Ecological Indicators 184 (2026) 114701

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Monitoring forest ecosystem services in Germany: How do data demand and operational supply match

Niclas Müller [a,b,*], Kristin Franz [a], Matthias Dieter [a]

[a] Thuenen Institute of Forestry, Leuschnerstraße 91, 21031 Hamburg, Germany
[b] Graduate School Forest and Agricultural Sciences, Georg-August-University Goettingen, Büsgenweg 5, 37077 Göttingen, Germany

ARTICLE INFO

Keywords:
ecosystem services
monitoring system
indicators
feasibility
suitability
forest management
forest enterprise

ABSTRACT

Ecosystem services represent a significant contribution that forest enterprises make to human well-being. However, the extent to which these services are recognized by society and politics varies considerably. On the one hand, political attention has so far been limited to a narrow range of ecosystem services, such as carbon sequestration and biodiversity. On the other hand, there is a lack of data availability, especially at the forest operational level, which impedes a comprehensive representation of ecosystem services. This is of particular relevance, as every operational decision has a direct impact on ecosystems and their associated services. To address this gap, politically relevant ecosystem services were first identified. Subsequently, a scoping review was conducted to determine applicable indicators for their representation. For these indicators to be integrated in an existing Forest Accountancy Network, they had to meet specific criteria. These criteria were evaluated through two separate surveys assessing the feasibility and suitability of these indicators at the forest operational level. Feasibility was examined through a survey of forest enterprises, whereas suitability was evaluated by a dedicated survey of ecosystem service experts. The results provide a set of applicable indicators that allow for representation of specific ecosystem groups at the forest operational level. In doing so, this research lays the foundation for a more transparent and precise evaluation of forest enterprise performance, thereby enhancing comparability among forest enterprises and offering policymakers and society a clearer understanding of the multifunctional contributions made by forest enterprises.

1. Introduction: Background and Goals

The basis for valid and well-founded decisions are adequate and sound information about the current status quo. Monitoring systems are used to obtain information about the status quo for these decisions (Burdekin et al., 2001). For the economic situation of forest enterprises, a Forest Accountancy Network (FAN) is a possible monitoring system that can provide the needed information. Decision-making in multifunctional forestry is not only based on monetary information but also on the provision of ecosystem services (ES) (Prins et al., 2023). Following the Millennium Ecosystem Assessment (MEA) ES are the benefits that society derives from ecosystems (MEA, 2005). Subsequent frameworks, such as the Common International Classification of Ecosystem Services (CICES) or The Economics of Ecosystems and Biodiversity (TEEB), have taken up this concept and further elaborated it from their perspectives (TEEB, 2010; Haines-Young and Potschin, 2018). In order to assess ES, they must be recorded. A monitoring system such as a FAN could provide comprehensive information on the provision of ES. However, current FANs usually only quantify monetary value; the non-market, public-good-oriented services provided by forest enterprises, such as ES, are not accounted in most cases.

The European countries Austria, Denmark, Finland, France, Germany, Netherlands, Norway, Slovakia, and Switzerland have implemented some kind of FAN. These systems share the common aim of collecting (socio-) economic data on forest enterprises to map forestry performance, especially wood supply and operational structures (Burdekin et al., 2001). Wood supply has been constantly measured over years because there has been a trading market. Therefore, this ES can be easily quantified in monetary terms through costs and revenues. Other ES, like water retention and purification, biodiversity, or recreation, are hardly considered in FANs, because they are usually not valued in monetary terms. Most of them are nonmarket (public) goods, which are characterized by the partial or complete absence of two attributes: consumer (beneficiaries) rivalry and the excludability of market

* Corresponding author.
E-mail address: niclas.mueller@thuenen.de (N. Müller).

https://doi.org/10.1016/j.ecolind.2026.114701
Received 3 July 2025; Received in revised form 6 February 2026; Accepted 9 February 2026

participants (Bergen et al., 2013; Elsasser et al., 2020). Hence, no (market) price can be formed for these ES, but they must be demonstrable so their performance, including economic terms, can be considered.

The provision of ES is closely linked to forest management. Their promotion is usually tied to a renunciation of utilization or restrictions on forest management activities, and should also be taken into account (Prins et al., 2023). This results in reduced revenues or increased operational costs, which are usually not offset by direct income, without reflecting the actual value of the ES provided (Bergen et al., 2013). This limits the comparability of forest enterprises – who differ in the extent to which they provide and promote ES – and results in an incomplete assessment of their contribution to the forest sector at the macroeconomic level (Schwaiger et al., 2015).

To present other ES than wood provision, Germany, the Netherlands, Switzerland, and Finland collect more information in their FANs. Germany and Switzerland collect revenues and expenditures of the forest protective and recreational function (BMEL, 2024; Bürgi et al., 2024). The recreational function is also recorded in value terms in the Netherlands (Woltjer et al., 2024). However, the recorded values raised in these countries represent only the financial transactions and do not capture the full value of the recreational function (BMEL, 2024; Bürgi et al., 2024). Finland is the only country that includes information on biodiversity and water protection in its reporting beyond purely monetary value (LUKE, 2025). The Finnish FAN shows indicators that describe biodiversity and the quality of water protection in non-industrial, private forests. Additional biodiversity data in the Finnish FAN are derived from the METSO project[1].

