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A novel approach for assessing the importance of forest ecosystem services using indicators of potential and demand

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ABSTRACT

Identifying the potential and demand for forest ecosystem services (FES) in a spatially explicit manner is crucial for multi-objective forest management. We developed a robust and transparent procedure for i) selecting indicators for assessing the potential and demand for three FES (timber production, recreation and nature conservation) and ii) determining their relative importance (weights) as perceived by forest planning experts from four European countries (Estonia, Finland, Poland and Slovenia) with different forestry traditions. A total of 19 indicators of FES potential and 10 of FES demand, linked to each of the three FES, were selected based on established indicators that were updated and downscaled through iterative, multistep group communication. The selected indicators describe site and stand characteristics, accessibility, infrastructure and attractiveness, legal status and forest use. Indicators describing expert assessments of FES potential and demand were also included. We applied the fuzzy Best-Worst Method to derive weights for FES indicators incorporating experts' preferences. For FES potential, evidence-based indicators relying on empirical data received higher weights, whereas for FES demand, expert-based assessments were prioritized. Pairwise statistical comparisons of indicator weights revealed notable differences in the importance assigned by experts across countries. By considering both the potential and demand for FES and combining evidence-based indicators with expert preferences, we contribute to a comprehensive and context-sensitive framework for FES assessment. Our approach enables forest planners to identify priority areas for promoting desired FES and tailor management strategies that balance multiple FES, ensuring that decisions align with ecological potential and societal demand.

1. Introduction

Identifying the potential and demand for forest ecosystem services (FES) in a spatially explicit manner is crucial for the implementation of multifunctional forest management (Winkel et al., 2022). FES potential can be defined as the capacity of a forest landscape or ecosystem to provide services, regardless of whether they are currently utilized (Barredo et al., 2015). FES demand reflects the relationship between forest ecosystems and people, such as individuals, landowners, local stakeholders or society in general (García-Nieto et al., 2013; Schägner et al., 2013) and can be defined as “the need for specific ecosystem services by society, particular stakeholder groups or individuals” (Burkhard and Maes, 2017: 154).

Demands for FES are increasing and becoming more diverse (Eyvindson et al., 2018), while forest areas are spatially bounded and differ in their capacity to meet multiple demands (Maier et al., 2021; Caicoya et al., 2023). Both FES potential and demand are unevenly distributed across the forest landscape (Bončina et al., 2019), leading to

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a spatial mismatch between potential and demand. While FES potential is commonly considered in forest planning (Bončina et al., 2019; Tiemann and Ring, 2022), demand and its interaction with potential are often overlooked (Raum, 2018; van Winckel et al., 2026). Spatial analyses of FES can reveal synergies and trade-offs (Meyer and Schulz, 2017), guiding management to enhance provision where demand is high (Simončič et al., 2013).

Spatial analyses underpin multi-objective forest management by classifying forest land into spatial units with adapted management activities to prioritize desired FES (Simončič et al., 2015). These spatial units, defined as priority areas, have higher value for certain FES. They can be segregative, providing a single dominant FES, or integrative, providing multiple FES of varying quality within the same forest unit (Bončina et al., 2019). Effective classification of forest land into FES priority areas requires i) selecting spatially explicit indicators (variables, attributes, criteria) for assessing FES potential and demand, ii) defining the relative importance (i.e., weights) of these indicators for FES potential and demand and iii) developing procedures to merge indicators and weights into maps of FES potential and demand.

(i) Knowledge of FES potential and demand relies on indicators that estimate changes over time and space (Mendoza and Prabhu, 2003; van Oudenhoven et al., 2012). Indicators are used as proxies to assess FES and can be measured using available tools (Grima et al., 2023). Indicators vary according to the type of FES and the dimension considered (i.e., potential or demand). The temporal and spatial scales of the indicators used to assess FES potential and demand can also vary substantially (Egoh et al., 2012; Orsi et al., 2020). The choice of indicators also depends on the purpose of the assessment (e.g., whether they are used for spatially explicit assessment or economic evaluation), data availability and methodological approaches (Maes et al., 2020). Finally, consideration of specific social, economic, natural and jurisdictional conditions is essential for selecting suitable indicators (Başkent, 2018; Roces-Díaz et al., 2018).

(ii) The importance of the indicators depends on the accuracy and robustness with which they represent FES potential and demand across different forest landscape settings (Primmer et al., 2021). In addition, as perceptions and values of FES vary with social environments (Martín-López et al., 2012), there is a need to incorporate expert knowledge (Grêt-Regamey et al., 2013) and stakeholder preferences (García-Nieto et al., 2013) into the weighting of FES indicators to ensure they reflect diverse values, contextual priorities and locally relevant management objectives. However, determining the relative importance of the indicators and their acceptance by experts and other stakeholders (i.e., perceived importance) has received little attention (Burkhard et al., 2014).

(iii) Spatially explicit analyses of FES for defining priority areas as a tool for multi-objective forest management planning have been applied for decades in several Central European countries (Bončina et al., 2019). These analyses often addressed potential and demand indicators inconsistently and did not appropriately include stakeholder input when selecting and weighting FES indicators for the purpose of forest planning (Simončič et al., 2013). Recently, broader ecosystem mapping procedures, also applied to forest landscapes, have been used in several countries (Barredo et al., 2015). However, these approaches focus on mapping the potential of FES, while neglecting demand (Syrbe and Grunewald, 2017). This reflects persistent challenges when conducting large-scale assessments, where indicators are either insufficiently defined or too general to efficiently map FES. This obscures the actual potential of forests to provide goods and services or the tangible benefits these ecosystems deliver (Casado-Arzuaga et al., 2014). As ecosystem services mapping has a limited capability to define FES priority areas, there is a strong need to improve the set of indicators for spatial analyses of FES as a tool for multi-objective forest management.

Multi-criteria decision analysis is a useful approach for addressing the complex, multidimensional challenges of forest management planning (Uhde et al., 2015). Despite its methodological maturity, the application of multi-criteria decision analysis to assess and prioritize ecosystem service indicators remains limited. Among the most commonly applied methods are the Analytic Hierarchy Process (Grošelj et al., 2024), the Best-Worst Method (Abedi and Shahbaz Zadeh, 2025) and the Technique for Order of Preference by Similarity to Ideal Solution (Li et al., 2025). Among these, Best-Worst Method (Rezaei, 2015) is well suited to complex ecological assessments involving numerous indicators, interacting processes and diverse expert perspectives (Ecer, 2024). However, expert judgments on indicators are inherently uncertain and require approaches that can explicitly address this uncertainty. To incorporate such uncertainty into Best-Worst Method, fuzzy logic (Zadeh, 1965) can be used to better capture linguistic assessments, resulting in robust fuzzy Best-Worst Method applications in environmental studies (Majumder et al., 2023).

The overall objective of this study was to develop a robust and transparent procedure 1) for selecting indicators of FES potential and demand based on their relevance to selected FES and 2) for determining their relative importance (i.e., weights) as perceived by national forest planning experts. To achieve this objective, we developed indicators separately for the potential and demand of three types of FES that have traditionally been considered in forest planning and management: timber production, recreation and nature conservation. We then used a participatory approach to assign relative importance to the indicators of potential and demand for the selected FES. We developed and tested the procedure within the ForestValue2 "iForplan" project that included four countries: Estonia, Finland, Poland and Slovenia. These countries represent different forestry traditions in terms of forest management, silvicultural approaches and forest governance. The study addressed the following research questions: i) Which indicators and associated weights are most suitable for the spatial identification of priority areas for FES potential and demand? ii) Does the perceived importance assigned to these indicators by experts vary across countries when assessing the potential and demand of different FES?

2. Methods

2.1. Case study countries

The study was performed in four European countries (Table 1), which differ in forestry tradition, silvicultural systems applied, forest governance and general social and economic conditions (Pelkonen et al., 1999; Scherpenhuijzen et al., 2025).

In Estonia, diverse lowland hemiboreal forests prevail. Seventy percent of the forest area consists of commercial forests that are managed intensively, mainly through a clear-cutting system; 20% are strictly protected forests with no management allowed; and 10% are forests with restrictions on forest management (Sirkas and Valgepea, 2025). Forest management planning focuses primarily on timber production and nature conservation. Free access to all forests, regardless of ownership, is legally permitted, except in areas where access is restricted by law.

