCP normalized across management options. Thus for each indicator, grid cell, and RCP, the best possible future value across all management options was 1 and the worst was 0. This normalization is essential to enable comparisons of indicators with varying units. The following linear program ("*ORIGINAL*") was used to derive an optimally balanced provision of ESs. It incorporated a trade-off parameter $\lambda \in [0,1]$ to combine the optimization of the worst and the average ES performance. Figure S1 shows a schematic display of the methodology and Figure S6 a visualization of an optimized solution for a grid cell.

For the optimization of a grid cell, we define a portfolio vector $\omega \in [0,1]^m$ that assigns a fraction of the grid cell to any of the $m = 6$ management options. We define the performance of a portfolio ω by considering the ES performances across all climate scenarios (|ESI| and |RCP| indicate the number of ES indicators and RCPs, respectively):

$$\text{performance}(\omega) := (1-\lambda)\min_{esi,rcp}\sum_s \omega_s q(esi,s,rcp) + \lambda \sum_{esi,rcp} \frac{1}{|\text{ESI}|\,|\text{RCP}|}\sum_s \omega_s q(esi,s,rcp) \quad (1)$$

Then, for each grid cell, we find the best ω by solving this linear program that optimizes the performance:

$$\max_{\omega}\ \text{performance}(\omega) \quad (2)$$

$$\text{subject to } \sum_{s \in S} \omega_s = 1 \quad (3)$$

$$\omega_s \geq 0 \quad \forall s \in S \quad (4)$$

$$\text{fpc}(2100, s, rcp) \geq \min(0.1, \text{fpc}(2010)) \quad (5)$$

where $S = \{base,\ toBd,\ toBe,\ toCoppice,\ toNe,\ unmanaged\}$

ω_s: Share of management type s in the optimized portfolio

$\text{fpc}(year, s, rcp)$: Foliar projective cover of the grid cell under management option s in RCP rcp in year $year$

$q(esi, s, rcp)$: Per grid cell normalized quality of esi for management option s in rcp

$\sum_{s \in S} \omega_s q(esi, s, rcp)$: Quality of *esi* for the whole grid cell for a portfolio ω under *rcp*

2.2.2 | Integrating the independent optimizations into one optimization to enable Europe-wide constraints

To allow for Europe-wide constraints and compensation between grid cells, the previously independent grid cells were integrated into one pan-European optimization. Still, the methodology resulted in one portfolio per grid cell, viable for all RCPs. The normalization was still conducted per grid cell. Figure 2 visualizes the methodology. We implemented the compensation between grid cells by maximizing the sum of grid cell performances ("*SUM*"). We restricted the study to equally weighted ESs and $\lambda = 0.2$ as a reasonable balance between maximizing the worst-case outcome and allowing some degree of compensation among ESs (Diaz-Balteiro et al., 2018). The optimization looks similar as *ORIGINAL* (Section 2.2.1), only that each variable received a grid cell index as well (e.g., $\omega_s^{(gc)}$):

$$\max_{\omega} \sum_{gc} \text{performance}\left(\omega^{(gc)}, gc\right) \quad (6)$$

$$\text{subject to } \sum_{s \in S} \omega_s^{(gc)} = 1 \ \forall \text{ grid cells } gc \quad (7)$$

$$\omega_s^{(gc)} \geq 0 \quad \forall s \in S, \forall \text{ grid cells } gc \quad (8)$$

$$\text{fpc}^{(gc)}(2100, s, rcp) \geq \min\left(0.1, \text{fpc}^{(gc)}(2010)\right) \ \forall \text{ grid cells } gc \quad (9)$$

The performance of each grid cell was calculated similar to Equation (1), now also including grid cell indices:

$$\text{performance}\left(\omega^{(gc)}, gc\right) := (1-\lambda) \min_{esi, rcp} \sum_{s} \omega_s^{(gc)} q^{(gc)}(esi, s, rcp) + \lambda \sum_{esi, rcp} \frac{1}{|\text{ESI}| \ |\text{RCP}|} \sum_{s} \omega_s^{(gc)} q^{(gc)}(esi, s, rcp) \quad (10)$$

As long as no Europe-wide constraints are added, this optimization is equivalent to *ORIGINAL* where each grid cell was optimized independently. For an additional assessment, we maximized the worst-case grid cell performance ("*MAXIMIN*"), where the burden was shared in a more balanced way (see Section S1.1).

2.3 | Adding Europe-wide hard constraints to the optimization

To account for the protection goals and harvest demands, we included hard constraints into the optimization. The term *hard* means that they had to be met under every RCP. They did not have to be met within every grid cell, but across the entire modeled area (encompassing the whole of Europe and not just the EU).

2.3.1 | Determining the required fraction of strictly protected forests currently available for wood supply

We deemed 66% of the European land area suitable for strict protection (forests, wetlands, shrublands, and grasslands). The remainder consists of artificial and barren land, water bodies, and cropland (Eurostat, 2023b). According to the biodiversity strategy, 10% of Europe's land area should be strictly protected, including all remaining primary and old-growth forests (European Commission, 2020). The identification and mapping of these forests is part of the EU strategy and relies on indicators such as deadwood, snags, and large trees, which vary depending on the forest type and region (European Commission, 2023). Here, we only optimized the area of forests available for wood supply. We assume that existing old-growth forests do not fall in this category and therefore lie outside of this considered area. Since old-growth forests cover about 1% of the land area (European Commission, 2021), they will contribute one percentage point to the 10% strict protection constraint. Consequently, assuming an equitable distribution of the other 9% among the remaining 65% of suitable land would require 13.8% of forests available for wood supply to be strictly protected in the future.

