A standardised approach towards selecting forests for strict protection in Germany

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RESEARCH

A standardised approach towards selecting forests for strict protection in Germany

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Abstract

Forests serve as key ecosystems for biodiversity conservation and climate change mitigation. The achievement of ambitious biodiversity targets, such as the EU Biodiversity Strategy's target of strictly protecting 10% of the EU's land area, requires the systematic identification of key forest areas for protection. However, clear guidance on selecting such forests is lacking. In this study, we address this issue by developing forest protection scenarios based on different conservation criteria and data from the third German National Forest Inventory. We used state-of-the-art indicators capturing different aspects of biodiversity: forest structure, habitat conservation, legal protection status, and the presence of old forests, alongside sociopolitical considerations including public ownership and equal distribution across federal states. Using a standardised, multi-criteria approach, we systematically identified forest areas for strict protection that best complied with each scenario's criteria. Each scenario was then tested against three targets: strictly protecting 5%, 10%, and 30% of the total forest area. Our analysis revealed that, despite the application of different selection criteria in each scenario, the characteristics of the forests ultimately selected showed only moderate differences. Achieving higher protection targets, such as 10% or 30%, required including stands with lower conservation value, as evidenced by lower criterion overlap within selected forest areas. Although existing forest habitat types with no or minimal management requirements (i.e. 15.24% of German forest area) could theoretically serve as the selection pool for the 5% and 10% targets, sociopolitical considerations, such as having an equal spread of protected areas across federal states, required the incorporation of other forest areas. Overall, our findings provide a foundation for implementing Germany's and the EU's strict nature protection targets and demonstrate that multiple pathways exist to achieve them. However, strategic compromises may be required as the goals become more ambitious.

Keywords Strict forest protection · Conservation planning · Biodiversity indicators · National forest inventory · Multi-criteria analysis · EU biodiversity strategy

Introduction

Climate change and biodiversity loss are two interconnected global challenges (Pörtner et al. 2023). Biodiversity loss has already crossed the global boundary beyond which irreversible consequences for nature and humans are likely, and climate change is projected to cross such a threshold in the near future (Rockström et al. 2023; Steffen et al. 2015). Forests play a crucial role in both challenges, contributing to climate mitigation (Guug et al. 2025; Steffen et al. 2015), being strongly affected by climate change (Anderegg et al. 2022), and providing habitat for more than two-thirds of the world's mammal, bird, and amphibian species (FAO, UNEP 2020).

In addition to climate change, other drivers including land-use change and the historical focus on timber production (Steffen et al. 2015), have substantially reduced forest biodiversity (Schulze et al. 2015) and carbon stocks (Erb et al. 2018). This issue is particularly prevalent in Europe and other temperate and boreal regions, which have a long history of intensive forest use (Curtis et al. 2018). Thus, in Europe, which has few remaining primary forests (Sabatini et al. 2021), biodiversity conservation efforts focus on protecting natural processes and enabling natural regeneration.

Recognising that strictly protected forest areas where natural processes can occur are vital for biodiversity

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conservation in temperate forests (Bauhus et al. 2009; Sabatini et al. 2018), various international and national biodiversity strategies have been outlined, with ambitious protection targets (BMUB 2007; European Commission 2020). The EU Biodiversity Strategy for 2030 aims at protecting at least 30% of marine and terrestrial areas, with one-third of that area (10%) to be strictly protected, including all remaining primary and old-growth forests (European Commission 2020). In Germany, the National Biodiversity Strategy sets a target of 5% of the country's forested area under strict protection by 2030 (BMUB 2007; BMUKN 2024). Under the European Commission's working definition (European Commission, 2022), strictly protected areas correspond broadly to IUCN categories Ia (Strict Nature Reserve), Ib (Wilderness Area), and II (National Park) (Dudley 2008). Thus, strict protection implies restricting human intervention to activities essential to supporting natural processes rather than a complete absence of management.

These ambitious targets require systematic approaches to identify which forests to protect. However, apart from the requirement to include all primary and old-growth forests, clear guidance on how to implement strict protection in Germany's forests is lacking (European Commission 2023). The existing policies do not specify how to select additional areas, where they should be located, the minimum size of protected areas, or which ecological features should be prioritised.

Addressing this implementation gap requires understanding which factors make forest areas suitable for strict protection. From an ecological perspective, not every forest area is equally suitable for strict protection that allows natural forest development. The potential to foster biodiversity through natural processes depends on factors such as a forest's history, its current condition, and the surrounding landscape context and connectivity (Huxel and Hastings 2008; Rodrigues and Gaston 2008). These factors translate into multiple criteria that can guide the selection of forest areas suitable for strict protection. Moreover, different protection strategies may prioritise these criteria differently depending on their conservation objectives (Carver et al. 2021).

Ecological criteria include, first, the current conservation value of forest areas. Forests approaching old-growth conditions with complex structure, large amounts of deadwood, rare habitat types, or high species richness have high ecological value (Engel et al. 2016; Schultze et al. 2014). Likewise, forests with high structural diversity, heterogeneous age structures or diverse tree species composition are strongly associated with high biodiversity (Ćosović et al. 2020; Gao et al. 2014; Zeller et al. 2023). Because forests in Germany have historically been mostly young and even-aged, complex forest structures and old-growth forests are currently underrepresented (Sabatini et al. 2021, 2018). Thus, restoring forests with a high level of structural features is a key criterion for improving nature conservation (Carver et al. 2021; Navarro and Pereira 2012).

Upgrading existing legally protected areas that currently have a lower protection status (e.g. Natura 2000 sites) to strictly protected areas offers strategic advantages by providing established conservation infrastructure (Friedrichs et al. 2018; Gensch et al. 2025) and the potential to improve conservation effectiveness. Although protected areas represent a key strategy for biodiversity conservation (Adams et al. 2019; Branquart et al. 2008), their effectiveness is not always achieved in practice (Zehetmair et al. 2015). Adverse impacts on Natura 2000 sites, for example, have been attributed to ongoing forestry activities (Ellerbrok et al. 2025), which could be eliminated by stronger protection.

In addition to ecological criteria and existing protection status, sociopolitical factors determine feasibility and acceptance of strictly protected areas. For example, the designation of protected areas, which falls under the jurisdiction of Germany's federal states, involves complex administrative and legal processes (Stoll-Kleemann 2001b) and has historically been accompanied by conflicts between conservation objectives and forestry uses (Stoll-Kleemann 2001a; Winkel et al. 2015). These challenges show that forest ownership is a key criterion when selecting sites for strict protection. Germany's National Biodiversity Strategy explicitly expects public forests to contribute disproportionately to biodiversity conservation targets (BMUKN 2024), as designation in public forests generally involves fewer ownership conflicts, whereas private forests more often require negotiation, compensation, and contract-based instruments (Demant et al. 2020; Tiebel et al. 2021).

Moreover, it is important for public support and social acceptability that the potential adverse impacts of protected areas, such as loss of profitability, are equally distributed (Jones et al. 2022). In Germany, equitable distribution across federal states will be essential for framing strict protection as fair and politically acceptable.

However, no clear framework exists for systematically combining these criteria to achieve strict protection targets, and it remains unclear how different prioritisation strategies lead to different forest selections and what trade-offs they entail. To address this gap, we developed a hierarchical scenario framework exploring alternative criteria for selecting forests for strict protection. This includes individual scenarios focusing on forest structural diversity, habitat conservation value, existing legal protection status, or forest age, and sociopolitical scenarios prioritising public land or equal distribution across federal states. We then integrated multiple-criteria scenarios that meet diverse conservation priorities simultaneously.

The main objectives of this study were as follows: 1) to systematically identify suitable forest areas for strict protection across scenarios with different conservation foci using data from the German National Forest Inventory 2012 (NFI3), and 2) to analyse the implications of these alternative scenarios for achieving national and EU biodiversity protection targets. Specifically, we aimed to test three targets: 5% of forest area, aligned with Germany's National Biodiversity Strategy; 10%, assuming a proportional contribution of forests to the EU's 10% strict protection goal; and 30%, assuming full contribution of forests to the EU's strict protection goal (given that forests cover approximately 30% of Germany's land area).

Material and methods

Study region

Germany is one of the most densely forested countries in Europe (32% of land area, 11.4 million ha) and forest use has a long history. Compared to other land uses, forests in Germany are relatively close-to-nature ecosystems and still harbour much terrestrial biodiversity (Gibson et al. 2011; Lindenmayer 2009), while also providing significant timber resources and employment. Additionally, 48% of the forest area is privately owned, 19% is community forests, and the state (29%) and the federal government (4%) own the remaining area. Conifers, including both spruce (25%) and pine (23%), grow on more than half of the forest area, in many places out of their natural distribution range. Broadleaved tree species are found on 45% of the forest area, with beech (16%) and oak (10%) being the most widespread species (BMEL 2021).

Data

We used freely available data from the third German National Forest Inventory (NFI3), which was carried out from 2011 to 2012 (Thünen Institute 2012). The NFI3 is a large-scale sample-based forest inventory utilising a systematic terrestrial grid of permanently marked sample points. The primary sample unit is a square cluster with a side length of 150 m (tract). The tract corners (or plots) that intersect with forest are the centres for the measurements and the focus of our analysis. We used all inventory plots categorised as forests, giving 59,848 plots (forest stands) in total. As part of the NFI3, for each inventory plot, various forest characteristics were measured, such as tree dimensions, deadwood, tree species, and tree age. Additional variables were modelled from the sampled data, such as tree height and the degree of naturalness. Moreover, governance-related information regarding the location, federal state (in German 'Bundesland'), and ownership class of each plot is available. We used variables at the stand level, as well as governance-related information at the regional or federal state level. A detailed list of the variables used is provided in the Supporting Online Material (SOM) Table 1.