Finland is one of the most forested countries in Europe. Site conditions vary according to glacial geology, the cool climate and extensive peatlands that cover about one third of forest land. A clear north–south productivity gradient is evident. Forest ownership is largely private. The dominant management regime is a rotation system based on thinning and clear-cutting. Certain areas are designated as protected or restricted-use forests, amounting to about 15% of the forest area (Korhonen et al., 2021). Free public access to forests is ensured by law through Everyman's Right, supporting recreation and cultural attachment to forest landscapes.

Poland is situated mainly in the continental biogeographical region of Europe. Most forests are public. Scots pine (*Pinus sylvestris* L.) is the dominant tree species (Cierpiał-Wolan, 2025). In recent decades, considerable effort has been devoted to converting conifer-dominated forests into mixed forests, which are more resilient to environmental

Table 1
Basic characteristics of countries included in the study.

Country	Population density (km^{-2})	Forest cover (%)	Dominant forest types; main tree species	Average growing stock (m^3 ha^{-1})	Ownership structure (%)	Main silvicultural systems applied
Estonia	31	51.8	Hemiboreal; *Pinus sylvestris*, *Betula pendula*, *Picea abies*, *Alnus glutinosa*, *Populus tremula*, *Alnus incana*	193	State (50), private (50)	Clear-cutting
Finland	19	75.0	Boreal; *Pinus sylvestris*, *Picea abies*, *Betula pendula*	122	Private (69), state (31)	Clear-cutting, continuous-cover forestry applied locally
Poland	120	29.6	Hemiboreal and nemoral coniferous and broadleaved; *Pinus sylvestris*, *Betula pendula*, *Picea abies*, *Fagus sylvatica*, *Quercus robur*	293	State (77), other public (4), private (19)	Clear-cutting, shelterwood, continuous-cover locally
Slovenia	105	58.0	Temperate mountain and submountain; *Fagus sylvatica*, *Picea abies*, *Abies alba*, *Quercus petraea*, *Q. robur*	303	Private (77), state (20), other public (3)	Continuous-cover (mainly irregular shelterwood)

impacts. Increasing public demand toward forests is evident; therefore, a new forest category characterized by high societal value has recently been introduced in forest regulations.

Slovenia is characterized by diverse topography and site conditions. Most forests belong to multipurpose forests where close-to-nature silviculture is practiced. Due to the high importance of social or protective functions, some areas are declared as special-purpose forests or protective forests (Simončič et al., 2015). Clear-cutting is not permitted under the Forest Act (1993). Free access to all forests regardless of ownership is acknowledged by law.

2.2. Selecting indicators for spatially explicit assessment of FES potential and demand

Three principal FES categories relevant across all four study areas were considered: timber production, recreation and nature conservation. We selected these types of FES because of their importance in all studied countries, data availability and comparability across countries. However, the presented method could be applied to other FES categories as well.

Effective multi-objective forest management requires spatially

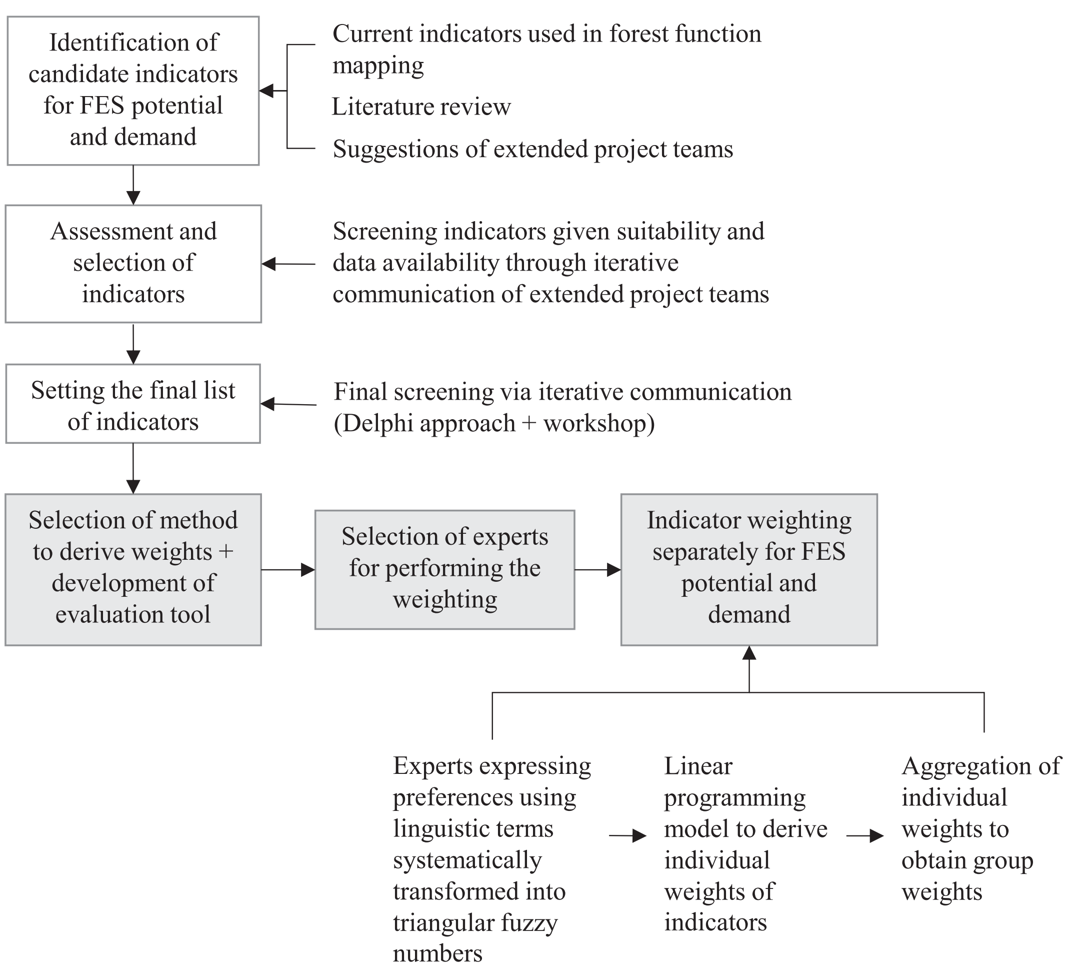

Fig. 1. Framework for developing indicators for forest ecosystem services (FES) potential and demand (white boxes) and deriving weights that define indicator importance (grey boxes).

explicit information on both the potential and demand for FES. To address this, we developed an approach that assesses these components separately (Fig. 1). We described the potential and demand for each of the three FES using a system of indicators. The indicators were selected according to general standards: they are representative and indicative, easily understood, acceptable to the audience, accurate, relatively simple, cost-effective and useful over the long term. Indicators of FES potential are generally easier to measure and less complex than those of FES demand (van Winckel et al., 2026). FES potential is commonly described by quantifiable biophysical indicators (Tiemann and Ring, 2022), whereas FES demand often requires indirect indicators or estimates (van Winckel et al., 2026). FES demand can also be assessed through social assessment approaches, including participatory methods such as expert elicitation, workshops, surveys and stakeholder-mapping techniques (e.g., Raymond et al., 2009).

Our study focuses on indicators suitable for FES mapping and defining priority areas. Our approach assumes that areas with high values of demand and potential, as indicated by the selected indicators for a given FES, are more important for providing this FES than areas with lower values. The development of a set of suitable indicators for the potential and demand of the three FES was based on a three-step screening procedure (Fig. 1): i) identification of candidate indicators; ii) assessing the suitability of candidate indicators; and iii) an iterative, multistep group communication process between extended project teams from the four countries, culminating in a final list of indicators.

The first step in indicator selection combined a literature review with an analysis of indicators used in traditional forest function mapping in Slovenian forestry. Because this established set of indicators has long been applied in Slovenia, and similar approaches are also used in other Central European countries (Simončič et al., 2013), it provided a well-founded starting point for the study. The literature review, combined with indicators already used in Slovenia, resulted in a set of baseline indicators adapted for application in other countries. Scientific papers on mapping FES potential and demand were reviewed, and indicators were selected based on two aspects: 1) they are linked to forest ecosystem services and 2) they are relevant and suitable for use within a spatial assessment framework. Therefore, indicators for assessing management effectiveness or economic importance/value were not considered in our selection. Indicators for the three FES were compiled and clustered separately for potential and demand, with duplicates removed and indicators reflecting similar concepts merged. This list was then compared to the list of the already available indicators used in forest function mapping in Slovenia and supplemented by indicators provided by extended project teams from the four countries. This resulted in a final list of 41 candidate indicators shared and approved by the four countries.