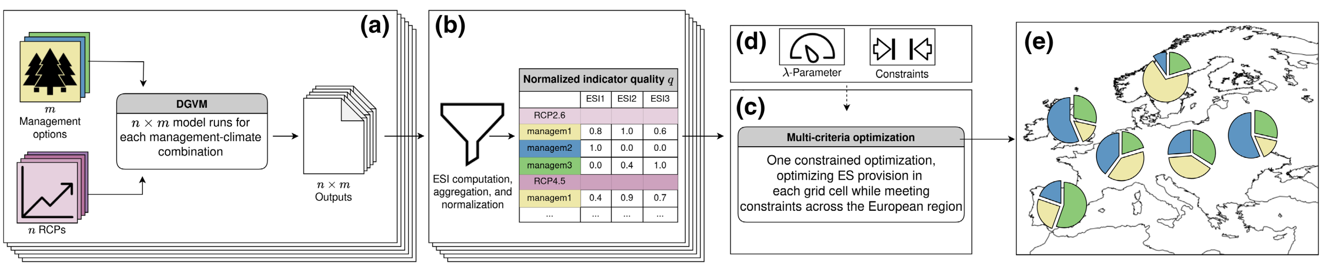

FIGURE 2 Visualization of the methodology, which computes one collection of portfolios for the entire modeled area. (a) For each grid cell, the *m* management options are simulated for the *n* RCPs, resulting in $n \times m$ model simulations. (b) ESIs are derived from model outputs, aggregated to the 2100–2130 mean, and normalized. Thus for each grid cell, there was one table containing the normalized values for all RCPs and management options. (c) One optimization for all grid cells, configured with Europe-wide constraints (d) computes (e) one set of optimized portfolios. Within grid cells, this ensures an optimally balanced provision of all ESIs across all RCPs and that the constraints are met, either on a per-grid-cell basis, or on a Europe-wide level, depending on the nature of the constraint, see Section 2.3. (d) The parameter $\lambda \in [0, 1]$ specifies the focus on the balanced provision of the ESI. A low λ focuses more on a balanced provision of ESIs while a high λ improves more the average ESI performance (see Section 2.2.1).

Note that the Forest Strategy also requires 30% of protection of the land surface and the promotion of "closer-to-nature forest management" (Larsen et al., 2022). As of 2024, 26% of European forests are under some form of protection (European Commission, 2021), undergoing various forms and degrees of management, or non-management (Verkerk, Zanchi, & Lindner, 2014). Achieving the 30% goal requires the allocation of additional forest areas with different degrees of protection and management, and the definition of regionally applicable implementations of closer-to-nature management. While these are important aspects, they were out of scope for this study.

2.3.2 | Formulation of the constraints

In addition to the unconstrained optimization ("*default-opt*"), we explored the impact of five Europe-wide constraints to be met by 2100–2130 under every RCP:

1. *min-harv*: Total harvests on the continent must remain at or above present-day values (Equation 11).
2. *min-harv-cell*: In every grid cell, harvests must remain at or above present-day values (Equation 12).
3. *min-hlp*: Harvests for long-lived wood products must remain at or above present-day values (Equation 13). This is relevant because the EU Forest Strategy promotes long-lived wood products and *min-harv* does not distinguish between wood usages (European Commission, 2021).
4. *all-constraints*: In addition to meeting constraints *min-harv* and *min-hlp*, 13.8% of the forest area available for wood supply must be left unmanaged (Equations 11, 13, and 14).
5. *all-constraints-protect-cell*: Like *all-constraints* but the unmanaged fraction needed to be met in every cell (Equations 11, 13, and 15).

$$\sum_{gc}\sum_{s} \mathrm{harvest}(gc, s, rcp, 2100) \cdot \omega_{s}^{(gc)} \geq \sum_{gc} \mathrm{harvest}(gc, 2010) \quad \forall\ rcp \in \{\mathrm{RCP2.6},\ \mathrm{RCP4.5},\ \mathrm{RCP6.0},\ \mathrm{RCP8.5}\} \tag{11}$$

$$\sum_{s} \mathrm{harvest}(gc, s, rcp, 2100) \cdot \omega_{s}^{(gc)} \geq \mathrm{harvest}(gc, 2010) \quad \forall\ rcp,\ \forall\ gc \tag{12}$$

$$\sum_{gc}\sum_{s} \mathrm{hlp}(gc, s, rcp, 2100) \cdot \omega_{s}^{(gc)} \geq \sum_{gc} \mathrm{hlp}(gc, 2010) \tag{13}$$

$$\sum_{gc} \mathrm{area}(gc) \cdot \omega_{\mathrm{unmanaged}}^{(gc)} \geq 0.138 \sum_{gc} \mathrm{area}(gc) \tag{14}$$

$$\omega_{\mathrm{unmanaged}}^{(gc)} \geq 0.138 \quad \forall\ gc \tag{15}$$

It is important to note that the decision to strictly protect forests in a grid cell in our simulations is made, for reasons of simplicity, at the time of the final harvest. These situations often occurred much later than 2030, the year in which the EU strategies would already demand a decision on which forests should be strictly protected.

2.3.3 | Implementation

The optimization was implemented in Python using *scipy* (Virtanen et al., 2020). We employed the *highs-ipm* solver (Huangfu & Hall, 2018) that was capable of solving the large optimization problem within reasonable time and memory consumption which was not the case for other solvers.

3 | RESULTS

3.1 | Model performance

The model represented the present-day situation in Europe adequately. Key vegetation variables, including gross and net primary productivity, vegetation carbon content, tree cover, evapotranspiration, and runoff aligned with literature estimates (Table S1). According to the forest age data, we identified 72% of forests as managed for timber, aligning with recent estimates that 75% of European forests are available for wood supply, with high agreement at the country level (Figure S3, Forest Europe, 2020). The simulated total forest vegetation carbon was 13.7 GtC for the Year 2010. This figure exceeds older estimates (11.6–13 GtC, Forest Europe, 2015; Liu et al., 2015; Pan et al., 2011) but remains below a recent estimate of 16.2 GtC (Figure S7, Santoro et al., 2021). Roundwood harvests were simulated as 572 million m^3/year on average for the period 2000–2010, comparable to observations (542 and 582 million m^3/year, Forest Europe, 2015, 2020). They also aligned on a country level for multiple periods (Figure S4).