Examples of biodiversity monitoring programs at the European level are Federal Forest Inventories (e.g., Germany, Finland), the MOBI-e (Austria)[2], and various monitoring programmes in Switzerland (such as BDM-CH)[3]. These programs provide an overview of the current state of biodiversity and other ES in the respective country. However, their main limitation becomes apparent here: the study areas are typically not aligned with forest enterprise boundaries. Most indicators in the field of biodiversity or ES in general relate to a local or regional level, according to the study by Feld et al. (2009). Many (especially biotic) indicators also refer to a small-scale level (patch-scale) and act as the basis for extrapolation or as proxies (Plummer, 2009). In this context, homogeneity of the entire area to be extrapolated is assumed (Feld et al., 2009). But ES are neither homogeneous nor static over larger areas (Fisher et al., 2009). Indicators should have a clear spatial reference and refer to process-related (landscape)units. Forest enterprises are process-oriented and heterogeneous entities often consisting of a diverse mosaic of land "patches", which require a multitude of distinct proxies to represent them. This complicates the visualization of ES at the operational level, which is exacerbated by the current lack of explicit forest enterprise-specific indicators. Yet it is precisely the operational level that bears responsibility for the protection, conservation, and development of ES. Every operational decision has a direct impact on the forest ecosystem and the service it provides (Latruffe et al., 2016).

The need to visualize ES provided by forest enterprises is underscored by growing political interest in recent years as reflected in the (inter)national strategies such as biodiversity or forest strategies (Schmithüsen, 2007; Moser and Zimmermann, 2011; Maes et al., 2016; Posner et al., 2016). In Germany, initial approaches have also been developed to make ES visible at different spatial levels (Elsasser et al., 2020; Knoke et al., 2021; Hermes et al., 2023). Comparable developments in agriculture led to the FLINT project, which explored farm-level indicators in response to emerging sustainability policy demands (Poppe et al., 2016). The German FAN is characterized by an accounting framework that has remained constant over the last 20 years. The framework is structured into five product areas: three of them address the monetary valuation of timber production, protection, and recreation services, thereby defining forest enterprises in the narrower sense (Müller et al., 2024). The remaining two focus on services provided by forest enterprises to third parties, as well as on sovereign responsibilities carried out by state-owned enterprises. Expanding the FAN to include indicators that capture the actual performance of ES would substantially enhance its information value and provide stronger data foundation for benchmarking, research, and policy making (Müller et al., 2024). The key figures within the FAN are voluntarily and largely free of charge provided by the private, corporate, or state-owned forest enterprises managing operations larger than 200 hectares (Müller et al., 2024). For this reason, certain requirements are placed on new key figures: the effort and scope for the forest enterprises must be kept as low as possible (parsimony), so that enterprises continue to participate in the FAN. Furthermore, the forest enterprises must be able to collect the key figures (feasibility) and the figures must provide reliable information about the entire forest enterprise (suitability).

This study aims to identify indicators that allow politically relevant ES to be addressed at the operational level and integrated into the German FAN. To achieve this, the paper explores three key research questions:

- Which forest-related ecosystem services are politically relevant in Germany?
- What indicators can be used to map these forest-related ecosystem services?
- Which identified indicators have the potential to be integrated into the German FAN?

2. Methods

The paper is structured in three parts: first, ES were identified through a document analysis of forest-policy relevant strategies. The fact that ES are included in these studies indicates that they hold (societal) relevance. For the extension of the FAN, we aim to recommend only those ES considered relevant. Second, a scoping review was carried out on possible indicators to represent the identified ES. Third, a two-part survey was conducted to evaluate the indicators in terms of their feasibility and suitability.

2.1. Identification of politically relevant forest-related ecosystem services

To identify the politically relevant forest-related ES in Germany, the current political strategies and regulations of Germany, the European Union (EU), and the United Nations (UN) from the past 15 years were analyzed (table 1). The national (4) and EU level (5) strategies are not binding but reflect the current political priorities. Decisions of the United Nations (2) were also considered. Although ES have received considerable scientific attention, there is still no consensus on their precise definition or terminology (Saarikoski et al., 2015; Danley and Widmark, 2016; Costanza et al., 2017; Hermelingmeier and Nicholas, 2017; La Notte et al., 2017; Ferraro et al., 2025). As a result, ES sometimes appeared under different terminological variants or descriptions. These were identified and harmonized by comparing their content and functional meaning (Shvidenko et al., 2005; De Groot, 2006; Burkhard et al., 2009; De Groot et al., 2009; Elmqvist et al., 2010). For example, the terms 'water purification' and 'water filtration', which refer to closely related processes, were unified under the common term 'water purification'. This approach enables the establishment of a consolidated list of ES for this paper, based on consistent terminology.

