AN INTERDISCIPLINARY STORY-AND-SIMULATION APPROACH FOR ASSESSING FOREST TYPE CHANGES AND SHIFTS IN ECOSYSTEM SERVICE POTENTIAL

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With 6 figures, 3 tables and supplement
Received 12 October 2025 · Accepted 5 February 2026

Summary: Forest management has increasingly shifted from timber-focused production to multifunctionality, requiring scenario approaches that integrate socio-economic contexts and expert knowledge. For robust assessments of ecosystem service potentials (ESP), three key dimensions must be addressed: realism, by incorporating expert-based knowledge and socio-economic constraints; scalability, through standardized modeling techniques; and comparability, by ensuring applicability across different regions and forest types. We developed an interdisciplinary 'story and simulation' approach, combining expert-based Delphi assessments with spatially explicit scenario modeling to assess ESP changes in Bavaria, Germany. This method integrates stakeholder perspectives with empirical ecosystem service models to enhance realism while maintaining scalability and comparability for broader applications. We assessed three scenarios of forest change: a Status Quo Scenario with stable drivers, an Intensified Use Scenario, and a Close-to-Nature Forestry Scenario. Across all scenarios, a transition from conifer-dominated forests toward mixed and broadleaf forests was expected, affecting between one-third and nearly half of the current coniferous forest area. The empirical ESP models revealed stable ESP levels at the landscape level, with only minor scenario-driven variations. We show that including socio-economic factors through an expert-driven approach reveals more moderate shifts than those predicted by purely optimization-based models. The projected transition towards mixed forests aligns with current European forest policy trends, but the speed and extent of this shift remain uncertain. Our interdisciplinary framework enhances realism by incorporating expert knowledge, improves scalability by utilizing empirical ESP models, and ensures comparability through a structured, transferable approach. This methodology provides a robust foundation for evidence-based forest policy, adaptable to diverse forest ecosystems and governance structures.

Keywords: Bavaria, Delphi method, ecosystem services, forestry, forest scenarios and development, InVEST Generator, story and simulation approach

1 Introduction

Forests generate multiple ecosystem services (ES) that are the basis for human well-being and a good livelihood (IPBES 2019, Jenkins & Schaap 2018). In this context, the public and policy expectation on forest management has changed from a focus on economic aspects to forests as multifunctional ecosystems (Borrass et al. 2017) with the aim to guarantee the sustainable and long-term supply of multiple ES (Nelson et al. 2009, Manning et al. 2018). This shift requires forest managers to consider a wide range of goods and services during planning and management activities. Because trees are growing slowly, foresters need to integrate manifold drivers and potential developments across long temporal timeframes into their decisions.

A valuable tool for decision making is the modelling and mapping of changes in ES provisioning under different forest development scenarios (Duguma et al. 2022). Two types of basic information are needed for this: projections of forest development and ES indicators. Different approaches have been developed to acquire those, first independently and in recent years also in combination (Hoogstra-Klein 2017). While specific case-studies might require tailored approaches for both forest projection and ES modeling, the growing interest in forest ES models calls for approaches which are generalizable but at the same time realistic in different situations. In our view, this can be achieved if combined approaches heed the following three dimensions: scalability, comparability and realism (Fig. 1). While the dimension of comparability mainly applies to comparing different ES, scalability and realism are important for both ES models and forest development projection.

Here, realism primarily refers to the integration of socio-economic drivers, management constraints, and expert knowledge into plausible forest development pathways; ecological processes such as disturbance regimes or climate change impacts are represented indirectly through their effects on forest structure and composition rather than being modelled explicitly. To predict forest development, two

https://doi.org/10.3112/erdkunde.2026.02.01 ISSN 2702-5985 (Online)

				Modelling of ecosystem services		
				Qualitative (levels assigned by experts)	Quantitative (based on forest characteristics*)	Quantitative (based on empirical models)
		Scalability		+	++	++
		Comparability		+	++	++
		Realism		--	+	++
		Scalability	Realism			
Prediction of forest development	Forest growth model (tree-based, e.g. SILVA)	--	+		Biber et al. 2015 Nabhani et al. 2024	Schwaiger et al. 2019 Stadelmann et al. 2019
	Forest growth model (stand-based, e.g. 3PG)	-	+		Augustynczik & Yousefpour 2021 Eriksson et al. 2020 Montigny & MacLean 2006 Mozgeris et al. 2017 Suarez-Munoz et al. 2023	Czembor & Vesk 2009
	Forest cover change (based on theory or optimization)	+	--	Begemann et al. 2021 Filyushkina et al. 2022	Karjalainen et al. 2003 Palaiologou et al. 2021	Kamusokoi et al. 2011 Eggers et al. 2019 Lodin et al. 2020 Hallberg-Stramek et al. 2023 Trubins et al. 2019
	Forest cover change (based on expert consultation)	+	++	Dupras et al. 2016 Frittaion et al. 2010 Kassa et al. 2009	MacLean et al. 2021 Malek et al. 2015 Mozgeris et al. 2017 Price et al. 2012 Eggers et al. 2020	our approach

Fig. 1: Most commonly used approaches to model ecosystem services (columns) and predict forest development (rows) and exemplary studies having applied a specific combination. Each approach is assessed relative to the three dimensions scalability, comparability and realism relative to the other approaches (with ++ fulfilling a dimension best and – – worst). The grey box highlights the combination we applied in this study, which we consider a promising balance of scalability, comparability, and realism. We do not claim this is universally superior, but present it as one possible pathway alongside others in the literature. *: those studies only include ES that can be directly calculated using the outputs of the forest development models, i.e., carbon stocks or biomass production.

types of approaches are most commonly used: forest growth models and models of forest cover change. Forest growth models allow modeling of forest development for different management actions or optimization strategies (e.g. SILVA used by Schwaiger et al. 2019). Forest growth models based on individual tree growth, combined with an estimation of resource outputs and economic value are used as decision support systems at local scales (an overview is given in Nordström et al. 2019). At larger spatial scales, modeling forest growth based on individual trees becomes increasingly complex and resource intensive (Poschenrieder et al. 2013). Hence, forest growth models are also calculated at the stand level (Augustynczik & Yousefpour 2021), based on typical forest stand characteristics (e.g. tree species composition, basal area, age composition). Those stand characteristics can directly be used as indicators for ES, such as timber production or carbon storage (Augustynczik & Yousefpour 2021, Mozgeris et al. 2017). Nevertheless, forest growth models remain resource intensive and require detailed knowledge about the mechanisms as well as the biotic and abiotic conditions of forest growth. Hence, forest growth models are often specific to certain regions or forest types. Less complex, but more **scalable** approaches model the change in overall forest cover or cover of different forest types (Filyushkina et al. 2022) under different scenarios, often based on standardized forest inventory data (Eggers et al. 2020).

The first studies which mapped forest ES across large scales typically assigned qualitative levels of ES to specific forest types (Hauck et al. 2013, Kassa et al. 2009, Mozgeris et al. 2017). Recently, an increasing number of large-scale monitoring programs with detailed measurements of both forest characteristics (as in forest inventory programs) and ecosystem functions across forest types (Trombetti et al. 2015) has made it possible to empirically and quantitatively model ecosystem functions and the resulting ES (Simons et al. 2021, Eggers et al. 2020). Empirical or process-based models not only cross different spatial scales, they also capture the cascade character of ES (Zhang et al. 2022) in which ecosystem service potential (ESP) describes the ability of a specific ecosystem to provide an ES. In turn, ES are dependent on ecosystem functions (EF) which are defined as mathematical functions, depending on the respective ecosystem characteristics (Glatthorn et al. 2021). For example, the ESP of climate change mitigation is related to the EF of carbon storage in trees and forest soil which depend on several ecosystem characteristics such as wood volume or carbon-uptake of a specific soil type. In this study, ES are operationalized as ESP, defined as the capacity of forest ecosystems to provide services under given structural and ecological conditions. ESP are quantified using measurable indicators that reflect underlying ecosystem functions. Some of these indicators are closely linked to biodiversity attributes, which reflects the well-established interdependence between biodiversity, ecosystem functioning, and service provision. Quantitative ES models have also been a big improvement in terms of **comparability** (Meraj et al. 2022). While qualitative estimation allows for a relative comparison or ranking of forest types in terms of ES provisioning, the results are specific to the set of considered forest types. Quantitative estimation of ES levels based on standardized forest characteristics or empirical models however ensures **comparability** across scales, forest types and studies.

In principle, empirical ES models can provide information on how ESP will change under any type of forest development scenario. The challenge in scenario development is the complexity of the multiple drivers of forest development at different spatial scales. Besides, interacting effects of drivers are often unknown and hence difficult to predict (Biber et al. 2015, Duguma et al. 2022). Forest managers are also not acting independently of human-influenced drivers like institutional arrangements (e.g. forest laws and regulations, land use planning, nature protection etc.), forestry traditions or economic influences such as fluctuating timber demand. Hence, forest management decisions and individual forest development at the stand scale as well as the distribution of forest types at the regional scale are not only influenced by natural processes but also by complex socio-economic drivers (e.g., the transition to green energy).

Scenarios of forest and ES development are often exploring theoretical extremes or compare scenarios in which only single drivers differ (e.g. Albert & Schmidt 2010 for climate change). These approaches are certainly invaluable for a mechanistic understanding of the relationships between forest development and ES provisioning, but they are less suited to evaluate changes that can be implemented by forest managers or are most likely to occur. While expert assessments are not necessarily more ‘realistic’ than formal models, they offer a way to capture socio-economic drivers that are difficult to model explicitly and can integrate experiential knowledge and practical constraints that may otherwise be overlooked. In this sense, expert-informed scenarios can complement, rather than replace, model-based approaches. Hoogstra-Klein and colleagues (2017: 228) have nicely summarized this in their review on scenario approaches for forest management in Europe: “By including and engaging stakeholders in scenario development, one can not only extend the knowledge that forms the basis for developing scenarios, it also builds consensus [and] creates legitimacy […].”