Developing the nature protection scenarios

To cover the different foci that nature protection strategies may have, we developed hierarchical scenarios that each encompassed different objectives for protection (Fig. 1). To represent the specific role of forest structure, high existing habitat conservation value, existing areas with legal protection of specific species and areas, as well as old forests, we designed scenarios called 'Forest Structure', 'Habitat Conservation', 'Protection Status', and 'Old Forests', respectively, in addition to a combined scenario named 'Conservation Value'. To cover sociopolitical aspects, scenarios were designed focusing on 'Public Forests' (i.e. protecting public-owned forests only) and 'Equal Distribution' (i.e. having an equal share of protected areas across federal states). Finally, a scenario called 'Combined A' was designed to include all previous criteria, while 'Combined B' excluded the criterion of equal distribution across federal states.

These nature protection scenarios were applied under three assumptions regarding the percentage of forest area to be strictly protected. The first assumption was based on the protection of 5% of the forest area, in line with Germany's National Biodiversity Strategy. Secondly, two interpretations of the 10% protection target in the EU Biodiversity Strategy 2030 were explored, one assuming that 10% of forest areas should be strictly protected and the other that 10% of the total German land area must be protected solely on forested land, resulting in approximately 30% of forest area being strictly protected.

Scenario: 'Forest Structure'

This scenario labelled 'Forest Structure' focuses on forest structural diversity, which is an important aspect of biodiversity. We used the Forest Structural diversity Index (FSI) from Storch et al. (2018) to derive the criteria for this scenario from the German NFI3 data. Individual NFI3 plots were grouped together based on NFI3 categories, such as the number of canopy layers, to aggregate the data from individual sample points to higher levels (Storch et al. 2018). The FSI scores ranged from 0.04 to 0.55, with 1 representing the highest possible value (SOM Fig. 1). The highest structural diversity was observed in older forest stands, especially those aged over 180 years (mean FSI: 0.24). High mean FSI scores were also observed in multi-layered forest stands (mean FSI: 0.22), and those in the late developmental phases 4 (mean FSI: 0.24, in German 'Terminalphase') and 5 (mean FSI: 0.22, in German 'Zerfallsphase'). Finally, high mean FSI scores were

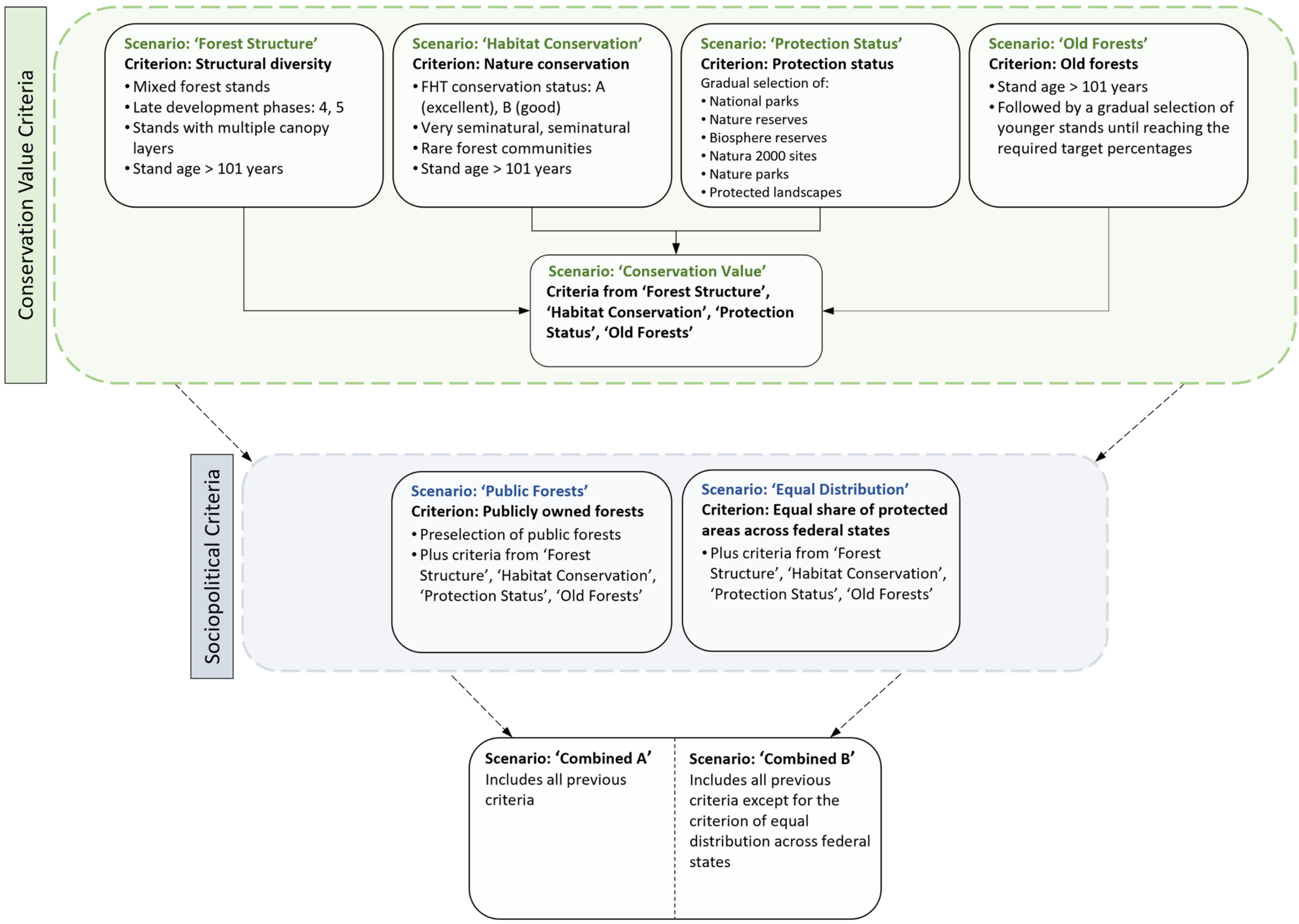


Fig. 1 The hierarchical scenario framework developed in this study. The top-level scenarios address various criteria related to the conservation value of forests, the second level incorporates sociopolitical criteria, and the third level integrates all criteria to create combined scenarios for selecting strictly protected forest areas

observed in mixed stands with broadleaved and coniferous tree species.

Accordingly, we selected the following criteria to identify forest plots from the NFI3 for this scenario:

- Stocking type: Plots classified as 'coniferous forests with admixture of broadleaved trees', 'broadleaved forests with admixture of coniferous trees', and 'mixed forests with equal amounts of broadleaved and coniferous trees', collectively referred to as 'mixed forest stands'
- Developmental phase: Plots in the late developmental phases 4 and 5
- Vertical structure: Plots with multiple canopy layers
- Age of forest stands: Plots with stand ages of 101–140 years, 141–180 years, and over 180 years

Scenario: 'Habitat Conservation'

This scenario labelled 'Habitat Conservation' focuses on identifying high-value habitats within the forest using proposed habitat-level criteria (SOM Table 4) for designating forests for strict protection and evaluating their conservation status. These criteria are usually based on indicators such as naturalness, habitat continuity or representativeness (Engel et al. 2016; Schultze et al. 2014). We selected indicators that could be calculated from the NFI3 variables or were already included in the NFI3, including naturalness, rarity and habitat continuity.

Firstly, naturalness describes the similarity of tree species composition in the current forest stand to its natural state (Winter 2012). While naturalness can encompass structural, functional, and compositional dimensions, we use the compositional approach based on the NFI's standardised parameter 'naturalness of tree species composition' (in German 'Naturnähe der Baumartenzusammensetzung'). This parameter compares current tree species composition with potential natural vegetation across four criteria: proportion of natural forest community species, proportion of main tree species, completeness of main tree species, and proportion of non-European species. Each criterion is evaluated separately for each NFI plot, with the poorest rating determining the overall classification into the naturalness classes (Riedel et al. 2017). Forests with a high degree of naturalness should be assigned a higher conservation value than less natural forests. The NFI3 specifies five levels of naturalness, and we chose plots categorised as 'very seminatural' and 'seminatural' for this scenario. Secondly, rarity describes forest types that occur with low frequency, and we selected plots with natural forest communities that occur in less than 1% of plots within the NFI3 forest area (24 forest communities in total; SOM Table 5). Finally, forests with high habitat continuity include old-growth forests and ancient forests. As there is no uniform definition of old-growth forests, we chose NFI3 plots with forest stand ages exceeding 100 years. Additionally, NFI3 plots with a high conservation status were included, specifically those labelled as 'excellent' and 'good' based on a grading system by the Thünen Institute of Forest Ecosystems for assessing the conservation status of Flora-Fauna-Habitat (FFH) forest types as part of the NFI3 (Kroiher et al. 2017).

Scenario: 'Protection Status'

Since areas with protected legal status provide information on existing conservation infrastructure and management restrictions, we used protection status as the primary criterion for this scenario. In Germany, the categories of protected areas are based on the Federal Nature Conservation Act (BNatSchG 2009), and these areas vary in size, conservation purpose, management objectives and usage restrictions. However, spatial overlap between categories is common, meaning that summing individual category areas would overestimate Germany's total protected area coverage.