To adapt the identified and standardized ES to the framework of the German FAN and based on considerations in the literature (Boyd and Banzhaf, 2007; Costanza, 2008; Fisher et al., 2009; Saarikoski et al., 2015; Potschin and Haines-Young, 2016), the ES were thematically

[1] https://metsonpolku.fi/en/metso-programme
[2] https://www.biodiversityaustria.at/
[3] https://www.biodiversitymonitoring.ch/index.php/de/

Table 1
Evaluated political strategies and regulations

year	strategy or regulation	publisher	abbr.	source
2011	Forest Strategy 2020	Germany	FS2020	(BMELV, 2011)
2015	Paris Agreement	United Nations	UN.PA	(UNFCCC, 2015)
2016	Climate Protection Plan 2050	Germany	CPP2050	(BMUB, 2016)
2016	Transforming our World: Agenda 2030	United Nations	UN.A2030	(UN General Assembly, 2015)
2019	The European Green Deal	European Union	EU.GD	(COM, 2019)
2020	The European Biodiversity Strategy	European Union	EU.BS	(COM, 2020b)
2021	Forest Strategy 2050	Germany	FS2050	(BMEL, 2021)
2021	Common Agricultural Policy (CAP)	European Union	EU.CAP	(COM, 2021b)
2021	European Forest Strategy 2030	European Union	EU.FS2030	(COM, 2021c)
2023	CAP Strategy Plan 2023-2027 (Conclusion)	Germany	CAP SP23-27	(BMEL, 2023)
2024	European Climate Targets 2040	European Union	EU.CT2040	(COM, 2024)

aggregated. For example, all ES describing protective functions of forests (local protective functions, no climate protection) were grouped, like those directly to water (table 2). This grouping was primarily based on their predominant thematic characteristics; for instance, flood protection is classified under protection services of forests rather than drinking water supply. The idea of grouping ES can be traced back to Costanza et al. (1997), who categorized ES based on their direct and indirect benefits to human well-being. Over time, several alternative approaches have emerged to classify ES based on their characteristics or overlaps (De Groot et al., 2002; MEA, 2005; Boyd and Banzhaf, 2007; Wallace, 2007; Costanza, 2008; Fisher and Turner, 2008; Maes et al., 2016; Haines-Young and Potschin, 2018). All of these concepts have evolved through processes that integrated new insights and revealed existing limitations. Some of them continue to be developed to this day (e.g., CICES).

All classification frameworks presented here pursue the aim of capturing the services provided by nature and their benefits to humans across all ecosystems and on a global scale – initially independent of whether they are assessed monetarily or biophysically (MEA, 2005; TEEB, 2010; Haines-Young and Potschin, 2018). The idea of these established classification frameworks, to make ES visible, is also pursued with the classification scheme developed in this study. The conceptual approaches of the existing classification frameworks cannot be fully reconciled with the considerations of this work. Each of these concepts were developed in a specific context, is based on its own theoretical foundation, and is tailored to a particular field of application (Forest Europe, 2016; Haines-Young, 2023). The aim of the classification schemes included in these frameworks is to develop a standardized and universally applicable system. The present study follows a different approach: it identifies ES that are derived directly from political strategies and regulations, which mostly do not orient themselves towards established classification frameworks.

For instance, common frameworks describe the storage function of ecosystems in relation to atmospheric deposition in general, whereas the documents analyzed in this study explicitly report carbon sequestration, often differentiated into ́storage biomass ́ and ́storage soil ́. Likewise, in the examined strategies and regulations, the categorization into groups like provisioning or regulation and maintenance is largely absent, nor do these documents consistently follow established frameworks. Instead, services are combined into a societally usable added value—for example, the combination of groundwater recharge and water purification enables drinking water provision in the first place (e.g., table 2 – FS2050). Political strategies also name services that are not treated as independent ES in international classification systems, such as the fundamental conditions required for wood provision: wood increment and wood stock.

These context-dependent differences complicate the harmonization of the ES extracted here with existing classification frameworks (Forest Europe, 2016; Haines-Young, 2023). For this reason, the groups developed in this study were deliberately adapted to the specific context of the analyzed political strategies and regulations. The group's focus exclusively on services of forest ecosystems as provided or supported by forest enterprises and as formulated in political documents. The ES groups presented here are therefore, in some cases, more broadly defined than in existing classification frameworks. Furthermore, some services were included that are recognized as such in Germany but not necessarily at an international level — for example, providing workplaces or burial forests.

The aim of this work was not to develop an entirely new classification. Rather, it seeks to present the services provided or supported by forest enterprises in a transparent and comprehensible way for all sectors of society. Therefore, a thematically structured classification for forest-related ES in Germany was developed (table 2). For the identified ES, coherent and defined groups were formed that can be referred to as final ES in the application context. These newly established groups were termed Forest Ecosystem Service units (FES units) and are named to the thematic interrelations that connect the respective ES.