3.2 | Results of the optimization

3.2.1 | Optimization without constraints

The unconstrained optimization *default-opt* led to diverse portfolios containing a shift toward more broad-leaved species from 39% to 56% and a transition to 26% unmanaged forests, far more than what is aimed for by the EU strategies (Figure 3). The proposed unmanaged forests were relatively evenly distributed throughout the continent. The portfolios led to a balanced provision of all ESs across all RCPs (Figures 7a and 8b). However, future (2100–2110) harvests dropped 23% below current values.

3.2.2 | Optimizations with constraints on harvest levels

The optimization *min-harv* successfully identified management portfolios that met the harvest constraint across all RCPs. This stands in contrast to *min-harv-cell* where the constraint had to be met in every grid cell and no feasible solution was found. The compensation among grid cells in our study thus appears to be pivotal to achieve such harvest levels in the future. The proportion of unmanaged forests was

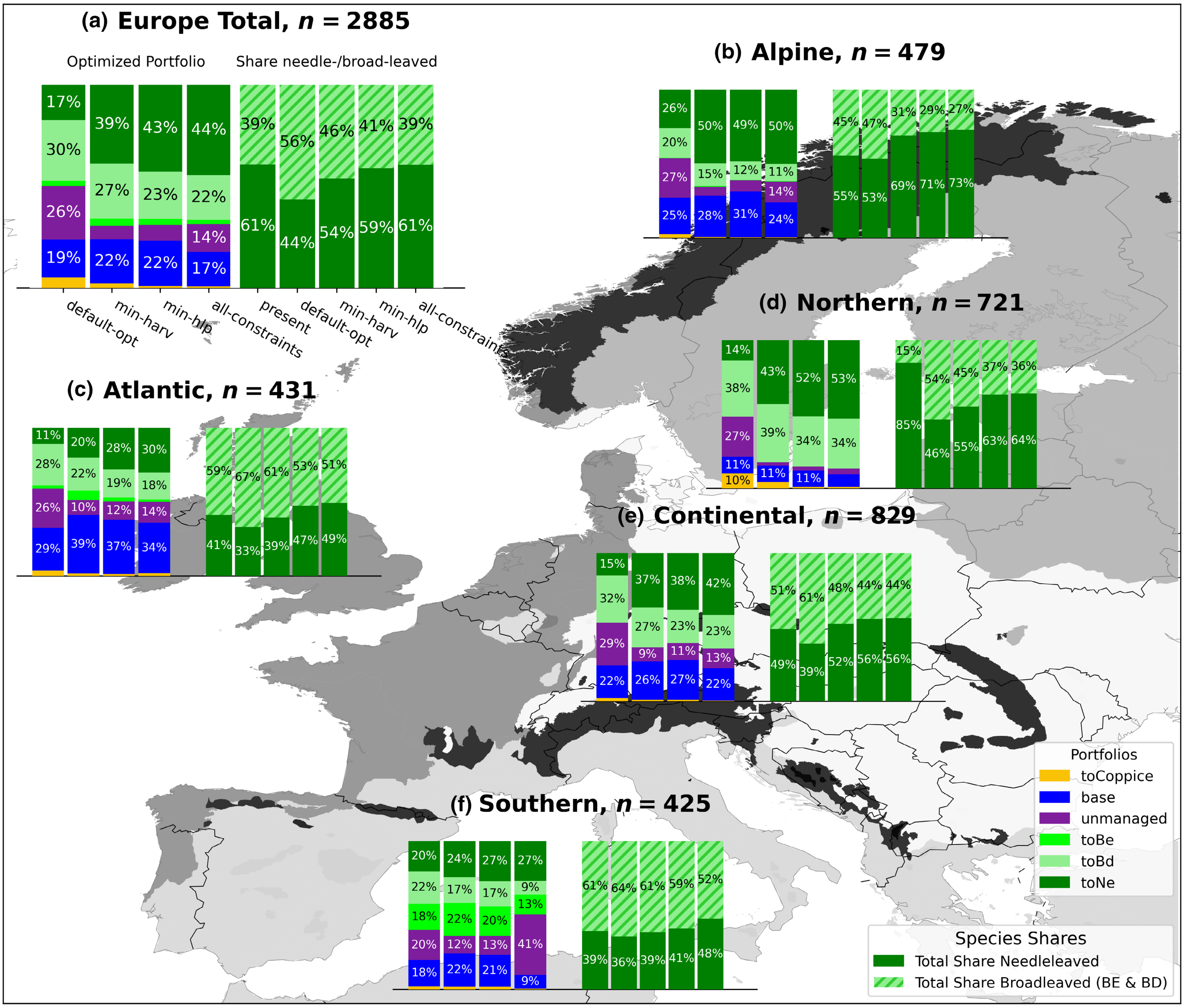

FIGURE 3 Portfolios of management options and species shares for optimizations with and without constraints for all of Europe (a) and different European regions (b–f). "Broad-leaved" contains broad-leaved evergreen and deciduous species. The six management options are shown in Figure 1. Note that the *default-opt* portfolios marginally differed from the results of Gregor et al. (2022) due to an improvement in the simulation of harvesting and the higher resolution. The number *n* refers to the modeled grid cells in the given region. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

reduced in the optimized portfolios, declining from 26% in *default-opt* to 6% in *min-harv* (Figure 3a). In *min-harv*, a total of 58% of grid cells exhibited no unmanaged forests, whereas in *default-opt*, this figure was merely 8% (Figure 4). There was a smaller transition to broad-leaved forests in *min-harv* (Figure 3), because needle-leaved forests enabled higher harvest volumes. Thus, they were needed to compensate for the other forest types in the portfolios. Coppice management practically vanished from Europe's forests in *min-harv*, compared with 5% in *default-opt*, and was replaced predominantly by needle-leaved forests for the same reason. This sustained importance of managed needle-leaved forests contrasts the strong shift toward broad-leaved species in *default-opt* and adaptation strategies for European forests.

The portfolios within grid cells were less diverse in *min-harv*, with two management options per portfolio in the median, compared with three in *default-opt*. Especially in northern Europe, many portfolios consisted of only one management option (Figure 5). The constraint for an increased provision of long-lived products (*min-hlp*) resulted in similar portfolios as *min-harv*, but with even higher proportions of needle-leaved forests (59%), also because of the higher suitability of wood from needle-leaved trees for long-lived products (Eurostat, 2023a).