For the scenario, we initially selected NFI3 plots with the strictest protection status concerning their management restrictions. The strictest protection status is held by national parks, which generally aim for non-intervention management in core zones, allowing natural processes to occur with minimal human interference. Secondly, nature reserves (Naturschutzgebiete) focus on protecting specific habitats or species, often with strict regulations prohibiting activities that could harm conservation objectives. Thirdly, biosphere reserves (Biosphärenreservate) comprise zones with varying degrees of protection, including core areas with strict protection and buffer zones that allow for sustainable use. Fourthly, Natura 2000 sites have management plans tailored to conservation objectives. Finally, landscape protection areas (Landschaftsschutzgebiete) permit certain sustainable land uses under specific regulations (BNatSchG 2009). To reach the required percentages of forest area under strict protection for each scenario, we gradually included NFI3 plots with less stringent protection statuses.

Scenario: 'Old Forests'

The EU Biodiversity Strategy aims to strictly protect 10% of the EU's land area, which should include all remaining primary and old-growth forests within the EU. However, very few remain (Sabatini et al. 2018), and the standardised EU definition for primary and old-growth forests is complex, making it difficult to translate into the variables available in the NFI3 data (European Commission 2023; Wirth et al. 2009). Therefore, for this scenario, we focused on 'old forests', defined as stands exceeding typical rotation ages for European tree species groups (Dieter et al. 2020; SOM Table 6). Since spruce has the shortest rotation period of 100 years, we classified all NFI3 stands over 100 years as 'old forests' (age classes: 101–140, 141–180, and > 180 years). We initially selected these old forests and then gradually included younger stands until the required percentages of protected areas were achieved under the three assumptions (i.e. 5%, 10% and 30%).

Scenario: 'Conservation Value'

This scenario labelled 'Conservation Value' integrates all selection criteria from the previous scenarios without prioritising any specific criterion. By assigning equal weights to each criterion, we aimed to identify NFI3 plots that represent the highest conservation value, considering multiple factors related to biodiversity and conservation importance.

Scenarios: 'Public Forests' and 'Equal Distribution'

The scenario 'Public Forests' prioritises implementing nature protection goals in public forests, as outlined in Germany's National Biodiversity Strategy, which expects these forests to contribute disproportionately to biodiversity conservation (BMUKN 2024). Following this directive, we focused exclusively on NFI3 plots owned by federal and state governments (referred to as 'public forests'). We did not consider communal forests in this scenario because their diverse ownership structures create complex management challenges that would complicate uniform conservation implementation. We then applied the 'Conservation Value' criteria to identify plots with high conservation value within this public forest subset.

The scenario 'Equal Distribution' assumes that each German federal state should achieve forest protection goals in proportion to its share of the national forest area. Accordingly, we selected NFI3 plots based on the criteria from the scenario 'Conservation Value' but allocated the protected area shares among the federal states relative to their respective forest areas.

Scenarios: 'Combined A' and 'Combined B'

The scenario 'Combined A' integrates all criteria from the previous scenarios, without giving priority to any specific criterion within or among the scenarios. Similarly, scenario 'Combined B' integrates all criteria from the previous scenarios but excludes the criterion of 'equal distribution', as this could limit the selection process by forcing the inclusion of NFI3 plots that meet fewer criteria simply to maintain equal area shares across federal states.

Selection of candidate NFI3 plots

For each scenario, we selected NFI3 plots that met the specific criteria. For this, firstly, NFI3 plots that are already strictly protected were excluded. According to the NFI3 data, a total of 210,553.8 ha of accessible and inaccessible forest area is classified as 'without use due to external causes (nature conservation, protective forest)', and given the total forest area of 11,292,669 ha (based on the representative forest plot size of NFI3), strictly protected areas account for approximately 1.86% of the forest. Consequently, 98.14% of the forested NFI3 plots remained available for further selection to achieve the 5%, 10%, or 30% strict forest protection targets (Fig. 2a). As such, for the 5%, 10%, and 30% protection targets, an additional 3.14%, 8.14% and 28.14% of the NFI3 plot areas were selected for strict protection. Secondly, we prioritised NFI3 plots representing forest habitat types (FHTs) designated under the EU Habitats Directive that do not require ongoing management interventions to maintain their conservation status. These FHTs, including various beech forests, alluvial forests, and subalpine forests, naturally develop toward their target conservation state through successional processes alone (Entenmann and Schaich 2014; full list in SOM Table 2). After applying this criterion, suitable FHTs comprised approximately 15.24% of the total forest area in the NFI3 (Fig. 2b).

Unless indicated otherwise in the scenario descriptions in Sect. 2.3, NFI3 plots with the highest overlap of specified criteria were prioritised. To systematically select NFI3 plots that met the specific criteria for each scenario, we developed an automated selection function, which prioritised plots based on the number of criteria they fulfilled and ensured that the cumulative area of selected plots met the target proportion of the total forest area. To develop this function, the set of selection criteria relevant to each scenario were defined, and then a score S was calculated for each NFI3 plot i based on n criteria:

$$S_i = \sum_{j=1}^{n} C_{ij} + \varepsilon_i \tag{1}$$

where C_{ij} is a binary indicator (1 if plot i meets criterion j, 0 otherwise). This score quantifies how well each plot matches the desired characteristics with 1 indicating a perfect match. To address cases where multiple plots had the same score, we introduced a small random component to the scoring system by adding a uniformly distributed random number $\varepsilon_i \sim U\left(0, 10^{-5}\right)$ to each row score.

Second, for each scenario iteration t, we systematically selected plots i starting from the highest rank position r until the cumulative representative area w_r reached the target proportion α of total forest area A_{total}. Therefore, the selected plot set P_t was calculated as follows:

$$P_t = \left\{ i \middle| \sum_{r=1}^{k} w_r \leq \alpha * A_{total}, where\, S_{ir} \geq S_{ir+1} \right\} for\, t = 1, 2, \ldots, 500 \tag{2}$$

where plots were selected in descending order based on their scores ($S_{ir} \geq S_{ir+1}$). Given that multiple combinations of plots could satisfy the target proportion area, we conducted 500 iterations of the selection process for each scenario using a different random seed each time, which allowed us to explore the range of possible plot combinations. Since NFI3 plots in different federal states represent different forest areas (from 99.3 ha to 411.4 ha; SOM Table 8), the actual number of NFI3 plots selected in a given iteration varied depending on the federal states from which the plots were selected.

Plot selection probability and further statistical analysis

The selection probability of each NFI3 plot was calculated as its occurrence frequency across 500 iterations. For instance, plots selected in 400 of 500 iterations had a selection probability of 0.8. All subsequent analyses were based on mean values and standard deviations of the selected forest area, number of selected plots, and criteria composition calculated across the 500 iterations for each scenario and target proportion of protected forest area. Specifically, spatial patterns and similarities between scenarios were analysed using descriptive statistics, including mean proportions of various selection criteria and frequency distributions of selection probabilities as well as spatial distribution patterns across federal states. Additionally, based on all 19 criteria used across the scenarios, we examined the proportion of the newly selected forest area that met a certain number of different criteria from within a scenario (i.e. scenario-specific criteria) and associated with all scenarios (i.e. co-occurring criteria). Only a maximum of nine criteria could co-occur within the same plot area, since some were mutually exclusive. For instance, a forest stand could be classified as either seminatural or very seminatural, but not both. Legal protection is an exception, since several legally protected area statuses can overlap; however, for simplicity, we treated them as mutually exclusive criteria in this analysis. All data processing and statistical analyses were performed in R version 4.4.2 (R Core Team 2023).