Many studies use input by experts or stakeholders to either evaluate different scenarios of ES change (Filyushkina et al. 2022, Dupras et al. 2016, Jurmalis et al. 2023) or to define scenarios for which ESPs are then modeled (Strand et al. 2017, MacLean et al. 2021, Duguma et al. 2022, Hallberg-Sramek et al. 2023, Suárez-Munoz et al. 2023). Typical methods to reap expert knowledge are unstructured interviews with selected experts (Schwaiger et al. 2019, Hallberg-Sramek et al. 2023), structured surveys (Lodin et al. 2020), round table discussions that facilitate deliberative exchange among experts and stakeholders (Egri 1999), mapping exercises or workshops (Duguma et al. 2022) and the Delphi method. The Delphi method systematically gathers expert judgments through iterative surveys with feedback (Delbecq et al. 1975). It is particularly suited to research fields with high levels of uncertainty, such as environmental change, where diverse perspectives and incomplete information complicate forecasting (Dalkey & Helmer 1963, Kendall et al. 1992, Lee & King 2009, Strand et al. 2017, Filyushkina et al. 2018, Lee et al. 2019, Petrolia et al. 2020). The approach of combining expert-derived future scenarios, which in accordance with Kok et al. (2015: 188) we understand as “a story about the future that can be told in both words and numbers”, with quantitative representations of changes in space is called a “story and simulation approach“ (Alcamo 2008) and has already been implemented successfully in forestry contexts to visualize land-cover changes (e.g. Duguma et al. 2022). Story and simulation approaches are increasingly used when future scenarios are combined with quantitative data to forecast ecological parameters, but usually these scenarios are based on theoretical or literature-based stories (Regos et al. 2016) or – when expert knowledge is the starting point – developed in an iterative way from qualitative to quantitative assessments (Kok et al. 2015). Although recent studies have made substantial improvements in the realism and scalability of forest development as well as in realism and comparability of forest ESP, their implementation has remained within a disciplinary focus.

Here, we demonstrate how an interdisciplinary approach can effectively address the three main challenges of ES scenario development, using the state of Bavaria, Germany as a case. We ensure scalability and realism of forest development projection with a Delphi-based 'story and simulation' approach focused on forest cover change and combine it with empirical ES models to provide scalability, comparability and realism of ecosystem service potentials. With this case study, we explore the potential of combining Delphi-based story-and-simulation with empirical ESP models. Our aim is not to present a universally superior method, but to test how such an approach performs in practice, to reflect on its strengths and limitations, and to provide spatially explicit insights into forest development and ESP change in Bavaria.

2 Materials and methods

2.1 General approach, study area and expert selection

To determine the ESP changes under different expert-based scenarios of forest development in Bavaria, we conducted a multi-stage research process centered on a two-step Delphi survey (Delphi I and Delphi II; Sacher & Mayer 2019; Fig. 2). Although the Delphi surveys were conducted in 2016-2017, the elicited expert knowledge primarily reflects long-term forest development processes, management trajectories, and structural change drivers that operate over several decades and remain highly relevant under current forest policy and climate change debates. In doing so, we asked the experts to identify key forest characteristics which were then used to statistically define and map the main forest types in our study region. Based on the expert input, we modeled the spatial distribution of forest types under three forest development scenarios. For each forest type, we estimated ESP for 13 ES using empirical models from Simons et al. (2021) and Forest Inventory data. After each Delphi round, experts received feedback on results (Strand et al. 2017) and could refine scenario narratives, particularly after the first round (Fig. 2). Instead of pursuing strict consensus, we applied a *policy Delphi* (Turoff 1970), which emphasizes the range of plausible viewpoints and allows experts to determine levels of agreement themselves. Mean values were used to summarize survey ratings, supporting a more open-ended assessment. This variant was chosen because it balances realism, by capturing heterogeneous views; comparability, by structuring expert input into standardized indicators; and scalability, by linking expert scenarios to spatial data. A similar Delphi-based scenario development was used by Dörr et al. (2015) to evaluate future landscape changes in the European Alps.

The German state of Bavaria was selected as study area because a diverse set of forest types common for Central Europe can be found here and because the state plays a strong role in forest policy and

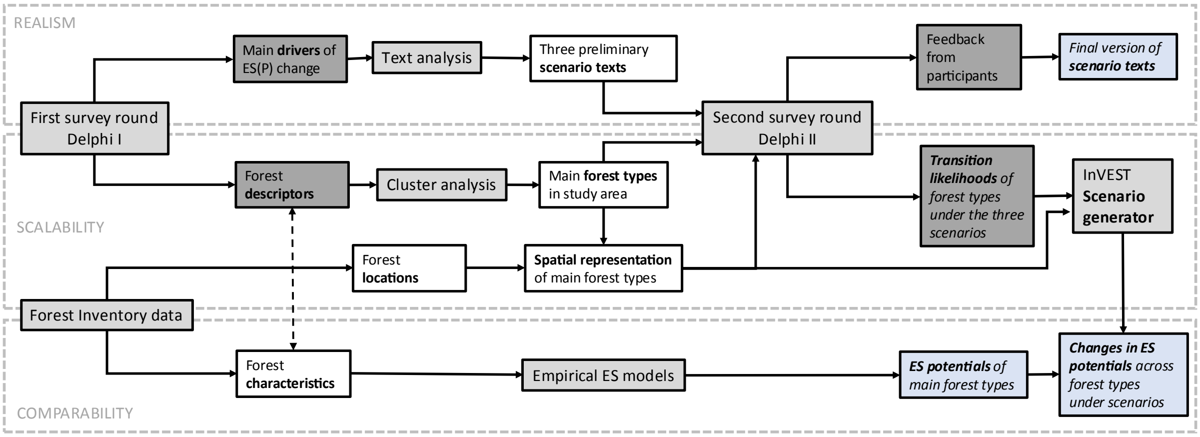


Fig. 2: Workflow of the research process from left to right. Light grey indicates the different methods used to generate outputs. Dark grey indicates output generated by experts, white and blue indicates output generated by the researchers. Italic fond indicates the main outcomes of each workflow. The dashed arrow indicates an alignment between the output generated by experts and empirical data. The forest inventory data were taken from the third German National Forest Inventory (NFI), empirical models for ecosystem service potential (ESP) are based on Simons et al. (2021).

forest management. Forests cover 37% of Germany's land (BMEL 2014), and in Bavaria - Germany's largest state (70.542 km^2) - they cover 37%, with over 95% being managed (BMEL 2014, Zukunftsbaum-Bayern 2023). Forests in Bavaria are owned by diverse stakeholders, including the state, municipalities, public trusts, religious institutions, and private owners, resulting in a wide range of different management strategies being implemented across different natural regions.

Selecting suitable experts is crucial for Delphi studies (Häder 2009, Lee et al. 2019). We used a Knowledge Resource Nomination Worksheet (KRNW; Okoli & Pawlowski 2004) to identify relevant organizations and individuals. Experts were defined as those actively shaping forest-related discourse, whether through research, practice, policy, or stakeholder engagement (Peltola & Tuomisaari 2016). The final panel consisted of 33 experts (Tab. 1). While we aimed for balance, academic representatives were overrepresented due to professional specializations, which influenced the results. This selection bias was further reinforced by the male-dominance in forest sciences, though it aligns with the real-world gender ratio among forest practitioners. To capture an external perspective, we also included experts from the whole of Germany. Although some experts were less familiar with forests in Bavaria specifically, they had relevant knowledge of the region's forestry challenges. Given the diverse expertise, not all experts were equally qualified to answer every question. However, our goal was to combine specialized knowledge with broader discourses in land cover change beyond technical expertise.

2.2 Delphi I: Forest types and drivers of ES(P) change

In the first Delphi survey round (Delphi I, April to May 2016), 22 out of 33 experts participated (response rate of 66.7%), including 75% of experts affiliated with Bavaria. The average age was 48 years (ranging from 29 to 82), the proportion of female participants was low (18%). The educational level was notably high, with 21 out of 22 experts holding a university degree or general university qualification, resulting in an academic share of 95%. Over 80% of the experts self-assessed their knowledge of forest conditions, forest development in Bavaria, and the ES concept as very good or good, affirming their suitability for the Delphi. Only one expert reported a lack of familiarity with the ES concept. We used a semi-standardized online-questionnaire (see Supplementary 1st round) which was accessible via personalized links. The aim of Delphi I was that the experts identified key forest characteristics to classify Bavaria's dominant forest types. Twelve characteristics were translated into categorical variables and matched with data from the 2012 German National Forest Inventory (NFI; Polley 2011, Thuenen-Institute 2016). A cluster analysis

Tab. 1: Stakeholder groups and shares of experts in the final panel

Stakeholder group	Number of experts that gave consent to participate	Number of experts who participated in Delphi I	Number of experts who participated in Delphi II
Agriculture, forestry and timber production lobby	5 (3*)	3 (2)	1
Forest owners	4 (4)	1 (1)	1 (1)
Academic institutions related to forestry	13 (9)	10 (9)	7 (7)
Spatial planning representatives	1	1	0
Politicians and administration	2 (2)	1 (1)	1 (1)
Environmental conservation agencies	4 (3)	3 (2)	3 (2)
Environmental education institutions	2 (2)	1 (1)	1 (1)
Landscape planning offices	1 (1)	1 (1)	1 (1)
Hunting associations	1 (1)	1 (1)	1 (1)
n	33 (25)	22 (18)	16 (14)

*In brackets: Number of experts affiliated with Bavaria of 7,458 NFI plots (Dice index, k-means algorithm in R v.3.3; Dice 1945, Hartigan & Wong 1979, R CORE TEAM 2023) resulted in eight forest types, validated through expert consultation. Experts also ranked the drivers influencing forest development over 30- and 60-year horizons, balancing forecast realism (Häder 2009) with management relevance. Their input formed the basis for three distinct forest development scenarios.

- **Status Quo (SQ):** constant drivers, minimal change.
- **Alternative Scenario I (ASC I – Intensification of use):** stronger impact of drivers, higher timber demand.
- **Alternative Scenario II (ASC II – Resilient close-to-nature forests)**: explorative vision of desirable developments.

Figure 3 shows the spatial distribution of forests across Germany represented by NFI inventory sites while Figure 4 presents in detail the eight forest types identified in Bavaria for each dot. The full first-round scenario texts are available in the Supplement, while Table 2 summarizes the scenario narratives.