3.2.3 | Combining constraints on harvests and strict protection

The *all-constraints* optimization successfully yielded portfolios with stable harvest levels and the minimal required level of

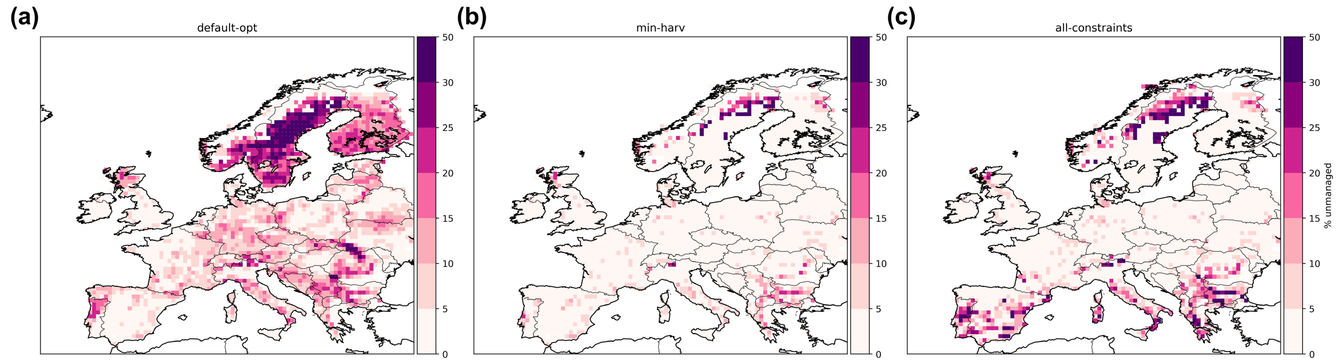

FIGURE 4 Share of unmanaged forests of the total land area of each grid cell in (a) the default optimization without any constraint, (b) when imposing the *min-harv* constraint on harvest levels, and (c) when imposing constraints on harvests, harvests for long-lived products, and unmanaged areas at the same time. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

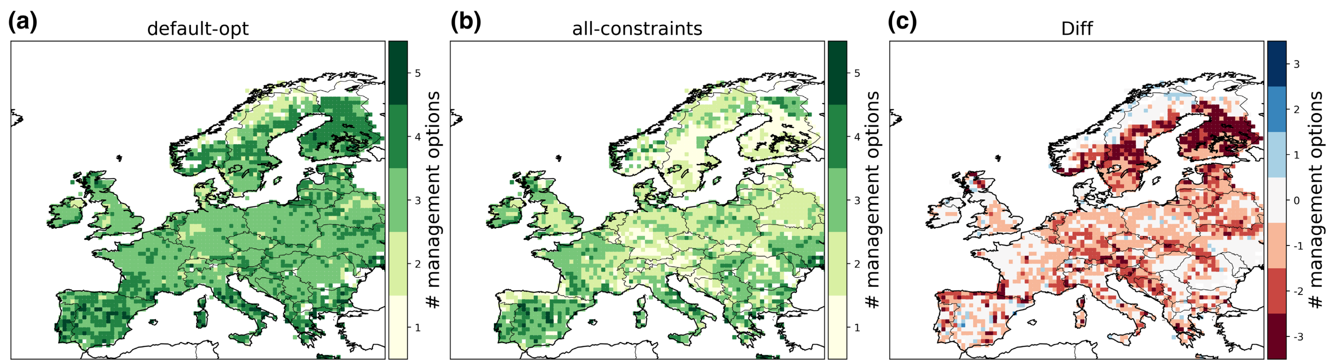

FIGURE 5 Number of management options in the portfolios without constraints (a), and for *all-constraints* (b). (c) The difference between the two (b–a). Including the constraints led to less diverse portfolios, sometimes even consisting of only one management option, particularly in the Northern region. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

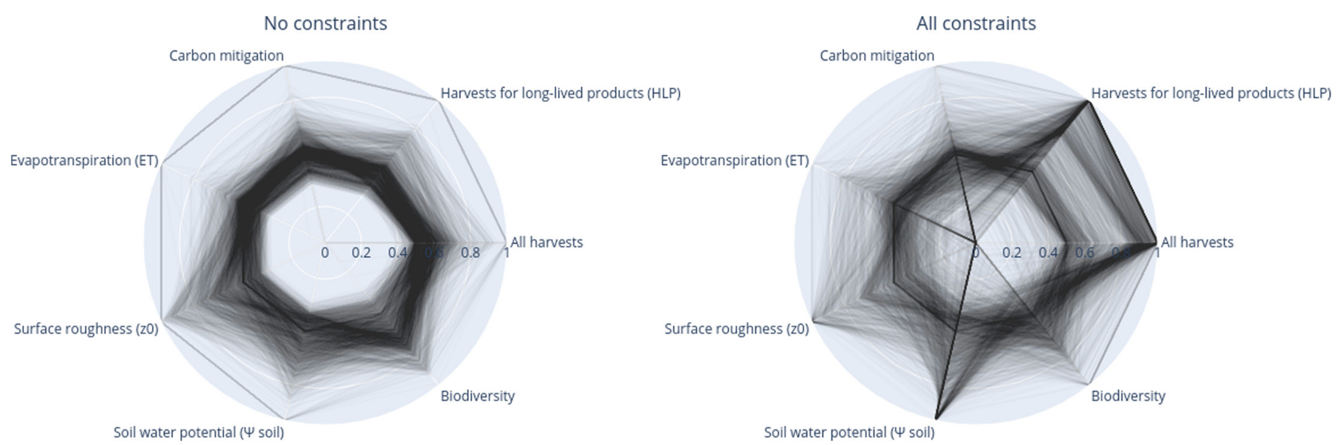

FIGURE 6 Provision of ecosystem services across all grid cells. Note that the ecosystem service provision is much more balanced in the unconstrained *default-opt* optimization, that is, almost all grid cells provide all ecosystem services in a balanced way (left). When imposing *all-constraints*, the provision is much more imbalanced (right). Various cells are required to utilize the maximal possible harvests, affecting also other ecosystem services, often negatively.