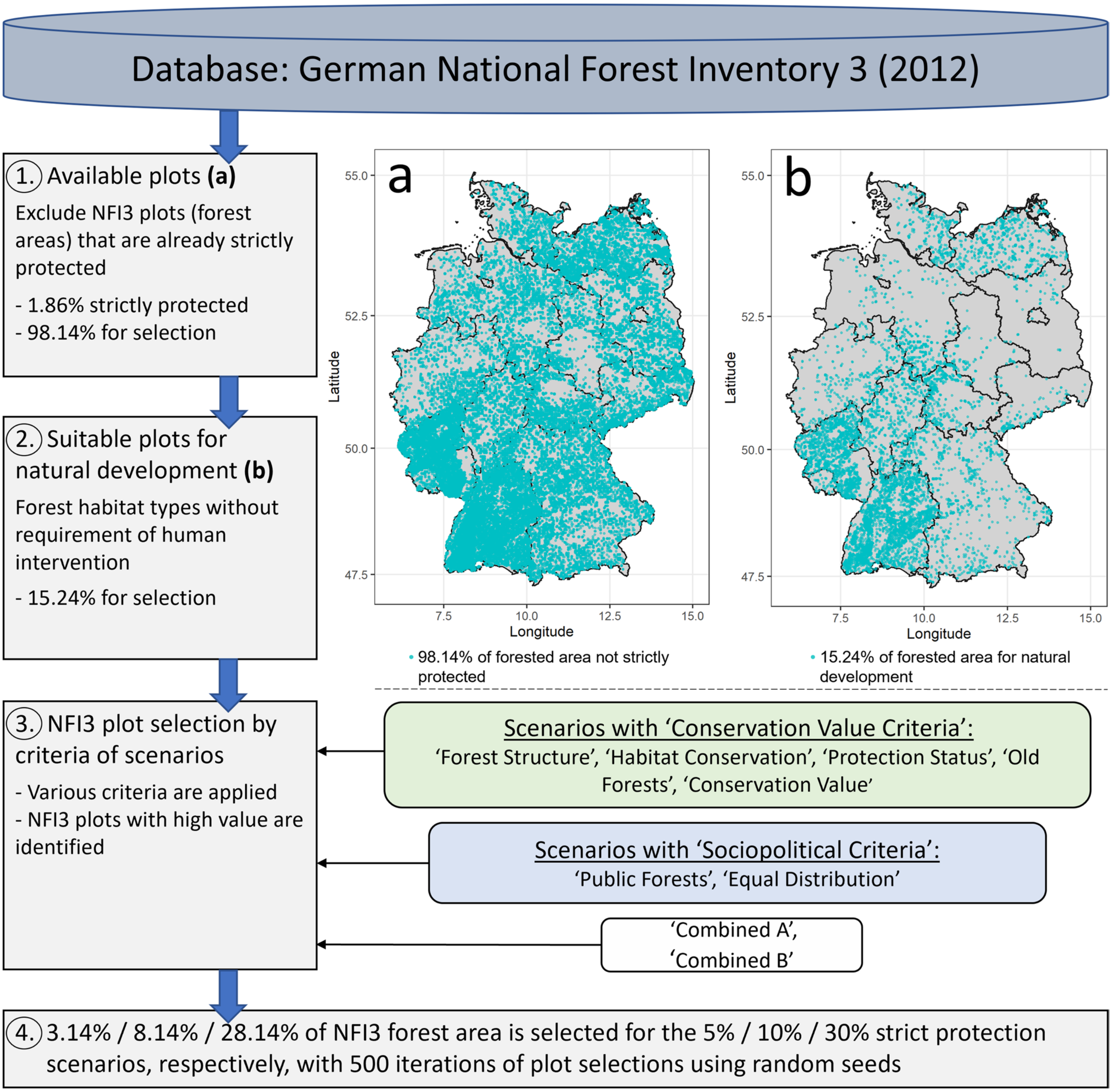


Fig. 2 Methodological steps to identify candidate NFI3 (National Forest Inventory 2012) forest plots for various nature protection scenarios

Results

Selection probability of NFI3 forest plots across scenarios

5% forest protection target Across all the scenarios, a mean area of 340,900 ha (±27,221 ha), representing 3.02% (±0.24%) of the total forest area, was selected. This forest area proportion is lower than required because, when relying on the pre-selection of suitable FHTs, the scenarios 'Equal Distribution' and 'Combined A' could not achieve the 3.14% of protected area needed for a total of 5% of the area to be strictly protected. For these scenarios, only a mean area of 292,887 ha (±0.63 ha), representing 2.59% (±0.01%) of the total forest area was selected.

The different scenarios showed distinct patterns of plot selection probabilities (SOM Fig. 3, Table 9-17). The scenarios 'Forest Structure' and 'Combined B' showed the most consistent selection patterns, with over 85% of selected plots having high selection probabilities (≥ 0.8). The scenario ‘Old Forests’ showed the highest possible selection probability ($p = 1$) on 93% of the selected area. In contrast, the scenarios ‘Equal Distribution’ and ‘Combined A’ displayed more variability, with the selected plots being distributed across all probability intervals. For most scenarios, plots with high selection probabilities ($p = 1$) were concentrated in southern Germany (i.e. Baden-Württemberg and Bavaria), along the western border (i.e. Rhineland-Palatinate), and in parts of central Germany (i.e. Hesse) (SOM Fig. 3).

10% forest protection target The selection process across all scenarios and 500 iterations resulted in an average area of 919,319 ha (± 152 ha) and achieves the required 8.14% (± 0.01%) of the total forest area. Pre-selection based on suitable FHTs was not possible for three scenarios: ‘Public Forests’, ‘Equal Distribution’, and ‘Combined A’. For ‘Public Forests’, the combination of FHT-filtered areas (15.24% of total forest area) and forests with public ownership yielded 530,547 ha of eligible forest area (4.7% of the total area), which was insufficient to achieve the 10% protection target. Similarly, pre-selection could not be used in the ‘Equal Distribution’ and ‘Combined A’ scenarios due to some federal states lacking sufficient FHT-eligible areas.

The analysis of selection probabilities for the 10% protection target revealed different patterns compared to the 5% target, as most scenarios showed medium selection probabilities (0.4–0.8) (Fig. 3, SOM Tables 9–17). The scenario ‘Forest Structure’ maintained relatively high selection probabilities, with 69% of selected plots having probabilities between 0.6–0.8 and 31% having a probability of 1. High-probability plots were predominantly located in southern Germany but expanded into additional regions, particularly in the central and western federal states.

30% forest protection target The selection of plots across all scenarios and 500 iterations resulted in a mean area of 3,201,309 ha (± 66,111 ha), equivalent to 28.34% (± 0.6%) of the total forest area. For the target of 30% strict forest protection, pre-selection by suitable FHTs was not possible for any scenario. Since FHT-eligible areas comprised only 15.24% of the total forest area, this pre-selection criterion had to be abandoned to achieve the required additional 28.14% of protected area. For the scenario ‘Public Forests’, all public forest areas were automatically included (21.9%), with an additional 6.24% selected from private forests based on the selection criteria.

The selection probabilities across the various scenarios showed different patterns compared to those for both the 5% and 10% targets (SOM Fig. 4, Tables 9–17). The scenario ‘Old Forests’ showed a distinctive pattern, with 95% of selected plots showing the highest possible selection probability ($p = 1$). The scenario ‘Public Forests’ also had a relatively high proportion (76%) of plots with $p = 1$. Unlike for the 5% and 10% targets, high-probability plots were no longer concentrated in specific regions but distributed widely across Germany.

Proportions of various selection criteria across scenarios

Despite the use of different initial plot selection parameters across the scenarios, the resulting selected plots showed some similarities in their criteria compositions. Specifically, each scenario contained all possible selection criteria, but due to their different foci, there were differences in the proportional representation of plots meeting each criterion between them (Fig. 4, SOM Fig. 5 and 6).

Scenario group ‘Conservation Value Criteria’ For the 10% target and within the first scenario group, ‘Conservation Value Criteria’ (i.e. ‘Forest Structure’, ‘Habitat Conservation’, ‘Protection Status’, ‘Old Forests’ and their combination ‘Conservation Value’), scenario-specific criteria had the highest proportional representation in terms of plots fulfilling these criteria within their respective scenario compared to other scenarios. In most cases, these criteria showed their second highest proportional representation in the ‘Conservation Value’ scenario (Fig. 4), indicating that this combined scenario balances the different criteria well. This overall pattern also applied to the 5% (SOM Fig. 5) and 30% targets (SOM Fig. 6).

For the specific scenario ‘Forest Structure’ under the 10% target, the scenario-specific criteria ‘mixed forest stands’ and ‘stands with multiple canopy layers’ achieved the highest proportions of newly selected forest area (89.90 ± 0.64% and 58.10 ± 0.48%, respectively) (Fig. 4). The criterion ‘stands with multiple canopy layers’ showed considerably lower representation in the other scenarios in this group (e.g. only 5.4 ± 0.06% in ‘Old Forests’) and stands in a late development phase (i.e. criterion ‘P4 – Late development phase 4’) occurred much less frequently in other scenarios as well. These patterns persisted under the 5% (SOM Fig. 5) and 30% targets, although for the latter, there were more plots meeting the criterion of ‘mixed forest stands’ compared to plots for any other criteria (SOM Fig. 6). Overall, we found that there was the least overlap between the two criteria ‘mixed forest stands’ and ‘stands with multiple canopy layers’ compared to all other criteria in this scenario group.

For the scenario ‘Habitat Conservation’ under the 10% target, the criterion ‘Conservation status B’, contributed the most forest area and showed a higher proportion compared to others within this scenario group. However, under the 5% target, plots meeting the criterion ‘Conservation status B’ showed similar proportions across the scenarios (SOM