During the second step, candidate indicators and their definitions and measurement units were discussed through iterative communication within extended national project teams and across all partners. Indicators were assessed based on experience and local conditions in each country according to four assessment criteria: i) the indicator's value for describing potential or demand for a given FES; ii) appropriateness for spatially explicit use; iii) clarity, simplicity and understandability for the broader public; and iv) data availability for the proposed indicators. For practical and communication reasons, the number of indicators needed to be reduced. This was done by ranking the 41 candidate indicators using a three-level scoring system separately for suitability (i–iii) (0 – not suitable at all; 2 – very suitable) and data availability (0 – no data; 2 – high data accessibility). Each extended national project team ranked all 41 indicators separately for the selected FES and for potential and demand. After ranking, each indicator received a final grade that represented the sum of the two scores for suitability and availability. Finally, the average score for each indicator was calculated based on evaluations from all four countries, and the indicators with the lowest grades were excluded from further analysis. The output of this step was the downscaled list of indicators linked to potential and demand, separately.

In the third step, final indicator screening was conducted through iterative communication, using a Delphi-like approach, within each country's extended project team. An online workshop involving researchers from extended project teams of the four countries was used to develop the final list of potential and demand indicators, including their definitions and measurement units.

To enable future landscape-scale analyses, FES indicator selection explicitly accounted for the relevance, potential impact and meaning of the indicators at the spatial scale of interest. The set of FES indicators in this study was designed to capture fine grid information, even though most data for the indicators originate at the stand or landscape level and therefore require downscaling. Participation of local communities and domain experts, which is essential when developing an indicator system, informed the selection of indicators applicable at the landscape scale, supported by expert judgment and cognitive mapping techniques. Differences in data availability across countries were acknowledged, allowing for variation in variables and quantification methods.

2.3. Determining weights of FES indicators using fuzzy Best-Worst Method

The determination of weights of FES indicators followed a three-stage procedure: 1) identifying and selecting of the optimal method for deriving weights; 2) selecting experts to perform the weighting and 3) conducting expert evaluation and weighting of indicators separately for potential and demand for all three FES, resulting in aggregated group indicator weights for each country.

2.3.1. Fuzzy numbers

In complex decision problems, precise numerical evaluations are difficult due to uncertainty and subjectivity. Fuzzy set theory (Zadeh, 1965) provides a mathematical framework for representing such imprecise information. Fuzzy numbers align with human reasoning by enabling experts to express their judgments linguistically rather than numerically, making them well suited to characterizing expert judgments. Linguistic evaluations are converted into triangular fuzzy numbers, defined as triplets (l, m, u), where l and u denote the lower and upper bounds and m represents the most probable value. Their triangular-shaped membership function is defined by Eq. (1).

$$\mu(x) = \begin{cases} \dfrac{x-l}{m-l}, & l \le x \le m \\ \dfrac{u-x}{u-m}, & m < x \le u \\ 0, & x < l \text{ or } x > u \end{cases} \tag{1}$$

To support the implementation of fuzzy logic within multi-criteria decision analysis, a predefined linguistic scale is commonly used

Table 2
Linguistic scale and corresponding triangular fuzzy numbers *(l,m,u),* where *l* and *u* denote the lower and upper bounds and *m* represents the most probable value (Paksoy et al., 2012).

Linguistic preferences	Corresponding triangular fuzzy number
Equally preferred	(1,1,1)
Equally to moderately preferred	(1,2,3)
Moderately preferred	(2,3,4)
Moderately to strongly preferred	(3,4,5)
Strongly preferred	(4,5,6)
Strongly to very strongly preferred	(5,6,7)
Very strongly preferred	(6,7,8)
Very strongly to extremely preferred	(7,8,9)
Extremely preferred	(9,9,9)

(Table 2), enabling the mathematical treatment of qualitative evaluations.

2.3.2. Similarity-rewarding fuzzy group Best-Worst Method

Best-Worst Method offers clear advantages for weighting FES indicators, especially in cases with a larger number of indicators and multiple expert groups, as it requires fewer pairwise comparisons than Analytic Hierarchy Process, reducing respondent burden and improving consistency (Ahmad et al., 2017), while also avoiding the need for predefined performance scores required by Technique for Order of Preference by Similarity to Ideal Solution. To incorporate uncertainty into Best-Worst Method, fuzzy sets (Zadeh, 1965) are used. It enables approximate reasoning beyond Boolean true/false classifications (Novák et al., 1999).

The Similarity-Rewarding fuzzy group Best-Worst Method integrates the traditional Best-Worst Method with fuzzy set theory and a consensus-oriented group aggregation approach. The method consists of six steps. The first four steps retain key features of Best-Worst Method while enabling experts to express their preferences using linguistic terms that are systematically transformed into triangular fuzzy numbers. In Step 4, linear programming is applied to derive the individual weights of the indicators. Steps 5 and 6 aggregate the individual weights to obtain group weights. A distinguishing feature of the Similarity-Rewarding fuzzy group Best-Worst Method is its emphasis on expert consensus, where greater influence is assigned to experts whose assessments align in identifying the best indicator.

Step 1: Let n be the number of indicators. The expert selects the best (i.e., most important) and the worst (i.e., least important) indicator from n options.

Step 2: The expert assesses the relative preference of the best indicator over all other indicators using a predefined linguistic scale (Table 2), which is then converted into corresponding triangular fuzzy numbers. The resulting pairwise comparisons are organized into a best-to-others vector $(\widetilde{a}_{B1}, \widetilde{a}_{B2}, \ldots, \widetilde{a}_{Bn})$, with each element $\widetilde{a}_{Bj} = \left(a_{Bj}^L, a_{Bj}^M, a_{Bj}^U\right)$ representing the triangular fuzzy number expressing the expert's preference for the best indicator B over indicator j.

Step 3: The expert assesses the relative preference of all indicators over the worst indicator. The resulting pairwise comparisons are organized into an others-to-worst vector $(\widetilde{a}_{1W}, \widetilde{a}_{2W}, \ldots, \widetilde{a}_{nW})$, with each element $\widetilde{a}_{jW} = \left(a_{jW}^L, a_{jW}^M, a_{jW}^U\right)$ representing the triangular fuzzy numbers expressing the expert's preference for indicator j over the worst indicator W.

Step 4: The indicator weights are determined by solving a fuzzy linear programming model. Specifically, we determine the weights with properties $\frac{w_B}{w_j} \simeq \widetilde{a}_{Bj}$ and $\frac{w_j}{w_W} \simeq \widetilde{a}_{jW}$ for $j = 1, \ldots, n$ by applying the following fuzzy optimization model

$$\begin{aligned} &\min \varepsilon \\ &\text{s.t. } \left|w_B - \widetilde{a}_{Bj} w_j\right| \lesssim \varepsilon \text{ for all } j, \\ &\quad \left|w_j - \widetilde{a}_{jW} w_W\right| \lesssim \varepsilon \text{ for all } j, \\ &\quad \sum_{j=1}^{n} w_j = 1, w_j \geq 0 \text{ for all } j. \end{aligned} \tag{2}$$

In this formulation, the symbol "$\lesssim$" stands for the fuzzy relation "less than," which is interpreted as "almost less than." Model (2) can be reformulated into a standard linear programming model with crisp (non-fuzzy) inequalities, as proposed by Ficko et al. (2025) and Hafezalkotob and Hafezalkotob (2017):

$$\begin{aligned} &\min \varepsilon \\ &\text{s.t. } w_B - \varepsilon \leq \left(a_{Bj}^M + (1-\alpha)\left(a_{Bj}^U - a_{Bj}^M\right)\right) w_j \text{ for all } j, \\ &\quad w_B + \varepsilon \geq \left(a_{Bj}^M - (1-\alpha)\left(a_{Bj}^M - a_{Bj}^L\right)\right) w_j \text{ for all } j, \\ &\quad w_j - \varepsilon \leq \left(a_{jW}^M + (1-\alpha)\left(a_{jW}^U - a_{jW}^M\right)\right) w_W \text{ for all } j, \\ &\quad w_j + \varepsilon \geq \left(a_{Bj}^M - (1-\alpha)\left(a_{jW}^M - a_{jW}^L\right)\right) w_W \text{ for all } j, \\ &\quad \sum_{j=1}^{n} w_j = 1, w_j \geq 0 \text{ for all } j. \end{aligned} \tag{3}$$

The optimal value ε represents the level of consistency in the fuzzy preference judgments. The parameter α, with values in the interval $0 \leq \alpha \leq 1$, denotes the predefined possibility level and influences the tightness of the constraints. Higher values of α correspond to tighter constraints, which may lead to increased inconsistency. Following Ficko et al. (2025), we set $\alpha = 0.5$, representing a balanced possibility level commonly used in fuzzy modeling.