2.2. Identification of ecosystem service indicators

To represent the FES units introduced in Chapter 2.1., the respective ES must first be spatially mapped as the basis for these groupings. To this end, a scoping review of scientific literature was conducted according to Elm et al., (2019), supplemented by an analysis of grey literature. The scoping review was carried out from July to September 2024. The main databases searched were Web of Science and Scopus. The search queries used were: *(1) European forest* AND ecosystem service* And indicator* and *(2) Indicator* AND ecosystem services* OR ecosystem goods**. For the last search term (2) the keywords *Europe* and *Forest* were used in combination, to obtain only results for ES specific to forests in Europe. To ensure that no articles are excluded that relate directly to German forests, Google Scholar, the databases of German authorities (such as UBA[4] or BMEL[5]), and several German research institutes (such as NW-FVA[6] or FAWF[7]) were searched for grey literature. When reviewing the databases, only articles were selected whose titles apparently match the previously identified ES.

The search resulted in 2026 articles in total. 1985 articles were found in the database search and 41 articles in the grey literature. Duplicates were removed and 1402 articles remained. In the title screening, all articles that seemed irrelevant were excluded and 277 remaining articles were included in the following abstract screening. For this purpose, the following four criteria were taken into account: a) focus on forest-related ES, b) focus on previously identified ES from chapter 2.1., c) focus on ES in temperate regions/zones, and d) focus on ES in Europe. Criteria c) and d) were selectively applied. The climate zone criterion (c) refers to indicators for ES that are independent of cultural and spiritual aspects but subject to climate conditions. The Europe criterion (d), was specifically

[4] German Federal Environment Agency
[5] Federal Ministry of Food and Agriculture
[6] Northwest German Forest Research Institute
[7] Research Institute for Forest Ecology and Forestry of Rhineland-Palatinate

Table 2
Identified ecosystem services and their associated sources (based on table 1)

FES unit	definition of the FES unit	ecosystem service	FS2020	UN. PA	CPP2050	UN. A2030	EU. GD	EU. BS	FS2050	EU. CAP	EU. FS2030	CAP SP23-27	EU. CT2040	total
wood provision	This FES unit comprises all services directly related to the storage, growth, and provision of wood as a raw material and source of energy	timber provision (fibre)	x		x			x	x	x	x		x	7
		wood increment	x		x				x					3
		growing stock	x		x				x					3
		timber provision (energy)	x		x		x	x	x	x	x		x	8
non-timber forest products	This FES unit comprises all forest products that are not directly related to timber production	food	x				x	x	x	x	x		x	7
		medical resources	x					x			x			3
		ornamental resources									x			1
biodiversity	This FES unit encompasses services that support the conservation and development of biological diversity within forest ecosystems, including processes that sustain ecosystem functions, resilience, and regenerative capacity	biological diversity	x		x	x	x	x	x	x	x	x	x	10
		pollination						x						1
		nutrient regulation	x					x	x	x			x	5
		deadwood	x						x		x			3
		biotope areas							x					1
		rejuvenation							x		x			2
		soil formation	x					x	x	x	x	x	x	7
		genetic materials/ biological regulation	x					x	x		x			4
air pollution control and climate regulation	This FES unit encompasses services that influence air quality and climate stability by regulating the exchange, transformation, and storage of atmospheric substances within forest ecosystems	air quality regulation						x	x		x			3
		air filter function	x					x	x		x			4
		oxygen production						x						1
		carbon storage (biomass)	x	x	x			x	x	x	x		x	8
		carbon storage (soil)	x	x	x			x	x	x	x	x	x	9
		climate regulation	x				x	x	x					4
protection services of forests	This FES unit comprises services that contribute to the protection of ecosystems, infrastructure, and human well-being by mitigating natural hazards and regulating environmental risks	protection against natural hazards					x	x	x		x			4
		noise protection						x	x					2
		soil protection/ erosion regulation	x						x		x	x		4
		flood protection	x					x	x		x			4
		control of pests and disease					x				x			2
drinking water supply	This FES unit comprises services that ensure the availability, regulation, and quality of freshwater resources	drinking water supply	x				x	x	x	x	x	x		7
		water purification	x				x	x	x		x			5
		ground water recharge				x			x					2
		water regulation and reservoir	x		x	x		x	x					5
culture, health and recreation	This FES unit comprises services that support human well-being through cultural, spiritual, and recreational benefits. These services	health and recreation	x		x			x	x		x			5

(*continued on next page*)

Table 2 (*continued*)

FES unit	definition of the FES unit	ecosystem service	FS2020	UN. PA	CPP2050	UN. A2030	EU. GD	EU. BS	FS2050	EU. CAP	EU. FS2030	CAP SP23-27	EU. CT2040	total
	are provided free of charge and contribute to mental and physical enrichment	cultural achievements	x			x					x			3
		spiritual achievements							x		x			2
		heritage and identity	x											1
		landscape asthetics	x						x					2
		sports	x						x					2
economics, science and education	This FES unit comprises services that contribute to societal/economic development and knowledge generation. These benefits are associated with monetary value or require investment	economic performance			x				x	x	x			4
		providing workplaces							x	x	x			3
		eco-tourism				x			x	x	x			4
		burial forest							x					1
		science and education			x			x	x		x			4

introduced to take cultural and spiritual ES into account and to focus on regional peculiarities in Europe. In the abstract screening 226 articles were eliminated. The subsequent full-text screening of the remaining 51 articles relied on the same criteria. Finally, 31 articles were included, from which the indicators used to represent the listed ES were extracted (table A.1 in appendix A).