unmanaged forests across all RCPs (Figure 3a). However, unlike in *default-opt*, the unmanaged areas in *all-constraints* were unevenly distributed: 48% of grid cells, mainly in the north, lacked unmanaged forests. Meanwhile, southern portfolios contained 41% unmanaged forests (Figures 3 and 4), corresponding to the most unproductive regions in terms of wood production according to the model (Figure S8b). The share of needle-leaved forests was 61% and thus higher than in the other optimizations (Figure 3),

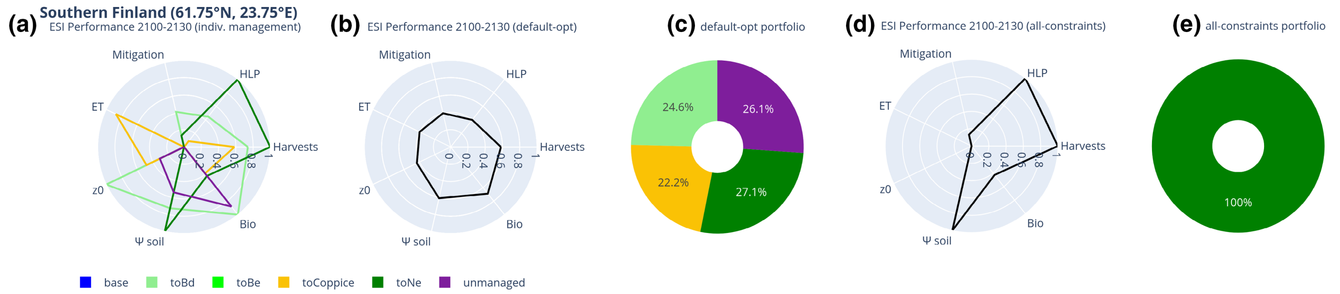

FIGURE 7 Example for a concrete portfolio computed by the methodology for a grid cell in southern Finland. (a) The ecosystem service provision in the worst case across all RCPs for each management option as measured by the normalized ecosystem service indicators (ESIs). (b) The worst-case ecosystem provision of the optimized portfolio without constraints (*default-opt*) and (c) the portfolio shares for *default-opt*. (d) and (e) are like (b) and (c), respectively, but for *all-constraints*. It is obvious that the ecosystem service provision in *default-opt* is more balanced than in *all-constraints* and that there is no risk diversification in *all-constraints*, as opposed to *default-opt*.

due to higher volumes of timber from needle-leaved forests and the higher suitability for long-lived products, both contributing to meeting the *min-harv* and *min-hlp* constraints (Eurostat, 2023a). Note that in the *all-constraints* optimization, the needle-leaved forests were mainly managed, whereas in *default-opt* a large fraction of the needle-leaved forests in the portfolios were also unmanaged (Figure 3a).

Enforcing strict protection within every grid cell (*all-constraints-protect-cell*) made the optimization infeasible. No portfolio allocation could meet the Europe-wide harvest targets while simultaneously achieving the strict protection targets in every grid cell under every emission scenario. Providing 13.8% strict protection in every grid cell required total harvests to decrease by at least 5%. It also forced all regions to focus on managed needle-leaved forests (74% overall, Figure S17) to compensate for the lower area of forests available for wood supply. This poses tremendous risks because of the low diversification of strategies, further exacerbated by the higher susceptibility of conifers and monocultures to various disturbance agents (Hlásny et al., 2021; Pardos et al., 2021; Schelhaas et al., 2010).

3.3 | Impacts on ecosystem service provision and burden sharing

The constraints resulted in a much less balanced provision of ESs (Figures 6 and 7). The productive regions in Fennoscandia, central, and eastern Europe needed to focus on supplying timber to others (Figure 8a,d). All ESs were impacted by the constraints in all RCPs. For example, the availability of coarse woody debris (one of three indicators used for biodiversity habitat provision) was much lower in those regions compared with the unconstrained optimization (Figure 8b). This highlights a potential threat for species that depend on this type of habitat.

The total carbon pool decreased virtually everywhere compared with the unconstrained optimization (vegetation + soil + deadwood, Figure 8c). The carbon pool also showed strong reductions compared with the present day for the regions that had to focus on timber provision (Figure 8f). This conflicts with the EU LULUCF (land use, land use change, and forestry) regulation demanding increases in forest carbon uptake in all member states (European Union, 2018). It was mainly driven by higher release of carbon from soils and litter due to climate change (Figures S11–S13), which in *default-opt* could be compensated for by the increasing vegetation and litter carbon stocks from the large areas of unmanaged forests.

This underscores that the burden of the constraints was not shared equally. In the grid cells that were most affected by the constraints, ESs were no longer provided in a balanced manner. These forests lost their multi-functionality and diversified portfolios, thereby hindering important risk diversification (Figure 7). To distribute the burden of the constraints more fairly, we applied the MAXIMIN instead of the SUM-method, maximizing the worst-case ES provision in each grid cell (Section 2.2.2). However, both optimizations yielded highly similar results, showing that the constraints significantly curtailed possibilities to enhance the provision of other ESs (Figure S16).

4 | DISCUSSION

Our methodology derives multi-functional forestry strategies in Europe under emission scenario uncertainty, providing suggestions for management portfolios that are viable for RCPs 2.6, 4.5, 6.0, and 8.5 simultaneously. While future work will also need to consider uncertainty related to the choice of climate and vegetation model, our results already suggest that constraints on stable harvest levels and protection goals inspired by EU strategies heavily restrict the possibilities to provide other ESs under climate change. Furthermore, achieving these targets conflicted with the goal of multi-functionality and with carbon sink targets, complementing findings of previous studies (e.g., Blattert et al., 2023). It is noteworthy that while the EU strategies outline plans for 2030, we examined potential long-term consequences in 2100–2130.