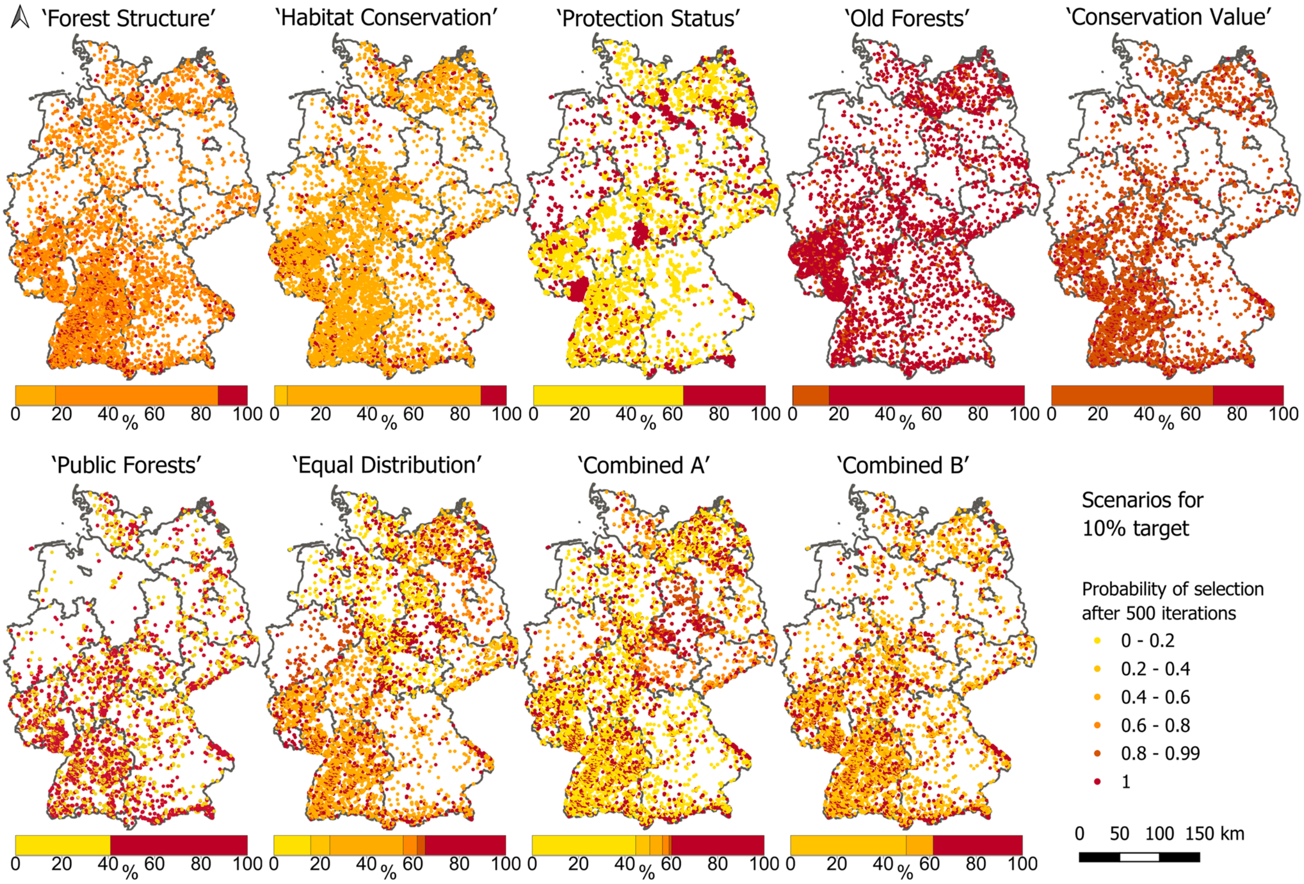


Fig. 3 Probability of selection for NFI3 plots after 500 iterations for the 10% target of forest area to be strictly protected. The colour gradient indicates the probability interval of the NFI3 plots, ranging from red (probability of selection = 1) to yellow (probability for selection ≤ 0.2). The percentage bars show the contribution of newly selected plots from each probability interval to the total number of newly selected plots. Only plots that fulfil at least one criterion of each respective scenario are displayed on the maps. The plot distribution shown does not represent actual forest area coverage

Fig. 5), while under the 30% target, its representation fluctuated (SOM Fig. 6). Overall, we found that the criterion 'Conservation status B' was the least congruent with the other criteria across scenarios in this group.

For the scenario 'Protection Status' under a 10% target, classification as a Natura 2000 site emerged as the most important criterion for plot selection. The scenario-specific criterion 'national parks' represented 5.4% (±0.01%) of the newly selected forest area in the 'Protection Status' scenario compared to only 0.7% (±0.08%) of areas in the 'Forest Structure' scenario. The criteria 'nature reserves' and 'biosphere reserves' were fulfilled for 49.8% (±0.01%) and 37.3% (±0.01%) of plots within the 'Protection Status' scenario compared to only 5.4% (±0.07%) and 3.8% (±0.06%) in 'Forest Structure'. The proportion of plots meeting the criteria 'protected landscape' and 'nature parks' remained relatively stable across scenarios. Similar patterns emerged across the scenarios for the 5% and 30% targets, although the criteria 'nature reserves' and 'biosphere reserves' showed lower relative proportions. Overall, we identified that being an existing Natura 2000 site was not a key criterion for plot inclusion in other scenarios compared to the 'Protection Status' one.

The scenario 'Old Forests' shared its criterion of forests older than 100 years with the scenarios 'Forest Structure' and 'Habitat Conservation'. Forests over 180 years represented 1.4% (±0.01%) of plot selection in the 'Old Forests' scenario under the 10% target, nearly 1% in 'Habitat Conservation' and 'Forest Structure', but only 0.4% (±0.03%) in 'Protection Status' which did not specifically include old forests as a criterion. As such, younger forests were selected in the 'Protection Status' scenario, whereas most available old forests were selected in the other scenarios. This pattern was consistent for the 5% and 30% targets, although the relative differences between scenarios varied. Overall, we found that the area of old forests is small, and most plots above a certain age were selected when age was used as a criterion, while old forests were not necessarily selected indirectly through other criteria such as the protection status.

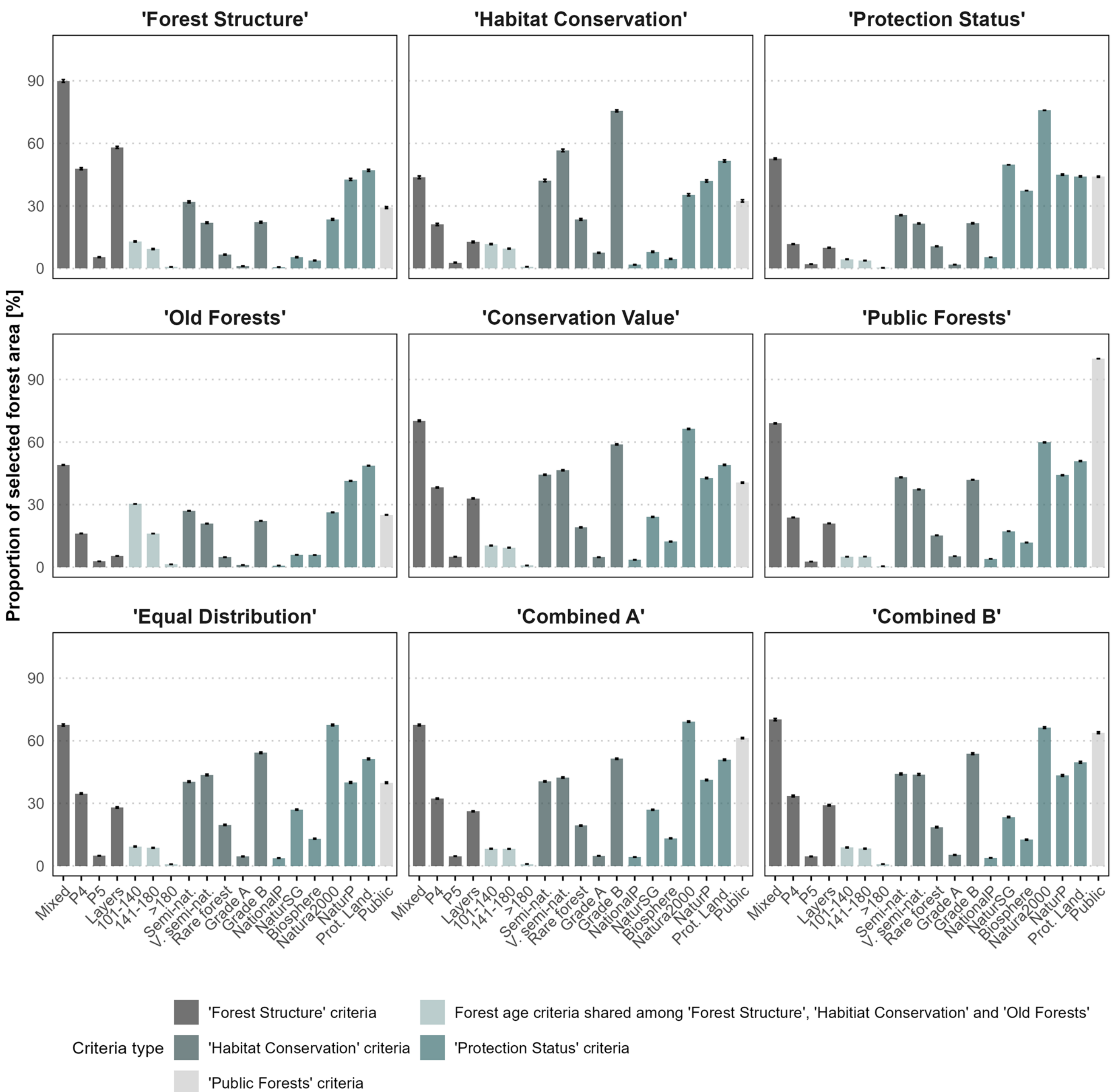


Fig. 4 Proportion of criteria contributing to the newly selected forest area for the various scenarios at the 10% target. The bars represent the mean and standard deviation of the proportions over 500 selection iterations. The colouring of the bars indicates the scenario-specific criteria. Forest age is a criterion in several scenarios, and hence, is indicated as 'Forest age criteria shared among 'Forest Structure', 'Habitat Conservation' and 'Old Forests'' in the legend. Abbreviations: Mixed – Mixed forest stands; P4 – Late development phase 4; P5 – Late development phase 5; Layers – Stands with multiple canopy layers; 101–140 – Forest stands aged 101–140 years; 141–180 – Forest stands aged 141–180 years; > 180 – Forest stands aged > 180 years; Semi-nat. – Seminatural forest stands; V. semi-nat. – Very seminatural forest stands; Rare forest – Rare forest communities; Grade A – Conservation status A (excellent); Grade B – Conservation status B (good); NationalP – National park (Nationalpark); NaturSG – Nature reserves (Naturschutzgebiet); Biosphere – Biosphere reserves; Natura2000 – Natura 2000 sites; NaturP – Nature parks (Naturpark); Prot. Land. – Protected landscape (Landschaftsschutzgebiet); Public – Public forests

Finally, the combined scenario 'Conservation Value' exhibited proportions of plots related to the individual criteria similar to those in their respective scenarios. In summary, three main differences occurred within the 'Conservation Value Criteria' group for the 10% target. Firstly, structural criteria ('stands with multiple canopy layers' and 'mixed forests') were not necessarily well represented by other criteria, especially not by the selection of old forests. Secondly, the criteria 'conservation status B' and 'Natura 2000 sites' were not covered well by criteria from other scenarios. Finally, all areas covered by forests older than 100 years were included if old forests were a selection criterion, but this was less apparent for the 'Protection Status' scenario, which did not focus on forest age.