2.3. *Evaluation of the usability of the indicators within the framework of the FAN*

Over time, several approaches have been developed for evaluating indicators. Most evaluation schemes include the following key aspects: indicators should be generally accepted by both science and practice, comprehensive yet parsimonious, and able to represent the relevant phenomena fully within a reasonable cost-benefit ratio. They should be understandable to a broad audience, sufficiently sensitive to detect change, useful for the intended purpose, and feasible to implement by those responsible (Doran, 1981; Harger and Meyer, 1996; Rice, 2003; Lebacq et al., 2013; Schliep et al., 2014; Oudenhoven et al., 2018). We assume that the indicators identified through the scoping review already meet some of these criteria. This assumption is supported by the fact that the development and validation of such indicators typically involves some form of assessment framework, as illustrated by the study of Hernandez-Morcillo et al. (2013). However, for inclusion in a FAN, the criteria of parsimony and feasibility are particularly crucial, as they save effort in terms of time and (monetary) resources. The reference area of the indicators varies in the literature depending on their context of application. For this study, it therefore needs to be standardized to the operational forest enterprise area. For these reasons, the following three criteria receive special attention when evaluating the identified indicators with regard to their usability within the FAN.

Parsimony	as few indicators as possible to minimize the burden on forest enterprises and retain the FAN participants
Feasibility	forest enterprises must be able to collect new indicators or calculate indicators from existing data (both with minimal effort) to ensure continued data provision
Suitability	the indicators should have a high degree of representativeness for assessing the ES to be represented at the operational forest enterprise area

To meet the criterion of parsimony, indicators identified in the scoping review that were closely related and shared the same reference object were aggregated into a single main indicator. The shared reference object served as the main indicator, while the original indicators were allocated as sub-indicators. To further enhance the efficiency of the parsimony criterion and minimize effort, a structured selection process was applied in the following three steps:

Step 1: For each FES unit, all associated ES were initially analyzed. The four indicators most frequently mentioned for each FES unit were selected, provided that at least four indicators appeared two or more times. If fewer than four indicators met this criterion, all such indicators were included. Also, if more than four indicators had the same frequency, the selection was based on those most frequently mentioned in the literature.

Step 2: Subsequently for each ES within the FES unit, the indicator with the highest number of mentions in the literature was selected. This ensured that every ES within the FES unit was taken into account. If there was an overlap with indicators selected in Step 1, no alternative indicator was chosen.

Step 3: Finally, matches between the selected indicators of a given FES unit and the non-selected indicators of other FES units were analyzed. Overlapping indicators were additionally incorporated into the indicator set of the respective FES unit.

To evaluate the criterias feasibility and suitability two surveys were conducted. They were carried out from February to March 2025 using the online survey tool "Limesurvey". When developing the questionnaires, it was necessary to balance the level of detail and complexity of the questions with the aim of ensuring a high willingness to participate. An overly detailed questionnaire could have discouraged respondents and led to non-response or early drop-out. Pre-tests were conducted within each respondent group to prevent misunderstandings in the wording and to ensure that the questionnaires were as comprehensible as possible. The surveys were conducted in German. The questionnaires included in appendix B.2 are translations of the original questionnaires, with the content preserved despite minor terminological differences. These translations are intended solely to facilitate the understanding of the results presented in this article. Some terms were revised during further editing; details are provided in the questionnaires.

The first survey is aimed at experts in the field of ES and is intended to assess the suitability of the previously selected indicators when their spatial level is the forest operational level. The survey is divided into nine thematic blocks. The first block contains questions relating to the ES-experts and their field of knowledge. The remaining eight question blocks are dedicated to the previously formed FES units and contain the main indicators resulting from the selection process. A three-level Likert scale with the categories 'high', 'medium', and 'low', following the approach of Schliep et al. (2017), is used to assess the suitability of the indicators. The scale includes the possibility of a non-response by leaving all answer options unselected. At the end of each thematic block was room for comments. Participants were also allowed to skip questions and respond only to those that matched their professional expertise. For each main indicator, a mean was calculated by multiplying the value assigned (1 – 3) to each response option (excluding non-response) by the frequency of that response. The resulting products were then summed and divided by the total number of valid responses. An adapted traffic light system was used to illustrate: Indicators with values between 1 and 1.6 were displayed in white (weak), with values between 1.7 and 2.3 were displayed in grey (medium) and with values from 2.4 were displayed in black (high).