2.3 Delphi II: Scenario and forest change probabilities

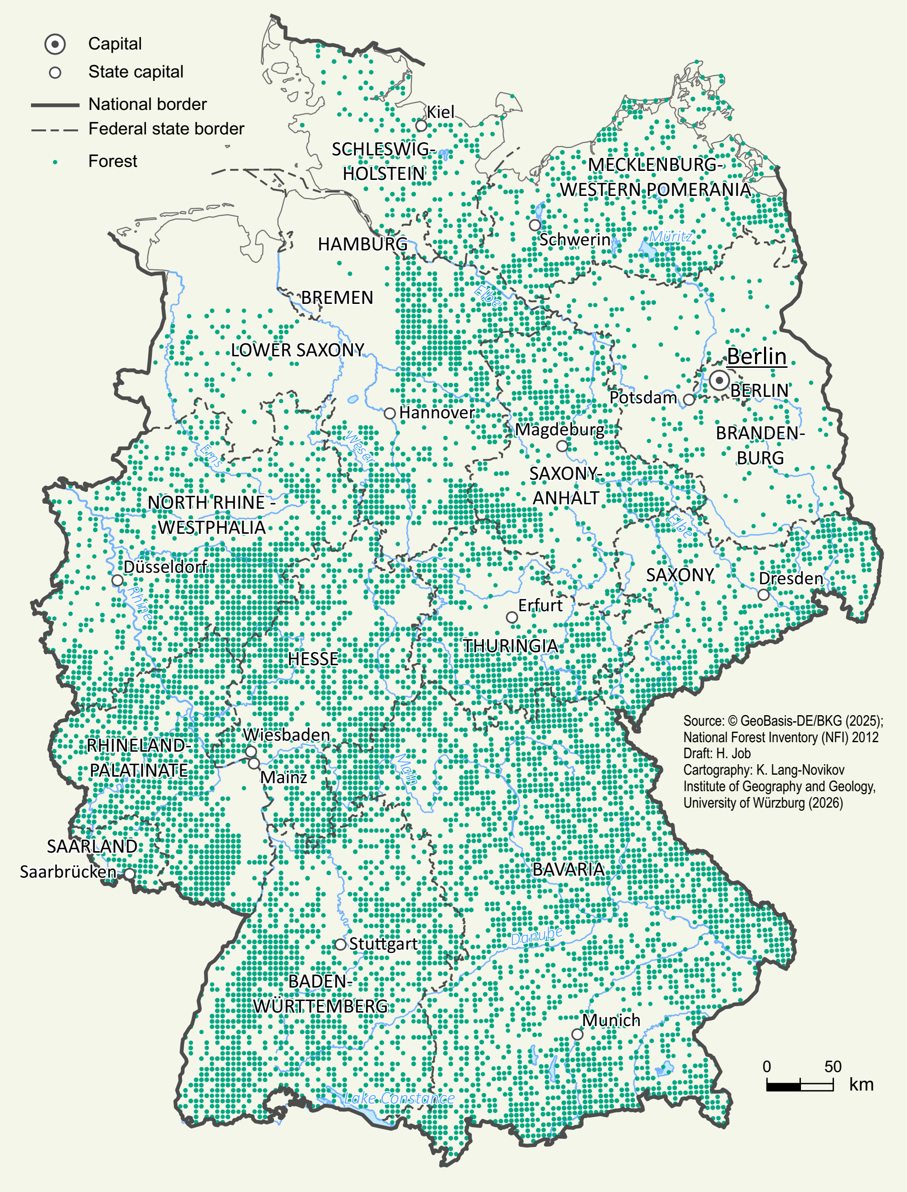
The primary objective of the second Delphi round (Delphi II, December 2016–February 2017) was to translate the qualitative scenario narratives into quantitative information by asking experts to directly estimate scenario-specific transition probabilities between forest types. These probability estimates, rather than predefined assumptions by the authors, formed the quantitative basis for the subsequent spatial modelling. To achieve this, Delphi II focused on quantifying probabilities of scenario occurrence and forest type transitions in a mainly standardized questionnaire (see Supplement 2nd round). Sixteen of the 22 Delphi I participants responded (panel mortality: 27.3%). Experts received descriptive feedback from Delphi I in the form of statistics highlighting rating scale distributions. The three scenarios developed in Delphi I shaped the structure of the second-round questionnaire. The questionnaire was divided into three blocks, each corresponding to one of the scenarios. Identical questions were used in each block, differing only in the underlying scenario. To assess forest type transitions, each forest type was given a descriptive name, a summary of its key characteristics, and a spatial distribution map based on the NFI (Fig. 4). Additional details, including the share of each forest type of the total forest area, were also provided. Experts rated the probability of transitions for the eight forest types on a ten-point-scale (0 = 'not likely at all' to 10 = 'very much likely'). They also reviewed and, if necessary, revised the first-round scenario texts. After incorporating their adaptions, the final scenario texts were completed.

2.4 Spatial modelling of forest change

We used the Scenario Generator v.3.5.0 within the InVEST® software suite (Sharp et al. 2014) to simulate forest type changes for the three scenarios and two time horizons (2045 and 2075). First, the transition probabilities given by the experts in Delphi II were averaged for each forest type combination. Secondly, we joined the publicly available geographic coordinates of the German Forest inventory points (which are arranged in a 4 x 4 km grid and scaled to match the INSPIRE standard) with an empty grid covering Bavaria and used QGIS v. 3.32.0 to create a map of the current distribution of forest types. Any grid cells which did not include an inventory point with one of our eight forest types (either because it is not covered with forest or because not all information was available to determine the forest type) were defined as land-cover type 'other'. Based on the transition probabilities between each pair of forest type and the estimated increase or decrease in percent per forest type, the Scenario Generator calculates priorities of forest type change and converts suitable grid cells into the target forest type until the estimated increase in cover for a specific forest type is reached. As the Scenario Generator only simulates the growing land cover types, increases are exact in terms of the estimated percentual change but decreases in forest type cover can be larger or smaller than estimated by the experts.

2.5 Modelling and evaluation of ecosystem service potential

We estimated the potential to provide 13 ES for each forest type in Bavaria using the predictive equations developed in Simons et al. (2021). The predictive models use the same set of explanatory variables (Supplementary Fig. 3) to model the 13 ES with different effect sizes assigned to the variables per ES. All explanatory variables can be derived from standardized forest inventory data (such as the NFI in



Source: © GeoBasis-DE/BKG (2025);
National Forest Inventory (NFI) 2012
Draft: H. Job
Cartography: K. Lang-Novikov
Institute of Geography and Geology,
University of Würzburg (2026)

Fig. 3: Distribution of forests across Germany. Each point represents an inventory point of the German National Forest Inventory of 2012 (NFI; Thuenen-Institute 2016) which was covered by forest. The NFI is done with a common grid size of 16 km x 16 km across all federal states (shown here). Some federal states (e.g., Bavaria) have an additional finer grid size of 4 km x 4 km (see Fig. 4). Bavaria has an overall forest cover of 37% relative to its total size, which places it slightly above the German average of 32%. With around 60% coniferous forests, Bavaria has a higher share of those forests than the German average of 50% coniferous compared to deciduous forests.

Germany). The set of 13 ES include regulating, material and non-material services, i.e. the three main categories established by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES 2019). For each category, several indicators were selected from the database of the large-scale and long-term research platform 'Biodiversity Exploratories' (BExIS 2023). Background information on how the indicators were selected is described in Simons et al. (2021) and summarized in Supplementary Table 2. It should be noted that while the selected indicators include non-material ES, they primarily capture directly measurable and biophysically mediated aspects of cultural ES, whereas more intangible dimensions such as spiritual values, place identity, or symbolic meanings of forests are not

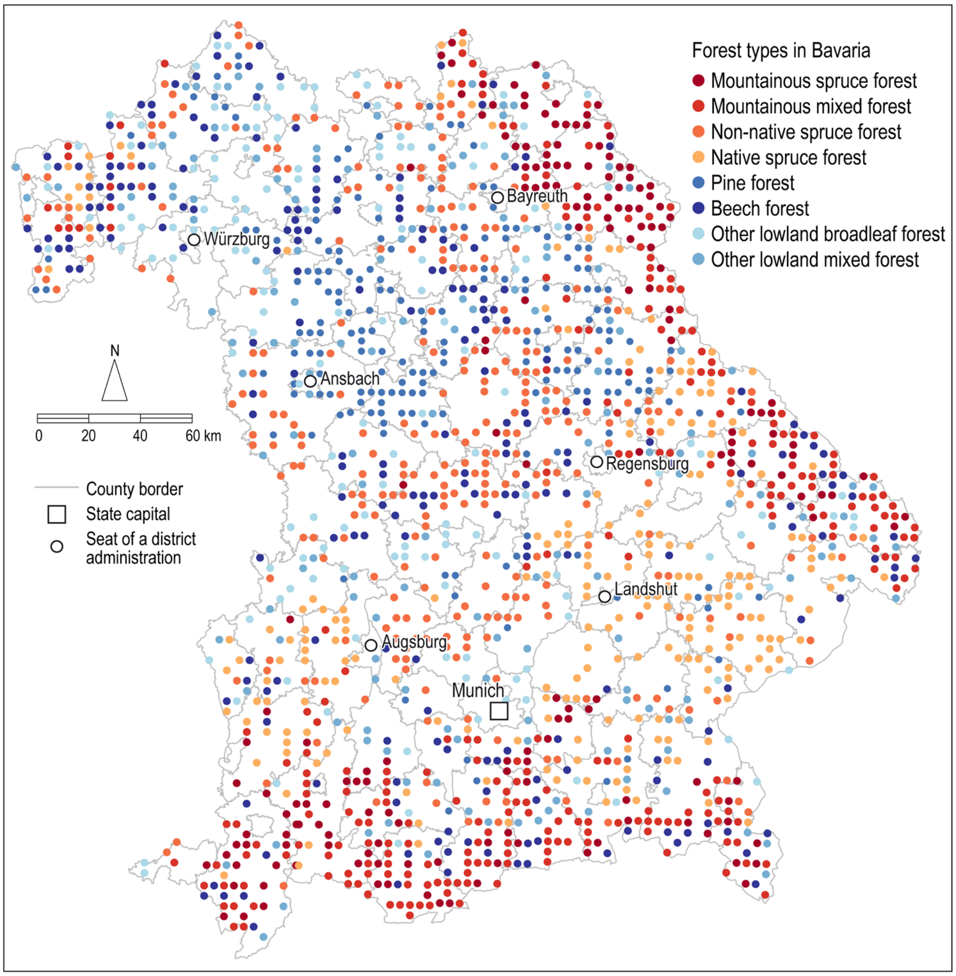


Fig. 4: Distribution of main forest types in Bavaria (each dot represents one forest inventory site) as provided for the expert panel in the Delphi II. Forest types were defined using a clustering algorithm based on the forest characteristics identified as important for forest type distinction in Delphi I. The shares among the complete forest inventory sites are distributed as follows: Mountainous spruce forest 17%, mountainous mixed forest 14%, non-native spruce (mixed) forest 10%, native spruce (mixed) forest 13%, pine (mixed) forest 12%, beech (mixed) forest 11%, other lowland broadleaf forest 15% and other lowland mixed forest 8%. The distribution of these types primarily reflects the historical forestry policy in the regions of Bavaria which foremost pursued the distribution of fast-growing, commercially usable types of wood.

explicitly represented and therefore fall outside the scope of this modelling approach.