Scenario group 'Sociopolitical Criteria' When comparing the scenario 'Public Forests' with the scenario 'Conservation Value' for the 10% target, the three largest relative differences were for the following criteria: public forests represented 100% of the area in 'Public Forests' versus 40.5% (± 0.25%) in 'Conservation Value'; the criterion '101–140 years', which represented 5.0% (± 0.05%) versus 10.4% (± 0.15%), respectively; and the criterion '> 180 years', which represented 0.4% (± 0.01%) versus 0.8% (± 0.03%) of the newly selected forest area. This pattern was the same for the 5% and 30% targets, but for the 30% target, not enough forests on public land were available to use the 'public forests' criterion. These differences between scenarios are moderate compared to the differences observed across the scenarios in the first scenario group. Overall, we found that with a focus on public forests, a similar range of selection criteria can be met by the same plots, with the exception of old forests, many of which are privately owned.

The scenario 'Equal Distribution' showed minimal variation from 'Conservation Value' for all criteria, with the highest relative difference being for 'stands with multiple canopy layers', which was met by 28.0% (± 0.31%) versus 33.0% (± 0.22%) of selected plot area, respectively. Comparison with the 5% and 30% targets revealed consistent patterns, although the similarities between scenario pairs decreased as the protection target increased. Overall, we found that, when ensuring equal area distributed across the federal states, the criteria across the scenarios in the 'Conservation Value' group can be met.

In summary, we found little influence of the sociopolitical criteria on the proportions of areas selected by the various criteria used in the 'Conservation Value' group for the 10% target, except for the proportion of forests on public land. The results for the 5% and 10% targets were similar, but there were not enough public forests available for the 30% target.

Scenario group 'Combined Criteria' The final scenarios, 'Combined A' and 'Combined B', showed small differences for the 10% target. The largest difference between them was in the representation for 'nature reserves' (26.9 ± 0.224% vs 23.4 ± 0.283%). This pattern was also true for the 5% and 30% targets (SOM Fig. 5 and 6).

Co-occurring criteria across scenarios

When examining the scenario-specific criteria for the 10% target, more than 80% of the selected area met two scenario-specific criteria out of a possible four for the scenarios 'Forest Structure' and 'Habitat Conservation' (Fig. 5). 'Old Forests' was the only scenario where many selected forest areas did not match the criteria of the scenario. For the 5% target, the results were similar (SOM Fig. 7), but for the 30% target, a much larger proportion of areas only met one scenario-specific criterion for the 'Forest Structure' and 'Habitat Conservation' scenarios (SOM Fig. 8).

For the 10% target, scenarios had areas that consistently met between one and eight co-occurring criteria, with most meeting between two and six. (Fig. 5). The 'Conservation Value' and 'Public Forest' scenarios, as well as the two combined scenarios, showed the highest proportion of forest areas that met five to seven co-occurring criteria. The scenarios for the 5% target showed generally higher proportions of areas meeting co-occurring criteria (SOM Fig. 7). For the 30% target, the opposite was observed, with most scenarios covering fewer criteria associated with other scenarios than under the 5% or 10% targets (SOM Fig. 8).

Distribution of selected forest areas across Germany's regions

Our analysis revealed differences in the absolute selected forest area between federal states across the scenarios (Fig. 6). The highest proportion of selected forest area across all scenarios was in Bavaria (BY), reaching 104,862 ha (± 1698 ha) for 'Public Forests' for the 5% target, 285,845 ha (± 1615 ha) for 'Public Forests' for the 10% target, and 879,646 ha (± 8175 ha) for 'Forest Structure' for the 30% target. Baden-Württemberg (BW) showed the second highest absolute forest area selected, followed by Hesse (HE). The smallest absolute areas were consistently selected in Schleswig–Holstein (SH) and Saarland (SL). These differences in absolute selected areas reflect not only the varying degrees of criteria fulfilment but also the variations in total forest area among the federal states.

The scenarios also selected different amounts of forest area within each federal state. For instance, the scenario 'Forest Structure' led to the highest absolute area selection within BW, with 91,873 ha (± 370 ha) and 202,030 ha (± 1937 ha), respectively. For the 30% target, the highest absolute area for this scenario was in BY with 879,646 ha (± 8175 ha), followed by BW with 569,944 ha (± 3964 ha). In contrast, 'Forest Structure' consistently ranked among the bottom three scenarios for absolute area selection in Brandenburg (BB), Mecklenburg-Western Pomerania (MV) and Thuringia (TH) across the targets. Similarly, 'Public Forests' selected the largest absolute area within BY

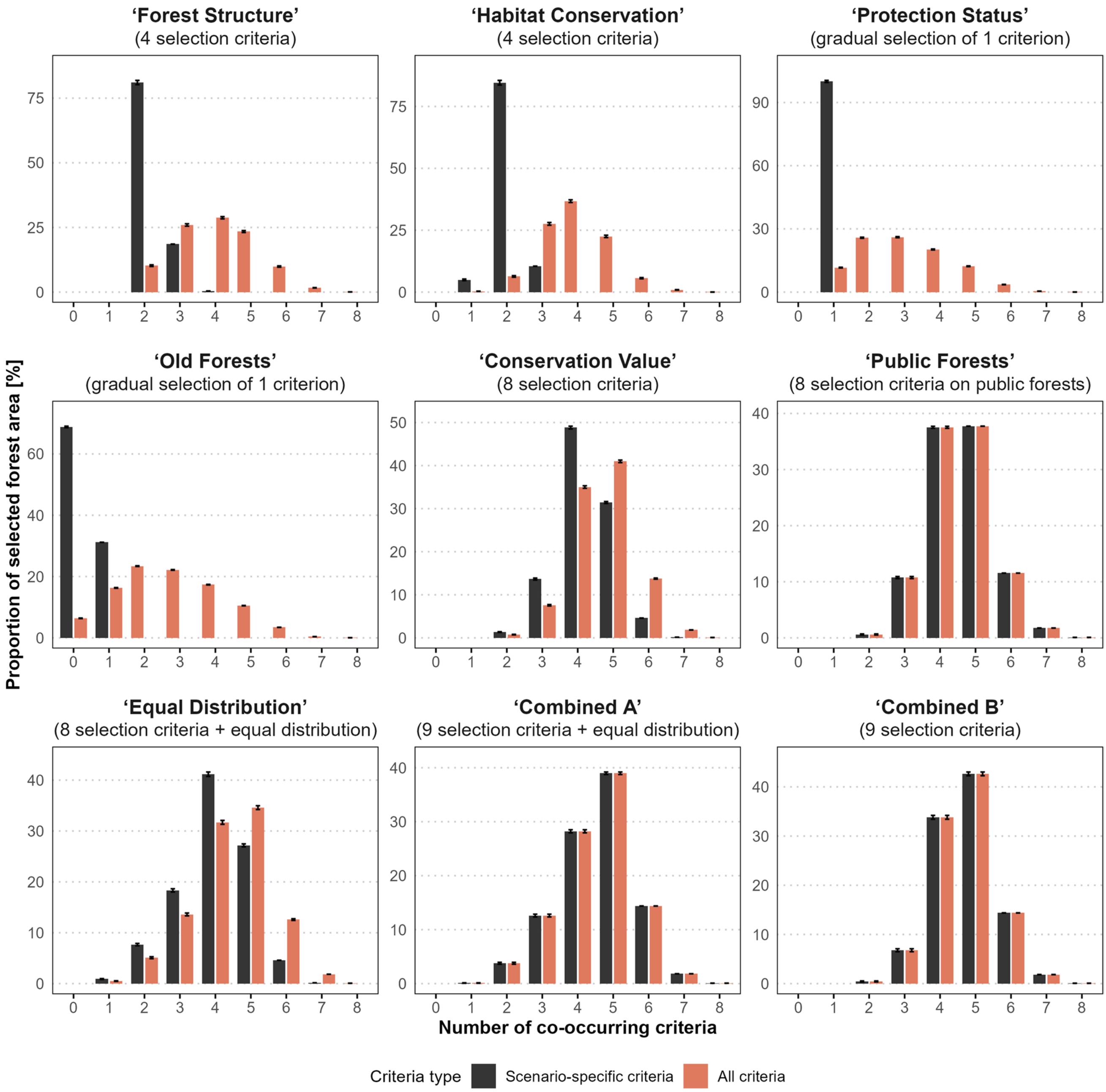


Fig. 5 Proportion of co-occurring criteria contributing to the newly selected forest areas for the various scenarios at the 10% target. The figure differentiates between the number of scenario-specific criteria met (black bars) and the total number of co-occurring criteria met (orange bars). The explanations in parentheses indicate the number of selection criteria for each scenario that can co-occur within the same forest area. The bars show the mean and standard deviation over 500 selection iterations

compared to other scenarios, with 104,862 ha (± 1697 ha) and 285,846 ha (± 1614 ha) for the 5% and 10% targets, respectively. In contrast, the 'Public Forests' scenario consistently ranked among the lowest in terms of absolute area selected in MV and Lower Saxony (NI) for all targets.

When the forest area was assessed as the mean proportion of the total forest area within the federal state, the highest proportion of protected forests was in HE (6.5%), while BB had the lowest proportion (1.5%) at the 5% target. For the 10% target, HE showed the highest proportion of selected areas at 17%, followed by ST at 14.3%, while BB had the lowest proportion at 3.9%. Finally, for the 30% target, ST showed the highest proportion of selected forest areas at 44.5%, while BB remained lowest at 25.2%.

All federal states showed systematic increases in both absolute and proportional selected forest area as the target proportions of protected areas increased from 5 to 30%. The standard deviations remained relatively small compared to the mean values, indicating consistent results across the 500 selection iterations.