Step 5: The importance weights of the experts are determined using the Similarity-Rewarding Group Method, with higher weights assigned to experts who selected the same best indicator. Let n denote the number of indicators and s the number of experts. Let I_j be the set of indicators assigned the highest rank by expert j, let b_j represent the number of indicators that expert j ranked as the highest ($b_j = card(I_j)$) and let c_{ij} represent the distribution of highest-ranked preferences across the experts and indicators, where:

$$c_{ij} = \begin{cases} \dfrac{1}{b_j}, & \text{if expert } j \text{ assigns the highest rank to indicator } i \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

To evaluate the cumulative contribution across all experts for a specific indicator, let this be represented by m_i and evaluated as:

$$m_i = \sum_{j=1}^{s} c_{ij}, \tag{5}$$

which represents the importance received from all experts. Let ω_j be the importance weight of each expert j, calculated using the following equation:

$$\omega_j = \frac{1}{b_j} \sum_{i \in I_j} \left(\frac{m_i}{\sum_{k=1}^{n} m_k^2} \right) \tag{6}$$

The sum of all expert weights of importance satisfies the normalization condition:

$$\sum_{j=1}^{s} \omega_j = 1. \tag{7}$$

Step 6: The individual weights are then aggregated into group weights by applying a weighted arithmetic mean using the importance weights of experts as coefficients:

$$w_i = \sum_{j=1}^{s} \omega_j w_i^{(j)}, i = 1, \ldots, n. \tag{8}$$

2.3.3. Selection of experts for weighting the importance of FES indicators

Experts were purposefully selected based on their professional experience and expertise in forestry to ensure a substantiated, evidence-based evaluation of indicators of FES potential and demand. Experts were selected based on their experience in forest planning, multi-objective forest management and the assessment of FES. In addition, in each country, experts needed to represent both the research/academic field and the practical management/planning field. Therefore, invitations to collaborate were sent to research, academic and management planning institutions. In Slovenia, a total of 23 experts participated, including 15 forest planners from the Slovenia Forest Service and 8 academics. In Finland, 11 experts from the Natural Resources Institute Finland (Luke) participated, including academics and applied researchers who also collaborate in planning and FES assessment. In Estonia, 15 experts participated, including 7 practitioners in forest management, nature conservation and nature-based tourism, and 8 academics. In Poland, the assessment involved two academics in forest management planning and silviculture from Poznań University of Life Sciences, one academic in forest inventory and management planning, and two forest managers representing the University's experimental forest divisions.

Indicator evaluation was conducted using a Microsoft Excel macro for Slovenia, Estonia and Poland and a Python-based application in Finland. The evaluation tool included detailed indicator descriptions to ensure consistent understanding. In Slovenia, experts participated in an introductory online meeting explaining the purpose of the evaluation, the meaning of the indicators and the procedure. Then, they individually assessed the indicators. In Estonia, assessments were conducted individually with support from project staff. In Finland, indicator descriptions were provided in the application, and detailed instructions were provided via email. Based on initial feedback on the Excel macro from the Finnish experts, we developed a Python tool to facilitate the assessment of indicators separately for each FES group and for potential and demand (details are provided in the supplementary material). In Poland, three group meetings were organized, where decisions about the importance and corresponding weights of each indicator were made and recorded. As the same BWM-based questionnaire and indicator definitions were used in all cases, differences in the evaluation tools represented only differences in implementation and are not expected to affect the resulting weights.

Following steps 1–6 of the Similarity-Rewarding fuzzy group Best-Worst Method, we obtained aggregated group indicator weights for each country. Expert judgments were elicited individually without prior group discussion, and consensus was incorporated through the similarity-rewarding aggregation procedure. These weights were subsequently applied in the weighted arithmetic mean aggregation of indicators for each FES, ensuring that each indicator's contribution to the composite index reflected its relative importance as determined by experts.

2.3.4. Statistical comparison of indicator weights across countries

Indicator weight robustness was analyzed using the leave-one-out method (Wang et al., 2024). The FES indicator weights were recalculated s times (where s is the number of experts), each time omitting the assessments of one expert. The results are considered robust if the indicator weights do not change significantly. The leave-one-out method accounts for the fact that the importance, or magnitude, of the weights assigned to each indicator in defining FES potential and demand varies across experts. Differences in indicator weights across countries were evaluated using Dunn's non-parametric test, with effect sizes quantified as Cohen's r.

Non-metric multidimensional scaling (Kruskal, 1964) was applied to visualize dissimilarity patterns among countries based on indicator weights. As a rank-based ordination method that does not assume linearity or normality, non-metric multidimensional scaling is suitable for complex, high-dimensional environmental data. A custom pairwise dissimilarity measure was constructed, defined as the mean absolute Cohen's r across indicator weights. Non-metric multidimensional scaling was implemented using the *metaMDS()* function in the vegan package (Oksanen et al., 2022) in R version 4.5.2 (R Core Team, 2025).

3. Results

3.1. Selection of indicators for the potential and demand of FES

We selected 29 out of 41 indicators: 19 for FES potential and 10 for FES demand across timber production, recreation and nature conservation (Table 3). The unselected indicators were considered redundant or less important by the extended project teams. Timber production potential is described by site and long-term stand productivity, harvesting accessibility (forest roads and skidding tracks) and topographic conditions. This potential can be constrained by vulnerable site conditions or legal protection (e.g., national and regional protected areas, Natura 2000 sites). Demand for timber production was evaluated using recent forest utilization patterns, supplemented by expert assessments.

Recreation potential indicators assessed accessibility, presence of hotspots and recreational infrastructure, and expert-based assessments of visual attractiveness and the availability of non-wood forest products. Recreation demand is described by proximity to settlements, visitor density, expert assessment and legal status of forest land (e.g., designated areas for recreation). Recreation demand refers to the level of interest or need people have for engaging in recreational activities in forested areas.

Nature conservation potential is described by a compound “nature conservation value” indicator consisting of rarity, special habitats, corridors and forest remnants. Additionally, it is described by remoteness, naturalness and expert assessment of nature conservation potential. Nature conservation demand is primarily defined by the nature conservation status under a variety of conservation schemes and by expert assessment.

The indicator “quick expert assessment” was specifically developed within the framework of this study. To apply expert assessment, the planning area should be divided into approximately 10–20 zones, each larger than 200 ha. Local experts from different fields of FES (timber production, nature conservation, recreation) are invited to a workshop to rate the level of demand and/or potential in each zone.

3.2. Weights of FES indicators

Expert assessments revealed distinct national patterns in the importance (weight) assigned to potential and demand indicators for the three FES (Figs. 2 and 3). Patterns of similarity and dissimilarity among countries are summarized in Fig. 4 and are supported by statistical comparisons in Table S2. The following section explores the main differences, indicated by highly significant z-values from Dunn's tests with large effect sizes, expressed by Cohen's r.

3.2.1. Indicators of timber production

Clear cross-country differences emerged in the weighting of timber production potential, with Estonia standing out most (Figs. 2–4; Table S1). These differences were evident for site productivity and long-term stand productivity. Finnish, Slovenian and Polish experts assigned higher weights to both indicators than Estonian experts, although significant differences were detected only when comparing Estonian experts with Slovenian and Finnish experts (Table S2).

Estonian, Polish and Finnish experts placed greater emphasis on site vulnerability than Slovenian experts, with the largest significant differences between Estonia and Slovenia. Estonian experts also assigned substantially higher weights to legal status than experts in the other countries, although significant differences were found only when comparing Estonia with Slovenia and Finland.