Using the function predict in the Rpackage 'stats' (Fox & Weisberg 2019), we estimated the level of each ES for all Bavarian NFI points which could be assigned to one of the eight forest types (i.e. a slightly larger set of points than used for the Scenario Generator). We compared the differences in ESP between forest types with linear models followed by post-hoc tests of pairwise differences based on Tukey's HSD. To ensure normality and homoscedasticity of the model residuals, we inspected Q-Q-Plots and estimated the linear model on square-root-transformed values for the cover of edible plants. The ESP at the landscape level was estimated by calculating the ESP level of each grid cell (according to the cell's forest type) relative to the maximum observed level of ESP across all forest types. Calculating relative levels of ESP allows a comparison between different ES and provides both a baseline (i.e. minimum observed level) and the achievable maximum level of ESP (based on the available options, i.e. forest types). To evaluate the overall ESP within each scenario, we calculated the proportion of raster points (from here on termed 'forest share') which provide a certain level (between 25% and 90%) of ESP relative to the highest potential observed among forest types. This provides a succinct overview of how much of the

Tab. 2: Scenario comparison based on key messages derived from an online survey with 22 forestry-related experts. Full scenario texts are available in the Supplement, an overview of experts' expertise can be found in Tab. 1.

Topic/Dimension	Status Quo Scenario	ASC I 'Intensification of use'	ASC II 'Resilient close-to-nature forests'
		Overall framework conditions in comparison to current situation	
Drivers of forest development	Constant impact	Stronger impact	Balanced impact
		Dimensions of forest development	
Change in overall forest area	Minimal increase	Small increase	Not mentioned
Proportion of deciduous trees	Increase, especially in state-managed forests	Strong increase, potentially reaching a balanced 50:50 ratio with coniferous trees (uncertainty factor: use of Douglas fir for timber production)	Native and newly established species showing strong resilience
Provision of Semi-natural areas	Increase	Increase	Not mentioned
Provision of deadwood	Increase	Stagnation or slight decrease	Not mentioned
Timber production	Conflicting trends	Gains importance	Following sustainable goals
Recreational value	General growth	Spatial differentiation	Similar to ASC I in terms of growing importance close to settlements
Nature conservation measures	Gains importance but heterogeneity in effectiveness	General decline	Reaching a 10% target of protected areas for natural development
Geographical distribution of forested land	Stable character, minor fragmentation	Slight shift to the north of Bavaria, altitudinal extension in the Alpine region	Not mentioned
Payment for forest ecosystem services	Not mentioned	Not mentioned	Increasing recognition and rewarding

forested area has a high, intermediate or low potential to provide a respective ES. We finally calculated the difference in the proportion of raster points at a certain level of ESP between the current situation and the three different scenarios.

3 Results

3.1 Expert perspectives on drivers of forest change

Together, the expert panel identified a total of 23 categories of forest development drivers (Supplementary Fig. 4). All experts named 'climate change' as an important driver, followed by 'timber demand / price' (17 mentions) and 'Influence of nature conservation' (11 mentions). A near majority of experts (48% and 50% respectively) anticipated that 'climate change' and 'calamities / pests' would show the strongest change in influence by 2045, especially as intensified climate change may lead to increased pest problems. One half of the experts also assesses a very strong to strong change in 'area requirements/ areal fragmentation' by 2045. For the remaining drivers, the experts anticipate weak changes in importance. A similar picture emerges for the time horizon up to 2075, but with significantly greater uncertainties overall. Experts agreed that the climate will change even more than by 2045 and that major changes in the ownership structure will develop in the long term. While the experts generally agreed on the importance of drivers under constant conditions, distinct differences emerged among the expert group in terms of how drivers should develop under optimal conditions. We did not pre-define what 'optimal conditions' meant; instead, experts were encouraged to rely on their own perspectives, which led to distinct preferences and underscored the diversity of views. Based on these preferences, we formulated the scenario texts (see Methods) for which experts were then asked to estimate the change of forest type cover.

3.2 Changes of forest type cover under different scenarios

The experts rated the Status-Quo scenario as the most plausible on average, though perceptions varied (mean probability 6.8/11, n=14). The first alternative scenario ASC I *'Intensification of use'* was assigned an average probability of 5.0 and the ASC II *'Resilient and close-to-nature forests'* an average probability of 3.9 by the experts. Looking at the overall amount of expected area change in the different scenarios, experts expected the least change under ASC I and the strongest change under ASC II, with the SQ-Scenario in between (Tab. 3).

Under all scenarios, the greatest changes regarding their area are assumed for all forests dominated by conifers (Tab. 3) with 'non-native spruce (mixed) forests' estimated to lose nearly a third of their area by 2075 under the SQ and up to 42% under the ASC II. Both 'native spruce (mixed) forests' and 'Mountain spruce forests' would decrease, although the drivers influencing forest development are expected to have less impact under this scenario. In contrast, under ASC I, 'spruce (mixed) forests' are expected to increase slightly in area by 2045 before decreasing again by 2075. Notably, under ASC I, several experts expected parts of the 'mountain mixed forest' to transition into spruce-dominated types depending on location, reflecting the continuing importance of spruce and pine in timber production, particularly at higher altitudes. Although these types are quite similar in terms of their appearance, this shows that spruce (and pine) is expected to still have a future as an important supplier for timber production under ASC I and are therefore converted less quickly, especially in higher altitudes of mountain ranges. This development becomes even clearer when looking at the transition probabilities up to 2075 (Tab. 3).

Regarding the forest types into which the previous ones will be transformed, the trend is towards mixed forests. For example, 'mountain spruce forests' will primarily transform into 'mixed mountain forests' (even more likely by 2075). At medium and lower elevations, the 'non-native spruce (mixed) forests' will be replaced by 'beech (mixed) forests' as well as other deciduous forest types. The 'beech (mixed) forests' would benefit most from this in the medium term, with an initial increase of 10% by 2045, and of 16.1% by 2075. In addition, the 'other lowland deciduous forests' (among them are oak-dominated deciduous forests) could gain considerably. In contrast to the SQ, there is less growth in broadleaf-dominated forests under ASC I, especially in 'beech (mixed) forests'. There are also transitions to spruce (mixed) forest in deciduous tree-dominated forest types, which corresponds to an opposite

Tab. 3: Estimated area changes of forest types under three different scenarios of forest development for Bavaria. Values are averages across the expert panel. For detailed transition probabilities between forest types see Supplementary Tab. 3.

Expected area change / **Initial forest types**	**2045**			**2075**		
	Status quo scenario "business as usual"	**Alternative Scenario I 'Intensification of use'**	**Alternative Scenario II 'Resilient and close-to-nature forests'**	**Status quo scenario "business as usual"**	**Alternative Scenario I 'Intensification of use'**	**Alternative Scenario II 'Resilient and close-to-nature forests'**
(I) Mountain Spruce forest	- 3.9 %	- 2.8 %	- 6.9 %	- 9.1 %	- 5.5 %	- 14.1 %
(II) Mountain mixed forest	2.0 %	2.5 %	5.2 %	5.6 %	5.6 %	9.1 %
(III) Non-native Spruce (mixed) forest	- 16.4 %	-14.4 %	- 26.8 %	- 31.4 %	- 28.3 %	- 42.0 %
(IV) Native Spruce (mixed) forest	- 6.1 %	0.8 %	- 7.3 %	- 10.4 %	- 1.2 %	- 13.8 %
(V) Pine (mixed) forest	- 3.2 %	- 4.7 %	- 6.7 %	- 8.8 %	- 10.9 %	- 12.1 %
(VI) Beech (mixed) forest	10.0 %	6.3 %	15.6 %	16.1 %	11.1 %	25.5 %
(VII) Other lowland deciduous forest	6.8 %	3.0 %	10.1 %	13.2 %	8.0 %	18.5 %
(VIII) Other lowland mixed forest	5.6 %	4.2 %	8.3 %	10.7 %	9.4 %	17.5 %
(IX) Other land use	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %

development compared to SQ. Under ASC II, the 'beech (mixed)' and other deciduous forests would gain importance to the detriment of the three coniferous forest types. The 'beech (mixed) forests' could therefore increase by 25.5% until 2075.

It should be emphasized that these projected changes concern only proportions of forests expected to shift between types within the forest estate; conversions to non-forest land uses (e.g., settlement, agriculture) were consistently estimated to be low. For both time horizons a similar pattern in terms of transitions probabilities occurs, but transitions were estimated to be more likely for 2075 (Tab. 3) and uncertainty regarding probabilities among experts was highest in the spruce and pine (mixed) forests (according to standard errors for most target types, see Supplementary Tab. 3).

While consensus emerged on general trends (decline of conifer dominance, rise of mixed and broadleaf forests), expert estimates diverged in magnitude and timing, especially for spruce and pine types, highlighting the uncertainties of long-term forest development under socio-economic and climate change.

3.3 Ecosystem service potentials across forest types and scenarios

When comparing the relative ESP across forest types and services, nine of the 13 ES show very similar average levels across the eight forest types (minimum value of 0.75). Only four ES show stronger differences between forest types: cover of salient and edible plants, bark beetle control and nitrification ability (Fig. 5). Comparing the absolute values of ESP between forest types, a more differentiated picture emerges with differences in average ESP between pairs of forest types (Supplementary Fig. 4). Although statistically significant, these differences are generally modest, suggesting that most forest types deliver a broadly similar baseline of most ES.