The second survey is aimed at the managers or owners of private or corporate forest enterprises and focuses on the measurability or calculability of indicators at the operational level. The survey is divided into five thematic blocks. The first and last blocks contain general information regarding the forest enterprise and the respondent. In the intermediate blocks, the indicators were thematically organized. The sub-indicators collectively constitute the main indicators. The measurability and calculability of the indicators were evaluated using a Likert scale. The average time necessary to provide each indicator was recorded across the entire forest enterprise and used as a proxy measure for feasibility. Indicators available through forest management plans or site mapping were excluded from this survey, as they were assumed to be accessible within the forest enterprises. Consequently, respondents were also queried regarding the existence of a forest management plan or site mapping. The analysis included all response sheets that were completed at least one-third. The response frequencies for each answer option were aggregated. To simplify the overview and adapt the traffic light system, the answers 'available in forest enterprise' and '< 2 hours' were combined into the category easily feasible (black). The answers '∼ ½ working day' and '∼ 1 working day' were grouped as moderately feasible (not represented in the evaluation). Response '2-3 working days' and 'entering own number of working days' were categorized as hard feasibly (grey). The answer option 'not collectible' was considered equivalent to not feasibly (white). The most frequently mentioned response option was subsequently selected as the representative value for the indicator. Since the actual feasibility of collecting indicators at the operational level is critical, the opinion of the forest enterprises is essential. Using an average value would obscure the important extremes – 'easily feasible' and 'not feasible'. Therefore, all indicators are presented in the tables, and the main indicators were determined based on the most frequent or least favorable responses.

3. Results

3.1. Politically relevant forest-related ecosystem services and their FES units

The politically relevant ES mentioned in the analyzed strategies are listed in table 2. Although research is heavily focused on ES, there is still disagreement among scientists about a precise definition of these services (Saarikoski et al., 2015). In the studies analyzed, 41 ES were identified. The most comprehensive strategies concerning ES are those that relate directly to forests or biodiversity (e.g., FS2020, EU.BS, FS2050, EU.FS2030). These can be found at both the national and European level. The other strategies consider more or fewer ES, depending on the scope of their forest theme (e.g., UN.PA, UN.A.2030, EU.CAP). The most frequently mentioned ES is biodiversity (10), followed by carbon storage soil (9), carbon storage biomass (8), energy wood (8), and non-wood forest products (8). The least frequently mentioned ES occur only once in all the strategies analyzed. These are ornamental resources, pollination, biotope areas, oxygen production, heritage and identity, as well as burial forest. The number of ES included within each FES unit ranges from three to eight, depending on the scope of the respective FES unit. The smallest FES unit is 'non-timber forest products'. It comprises 3 ES, while the largest FES unit 'biodiversity' includes 8 ES. The FES unit 'biodiversity' holds a special position within this framework, as biodiversity, depending on the perspective, can be understood both as the foundation of all ES and as an element affected by them. On the one hand, biological diversity is a prerequisite for the functioning and provision of ES (MEA, 2005). On the other hand, biodiversity itself is influenced to varying degrees by different ES (UN General Assembly, 1992). In this article, biodiversity was particularly assigned the services in the field of biological diversity and nutrient supply. Because defining the term biodiversity is challenging, some strategies referred solely to this term, leading to its inclusion as a separate ES (biological diversity).

3.2. Identified indicators and their evaluation

The scoping review identified 235 main indicators for all FES units, without eliminating potential duplicates across different ES or FES units – meaning that identical indicators assigned to multiple ES or FES units were counted repeatedly. The complete list of main indicators, sub-indicators, sources, and associated ES can be found in appendix B.1. The number of indicators and their frequency of mention in the literature vary across FES units: some contain few but frequently cited indicators (e.g., 'wood provision'), whereas other encompass a wide range of indicators that are rarely referenced.

Following the selection process described in chapter 2.3., 59 main indicators and 87 sub-indicators remained –. The most main indicators were found for the FES unit 'biodiversity' (12) and the fewest for 'non-timber forest products' (3). On the one hand, the number of selected indicators per FES unit varies because not all FES units had at least four indicators that were mentioned more than once. On the other hand, the selection process (step2) inherently leads to FES units encompassing a larger number of ES being associated with a greater number of indicators. In some cases, the identified literature of the scoping review represents only a secondary source of the indicators; original primary sources were not further considered, only indicators from the analyzed literature were adopted. Two indicators were modified for further use, resulting in minor deviations from the scoping review results in appendix B.1. For example, the main indicator tree- and stock-specific parameters summarizes all sizes that can be directly collected during a forest field visit or from a forest management plan without complex measurements (e.g., the calculation of indices or canopy cover), and was later divided into *tree-specific parameters* and *stock-specific parameters* for the surveys. The main indicator *forest area* in the FES unit 'air pollution and climate regulation' was also expanded by adding the sub-indicators

Table 3
Indicators of the FES unit "wood provision" with description, reference unit (ref.unit), sources and their evaluation by forest enterprises (feasibility) and ES-experts (suitability).