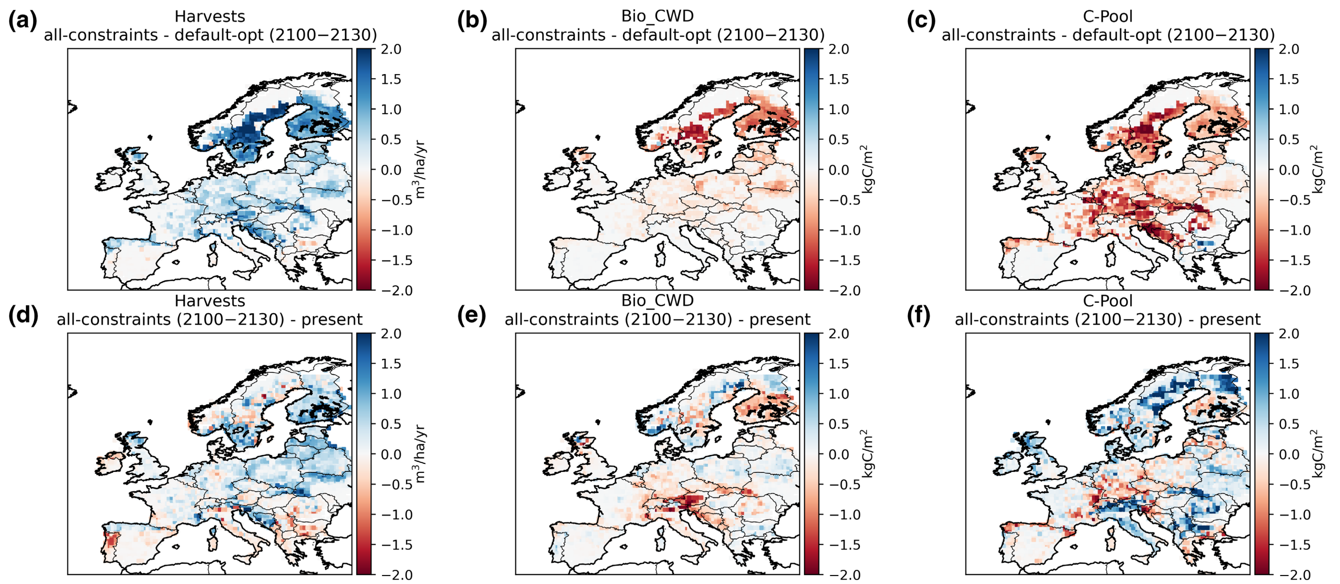

FIGURE 8 Comparison of ecosystem service provision between constrained optimization, unconstrained optimization, and present day. Modeled harvest provision (in m^3 ha^{-1} $year^{-1}$ dry biomass) in the future (2100–2130) for RCP4.5 for *all-constraints* compared with *default-opt* (a) and to present-day (d). The same is shown for coarse woody debris (b and e) and the forest carbon pool (vegetation + litter + soil, c and f), in kgC / m^2. Similar results were obtained for the other RCPs (Figures S14 and S15). Map lines delineate study areas and do not necessarily depict accepted national boundaries.

4.1 | Reconciling demands on forest protection, wood production, and mitigation

The unconstrained *default-opt* optimization indicated that leaving 26% of currently managed forests untouched benefits multiple ESs across all RCPs (Figure 3). This exceeds the EU Biodiversity Strategy requirements but implies a drastic reduction in harvests, reducing economic activity and the important role of wood products in climate change mitigation (Grassi et al., 2021; Gregor et al., 2024). To maintain current Europe-wide harvest levels, we found that inter-regional cooperation is critical, because the harvest constraint could only be met when allowing such cooperation (*min-harv*) and not when it was imposed on every grid cell independently (*min-harv-cell*). The constraint *min-harv* decreased the proposed shares of unmanaged forests to 5%, conflicting with strict protection goals (Figure 3). This was reconciled by the constraint on strict protection (*all-constraints*). However, the burden was not shared equally among regions. Some regions, particularly in the north, had to focus almost exclusively on wood production to compensate for decreased harvests due to strict protection elsewhere. This bears risks for nature protection in those regions (Figure 4b).

Due to climate change, the forest carbon pool declined in many regions (Figure 8f), driven by increased decomposition of litter and soil, especially under higher RCPs. In *default-opt*, this decrease was offset by higher shares of unmanaged forests, which increased vegetation and deadwood pools. In *all-constraints*, however, the carbon pools of the numerous, mainly northern, regions declined compared with present-day values (Figure S10), conflicting with the EU LULUCF regulation that aims to increase forest carbon uptake in all member states (Figure 8; European Union, 2018). Maintaining a European forest sink could be imposed as an additional hard constraint in the optimization, but this would further limit management options. Since from an atmospheric perspective, it is not relevant where the carbon is taken up, LULUCF goals could theoretically be reformulated to allow compensation between states. Although this could facilitate collaboration to achieve the desired atmospheric CO_2 reductions while optimizing other ESs, this would introduce additional problems of responsibility and accountability.

4.2 | Effect on other ecosystem services, multi-functionality, and the distribution of managed and protected areas

Applying *all-constraints* strongly reduced the diversity of the portfolios compared with *default-opt* (Figure 5). Many portfolios, particularly in Fennoscandia, contained only one or two management options, because there were only few feasible solutions to the constrained optimization. This made it rarely possible to include other management options for risk diversification and for the benefit of other ESs. At the grid cell level, a balanced provision of ESs was no longer guaranteed (Figures 6 and 7), conflicting with the aim of the EU strategies to foster multi-functionality. For instance, the harvest constraints significantly reduced the amounts of deadwood and large trees in the future, especially in southern Fennoscandia (Figure S9) where timber production was prioritized to meet the Europe-wide constraint. This poses a significant threat to biodiversity as many species require these habitats (e.g., Berg et al., 1995). This issue was exacerbated by faster decay of deadwood under higher RCPs (Figures S11 and S12). The performance of other ESs also declined, showing that focusing on wood production will undermine other ESs and vice versa, illustrating a clear trade-off.