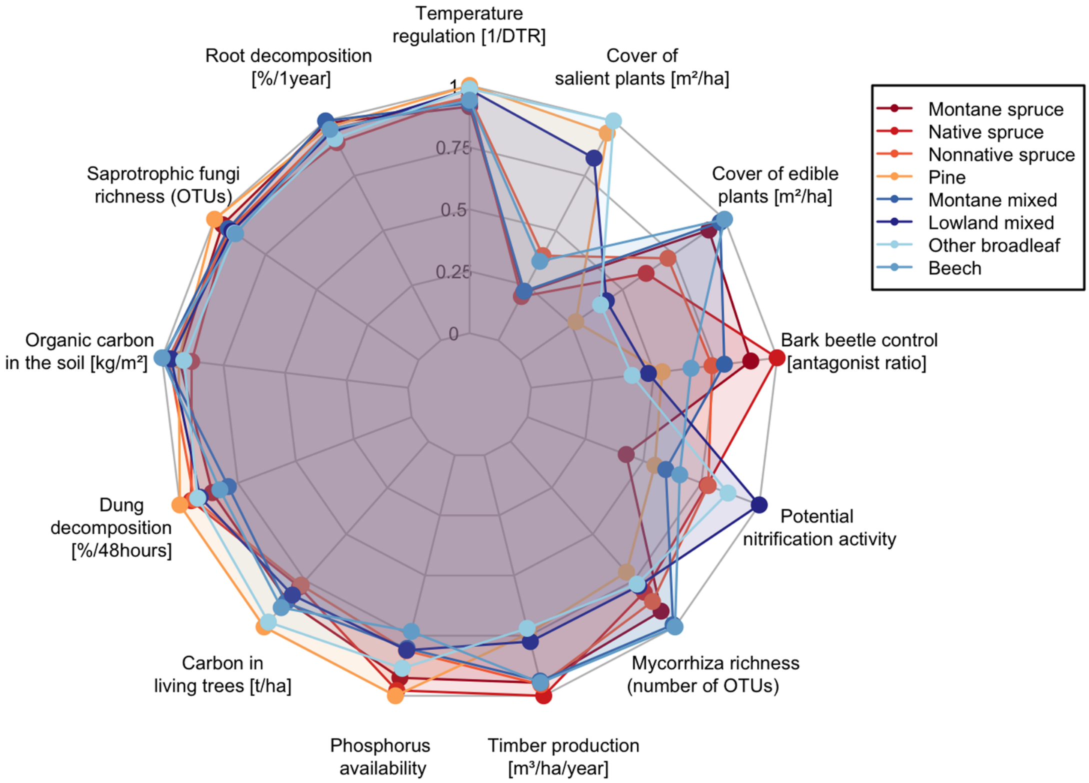


Fig. 5: Estimated average ecosystem service potential for eight forest types in Bavaria, indicated with colors. The ecosystem service potentials are calculated relative to the maximum observed level across all forest types for each service and range from 0 to 1 (maximum level). Ecosystem services are ordered counterclockwise based on the difference between highest and lowest ecosystem service potential, beginning with the ecosystem service that shows the smallest difference between forest types.

Under the current composition of forest types (NFI 2012; Thuenen-Institute 2016), root decomposition and temperature regulation are the only ES provided at the maximum relative level of 0.90 across the whole forested area (forest share of 100% given as numbers within panels in Fig. 6). Most of the other ES have a forest share lower than 50% at the maximum relative level except for dung decomposition, saprotrophic fungi richness, soil organic carbon and timber production (Supplementary Fig. 5). When looking at lower levels of ESP (i.e. representing a strategy that does not aim for a maximization of all ES in all forest areas), the forest shares increase to a point where almost all ES are provided at a minimum level across the entire forest area (level 0.25 in Supplementary Fig. 5).

For some services, such as root decomposition and temperature regulation, no scenario-related differences emerged, largely because these services already reach near-maximum levels across Bavaria's forests. Both ES are mainly influenced by the evenness of the shrub layer in the predictive models used to estimate the ES (Simons et al. 2021) which itself shows only little variation across forest types in our study.

The differences between scenarios and the current situation as well as within scenarios show very variable patterns (Fig. 6, Supplementary Fig. 5). However, in almost all cases within ES, only the magnitude but not the direction of change differs between scenarios or time horizons. The only exceptions are carbon in living trees, timber production and cover of salient plants. For those ES, the ASC II shows changes in the opposite direction than the SQ or ASC I. When comparing the direction of change across those three ES, clear trade-offs between scenarios can be seen (Fig. 5). While the SQ and ASC I will lead to only slight declines in forest share for cover of salient plants and carbon in living trees, timber production shows much stronger declines in forest shares. The trade-off becomes even more pronounced under ASC II as timber production will lose up to 4% in forest share while carbon in living trees and salient plants will gain. Although a change in forest shares below 5% has relatively minor implications for ES with large forest shares, such a change can have a potentially large effect if the current forest share is relatively small. For example, forest shares for cover of salient plants and potential nitrification at the highest level are only 20% and 10%, meaning that an increase of 2% forested area is equivalent to an increase by a tenth or a fifth of the current forest area respectively.

Overall, the ESP modeling suggests relative stability across forest types and scenarios, though trade-offs between provisioning and regulating services persist and may intensify depending on scenario pathways.

4 Discussion and conclusion

This study introduced a novel interdisciplinary approach to scenario-based ES modeling which bridges the gap between theoretical scenario development and stakeholder perspectives and achieves realism, scalability, and comparability of ES scenarios in forests. Combining expert-driven Delphi-derived scenarios, standardized modeling of forest cover change, and quantitative ES assessments, it accounts for diverse drivers of forest change while ensuring spatially explicit and scalable outcomes. Using Bavaria as a case, this study demonstrates how this framework captures complex ES trade-offs and transitions across forest types, illustrating the potential of a stakeholder-based framework to explore possible ES futures and inform sustainable forest management across scales.

4.1 Realism, scalability and comparability of our approach

Sustainable forest management needs to address different drivers of forest development like climate change, pests, and declining tree health (Hoogstra-Klein et al. 2017, Begemann et al. 2021), but previous approaches have failed at comprehensive scenario-building and hence lack **realism** (Morán-Ordóñez et al. 2019). Instead of trying to build complex theoretical scenarios, our approach uses expert knowledge which integrates a broad range of drivers, including climate change, socio-economic factors, and policy to develop plausible scenarios of forest change. While there is a trend to extend scenario timelines to longer horizons, particularly in the forest context, this challenges realistic expert assessments due to the increasing uncertainty of predictions (Hoogstra-Klein et al. 2017) which we also saw in our case study. To address this, we recommend a balanced approach with medium- and long-term perspectives, ensuring scenarios of forest development are both plausible and sufficiently forward-looking.

A central contribution of our approach lies in enhancing **realism** by linking expert-based scenarios with spatially explicit forest composition, re-

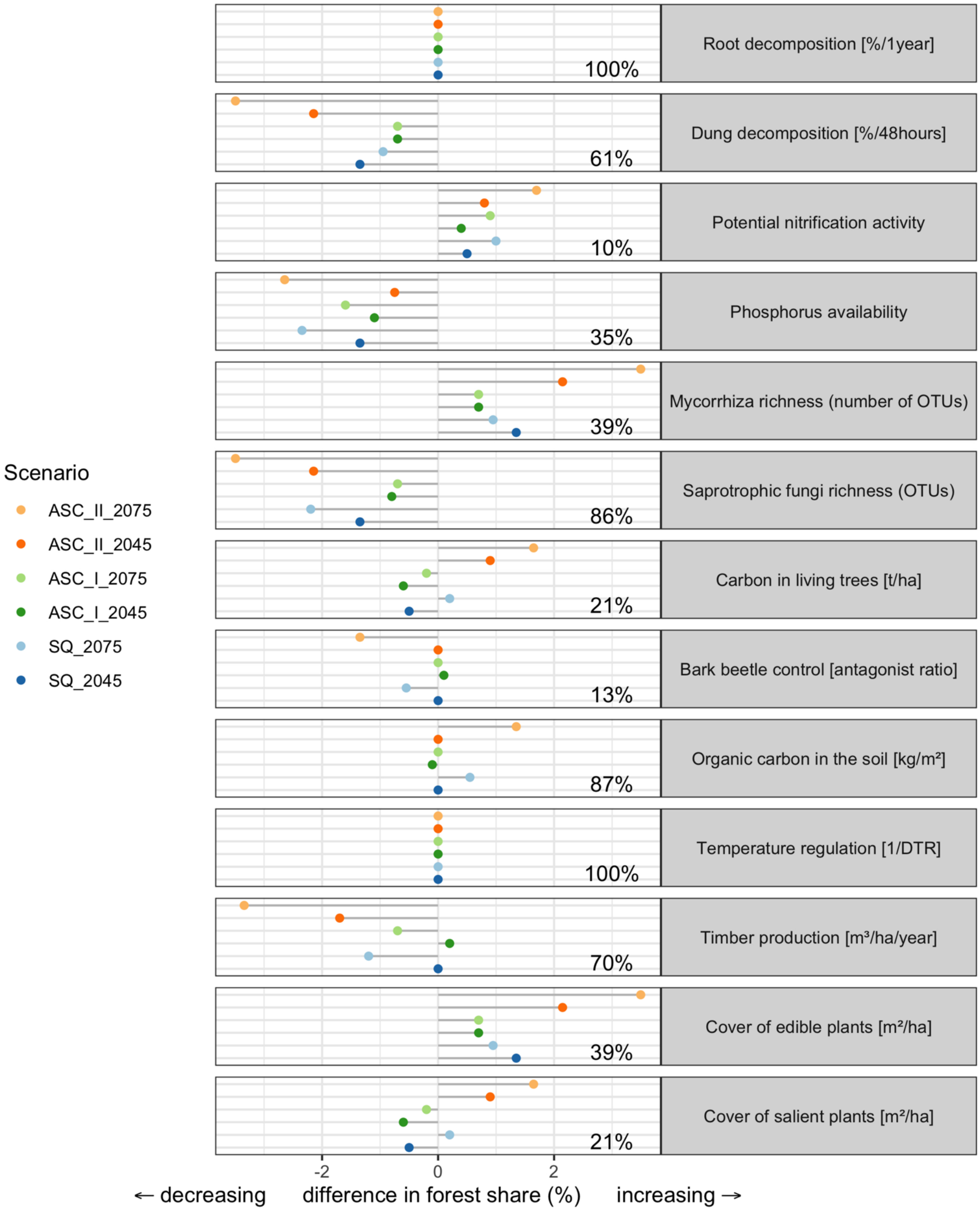


Fig. 6: Percentage of the forest area (forest share) which reaches at least a relative level of 0.9 in ecosystem service potential (ESP) and its change under different scenarios. Colors indicate the different scenarios and timespans. SQ (blue): Status quo scenario with no change in drivers. ASCI (green): Alternative scenario I 'Intensification of use'. ASCII (orange): Alternative scenario II 'resilient and close-to-nature forests'. The relative level of ESP is calculated relative to the maximum observed level across forest types within each ecosystem service (panels). The difference in forest share (x-axis) is calculated in comparison to the current situation which is given as percentage in the lower right corner of each box. For example, according to the 2012 NFI, 61% of the forest area has a dung decomposition rate at or above an ESP level of 0.9. Changes in forest share for different ESP levels are given in Supplementary Fig. 5.