Accessibility for timber extraction showed the smallest cross-country differences; only small but significant differences were observed when comparing Slovenian weights with those from Poland and Estonia. With respect to distance to forest roads, Slovenian experts assigned the highest weight to distance to forest roads, whereas Estonian experts assigned the lowest. The largest significant differences in distance to

Table 3
Indicators for the assessment of the potential and demand of three forest ecosystem services (FES).

FES	Indicator name (unit)	Abbr.	Description
Timber production potential	Site productivity (m^3 ha^{-1} y^{-1})	SP	It quantifies the amount of timber that can be produced at a given site under natural tree species composition (i.e., production capacity of forest sites)
	Long-term stand productivity (m^3 ha^{-1} y^{-1})	StP	It quantifies the amount of timber that can be produced in the long term at a given site, considering actual forest vegetation (e.g., tree species composition, succession stages) (the annual increment of stand volume can be used in uneven-aged forests)
	Distance to forest roads (m)	DistFR	Distance to the nearest forest road
	Accessibility for timber extraction (m)	AccessTE	Determined according to the distance to the nearest skidding track (in the case of tractor harvesting) or the distance to the nearest forest road (in the case of a cable logging system)
	Topography – slope (°)	Incl	Slope
	Topography – rockiness (%)	Rock	Rockiness (% of forest area covered by rocks)
	Vulnerability of forest site (soil, water) to timber harvesting (–)	Vuln	Assessed according to forest site type
	Legal status of forest area (–)	TPLegS	Legal status indicating the potential for timber production: forest categories, protected areas/nature conservation categories or other categories that affect timber production
Timber production demand	Recent timber cut (m^3 ha^{-1} y^{-1})	Tcut	Long-term harvesting volume (over 10 or 20 years), based on harvest inventory
	Timber demand – expert assessment (–)	Tdem	Quick expert assessment of timber demand (*)
Recreation potential	Accessibility – road infrastructure (m)	DistFR	Distance to the nearest forest or public road
	Accessibility – presence of parking lots (m)	DistPA	Distance to the nearest parking lot
	Accessibility – availability of public transport (m)	DistPT	Distance to the nearest public transport
	Presence/vicinity of recreation infrastructure (m)	DistRI	Distance to recreation infrastructure, such as paths and trails for outdoor activities
	Presence/vicinity of recreational hotspots (m)	DistRH	Distance to recreation hotspots (e.g., scenic viewpoints or thematic locations) and attractive sites (e.g., lakes, fishing sites)
	Visual attractiveness (–)	VisA	Quick expert assessment of visual attractiveness (*)
	Gathering non-wood forest products (–)	NWFP	Quick expert assessment of the availability of non-wood forest products (e.g., mushrooms, berries, game species) (*)
Recreation demand	Proximity to populated areas/settlements (m)	DistS	Weighted distance from settlements (settlement size, population density)
	Density of visitors (number)	DensV	Number of visits in a certain period of the year
	Recreational demand – expert assessment (–)	DemR	Quick expert assessment of recreational demand (*)
	Legal status – designated areas for recreation (–)	RLegS	Whether an area has been legally designated for recreation
Nature conservation potential	Nature conservation value (–)	NatCV	Nature conservation value according to multiple criteria: Rarity of forest ecosystems (forest communities, forest stands, species), special habitats, corridors and forest remnants (islands)
	Remote areas (–)	RemA	The extent and distribution of forested regions minimally affected by human activities, characterized by their isolation from urbanized or developed areas, serving as critical habitats for biodiversity and preserving natural ecological processes
	Naturalness of forest stands (–)	Natural	The degree to which forest stands resemble their natural state, considering factors such as species composition, age structure and ecological processes, with minimal human intervention or management
	Nature conservation potential – expert assessment (–)	NatCVEA	Quick expert assessment of nature conservation potential, based on criteria such as biodiversity, habitat quality, presence of rare or endangered species and ecological significance (*)
Nature conservation demand	Nature conservation status – IUCN category (–)	IUCN	Nature conservation status/category (IUCN category)
	Nature conservation status – local/national category (–)	NatCS	Nature conservation status/category at the local/national level (e.g., forest reserves, protected areas, Natura 2000 sites)
	Areas designated for nature conservation (–)	ProtA	Other areas designated for nature conservation, such as quiet zones and temporarily unmanaged areas
	Nature conservation demand – expert assessment (–)	DNatCEA	Quick expert assessment of nature conservation demand (*)

In the expert assessments (*), the planning area is divided into approximately 10–20 zones, each larger than 200 ha; local experts from different fields of FES rate the level of demand and/or potential in each zone using ranks.
Note: (–) indicates a categorical variable.

forest roads were observed between Slovenia and Estonia.

For timber production demand, recent timber cutting revealed clear national differences. Polish and Slovenian experts assigned higher weights to recent timber cutting, with the largest significant differences

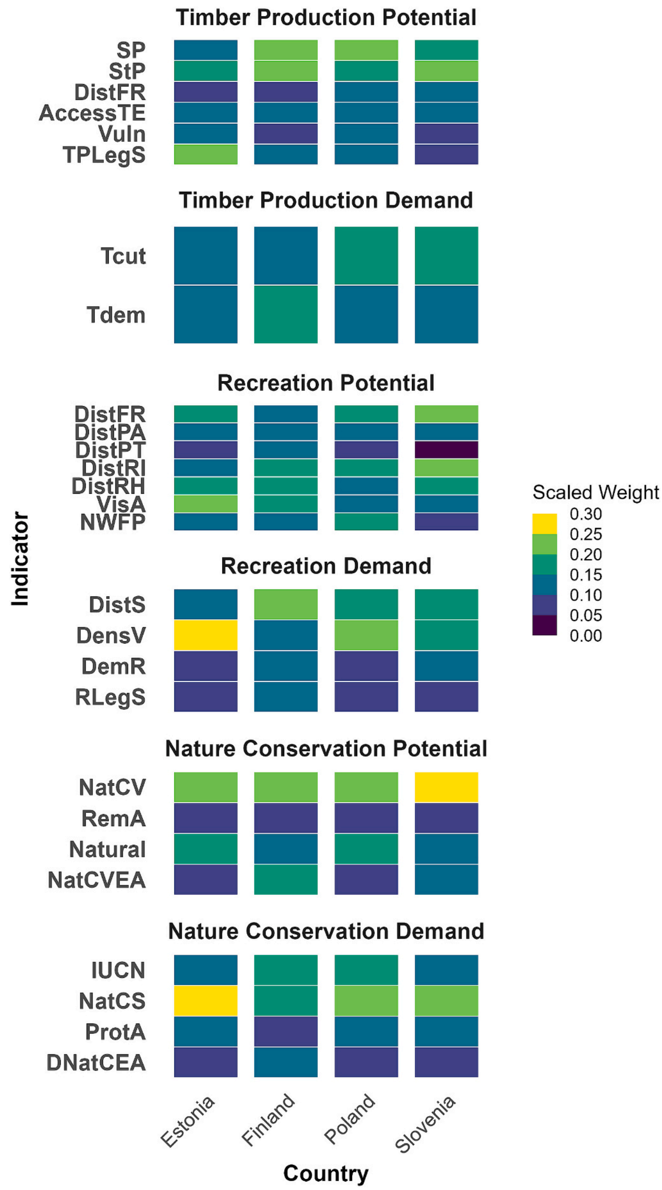

Fig. 2. Comparison of indicator weights across four countries and three forest ecosystem services (FES) separately for potential and demand using a scaled heatmap. Color intensity represents the relative importance of each indicator (scaled weights ranging from 0 to 0.30, from low to high). This visualization highlights differences in indicator importance both across countries and within FES categories. Weights were scaled by the maximum number of indicators within a single FES to allow comparison among FES categories. Original (unscaled) baseline weights are reported in Table S1. Indicator abbreviations are reported in Table 3.

involving comparisons between Slovenia and Finland and between Slovenia and Estonia. Conversely, Estonian and Finnish experts prioritized expert-based timber demand assessment, whereas Polish and Slovenian experts assigned lower weights to this indicator. Significant differences were particularly evident between Estonia and Slovenia, and between Slovenia and Finland.