Discussion

Selection patterns and scenario differentiation across different protection targets

Using data from the NFI3 and a systematic selection approach, we showed that suitable forest areas can be identified to meet the strict protection targets of 5%, 10%, and 30% of Germany's forest area across a wide range of ecological and sociopolitical conservation criteria. However, the selection probabilities for individual forest plots differed based on the protection targets. For the 5% target, selection probabilities were high, as plots that fulfilled several criteria simultaneously were selected primarily. However, there were not enough plots fulfilling several criteria for the 10% target, and having a wider pool of possible plots diluted selection probabilities. With the 30% target, the selection probabilities increased again, as most plots fulfilling even just one or two scenario criteria need to be selected for inclusion.

In addition to these differences in selection probabilities, for a specific target of forest protection, there were only moderate differences in the composition of area selection criteria across the scenarios. This pattern held despite the implementation of criteria focusing on different aspects of nature protection, including forest structure, habitat conservation, legal protection status, old forests, forest ownership, and equal distribution across federal states. Notably, the criteria 'mixed forest stands', 'stands with multiple canopy layers', 'conservation status B', and 'Natura 2000 sites' showed the least overlap with other criteria and, hence, may require special attention if they are to be the focus of conservation efforts. Moreover, because the existing area of old forests is small, all plots above a certain age were selected when age was used as a criterion. In contrast, old forests were not necessarily selected indirectly through other criteria, such the protection status or public ownership.

Regarding sociopolitical considerations, we found that even if the selected areas must be equally distributed across the federal states, many of the ecological criteria related to the conservation value of forests can still be met. However, there were notable spatial differences between the scenario 'Equal Distribution' and the other scenarios. For example, in the northwestern parts of Germany, fewer forests were selected for strict protection if this selection was not enforced by the 'Equal Distribution' scenario.

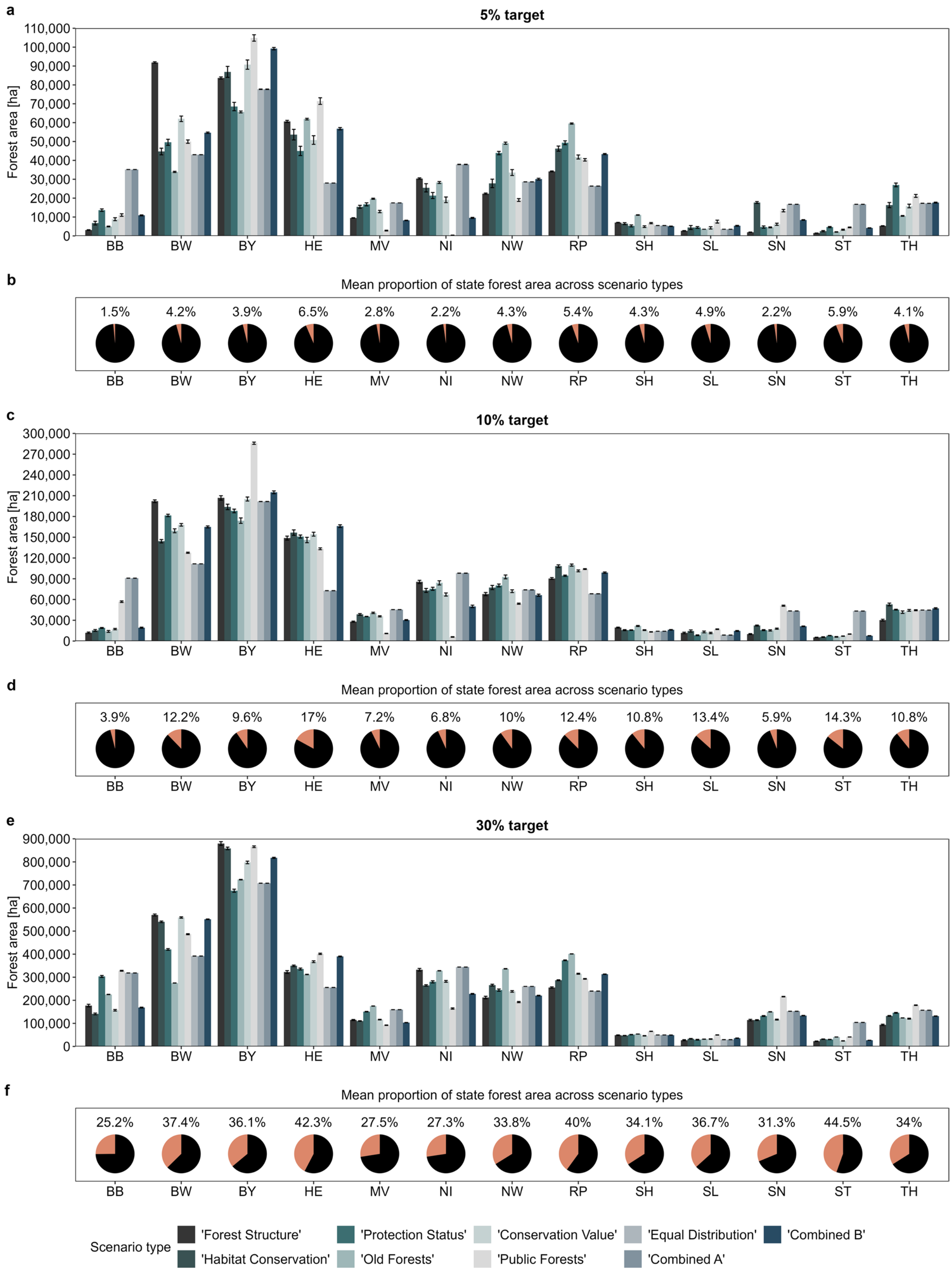
Beyond the composition of criteria, the outcomes of our protection scenarios were also shaped by the availability of FHTs whose conservation status can be maintained without ongoing management interventions. Although these FHTs (i.e. 15.24% of total German forest area) could theoretically serve as the selection pool for the 5% and 10% targets, there were insufficient public forests to fulfil this criterion, and the FHTs were not distributed equally across the federal states. Thus, we had to abandon the FHT pre-selection for the 10% and 30% targets to maintain methodological consistency across all scenarios. Overall, although these suitable FHTs have high potential to form the ecological core of any strictly protected forest network, Germany likely cannot reach more ambitious strict protection targets with these existing forests alone. This finding is consistent with the broader recognition that, given the pervasive human imprint on most European landscapes, strict protection targets cannot be achieved through protecting near-natural habitats alone (Carver et al. 2021; Cazzolla Gatti et al. 2023; Navarro and Pereira 2012).

In interpreting these results, it should be emphasised that our 30% target is unrelated to the EU's 30% protected area objective. Rather, this target constitutes a hypothetical upper-bound scenario for Germany's potential forest contribution to the EU's 10% strict protection target. The extent to which forests compared to other ecosystems will contribute to the 10% target remains undefined, although they are likely to contribute disproportionately given that they represent relatively close-to-nature ecosystems and harbour much terrestrial biodiversity (Gibson et al. 2011; Lindenmayer 2009). Thus, our 10% to 30% target protection range explores this potential spectrum.

Comparison with previous studies and methodological approaches

Regarding wider implications, our study presents a novel, data-driven framework to support systematic forest conservation planning in Germany by developing nature protection scenarios based on ecological and sociopolitical criteria derived from NFI data and using a simple selection algorithm. More complex approaches exist; however, they also require more comprehensive input data (Malcangi et al. 2024).

We acknowledge that our analysis does not incorporate criteria for the spatial patterns and sizes of protected areas, unlike Brackhane et al. (2019), who identified large, contiguous areas in Germany suitable for wilderness development. Their approach used spatial criteria, including fragmentation analysis with buffer zones around anthropogenic infrastructure and a compactness analysis to identify coherent forest patches across several size classes (≥ 100, ≥ 1,000, ≥ 3,000 and ≥ 10,000 ha). In contrast, our NFI-based framework operates at the forest stand level, resulting in more spatially distributed areas that include structurally diverse stands in southern and central Germany, even if they are smaller or


a
5% target
Forest area [ha]
110,000
100,000
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
BB BW BY HE MV NI NW RP SH SL SN ST TH
b
Mean proportion of state forest area across scenario types
1.5% 4.2% 3.9% 6.5% 2.8% 2.2% 4.3% 5.4% 4.3% 4.9% 2.2% 5.9% 4.1%
BB BW BY HE MV NI NW RP SH SL SN ST TH
c
10% target
Forest area [ha]
300,000
270,000
240,000
210,000
180,000
150,000
120,000
90,000
60,000
30,000
0
BB BW BY HE MV NI NW RP SH SL SN ST TH
d
Mean proportion of state forest area across scenario types
3.9% 12.2% 9.6% 17% 7.2% 6.8% 10% 12.4% 10.8% 13.4% 5.9% 14.3% 10.8%
BB BW BY HE MV NI NW RP SH SL SN ST TH
e
30% target
Forest area [ha]
900,000
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
BB BW BY HE MV NI NW RP SH SL SN ST TH
f
Mean proportion of state forest area across scenario types
25.2% 37.4% 36.1% 42.3% 27.5% 27.3% 33.8% 40% 34.1% 36.7% 31.3% 44.5% 34%
BB BW BY HE MV NI NW RP SH SL SN ST TH
Scenario type
'Forest Structure'
'Habitat Conservation'
'Protection Status'
'Old Forests'
'Conservation Value'
'Public Forests'
'Equal Distribution'
'Combined A'
'Combined B'

◂**Fig. 6** The mean selected forest area per federal state across 500 iterations for (**a**) the 5% target, (**c**) the 10% target, (**e**) the 30% target, and (**b**), (**d**) and (**f**) show the respective mean proportions of selected forest area for each federal state across all scenarios. For the 5%, 10% and 30% targets, an additional 1.4%, 6.4%, and 26.4% of the total forest area were selected. The bars show the mean and standard deviation across 500 iterations. Abbreviations: BB – Brandenburg; BW – Baden-Württemberg; BY – Bavaria; HE – Hesse; MV – Mecklenburg-Western Pomerania; NI – Lower Saxony; NW – North Rhine-Westphalia; RP – Rhineland-Palatinate; SH – Schleswig–Holstein; SL – Saarland; SN – Saxony; ST – Saxony-Anhalt; TH – Thuringia

more fragmented (see Sect. 4.3 for a detailed discussion of spatial criteria).