main indicator	sub-indicator	description	ref.unit	sources	feasibility	suitability
logging		total amount of timber felling per hectare in the reporting year (less crop lose or unusable wood)	$m^3\ ha^{-1}\ a^{-1}$	[3], [4][1],[5], [9], [10], [14], [17], [19], [20], [22], [25], [27]	●	●
wood increment		Ø wood increment per hectare in the reporting year (less natural mortality)	$m^3\ ha^{-1}\ a^{-1}$	[3],[4][1],[5], [9], [14], [17], [19], [20], [22], [25], [27]	●	●
growing stock		Ø growing stock (total biomass) of living trees per hectare for the reporting year	$m^3\ ha^{-1}$	[4][2], [10], [14], [16], [18], [19], [20], [25], [27], [31]	●	●
forest area		size of the (usually) stocked forest area	ha	[14]	●	◐

[1] Schuck et al., (2012) : Kategorien, Indikatoren und Datenlage der Waldfunktionskartierung
[2] Bastian et al., (2012): Verfahrensansätze der Landschaftsökologie zur Erfassung und Bewertung von Ökosystemdienstleistungen

● easy / high
◐ hard / medium
○ not feasible / weak

carbon storage capacity and *rate of change in carbon (greenhouse gas) storage*, as both are directly linked to forest area. All modified or previously specified indicators using qualitative information from the free-text response in the surveys are marked with a corresponding superscript (d).

Tables 3 – 10 contain the results concerning suitability and feasibility. A total of 291 forest enterprises and 83 ES-experts participated in the respective surveys. Out of these, 173 forest enterprises and 51 ES-experts met the minimum response requirements and were included in the further analysis. A condensed presentation of the results is provided in appendix B.3. 51 % of the forest enterprises manage contiguous (spatially connected and unbroken) forests and in response to the question regarding the existence of a forest management plan, 88 % indicated that they have one. Among those without a forest management plan, 9% are small enterprises managing less than 50 hectares. Accordingly, all indicators that rely on information from a forest management plan can be considered easily feasible. Regarding site mapping, only 63 % of forest enterprises reported having the relevant data. Indicators based on site mapping, here it is only soil type, are also classified as easily feasible, but marked with the subscript letter (c) - easy to collect only when site mapping is available. Several indicators are classified as easily feasible, as they can either be calculated by forest enterprises based on existing indicators (subscript letter (a)), or derived them from literature or statistical sources (subscript letter (b)). The subscript numbers next to the references in the source column indicate contributions within edited volumes, which are listed separately below the tables.

The sizes of the forest enterprises were also recorded in the survey in order to gain a clearer picture of the participants. A subdivision into size classes or a filtering based on minimum size was not applied in the overall summaries (table 3 – 10), as these are intended to provide a comprehensive overview of German forestry. Moreover, response distributions are nearly identical across all indicators, particularly for forest enterprises larger 200 ha or 500 ha. A depiction by size classes is provided in appendix B.3.

'wood provision' (table 3) –the indicators *logging*, *wood increment*, and *growing stock* are cited in almost all publications. They are also rated as easily feasible and highly suitable for mapping the FES unit. The indicator *forest area* is also easily collectible but it is only of limited use for making statements about this FES unit. Consequently, three out of four indicators are deemed suitable for integration into the FAN.

'non-timber forest products' (table 4) – only the indicator *game meat* is the most viable candidate for this FES unit to integrate in the FAN, as it can be easily collected and possesses a medium level of suitability and has the most occurrences in literature. The indicator C*hristmas trees* is described as not feasible or suitable, whereas *species richness* is rated as hard feasible and medium suitable. These two indicators are also rarely mentioned in the literature. The sub-indicator *game meat sold* can be calculated with available data from the *hunting bag* and an average price for game meat from the literature. The sub-indicator *game density* can be derived from literature.

'biodiversity' (table 5) – no indicators are easy feasible and as well highly suitable. The most suitable indicators in this FES unit are *tree-specific parameters*, *stock-specific parameters*, *regeneration, designated areas*, *areas for nesting and foraging,* and the *Shannon Index* as they are easily feasible and their suitability at the operational level has been assessed as medium. The indicator *areas for nesting and foraging* can be derived by the forest area since any forest area is generally adequate for this purpose. Additionally, the sub-indicator *area by tree species* can be simplified derived using the *stock density* and the *diameter breast height (DBH)* per tree species, this also applies to further mentions of this indicator. The same relates to the *Shannon Index*, which could be calculated in a simplified manner: e.g., using the sub-indicators *number of tree species, stock density* and *age per tree species* in combination with specialist literature, like forest yield tables, to get an estimation for the number of individuum's per tree species. If such a calculation is intended to produce more precise or reliable data, or extended to include plant species (e.g., species richness), the current method becomes infeasible due to the low resolution of the available data. In this case, the feasibility rating would need to be rated down.