sulting in quantitative estimations of forest development which can be linked with empirical ES models. Previous studies often relied on either qualitative valuation of forest types for their ES potential (e.g., Hauck et al. 2013, Mozgeris et al. 2017, Hallberg-Sramek et al. 2023) or used indicators derived from forest-growth models that tend to prioritize wood biomass (Biber et al. 2015, Trombetti et al. 2015).

Although forest-growth indicators offer an improvement in quantitative accuracy, they fail to account for ecosystem characteristics beyond what the models explicitly represent. By using empirical models of ecosystem functions derived from real-world data, our approach captures how ES are tied directly to specific forest characteristics and ecosystem processes. Combining scenarios of forest development with empirical ES models offers deeper insights into the interplay of forest drivers and ESP, for instance between changes in dominant tree species and nitrification activity, edible plant cover, or bark beetle control. However, while these models capture important ecosystem processes, they remain simplifications of complex dynamics.

The **comparability** of ESP across forest types showed that despite differences in species composition among scenarios, most ESP were provided consistently at a minimum level throughout the landscape, with stronger variation observed only for a few services tied to specific forest structures or species. For example, beech (mixed) forests exhibited higher provisioning levels for certain cultural services, consistent with findings from other European studies (Tew et al. 2019). This suggests that targeted forest conversions – rather than widespread changes – can maintain key ESP while allowing for adaptability to future demands, such as biodiversity protection or climate resilience. Future studies could further enhance comparability by quantifying the relative importance of ESP across regions and integrating community preferences for ES provisioning (Fagerholm et al. 2020, Peter et al. 2022). However, the observed stability of ESP across scenarios should be interpreted cautiously. For many services, differences between forest types are relatively small in the underlying empirical models, which limits the magnitude of scenario-driven variation. In addition, ESP were expressed as relative values normalized to observed maxima, which facilitates cross-service comparison but may dampen absolute differences between scenarios. Consequently, the apparent stability of ESP reflects both genuine robustness of service provision across forest types and methodological characteristics of the ESP modelling and scaling.

Our approach can be adapted to different contexts or regions with varying socio-ecological conditions, ensuring **scalability** of both forest development scenarios and ESP. As ESP are based on forest types which can be defined based on the conditions and needs of each case study, forest management recommendations can be applied from local to regional levels. For example, a mix of forest types could be prioritized in landscape-level planning to address trade-offs effectively (Simons et al. 2021) while decisions at the local level can focus on forest types with high potential for specific ES.

4.2 Integrating socio-economic contexts enhances ecosystem service predictions

The most advanced estimations of ESP in European forests rely on standardized large-scale forest inventory data and detailed forest-growth models. These models simulate tree growth based on well-established biological processes and can incorporate climate change scenarios and management strategies. Gregor et al. (2024) recently extended this approach with mathematical optimization to project future ES provisioning across Europe. While powerful in offering impressive scalability and precision, such approaches remain constrained by reliance on mathematical assumptions, which may not fully reflect socio-political and value-based drivers. For instance, socio-economic considerations such as ownership structures, public acceptance, and policy drivers play an increasingly prominent role in shaping forest development trajectories (Kok et al. 2015, Eggers et al. 2019) and must be explicitly considered.

Interestingly, the expert-based scenarios developed in our study align with some results of Gregor et al. (2024), particularly in predicting a shift towards broad-leaved and mixed forests. However, the changes predicted by their optimization model were significantly more radical compared to our scenarios. Once Gregor et al. (2024) incorporated social and political constraints, the predicted forest composition resembled the more moderate transformations described by the experts in our case study. This comparison illustrates the added value of grounding scenarios in localized expertise and practical forestry contexts: diverse expert input captures socio-economic and value-based drivers that cannot be easily quantified or incorporated into algorithms, improving the realism of forest scenarios. Similar findings have been reported in other complex systems such as the energy transition (Revez et al. 2020). Both approaches – optimization-based and expert-informed – are therefore best seen as complementary, with potential synergies when combined.

In addition to integrating socio-economic aspects into forest development prediction, our approach also advances the realism of ES modeling.

For forest management, this combination is particularly valuable. It enables the development of strategies that balance trade-offs between ES, such as timber production and biodiversity conservation, while maintaining realistic assumptions about social, economic, and ecological constraints. Furthermore, by embedding diverse stakeholder perspectives into the modeling process, this approach ensures greater alignment with regional and local needs, ultimately improving the applicability of forest development scenarios for policy and management planning.

On a broader scale, combining expert-driven scenario development with empirical modeling offers valuable insights into the interplay between social values, ecological parameters, and their translation into actionable scenarios. This enables policymakers and stakeholders to ground decisions in both ecological realities and social expectations, facilitating more informed and adaptive strategies. Compared to more theoretical or mathematically optimized scenario assessments, our approach tends to generate scenarios that are less extreme and potentially more aligned with plausible, socially acceptable outcomes. This balance between ecological foresight and social grounding makes the methodology transferable to other contexts, where it can support the development of policies tailored to specific ecosystems and societal goals. Traceability between qualitative scenario narratives and quantitative outcomes is ensured through the explicit translation of expert assessments into forest type transition probabilities. Nevertheless, expert disagreement and necessary aggregation steps influence how narratives are reflected in the spatial modelling. Averaging transition probabilities produces internally consistent scenario inputs but may smooth divergent expectations, while technical constraints of the Scenario Generator further shape how expert-defined changes are implemented spatially. These factors contribute to the moderate, non-extreme character of the resulting scenarios.

4.3 Limitations and further research demands

Despite the strides toward creating realistic scenarios of ESP, several sources of uncertainty influence the results of this study. These include variation and disagreement among expert judgements, attrition between Delphi rounds, constraints of the spatial scenario implementation, and uncertainties related to transferring empirical ESP models beyond their original calibration contexts. Together, these factors affect both the range and the interpretation of projected forest transitions and ESP outcomes. In detail, the following limitations must be acknowledged. First, interdisciplinary methods such as ours inherently demand greater investment in expertise, time, and financial resources compared to simpler, unstructured expert consultations. Implementing the Delphi method, in particular, is time-intensive, and expert participation can be challenging. Similar to other studies (Strand et al. 2017), we observed moderate levels of participation and some panel attrition between rounds, which required additional effort to remind and motivate experts. Additionally, our expert panel was somewhat unbalanced, with a stronger representation of scientific experts compared to forest management practitioners. While some scientific participants had practical experience, the lack of a more even distribution could have influenced the perspectives captured in the scenarios. This imbalance implies that scenario narratives may more strongly reflect scientific framings of forest change, while practical implementation constraints and experiential knowledge from forest managers may be underrepresented.

Another limitation lies in the empirical data underlying the ecosystem function models. These models were built on observational studies covering a broad range of forest types but may not reflect the most current forest dynamics and extending these models to forest types outside the original study regions introduces uncertainty. This asymmetry may lead to deviations from expert expectations, particularly where substantial reductions in specific forest types were anticipated but could not be fully realized in the spatial implementation. Ideally, applying our approach to another case study would involve repeating the process with tailored empirical data and expert input, which can be resource-intensive (Price et al. 2012, Eggers et al. 2019). Furthermore, the drivers of forest development in our scenarios were not fully explored in terms of their mutual interactions, which could be a focus for future research. Integrating these complex interactions might yield deeper insights into forest ecosystem dynamics and improve the accuracy of ESP projections.

Despite these limitations, the interdisciplinary framework we developed offers significant value. It moves beyond purely theoretical forest cover scenarios and qualitative ESP assessments to deliver grounded, policy-relevant insights. This approach can be adapted to other forest contexts, ecosystems, and landscapes globally, provided that the necessary data (e.g., forest inventory data) and expertise are available. By addressing key issues such as credibility, salience, and legitimacy in ESP modeling and scenario development (Hauck et al. 2013), the framework provides a robust foundation for evidence-based decision-making and sustainable forest management.

4.4 Policy implications

The assessment of forest types and their transition probabilities under various scenarios highlighted several key patterns. Experts rated the status quo scenario as the most likely, suggesting a strong tendency toward continuity in current forest management practices. This reflects a gradual shift toward climate-smart forestry, aligning with broader calls for adaptive forest management strategies (Bowditch et al. 2020). Unlike some other studies predicting more extreme forest composition changes under climate or policy pressures (e.g., Gregor et al. 2024), our expert-based approach anticipates slower, incremental adjustments. This tempered outlook underscores the importance of policy and management interventions to accelerate transitions toward multifunctional forests capable of supporting diverse ESPs. In conclusion, our approach demonstrates the potential for balancing trade-offs between forest ES, while achieving sustainable forestry goals, consistent with findings from similar European contexts (van der Plas et al. 2018). We emphasize that achieving balanced ESP provisioning does not require every forest type to meet all services equally. Instead, forests can be managed to specialize in different ESPs, depending on their local conditions and ownership structures, which require careful negotiation and social consensus.