The regional imbalance of unmanaged sites, with many in the southern regions and few in the rest (Figure 4c), contradicts the goal to protect various ecosystems throughout the continent (European Commission, 2020). The strictly protected areas in *all-constraints* were mainly allocated to the least productive regions. This would likely bias the assemblage of species benefiting from protection (see, e.g., Hämäläinen et al., 2018). To address this, we also constrained the optimization to uniformly distribute the strictly protected areas, but the *all-constraints-protect-cell* optimization was mathematically infeasible. It could be resolved with an at least 5% reduction in harvests across Europe but portfolios then strongly focused on needle-leaved forests (74% of all forests). Although a 5% reduction in harvests might be acceptable given the significant improvement in nature protection in this scenario, promoting managed needle-leaved forests contradicts current scientific evidence and policies targeted at improving forest resilience through mixed forests including broad-leaved species, as discussed below.

A land-sparing approach, as suggested by the optimization, can have benefits because assigning focus regions for certain targets can help using forests optimally by leveraging regional advantages (Gutsch et al., 2018; Lessa Derci Augustynczik & Yousefpour, 2021). This does not inherently conflict with multifunctionality, as for instance strictly protected areas can still provide multiple ESs apart from biodiversity provision, such as water regulation, or local climate regulation. Our results, however, suggest such a strong segregation that hinders promoting multi-functional forestry, because large regions had to focus on timber provision at the expense of other ESs. Even changing the optimization methodology—affecting how the burden of the constraints could be shared across regions—had practically no effect on the portfolios (Figure S16). This further underscores that the constraints heavily limited the forestry options in Europe and that intricate trade-offs need to be made.

Harnessing synergies between different aspects in the same region through land sharing might be necessary. In that regard, some biodiversity habitats and other ESs are compatible with some wood production (e.g., as part of close-to-nature forestry), for instance, by improving landscape-scale heterogeneity, retaining habitat trees and deadwood, and fostering species and structural diversity (e.g., Biber et al., 2020; Larsen et al., 2022; Mäkelä et al., 2023; Schall et al., 2018). Achieving such synergies would help meet wood demands while providing numerous ESs. This approach could make regions that we deemed crucial for timber provision more multifunctional and, with proper measures, also contribute to the 30% protection target.

The "triad" approach aims to combine and enhance land sharing and sparing, by combining intensive and extensive management with strict reserves, based on biodiversity-yield assessments (Betts et al., 2021). Nonetheless, while these are desirable approaches to optimally use forest land, they cannot fully resolve the issue of excessive demands imposed on forests that we identified in our simulations. Therefore, additional measures are necessary to alleviate pressure on forests, as discussed below.

Besides protection and multi-functionality, the EU also plans to promote broad-leaved species for their greater resilience (European Commission, 2021). This transition is encouraged by the scientific literature (Astrup et al., 2018; Felton et al., 2010; Hlásny et al., 2021; Pardos et al., 2021; Schelhaas et al., 2010; Schwaab et al., 2020). It was also reflected in *default-opt*, which considered multiple ESs and a higher vulnerability of needle-leaved forests to disturbances (Figure 3a). However, the constraints prevented this forest conversion and maintained the dominance of conifers due to their higher wood volumes and suitability for long-lived products (Eurostat, 2023b). This would hinder adaptation to climate change, especially in regions where needle-leaved species are projected to suffer more.

An important caveat is that, while we did account for increases in disturbance rates and higher baseline rates for needle-leaved forests, these rates did not depend on the specific species or forest structure. A more realistic representation of disturbances—especially for spruce monocultures—would likely decrease the share of needle-leaved forests in the optimized portfolios, making the constraint on harvests for long-lived products harder to meet.

4.3 | Ways forward

Although further studies should validate our results with model ensembles, our study already highlights the significant challenges of reconciling current forest demands without additional interventions. There are numerous options to address the conflicts that should be considered by future studies and policies: One potential avenue to alleviate the impact of the constraints is increasing the proportion of wood used for long-lived products. This involves promoting innovative products made from lower-quality wood and smaller-diameter trees (e.g., Ramage et al., 2017). The otherwise beneficial shift toward more broad-leaved trees also decreases the provision of long-lived wood products, affecting the economy and mitigation. This may be addressed by promoting new products derived from broad-leaved species (e.g., Hassan & Eisele, 2015). Also the increased material wood usage of needle-leaved trees would enable an increased share of broad-leaved species.

However, these measures conflict with Europe's current energy mix. Woody bioenergy plays a crucial role in renewable energy supply, with a significant fraction sourced from primary wood (Camia et al., 2021; European Commission, 2021). About one-fourth of all roundwood harvests are currently used for fuel wood, providing only 6% of the gross final energy consumption (Eurostat, 2023a; Scarlat et al., 2019). While increased rates of recycling and end-of-life energy recovery would help, these rates are already high in many EU countries (Eurostat, 2023c). Moreover, renewables like solar and wind offer power densities that are orders of magnitude higher than that of bioenergy (Smil, 2015), making their promotion paramount to meet future energy demands while achieving climate and biodiversity goals for forests.

Projected increases in wood demand are also driven by packaging, single-use products, expansion of living areas, and short lifespans of wood products due to aesthetic reasons (Bierwirth & Thomas, 2015; FAO, 2022b; Hill et al., 2022). Here, stable harvest levels already required intricate trade-offs, underscoring the need to address these increasing demands. Our study aligns with broader research highlighting that true sustainability in terms of resource usage, biodiversity, and ESs necessitates a reduction in demands (e.g., Hickel & Kallis, 2020; Richardson et al., 2023). It is also crucial that forest-related actions in Europe avoid an offshoring of impacts (Berlik et al., 2002; Mayer et al., 2005). While the strategies explicitly forbid activities leading to deforestation in other regions of the globe (European Commission, 2020), substantial risks remain (Cerullo et al., 2023; Rosa et al., 2023). Consequently, concerted efforts are required to balance resource demand and supply within Europe, or to establish frameworks that holistically account for resource footprints and prevent externalizing impacts.