3.2.2. Indicators of recreation

Clear cross-country differences emerged in the weighting of recreation potential indicators (Figs. 2–4; Table S1), with Slovenia standing out most. Estonian, Polish and Slovenian experts assigned similarly high weights to road accessibility, whereas Finnish experts gave significantly lower weight to this indicator (Table S2). In contrast, Finnish experts assigned significantly higher weight to public transport accessibility than Estonian and Slovenian experts.

Slovenian experts assigned substantially higher weights to proximity to recreation infrastructure and distance to parking lots than experts from the other countries. For distance to parking lots, significant differences were observed between Slovenia and all three other countries, whereas for proximity to recreation infrastructure the largest significant differences were between Slovenia and Estonia. Finnish experts prioritized proximity to recreational hotspots, with significant differences relative to all other countries. In contrast, Estonian experts assigned the highest weight to visual attractiveness, significantly higher than Slovenian and Polish experts.

Preferences for non-wood forest products revealed another thematic divide. Polish experts assigned the highest weight to this indicator, whereas Slovenian experts assigned the lowest. Significant differences in preferences for non-wood forest products were confirmed between Slovenian and each of the other countries.

Regarding recreation demand, indicators of actual use revealed clear contrasts, with Finland standing out most. The largest differences were observed for visitor density and proximity to settlements. Estonian experts prioritized visitor density, whereas Finnish experts assigned it the lowest weight; significant differences in visitor density were observed for most country pairs. Finnish experts assigned the highest weight to proximity to settlements, while Estonian experts assigned the lowest; significant differences were confirmed between Estonia and each of the other three countries.

Legislative support for recreation and expert-based demand assessment also showed distinct national patterns. Finnish experts assigned the highest weight to legislative support for recreation, followed by Estonian experts, while Slovenian and Polish experts assigned lower, similar weights. Expert-based demand assessment received the highest weights from Finnish and Slovenian experts, with Estonian experts assigning intermediate weights and Polish experts the lowest. Significant differences in expert-based demand assessment were observed for all country pairs, except Estonia–Poland.

3.2.3. Indicators of nature conservation

Regarding nature conservation potential, indicator weights also differed across countries, with Slovenia standing out most (Figs. 2–4; Table S1). Nature conservation value was prioritized by all countries, but Slovenian experts assigned significantly higher weight to nature conservation value than experts in the other three countries. Forest stand naturalness received the highest weight in Poland, whereas Slovenian experts assigned a significantly lower weight than experts in all other countries (Table S2). Remoteness showed the smallest cross-country differences, with Slovenian experts ranking it significantly lower than experts in the other three countries. Finnish experts assigned substantially higher weight to expert assessment of conservation potential than the other countries, with significant differences in all pairwise comparisons involving Finland.

Regarding nature conservation demand, indicators tied to structured conservation frameworks showed clear contrasts. Finnish and Polish experts assigned substantially higher weights to international conservation status than Slovenian and Estonian experts. National conservation status was prioritized in all countries, with Estonian experts assigning significantly higher weights than experts from the other countries, while Finnish experts assigned the lowest.

Slovenian experts assigned higher weights to protected or set-aside areas in private and public forests than experts in the other countries; differences between Slovenia and each of the other countries were significant. Finnish experts rated expert-based conservation demand assessment significantly higher than experts in the other countries. Polish experts assigned the lowest weights to expert-based conservation demand assessment, while Slovenian and Estonian experts occupied the middle ground.

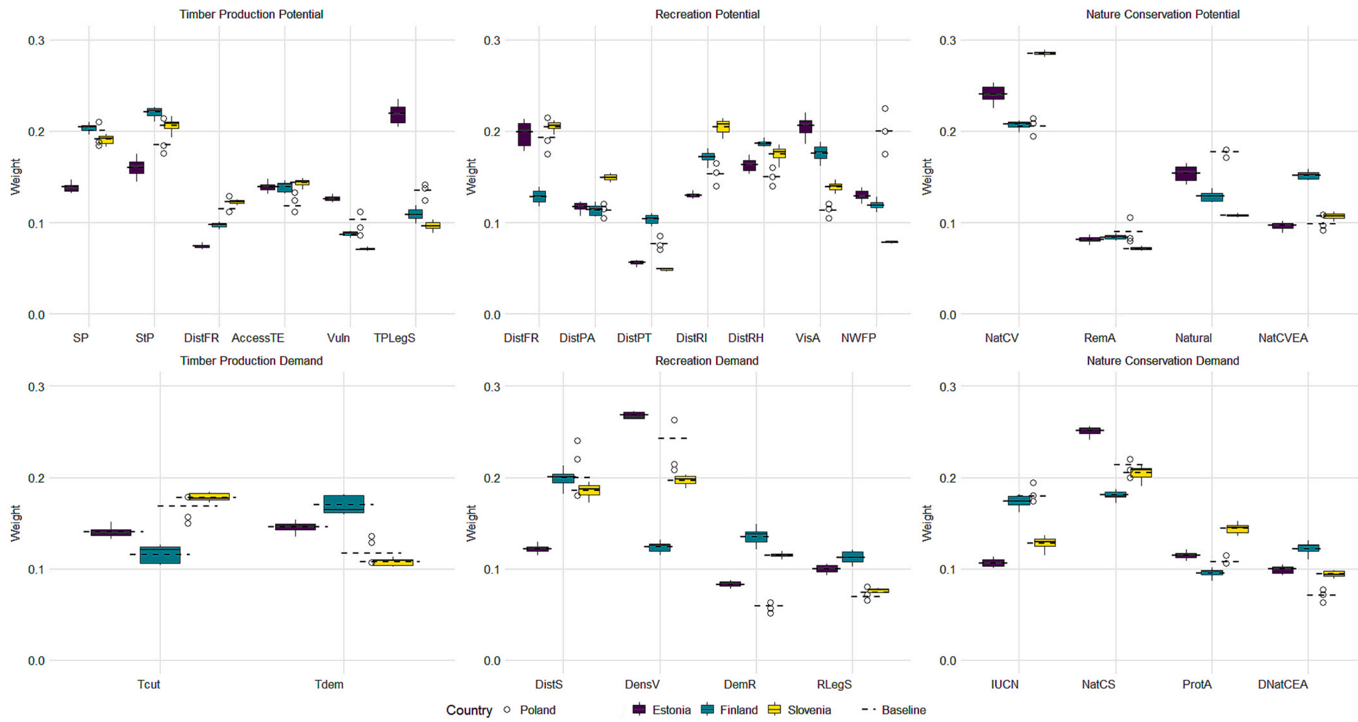

Fig. 3. Variation and robustness of forest ecosystem service (FES) indicator weights across four countries and three FES separately for potential and demand. The dotted horizontal lines represent the baseline weights derived from the full set of expert opinions. Colored boxplots (by country) illustrate the variability of indicator weights obtained from a robustness analysis, in which weights were recalculated by sequentially excluding one expert at a time. For Poland, three sets of values are shown, reflecting the presence of three expert groups. Within each boxplot, the central horizontal line represents the mean weight across robustness runs, the box spans the interquartile range (IQR, 25th–75th percentiles), and whiskers extend to the most extreme values within 1.5 × IQR. Weights were scaled (as in Fig. 2) by the maximum number of indicators within a single FES to enable comparison across FES categories. Indicator abbreviations are defined in Table 3.

4. Discussion

4.1. Selection of indicators for FES potential and demand

The selected indicators for timber production, recreation and nature conservation reflect the multidimensional nature of FES. Our approach aligns with previous studies emphasizing the need for both biophysical and socio-economic indicators to capture FES potential and demand (Burkhard et al., 2012; Olander et al., 2018; Tasser et al., 2020) and the integration of multiple data sources to conduct comprehensive assessments (Roces-Díaz et al., 2018; Grima et al., 2023). For timber production, the inclusion of accessibility and legal status indicators highlights the interplay between ecological constraints and operational feasibility, which is central to sustainable forest management (Sheppard et al., 2020). Recreation indicators related to accessibility and visual attractiveness align with previous findings showing that experiential quality is a key determinant of recreational use (Bell et al., 2007). For nature conservation, the compound indicator approach reflects growing recognition that conservation value cannot be captured by single metrics (Capmourteres and Anand, 2016).