At the sub-national level, Seebach and Braunisch (2021) applied ‘Marxan’, a decision-support tool for systematic conservation planning (Ball et al. 2009), to identify priority areas for naturally developing forests in Baden-Württemberg, Germany. Similar to our selection approach, ‘Marxan’ identifies the best possible solution by simultaneously matching multiple criteria. However, their framework was explicitly optimised for representativeness by ensuring a balanced coverage of forest habitat types while prioritising under-represented forest communities and rare site conditions. Our approach was not explicitly optimised for representativeness but rather incorporated rare forest communities as one criterion among others in the selection process.

Furthermore, while EU-wide studies such as Spiliopoulou et al. (2023) prioritise conservation based on distributions of threatened taxa, our approach was habitat-based and used biodiversity proxies. This method reflects the growing recognition that in temperate regions, structural habitat features and continuity often better predict biodiversity than species presence data, particularly when comprehensive monitoring is lacking (Winter 2012). However, this approach limited our ability to assess conservation gaps for specific taxa, which is also key for EU biodiversity assessments (European Commission 2023).

Methodological reflections and future directions

Despite the key insights our approach provides, the findings require cautious interpretation due to several limitations related to data resolution, spatial configuration, and temporal dynamics.

First, although angle-count sampling in the NFI3 provides robust broad-scale information, it may miss fine-scale ecological features critical for local conservation planning (Thünen Institute 2012). In principle, remote sensing could supplement NFI data: research in Germany has used wall-to-wall mapping techniques for several inventory attributes, including growing stock (Immitzer et al. 2016), forest structure (Kacic et al. 2023), forest type (Nink et al. 2019), tree species (Blickensdörfer et al. 2024), and disturbance dynamics (Reinosch et al. 2025), using airborne laser scanning, aerial photogrammetry, and Sentinel time series. However, no nationwide approach currently exists that captures the full set of detailed tree and stand characteristics required for our indicator-based approach, including deadwood and other fine structural attributes (Kirchhoefer et al. 2017; Thiel et al. 2020). Alternatively, forest cover data alone could be used for spatial pattern analyses, as demonstrated by Brackhane et al. (2019) (see Sect. 4.2). However, the strength of our approach is that it is the first to assess strict protection across multiple biodiversity and sociopolitical indicators simultaneously; such an analysis is only feasible with the detailed, multi-attribute data provided by the German NFI. A further advantage is the transferability of NFI data: the multi-criteria selection approach can be readily applied to future inventories, enabling temporal monitoring of how forest condition changes affect area identification for strict protection.

A further limitation concerns spatial criteria, namely ecological connectivity between forest areas and minimum patch-size requirements. Connectivity supports biodiversity conservation by enabling dispersal, recolonisation, gene flow, and climate-driven range shifts in fragmented temperate forest landscapes (Humphrey et al. 2014; Martínez-Richart et al. 2024; Taylor et al. 1993). Although its benefits are not universal and habitat quality may matter more than connectivity per se (Bailey 2007; Haddad et al. 2014; Hodgson et al. 2010), its integration into conservation planning remains valuable. Our NFI-based framework is limited in this regard; although it could, in principle, incorporate spatial pattern metrics such as nearest-neighbour distances or density-based clustering of forest attributes (e.g. Ramezani and Ramezani 2015), sample points provide only limited insight into landscape configuration compared to continuous spatial data. Future research could therefore integrate connectivity criteria into our scenario framework using graph-based methods, which are spatially explicit and incorporate basic movement assumptions without requiring extensive species data (Vidal-Llamas et al. 2025). Such methods can rank patch and link importance and aggregate results into prioritisation units (e.g. Saura and Pascual-Hortal 2007; Saura and Rubio 2010); however, their implementation depends on wall-to-wall forest maps with detailed stand attributes, which are not yet available for Germany at the level required by our framework.

Closely related to connectivity is the question of minimum forest patch size, which is important for long-term biodiversity conservation. Larger, less edge-dominated patches are more likely to sustain forest-interior birds and specialist plants, whereas very small patches often lose these groups (Dolman et al. 2007; Gardner et al. 2019; Honnay et al. 1999). However, any minimum-area threshold depends strongly on taxon, habitat quality, historical continuity, surrounding forest cover, and edge exposure rather than reflecting a single universal cutoff (van der Hoek et al. 2015; Villard et al. 2014), and small forest patches can still have high ecological value. Vanneste et al. (2024), for example, showed that edges of smaller patches also harbour significant biodiversity. Thus, our plot-based approach, which does not impose minimum size requirements, can capture conservation opportunities that area-based approaches might overlook.

Finally, conservation planning must account for temporal dynamics and future uncertainties, as the ecological features that protection aims to secure are not static. Climate change is projected to reduce climatic suitability for many species inside European protected areas (Araujo et al. 2011), while forest development is increasingly reshaped by succession and intensifying disturbance regimes driven by wind, fire, drought, and bark beetles (Patacca et al. 2023; Seidl et al. 2017). However, our scenario framework identifies suitable areas based on current forest attributes, thereby providing a static snapshot that does not capture how stand structure and composition may shift under future climate and disturbance regimes. Future research building on our study could address this limitation by linking our nature protection scenarios to process-based forest models, which simulate forest growth together with carbon, water, and heat fluxes (Gutsch et al. 2018; Lasch-Born et al. 2020). This approach would enable the assessment of strict protection suitability against projected changes in forest structure and composition under multiple climate and disturbance scenarios.

Implications for conservation planning and implementation

This work provides a systematic analysis of the potential for strictly protecting forests to fulfil policy targets and our results are relevant for guiding discussions about how to select additional areas. This approach was designed to inform conservation planning at regional or federal-state levels by identifying the types and characteristics of forest stands that should be prioritised for strict protection, rather than pinpointing specific locations to be protected. Although our assessment included a wide range of criteria, translating protection potential into implementation will require further site-specific evaluations that integrate ecological, social, and economic feasibility considerations beyond the scope of our analysis.

In the European context, the term 'strict protection' does not imply a complete absence of management, but rather a clear restriction of interventions to ecologically justified purposes (European Commission 2022). Management interventions may be necessary for addressing beetle disturbances, for example, when non-native species invade, when native beetles expand their range due to changing climatic conditions, or when particularly significant forest stands such as old-growth remnants are at risk (Hlásny et al. 2021). It should be emphasised, however, that outbreaks of native bark beetles in near-natural forests typically represent natural ecosystem processes that support biodiversity (Beudert et al. 2015; Müller et al. 2010) and promote increased habitat complexity over time (Donato et al. 2012; Svoboda et al. 2011). In this context, active management is not always needed. Clarifying this distinction in implementation guidelines will be important to align conservation outcomes with public and stakeholder expectations.

Beyond such ecological and practical considerations, acceptance by landowners is a critical factor, particularly on private land where protection measures directly affect ownership rights. Although research specifically addressing private forest owners' acceptance of strict protection in Germany remains limited (Höchtl et al. 2005), studies on conservation measures in managed forests may provide insights into the factors modulating acceptance. Research on less restrictive conservation measures shows that acceptance is heterogeneous and depends on factors such as perceived autonomy, economic compensation, meaningful participation, and credible communication (Joa and Schraml 2020; Tiebel et al. 2024, 2021). European research on permanent forest set-asides further suggests that stricter forms of protection require provisions for alternative economic opportunities to offset foregone timber revenues (Boon et al. 2010; Horne 2006; Mitani and Lindhjem 2015). To facilitate discussions about socio-economically acceptable implementation, our scenario framework includes options that prioritise public forests, thereby reducing the likelihood of ownership conflicts complicating implementation.

Overall, the future planning of strict conservation areas must combine broad-scale habitat assessments like ours with detailed evaluations of ownership patterns, stakeholder willingness, management costs, and legal frameworks (Schumacher et al. 2018). This multi-criteria approach will ensure that efforts to designate protected areas focus on sites where ecological potential aligns with practical feasibility, thus ultimately increasing the likelihood of achieving Germany's biodiversity conservation targets.

Conclusion

Given the ongoing climate and biodiversity crisis and the urgency of implementing effective forest protection strategies, critical knowledge gaps remain regarding which forest areas should be designated for strict protection and how different conservation criteria influence this selection. This work was conducted to identify suitable forest areas for protection in Germany by designing various protection scenarios based on different nature conservation and sociopolitical criteria and analysing their implications for meeting national and EU biodiversity targets of 5%, 10%, and 30% strict forest protection.

We found that many existing criteria overlap; however, those related to mixed forests, old forests, and Natura 2000 sites do not necessarily overlap with others. Thus, if these types of forests are to be strictly protected, relevant criteria must be included in the selection process. Finally, although the criteria overlapped well, regional differences in forests that are suitable for protection emerged, requiring further consideration when planning conservation efforts in Germany.

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Author contributions P.B. – Conceptualisation, methodology, formal analysis, figures, writing (original draft). C.R. – Conceptualisation, methodology, writing (original draft). J.B., E.F., M.G., A.H., U.M., T.N. and M.T. – Writing (review and editing).

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Data availability Data from the German National Forest Inventory 2012 are available at https://bwi.info. Additional data generated in this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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