Acknowledgements

This research was financed by the German Federal Ministry of Education and Research (BMBF) and the German Federal Agency for Nature Conservation (BfN) with funds from the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) in the project 'Biologische Vielfalt und Ökosystemleistungen von Wäldern mit Fokus auf Holz. Neue Wege der Nachhaltigen Nutzung im Spannungsfeld zwischen Ökologie, Ökonomie und Klimawandel (BioHolz)' (FKZ 01LC1323C).

References

Albert M, Schmidt M (2010) Climate-sensitive modelling of site-productivity relationships for Norway spruce (Picea abies (L.) Karst.) and common beech (Fagus sylvatica L.). *Forest Ecology and Management* 259 :739–749. https://doi.org/10.1016/j.foreco.2009.04.039

Alcamo J (2008) The SAS approach: Combining qualitative and quantitative knowledge in environmental scenarios. Alcamo J (ed) E*nvironmental futures: The practice of environmental scenario analysis*: 123–150). Amsterdam.

Augustynczik A, Yousefpour R (2021) Assessing the synergistic value of ecosystem services in European beech forests. *Ecosystem Services* 49: 101264. https://doi.org/10.1016/j.ecoser.2021.101264

Begemann A, Giessen L, Roitsch D, Roux JL, Lovric M, Azevedo-Ramos C, Boerner J, Beeko C, Cashore B, Cerutti P, de Jong W, Fosse L, Hinrichs A, Humphreys D, Pülzl H, Santamaria C, Sotirov M, Wunder S, Winkel G (2021) Quo vadis global forest governance? A transdisciplinary Delphi study. *Environmental Science and Policy* 123: 131–141. https://doi.org/10.1016/j.envsci.2021.03.011

BExIS (Biodiversity Exploratories Information System) editing status 2023-05-10. https://doi.org/10.17616/R32P9Q

Biber P, Borges J., Moshammer R, Barreiro S, Botequim B, Brodrechtová Y, Brukas V, Chirici G, Cordero-Debets R, Corrigan E, Eriksson L, Favero M, Galev E, Garcia-Gonzalo J, Hengeveld G, Kavaliauskas M, Marchetti M, Marques S, Mozgeris G, Navrátil R, Nieuwenhuis M, Orazio C, Paligorov I, Pettenella D, Sedmák R, Smreček R, Stanislovaitis A, Tomé M, Trubins R, Tuček J, Vizzarri M, Wallin I, Pretzsch H, Sallnäs O (2015) How sensitive are ecosystem services in European forest landscapes to silvicultural treatment? *Forests* 6: 1666–1695. https://doi.org/10.3390/f6051666

BMEL (Federal Ministry of Food and Agriculture) (2014) Der Wald in Deutschland. Ausgewählte Ergebnisse der dritten Bundeswaldinventur. https://www.bundeswaldinventur.de/dritte-bundeswaldinventur-2012

Borrass L, Kleinschmit D, Winkel G (2017) The "German model" of integrative multifunctional forest management—Analysing the emergence and political evolution of a forest management concept. *Forest Policy and Economics* 77: 16–23. https://doi.org/10.1016/j.forpol.2016.06.02

Bowditch E, Santopuoli G, Binder F, del Río M, La Porta N, Kluvankova T, Lesinski J, Motta R, Pach M, Panzacchi P, Pretzsch H, Temperli C, Tonon G, Smith M, Velikova V, Weatherall A, Tognetti R (2020) What is climate-smart forestry? A definition from a multinational collaborative process focused on mountain regions of Europe. *Ecosystem Services* 43: 101113. https://doi.org/10.1016/j.ecoser.2020.101113

Dalkey NC, Helmer O (1963) An experimental application of the Delphi method to the use of experts. *Management Science* 9: 458–467.

Delbecq A, Van de Ven A, Gustafson D (1975) Group techniques for program planning. A guide to nominal group and Delphi processes. Glenview IL.

Dice L (1945) Measures of the amount of ecologic association between species. *Ecology* 26: 297–302. https://doi.org/10.2307/1932409

Dörr H, Fiby M, Hilbert A (2015) Raumbezogene Ergebnisse der Delphi-Umfrage zur Zukunft der Landschaft in Regionen Süddeutschlands, Österreichs und der nördlichen Schweiz. https://doi.org/10.13140/RG.2.1.4001.2965

Duguma DW, Schultner J, Abson D, Fischer J (2022) From stories to maps: Translating participatory scenario narratives into spatially explicit information. *Ecology and Society* 27: 13. https://doi.org/10.5751/ES-13200-270213

Dupras J, Patry C, Tittler R, Gonzalez A, Alam M, Messier C (2016) Management of vegetation under electric distribution lines will affect the supply of multiple ecosystem service. *Land Use Policy* 51: 66–75. http://dx.doi.org/10.1016/j.landusepol.2015.11.005

Eggers J, Holmgren S, Nordström EM, Lämås T, Lind T, Öhman A (2019) Balancing different forest values: Evaluation of forest management scenarios in a multi-criteria decision analysis framework. *Forest Policy and Economics* 103: 55–69. https://doi.org/10.1016/j.forpol.2017.07.002

Eggers J, Räty M, Öhman K, Snäll T (2020) How well do stakeholder-defined forest management scenarios balance economic and ecological forest values? *Forests* 11: 86. https://doi.org/10.3390/f11010086

Egri CP (1999) The environmental round table role-play exercise: The dynamics of multistakeholder decision-making processes. *Journal of Management Education* 23: 95–112. https://doi.org/10.1177/105256299902300110

Fagerholm N, Martín-López B, Torralba M, Oteros-Rozas E, Lechner A, Bieling C, Olafsson A, Albert C, Raymond C, Garcia-Martin M, Gulsrud N, Plieninger T (2020) Perceived contributions of multifunctional landscapes to human well-being: Evidence from 13 European sites. *People and Nature* 2: 217–234. https://doi.org/10.1002/pan3.10067

Filyushkina A, Strange N, Löf M, Ezebilo EE, Boman M (2018) Applying the Delphi method to assess impacts of forest management on biodiversity and habitat preservation. *Forest Ecology and Management* 409: 179-189. https://doi.org/0.1016/j.foreco.2017.10.022

Filyushkina A, Widenfalk LA, Nordström EV, Laudon H, Ranius T (2022) Expert assessment of landscape-level conservation strategies in boreal forests for biodiversity, recreation and water quality. *Journal for Nature Conservation* 67: 126180.

Fox J, Weisberg S (2019) An R companion to applied regression. Thousand Oaks.

Glatthorn J, Annighöfer P, Balkenhol N, Leuschner C, Polle A, Scheu S, Schuldt A, Schuldt B, Ammer C (2021) An interdisciplinary framework to describe and evaluate the functioning of forest ecosystems. *Basic and Applied Ecology* 52: 1–14. https://doi.org/10.1016/j.baae.2021.02.006

Gregor K, Reyer C, Nagel, T., Mäkelä, A., Krause A, Knoke T, Rammig A (2024) Reconciling the EU forest, biodiversity, and climate strategies. *Global Change Biology* 30: e17431. https://doi.org/10.1111/gcb.17431

Häder M (2009) Delphi-Befragungen. Ein Arbeitsbuch. Wiesbaden.

Hallberg-Sramek I, Nordström EM, Priebe J, Reimerson E, Marald E, Nordin A (2023) Combining scientific and local knowledge improves evaluating future scenarios of forest ecosystem services. *Ecosystem Services* 60: 101512. https://doi.org/10.1016/j.ecoser.2023.101512

Hartigan JA, Wong MA (1979) Algorithm AS 136: A K-means clustering algorithm. *Applied Statistics* 28: 100–108. https://doi.org/10.2307/2346830

Hauck J, Görg C, Varjopuro R, Ratamäki O, Maes J, Wittmer H, Jax K (2013) "Maps have an air of authority": Potential benefits and challenges of ecosystem service maps at different levels of decision making. *Ecosystem Services* 4: 25–32. https://doi.org/10.1016/j.ecoser.2012.11.003

Hoogstra-Klein M, Hengeveld G, de Jong R (2017) Analysing scenario approaches for forest management - One decade of experiences in Europe. *Forest Policy and Economics* 85: 222–234. https://doi.org/10.1016/j.forpol.2016.10.002

IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services)(2019) Summary for policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn https://doi.org/10.5281/zenodo.3553579

Jenkins M, Schaap B (2018) Forest ecosystem services. Background study prepared for the thirteenth session of the United Nations Forum on Forests. https://www.un.org/esa/forests/wp-content/uploads/2018/05/UNFF13_BkgdStudy_ForestsEcoServices.pdf.

Jurmalis E, Bardule A, Donis J, Gerra-Inohosa L, Libiete Z (2023) Forest inventory data provide useful information for mapping ecosystem services potential. *Land* 12: 1836. https://doi.org/10.3390/land12101836

Kassa H, Campbell B, Sandewall M, Kebede M, Tesfaye Y, Dessie G, Seifu A, Tadesse M, Garedew E, Sandewall K (2009) Building future scenarios and uncovering persisting challenges of participatory forest management in Chilimo Forest, Central Ethiopia. *Journal of*

Environmental Management 90: 1004–1013. https://doi.org/10.1016/j.jenvman.2008.03.009

Kendall JE, Kendall KE, Smithson S, Angell IO (1992) SEER: A divergent methodology applied to forecasting the future roles of the systems analyst. *Human Systems Management* 11: 123–135. https://doi.org/10.3233/HSM-1992-11303

Kok K, Bärlund I, Flörke M, Holman I, Gramberger M, Sendzimir J, Stuch B, Zellmer K (2015) European participatory scenario development: Strengthening the link between stories and models. *Climatic Change* 128: 187–200. https://doi.org/10.1007/s10584-014-1143-y

Lee G, Jun KS, Kang M (2019) Framework to prioritize watersheds for diffuse pollution management in the Republic of Korea: Application of multi-criteria analysis using the Delphi method. *Natural Hazards and Earth System Sciences* 19: 2767–2779. https://doi.org/10.5194/nhess-19-2767-2019

Lee CF, King B (2009) A determination of destination competitiveness for Taiwan's hot springs tourism sector using the Delphi technique. *Journal of Vacation Marketing* 15: 243–257. https://doi.org/10.1177/1356766709104270