Our selection process introduced methodological improvements in developing the FES indicator set to support identifying priority areas for promoting desired FES. This approach integrates drivers of both FES potential and demand in a spatially explicit manner, which provides a basis for identifying spatial mismatches between the potential availability of FES and the actual demand for FES and can inform planning (Tian et al., 2025). In contrast to predominantly unidirectional approaches, which mainly rely on potential-based indicators for FES assessment, our framework explicitly develops a separate set of demand-oriented indicators based on social indicators, including expert evaluations. This enables the assessment framework to better capture societal needs, accessibility, infrastructure and management-related parameters alongside ecosystem capacity and long-term ecological constraints. As such, the approach provides a more holistic framework for FES assessment that can be adapted to specific national and regional contexts while maintaining ecological and socio-institutional relevance. Indicator selection was based on a literature review and indicators either already used in forest planning in the countries included in the study or supported by the opinions of national expert teams to ensure the validity, applicability and robustness of the selection. Indicators were selected based on their suitability and data accessibility and were designed in a way to be stored in a spatially explicit manner. This potentially enables data to be communicated with stakeholders through a useful and transparent tool supporting participatory forest planning (Tahri et al., 2021).

For each FES, multiple indicators were selected, including biophysical and social indicators necessary to assess both FES potential and demand (Olander et al., 2018; Breyne et al., 2021). Each FES, separately for potential and demand, was measured using multiple frequently used and relatively easily measurable indicators with good data accessibility, which is crucial for forest planning. For example, recreational potential was measured using seven indicators, including aspects of accessibility, presence of recreational infrastructure and hotspots, visual attractiveness and non-wood forest products, which cover the most important aspects of recreational potential in forest areas. For estimating FES demand, which presents a specific challenge in FES assessment procedures (van Winckel et al., 2026), expert preferences were included through the indicator "quick expert assessment," which integrates biophysical information with social perceptions, capturing how important a particular FES is in a given area based on experts' personal experiences and knowledge. Integrating measurable parameters with social valuation is highly important for FES assessment (Olander et al., 2018). Expert assessments of FES potential and demand have been used in previous research to support landscape zonation by identifying areas of possible

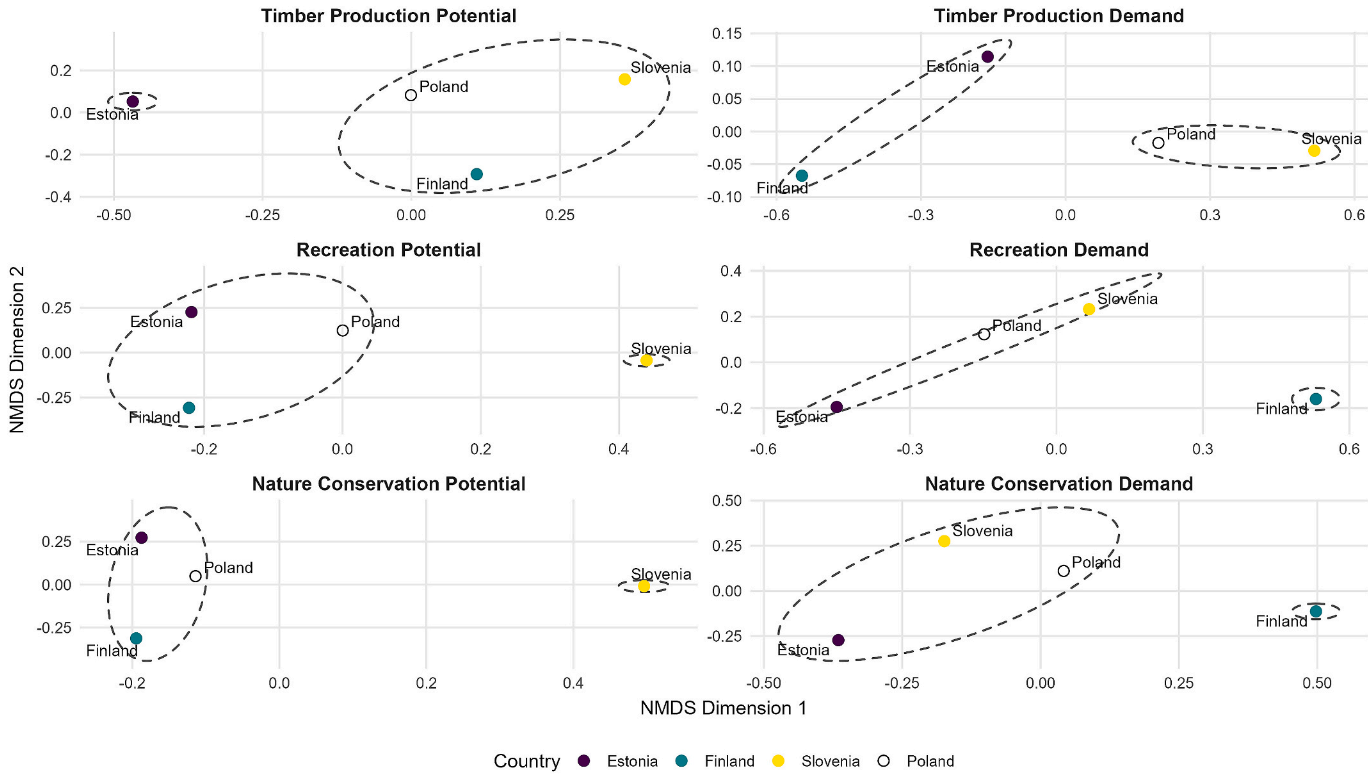

Fig. 4. Similarity among four countries in forest ecosystem service (FES) indicator weights separately for potential and demand visualized in reduced dimensional space. Within each panel, countries are positioned according to non-metric multidimensional scaling (NMDS) along two axes (NMDS Dimension 1 and NMDS Dimension 2), where the distance between points reflects pairwise dissimilarities in indicator weights based on Cohen's r values (Table S2). Thus, countries located closer together exhibit more similar indicator weight profiles, while those farther apart are more dissimilar. Dashed ellipses highlight groups of relatively similar countries within each FES category. Non-metric multidimensional scaling Kruskal's stress values are zero for all panels because the small number of countries ($n = 4$) allows exact representation of the dissimilarity matrices in two dimensions. Indicator abbreviations are defined in Table 3. Weights were scaled (as in Fig. 2) by the maximum number of indicators within a single FES to enable comparison across FES categories.

synergies or mismatches of FES, guiding management interventions (Albert et al., 2016). The indicator "quick expert assessment" is meant to include a broad range of stakeholders in delineating broad zones of the landscape, providing information on expected areas with substantial differences in indicator values, and complementing stand-level indicators with a broader landscape context. This use of expert judgment is consistent with expert elicitation methods used in ecosystem services planning (Raum, 2018).

The indicator selection incorporates multiple spatial and temporal horizons by distinguishing long-term ecosystem capacity to provide FES and management constraints from current or recent use and societal requirements. For example, timber production potential is measured using site productivity, which shows long-term production capacity, but also using stand productivity, which reflects current potential. In addition, the indicator of legal status reflects current constraints on timber production under national regulations. The combination of these indicators contributes to a more comprehensive, holistic and context-sensitive estimation of the potential of forests to provide timber production.

Importantly, spatially explicit stratification and assessment of ecosystem condition provide essential information on the capacity of ecosystems to continuously deliver services that support human well-being. As such, ecosystem assessments constitute a critical information base for evidence-based decision-making by integrating fundamental ecological and socio-economic information into sectoral policies, including regional planning, protected area management and forest management planning (Maes et al., 2020). In this context, the present study is particularly timely and policy-relevant in light of the EU Commission's Mapping and Assessment of Ecosystems and their Services (MAES) initiative, which promotes the systematic assessment of key ecosystems across the EU as a baseline for the EU Biodiversity Strategy 2030 and the EU Nature Restoration agenda (Barredo et al., 2015; Maes et al., 2020).

4.2. Cross-country comparison of indicator weights

Differences in indicator weights across the studied countries (Fig. 4) likely reflect variations in national governance frameworks, cultural preferences, ownership structures and forest management traditions, as well as land use and demographic patterns in the study areas. These findings are consistent with previous research showing that ecosystem service prioritization is shaped by land-use patterns and institutional settings governing landscape management (Primmer et al., 2015; Saarikoski et al., 2018; Başkent and Balci, 2024).