The fact that "only" 73% of the net annual increment is harvested in Europe's wood-supplying forests suggests potential for increased harvesting (Forest Europe, 2020). Studies have already suggested a necessary intensification of harvests outside of strictly protected areas to compensate for reduced wood supply areas due to protection goals (Pikkarainen et al., 2024). However, this could weaken the ecological benefits of the strategies (Räty et al., 2023). Moreover, Europe's felling rates (harvests per forest area) are already high compared with global rates (Figure S18) and increasing them has been linked to adverse effects on biodiversity, carbon sequestration, and recreation (Mäkelä et al., 2023; Schulte et al., 2022; Seppälä et al., 2019; Skytt et al., 2021; Soimakallio et al., 2021; Verkerk, Mavsar, et al., 2014). Critically, higher felling rates would reduce the buffer between harvests and net annual increment that keeps forests a carbon sink. While increased harvests could offer mitigation benefits through substitution effects, these benefits are likely short-lived (Brunet-Navarro et al., 2021; Gregor et al., 2024; Harmon, 2019).

Furthermore, the area available for wood supply (currently 75%) could be increased, but this would conflict with conservation goals. Additionally, many unmanaged forests are in unproductive or inaccessible areas, limiting their wood supply potential (Verkerk, Mavsar, et al., 2014). Supporting the ongoing reforestation trend in Europe, endorsed by the EU's plan to plant 3 billion trees by 2030, could alleviate pressure on forests (Forest Europe, 2020). However, it will take decades for these trees to provide timber. Furthermore, it is crucial that biodiversity considerations guide such plantings, for example, in terms of species selection.

4.3.1 | Uncertainty assessment

Our methodology derives forest management strategies under deep uncertainty, providing solutions that are viable under all considered climate scenarios. Further studies should use an ensemble of vegetation models that might consider different processes in different levels of detail to address uncertainty in the projections better. Additionally, studies with LPJ-GUESS for instance emphasize the importance of using also an ensemble of climate projections from general circulation models as forcing data due to significant variation among them for the same RCP (Ahlström et al., 2012). Finally, model parameter uncertainty was not considered here, though for LPJ-GUESS a smaller impact compared with the uncertainty from environmental data has been suggested (Oberpriller et al., 2022). The advantage of the robust optimization concept is that it can be fed not only with simulations of multiple RCPs, but also with simulations from multiple models and forcings. The outcome would again be one set of portfolios, providing the best options across all RCPs, forcings, and models. Also, diversity in the aims of decision-makers could be included (e.g., Knoke et al., 2023). This could be done by including multiple sets of preferences for ecosystems, for instance, with higher importance of water regulation on arid regions. Including all aspects, however, would pose significant computational challenges.

4.3.2 | Regional strategy development

We examined how legislative constraints impact the development of future forest management strategies at a coarse, Europe-wide scale. This work establishes a foundation for specific applications: Once general strategies, like broadly allocating protected areas among member states, are outlined, our methodology can be applied at a finer scale. At this level, detailed representation of terrain, soil, forest types, and management practices become crucial (Levin, 1992; Turner et al., 1989, 1996). Thus, in a next step, it may be beneficial to re-integrate fine-scale results into the broader framework, to address scaling issues (Seidl et al., 2013).

Our optimization can facilitate strategy development for specific regions through more detailed forest simulations. This should include more detailed changes in management regimes (e.g., targeting specific age classes), wood usage patterns, and species selection. Also, age and species composition, landscape heterogeneity and additional biodiversity indicators (e.g., Cordonnier et al., 2014; Müller & Bütler, 2010) should be assessed for estimating conservation values (Neugarten et al., 2024).

Furthermore, regional objectives and constraints can be included, such as connectivity of protected areas as endorsed by the EU strategies, and minimum reserve sizes to capture natural disturbance regimes ("minimum dynamic area," Pickett & Thompson, 1978). Additional constraints could include targets for deadwood availability, carbon sinks and constraints for the 30% (non-strictly) protected areas.

From a computational perspective, we propose a hierarchical approach. Here, we simulated and optimized 2885 grid cells spanning the entire continent. These results can inform assessments on a member-state level. Taking France as the largest EU country as an example, applying our methodology on a 10 km^2 scale is computationally feasible (i.e., 5400 grid cells). This enables strategy development for individual countries independently which can then guide regional optimizations based on high-resolution data of forest structure, existing old-growth forests, ownership structure, and accessibility, to formulate practical strategies.

5 | CONCLUSION

In this study, we combined forest management simulations with robust multi-criteria optimization to develop strategies for multifunctional forests in Europe under climate change. The derived management portfolios are viable for a range of emission scenarios simultaneously, and they reconcile demands for wood production and EU targets for biodiversity protection, climate change mitigation, and ES provision. Our approach used simplified management scenarios, moderate constraints, extended time scales, and ignored potential uncertainty from multiple models. Nonetheless, our findings already highlight significant conflicts between the various demands placed on European forests, requiring additional measures to alleviate the pressure on forests. They also emphasize the need for coordinated efforts to address the various objectives outlined in EU strategies. Moreover, our results offer insights that can inform the development of forest management strategies at a regional scale. By incorporating more detailed forest management and wood usage scenarios, along with detailed constraints, our methodology can help investigate how innovative practices may help harmonize or alleviate the conflicting demands on European forests. Our approach offers a tool for the necessary integrated view of conflicting climate, biodiversity, and bioeconomy demands.

AUTHOR CONTRIBUTIONS

Konstantin Gregor: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; resources; software; visualization; writing – original draft; writing – review and editing. **Christopher P. O. Reyer:** Conceptualization; methodology; writing – review and editing. **Thomas A. Nagel:** Conceptualization; writing – review and editing. **Annikki Mäkelä:** Writing – review and editing. **Andreas Krause:** Writing – review and editing. **Thomas Knoke:** Conceptualization; methodology; writing – review and editing. **Anja Rammig:** Conceptualization; funding acquisition; methodology; project administration; resources; supervision; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available at https://doi.org/10.5281/zenodo.12673490.The code to run the optimization based on the model outputs and reproduce the figures from the paper is available at https://doi.org/10.5281/zenodo.12675040.

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