Lodin I, Eriksson LO, Forsell N, Korosuo A (2020) Combining climate change mitigation scenarios with current forest owner behavior: A scenario study from a region in Southern Sweden. *Forests* 11: 346. https://doi:10.3390/f11030346

MacLean MG, Duveneck MJ, Plisinski J, Morreale LL, Laflower D, Thompson JR (2021) Forest carbon trajectories: Consequences of alternative land-use scenarios in New England. *Global Environmental Change* 69: 102310. https://doi.org/10.1016/j.gloenvcha.2021.102310

Manning P, van der Plas F, Soliveres S, Allan E, Maestre FT, Mace G, Whittingham MJ, Fischer M (2018) Redefining ecosystem multifunctionality. *Nature Ecology and Evolution* 2: 427–436. https://doi.org/10.1038/s41559-017-0461-7

Meraj G, Singh S, Kanga S, Islam M (2022) Modeling on comparison of ecosystem services concepts, tools, methods and their ecological-economic implications: A review. *Modeling Earth Systems and Environment* 8: 15–34. https://doi.org/10.1007/s40808-021-01131-6

Morán-Ordóñez A, Roces-Díaz JV, Otsu K, Ameztegui A, Coll L, Lefevre F, Retana J, Brotons L (2019) The use of scenarios and models to evaluate the future of nature values and ecosystem services in Mediterranean forests. *Regional Environmental Change* 19: 415–428. https://doi.org/10.1007/s10113-018-1408-5

Mozgeris G, Brukas V, Stanislovaitis A, Kavaliauskas M, Palicinas M (2017) Owner mapping for forest scenario modelling - A Lithuanian case study. *Forest Policy and Economics* 85: 235–244. https://doi.org/10.1016/j.forpol.2016.02.002

Nelson E, Mendoza, G, Regetz J, Polasky S, Tallis H, Cameron DR, Chan KM, Daily GC, Goldstein J, Kareiva PM, Lonsdorf E, Naidoo R, Ricketts TH, Shaw MR (2009) Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. *Frontiers in Ecology and the Environment* 7: 4. https://doi.org/10.1890/080023

Nordström EM, Nieuwenhuis M, Başkent EZ, Biber P, Black K, Borges J, Bugalho M, Corradini G, Corrigan E, Eriksson L, Felton A, Forsell N, Hengeveld G, Hoogstra-Klein M, Korosuo A, Lindbladh M, Lodin I, Lundholm A, Marto M, Masiero M, Mozgeris G, Pettenella D, Poschenrieder W, Sedmak R, Tucek J, Zoccatelli D (2019) Forest decision support systems for the analysis of ecosystem services provisioning at the landscape scale under global climate and market change scenarios. *European Journal of Forest Research* 138: 561–581. https://doi.org/10.1007/s10342-019-01189-z

Okoli C, Pawlowski SD (2004) The Delphi method as a research tool. An example, design considerations and applications. *Information & Management* 42: 15–29. https://doi.org/10.1016/j.im.2003.11.002

Peltola T, Tuomisaari J (2016) Re-inventing forestry expertise: Strategies for coping with biodiversity protection in Finland. *Forest Policy and Economics* 62: 11–18. https://doi.org/10.1016/j.forpol.2015.10.005.

Peter S, Le Provost G, Mehring M, Müller T, Manning P (2022) Cultural worldviews consistently explain bundles of ecosystem service prioritisation across rural Germany. *People and Nature* 4: 218–230. https://doi.org/10.1002/pan3.10277

Petrolia DR, Nyanzu F, Cebrian J, Harri A, Amato J, Walton WC (2020) Eliciting expert judgment to inform management of diverse oyster resources for multiple ecosystem services. *Journal of Environmental Management* 268: 110676. https://doi.org/10.1016/j.jenvman.2020.110676

Polley H (2011) Survey instructions for the 3rd National Forest Inventory (2011–2012). Bonn.

Poschenrieder W, Grote R, Pretzsch H (2013) Extending a physiological forest growth model by an observation-based tree competition module improves spatial representation of diameter growth. *European Journal of Forest Research* 132: 943–958. https://doi.org/10.1007/s10342-013-0730-1

Price J, Silbernagel J, Miller N, Swaty R, White M, Nixon K (2012) Eliciting expert knowledge to inform landscape modeling of conservation scenarios. *Ecological Modelling* 229: 76–87. https://doi.org/10.1016/j.ecolmodel.2011.09.010

R Core Team (2023). R: A language and environment for statistical computing. Vienna.

Regos A, Aquilué N, López I, Codina M, Retana J, Brotons L (2016) Synergies between forest biomass extraction for bioenergy and fire suppression in Mediterranean ecosystems: Insights from a storyline-and-simulation approach. *Ecosystems* 19: 786–802. https://doi.org/10.1007/s10021-016-9968-z

Revez A, Dunphy N, Harris C, Mullally G, Lennon B, Gaffney C (2020) Beyond forecasting: Using a modified Delphi method to build upon participatory action research in developing principles for a just and inclusive energy transition. *International Journal of Qualitative Methods* 19. https://doi.org/10.1177/1609406920903218

Sacher P, Mayer M (2019). Szenarien der Waldentwicklung in Bayern bis 2045 und 2075 – Ergebnisse einer Delphi-Studie mit ausgewählten Waldexperten. *Greifswalder Geographische Arbeiten* 56. https://geo.uni-greifswald.de/institut/schriftenreihen/greifswalder-geographische-arbeiten/

Schwaiger F, Poschenrieder W, Biber P, Pretzsch H (2019) Ecosystem service trade-offs for adaptive forest management. *Ecosystem Services* 39: 100993. https://doi.org/10.1016/j.ecoser.2019.100993

Sharp R, Tallis H, Ricketts T, Guerry A, Wood S, Chaplin-Kramer R, Nelson E, Ennaanay D, Wolny S, Olwero N, Tallis H, Vigerstol K, Pennington D, Mendoza G, Aukema J, Foster J, Forrest J, Cameron D, Arkema K, Lonsdorf E, Kennedy C, Verutes G, Kim CK, Guannel G, Papenfus M, Toft J, Marsik M, Bernhardt J, Griffin R, Glowinski K, Chaumont N, Perelman A, Lacayo-Emery M, Mandle L, Hamel P, Vogl A, Rogers L, Bierbower W, Denu D, Douglass J (2014) InVEST 3.5.0 user's guide. Stanford.

Simons NK, Felipe-Lucia MR, Schall P, Ammer C, Bauhus J, Blüthgen N, Boch S, Buscot F, Fischer M, Goldmann K, Gossner MM, Hänsel F, Jung K, Manning P, Nauss T, Oelmann Y, Pena R, Polle A, Renner SC, Schloter M, Schöning I, Schulze ED, Solly EF, Sorkau E, Stempfhuber B, Wubet T, Müller J, Seibold S, Weisser WW (2021) National Forest Inventories capture the multifunctionality of managed forests in Germany. *Forest Ecosystems* 8: 5. https://doi.org/10.1186/s40663-021-00280-5

Strand J, Carson RT, Navrud S, Ortiz-Bobea A, Vincent JR (2017) Using the Delphi method to value protection of the Amazon rainforest. *Ecological Economics* 131: 475–484. https://doi.org/10.1016/j.ecolecon.2016.09.028

Suárez-Muñoz M, Bonet-García FJ, Navarro-Cerrillo R, Herrero J, Mina M (2023) Forest management scenarios drive future dynamics of Mediterranean planted pine forests under climate change. *Landscape Ecology* 38: 2069–2084. https://doi.org/10.1007/s10980-023-01678-y

Tew E, Simmons B, Sutherland W (2019) Quantifying cultural ecosystem services: Disentangling the effects of management from landscape features. *People and Nature* 1: 70–86. https://doi.org/10.1002/pan3.14

Thuenen-Institute (2016) Dritte Bundeswaldinventur – Basisdaten (2016). Retrieved from https://bwi.info/Download/de/BWI-Basisdaten/ Retrieved 02.03.2026

Trombetti M, Ivits E, Vandecasteele I, Zulian G, Baranzelli C, Barranco R (2015) Mapping and assessment of ecosystems and their services: Trends in ecosystems and ecosystem services in the European Union between 2000 and 2010. https://data.europa.eu/doi/10.2788/341839

Turoff M (1970) The design of a policy Delphi. *Technological Forecasting and Social Change* 2: 149–171. https://doi.org/10.1016/0040-1625(70)90161-7

Van der Plas F, Ratcliffe S, Ruiz-Benito P, Scherer-Lorenzen M, Verheyen K, Wirth C, Zavala M, Ampoorter E, Baeten L, Barbaro L, Bastias C, Bauhus J, Benavides R, Benneter A, Bonal D, Bouriaud O, Bruelheide H, Bussotti F, Carnol M, Castagneyrol B, Charbonnier Y, Cornelissen J, Dahlgren J, Checko E, Coppi A, Dawud S, Deconchat M, De Smedt P, De Wandeler H, Domisch T, Finér L, Fotelli M, Gessler A, Granier A, Grossiord C, Guyot V, Haase J, Hättenschwiler S, Jactel H, Jaroszewicz B, Joly FX, Jucker T, Kambach S, Kaendler G, Kattge J, Koricheva J, Kunstler G, Lehtonen A, Liebergesell M, Manning P, Milligan H, Müller S, Muys B, Nguyen D, Nock C, Ohse B, Paquette A, Penuelas J, Pollastrini M, Radoglou K, Raulund-Rasmussen K, Roger F, Seidl R, Selvi F, Stenlid J, Valladares F, van Keer J, Vesterdal L, Fischer M, Gamfeldt L, Allan E (2018) Continental mapping of forest ecosystem functions reveals a high but unrealized potential for forest multifunctionality. *Ecology Letters* 21: 31-42. https://doi.org/ 10.1111/ele.12868

Zhang C, Li J, Zhou Z (2022) Ecosystem service cascade: Concept, review, application and prospect. *Ecological Indicators* 137: 108766. https://doi.org/10.1016/j.ecolind.2022.108766

Zukunftsbaum Bayern (2023) Waldfläche in Bayern. Retrieved from https://www.zukunftsbaum-bayern.de/wald-in-bayern/

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