For timber production potential, Estonian experts emphasized vulnerability and legal status, reflecting a strong compliance and risk management orientation, while also prioritizing stand productivity. Slovenian experts prioritized site and stand productivity and operational accessibility, consistent with ecologically based close-to-nature forest management typical of some Central European countries (Bončina et al., 2019) and reflecting the heterogeneity of the terrain and operational accessibility in the country. Finnish and Polish experts adopted a balanced approach, combining productivity with legal considerations, relying on extensive forest inventory systems and planning tools, while placing less emphasis on accessibility due to the generally accessible nature of the forest landscapes (Uotila and Viitala, 2000).

For timber production demand, Estonian and Finnish experts emphasized expert-based timber demand assessment over recent cutting, reflecting a forward-looking approach supported by extensive multisource forest data from the National Forest Inventory and forest planning tools (e.g., Korhonen et al., 2021). In Finland, this is reinforced by the strong role of the forest industry, where purchasing timber is driven by market demand rather than current or past harvesting patterns (Kurki et al., 2012). In contrast, Poland and Slovenia relied strongly on recent cutting intensity data. In Slovenia, this reflects the use of adaptive forest management, which has a rather stable harvest level and relies on monitoring implemented forest activities to determine future actions. In Poland, the emphasis on recent cutting is linked to forest conversion processes shifting from even-aged pine monocultures to mixed forests.

Recreation potential priorities differed across countries. Finnish experts prioritized accessibility to recreational infrastructure through public transport and proximity to settlements. This reflects a preference for inclusive, accessible recreational hotspots with high visual attractiveness (Store et al., 2015). Slovenian experts prioritized functional accessibility through parking and proximity to recreation infrastructure, reflecting the constraints of hilly and alpine landscapes. In contrast, Estonia and Poland leaned toward natural resource-based recreation, particularly non-wood forest products. This is emphasized in the Estonian Forest Act and reflects the traditional foraging practices in Poland, reinforcing the importance of socio-cultural and economic dimensions in recreation planning (Milcu et al., 2013).

Regarding recreation demand indicators, Estonian experts prioritized visitor density and designated recreation areas, relying on empirical data. Finnish experts emphasized legislative support, and both Slovenian and Finnish experts emphasized expert assessment and accessibility. In Slovenia, recreational demand is included in the mapping of forest functions and is strongly supported by legal acts that define specific forest categories related to the importance of forest functions. In Finland, the dense forest road network enables access to forests, and accessibility is guaranteed by "Everyman's Right," which allows free roaming in forests, as is also common in other countries. Polish experts focused on visitor density while giving less importance to demographic and legislative indicators.

Regarding nature conservation potential, Slovenian experts relied strongly on evidence-based indicators and placed less importance on remoteness, reflecting strong nature conservation regulations and widespread close-to-nature silviculture. Estonian and Polish experts emphasized ecological integrity and national priorities, reflecting strong domestic forestry traditions (e.g., Paluots et al., 2024). Naturalness of forest stands plays an important role as a comparison indicator between the tree species composition of the current forests and the potential forest community, especially in Poland, where large-scale historical anthropogenic changes are reflected in the dominance of Scots pine in the lowlands. Finnish experts favored expert-based evaluation, assigning moderate weight to naturalness, as pristine forests are rare due to a long history of forestry. Remoteness is less important due to dense forest road networks and limited untouched forests.

Regarding nature conservation demand indicators, Finnish and Polish experts emphasized structured frameworks of protected areas, particularly international categories. They differ in their views on expert-based assessments, with Finnish experts valuing them highly. Slovenian experts downplay international conservation frameworks while prioritizing national conservation statuses and the establishment of conservation areas in private and public forests. Estonian experts favor national conservation priorities, minimizing the importance of international status, reflecting practical considerations related to implementation and regulatory oversight.

Overall, the differences in priorities assigned to indicators highlight that weighting schemes are particularly important in the spatial assessment of FES potential and demand, since they enable consideration of local conditions and inclusion of local knowledge. In addition, they also enable harmonized assessments across regions, which is relevant for revealing driving forces of FES prioritization. Prioritization or weighting of indicators therefore represents an important step in the spatial assessment of FES.

4.3. Potential and limitations of the selected multi-criteria decision analysis method

The application of the Similarity-Rewarding fuzzy group Best-Worst Method provided a structured and transparent framework for deriving FES indicator weights. Although multi-criteria decision analysis methods have previously been applied in the assessment and mapping of FES, using approaches such as Analytic Hierarchy Process and Preference Ranking Organisation Method for Enrichment Evaluations (Fontana et al., 2013; Tahri et al., 2021), Best-Worst method and its extensions, including Similarity-Rewarding fuzzy group Best-Worst Method, have mainly been applied in other environmental decision-making contexts (Abedi and Shahbaz Zadeh, 2025; Dengiz and Demirağ Turan, 2023; Ficko et al., 2025). To the best of our knowledge, this study represents the first application of Similarity-Rewarding fuzzy group Best-Worst Method to the assessment of FES. The approach proved particularly suitable for handling complex indicator structures and group decision-making involving experts from practical forest planning and academic research. Expert participation ensured that local knowledge and context-specific interpretations of FES potential and demand were reflected in the weighting process. By assigning greater influence to experts who selected the same "best" indicator, the method encouraged convergence among expert judgments and strengthened the stability and reliability of the resulting weights. The use of fuzzy linguistic assessments enabled systematic treatment of the uncertainty and subjectivity inherent in expert judgments. Compared with Analytic Hierarchy Process, Best-Worst Method required fewer pairwise comparisons, reducing cognitive effort and improving the internal consistency of responses (Ahmad et al., 2017). The resulting indicator weights were applied in aggregating FES indicators for both potential and demand, ensuring that each indicator contributed proportionally to its assessed importance. Overall, the Similarity-Rewarding fuzzy group Best-Worst Method approach provided a robust and practically feasible framework for multi-expert, multi-country assessments of FES (Ficko et al., 2025), although its reliance on expert judgment remains a limitation that could be addressed in future studies through empirical validation or broader stakeholder involvement.

4.4. Conclusions

Our framework shows that assessing FES requires approaches that explicitly reflect local ecological conditions and societal preferences. By combining biophysical indicators with social indicators and expert-derived weights using the Similarity-Rewarding fuzzy group Best-Worst Method, our framework demonstrates how both the potential and demand for timber production, recreation and nature conservation can be jointly addressed in a policy-relevant manner across contrasting European settings.

The strong context dependency observed in indicator selection and weighting implies that standardized FES assessment frameworks should be applied with caution. Instead, locally adapted assessments and spatial prioritizations are critical for ensuring that forest management strategies remain effective, legitimate and resilient under diverse ecological and socio-institutional conditions. Explicitly accounting for both potential and demand and transparently weighting them can support the spatial prioritization of priority areas and more balanced decision-making, helping reconcile production, conservation and social objectives. From a practical perspective, our results underline the value of participatory weighting procedures for revealing societal priorities and improving the acceptance of FES-based planning outputs. For policy and planning, aligning national forest management practices with international sustainability targets will require flexible, multi-scalar governance mechanisms that allow context-sensitive implementation while maintaining overarching comparability.

Overall, advancing FES assessment and operational application requires balancing methodological consistency with sensitivity to local ecological and socio-economic contexts, thereby enabling forest management to more effectively sustain long-term ecosystem integrity and societal well-being. In this context, the present study provides significant methodological and empirical contributions toward the development of a robust information infrastructure for spatially explicit decision-making, through the systematic integration of ecological, socio-economic and management-related information into forest management planning processes.

CRediT authorship contribution statement

Tina Simončič: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Petra Grošelj:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Adriano Mazziotta:** Writing – review & editing, Methodology, Data curation. **Emin Zeki Başkent:** Writing – review & editing, Visualization. **Kyle Eyvindson:** Writing – review & editing. **Henn Korjus:** Writing – review & editing, Data curation. **Eneli Põldveer:** Writing – review & editing. **Sari Pynnönen:** Writing – review & editing. **Grzegorz Rączka:** Writing – review & editing, Data curation. **Anna Repo:** Writing – review & editing. **Andrej Bončina:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2026.101895.

Data availability

Data will be made available on request.

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