In literature, only the indicator *tree-specific parameters* appears frequently. The indicators *species richness*, *endangered species*, and *deadwood and habitat trees* are highly suitable but exhibit a hard feasibility. Among these, *species richness* as well as *deadwood and habitat trees* are frequently referenced in the literature. The indicators *logging,* and *wood increment* have a weak suitability but high feasibility, but are mentioned rarely in the literature. Apart from *forest soil*, the remaining indicators are considered easily feasible, but show medium suitability. The indicator *forest soil* is not only of medium suitability: its classification as hard feasible is primarily based on that the first sub-indicator *soil type* is considered easily feasible – at least where site mapping is available. The second sub-indicator *humus type* is challenging to determine. As a result, the main indicator *forest soil* is classified as hard feasible.

In conclusion, no indicator is directly appropriate for integration into the FAN, as none are both easily feasible and highly suitable. The closest candidates are those indicators that are easily feasible and have medium suitability. Indicators that are difficult to collect and only have a medium suitability should be excluded, as well as those that have received a red-rating for either feasibility or suitability.

'air pollution and climate regulation' (table 6) – *forest area (including sub-indicators)* represents a highly suitable and easily feasible indicator for this FES unit and is most frequently mentioned in literature. The *carbon storage capacity* and *the rate of change* initially refer only to the trees within the forest area. Both sub-indicators could be calculated using data from tree specific-parameters, supplemented by information from specialized literature, e.g., auxiliary tables for estimating carbon storages in stand (Brinkord et al., 2024). Other highly representative indicators for this FES unit include *logging*, *wood increment*, and *growing stock,* although their occurrence in the literature is somewhat lower. The indicator *tree-specific parameter* is easy to collect but provides a medium suitability and is infrequently cited in literature. The remaining indicators, such as *deadwood and habitat trees*, and *forest soil*, are characterized by both hard feasibility and medium suitability. In conclusion, the indicators *forest area*, *logging, wood increment*, and *growing stock* are particularly suitable for integration into the FAN.

'protection services of forests' (table 7) – only the indicators *designated areas* and *floodplains* are both easily feasible and highly suitable and also mentioned relatively frequently in literature. The indicators with the highest occurrences in literature are *tree-specific parameters* and *rockfall/ avalanche protection index.* The first indicator, while easily feasible, has only medium suitability. The second indicator is highly suitable, but two sub-indicators are not feasible. Due to the significant overlap of required sub-indicators, the rockfall protection index and avalanche protection index have been consolidated into a single main indicator. This integration also reflects their joint representation in relevant literature and publications. Most sub-indicators associated with the *rockfall/ avalanche protection index* are already available in the forest enterprises. The absence of the key data rock diameter and rock distribution renders the rockfall protection index non-operational. In contrast, the avalanche protection index can still be assessed with the available data, as rock-specific parameters are not essential for its evaluation. For this reason, the indicator was classified as both easily feasible (avalanche index) and not feasible (rockfall protection index). It should also be noted that avalanche risk is relevant primarily in high alpine regions, whereas rockfall poses a broader hazard across larger parts of Germany.

Additionally, the sub-indicators *slope,* and *wooded slope* were adjusted. These were the only indicators in the survey where forest enterprise size – specifically those smaller than 50 hectares – had a substantial impact, potentially shifting the assessment from easy feasible to not feasible. Since the aim of this study is to demonstrate the integration of ES into the FAN (primarily includes forest enterprises > 200

Table 4
Indicators of the FES unit "non-timber forest products " with description, reference unit (ref.unit), sources and their evaluation by forest enterprises (feasibility) and ES-experts (suitability).

main indicator	sub-indicator	description	ref.unit	sources	feasibility	suitability
Christmas trees				[7][1], [14]	○	○
	area	area intended for Christmas tree production	ha	[14]	○	
	sold	income from Christmas tree and ornamental twig sale	€ ha^{-1}	[14]	○	
game meat				[3], [4][2], [9], [11], [14]	●	◐
	game meat sold	income from game meat sold	€	[3], [11], [14]	● *a b	
	game density	Ø game density (hoofed game) on the area	species(n) ha^{-1}	[4][2], [9], [14]	● *b	
	hunting bag	Ø hunting bag seperated by game species	(n) species^{-1}	[4][2], [11], [14]	●	
species richness		Ø number of trees and herbs on the area	(n) ha^{-1}	[31]	◐	◐

[1] Schäfer, (2013): Ökonomische Bewertung von Biodiversität und Ökosystemleistungen in Wäldern
[2] Schuck et al., (2012) : Kategorien, Indikatoren und Datenlage der Waldfunktionskartierung
*a calculable with available data
*b derivable from statistics or literature
● easy / high
◐ hard / medium
○ not feasible / weak

Table 5
Indicators of the FES unit "biodiversity" with description, reference unit (ref.unit), sources and their evaluation by forest enterprises (feasibility) and ES-experts (suitability).

main indicator	sub-indicator	description	ref.unit	sources	feasibility	suitability
species richness				[2], [3], [4][1,3], [5], [11], [14], [24], [31]	○	●
	species richness	Ø number of tree species and herbs on the area	(n) ha^{-1}	[2], [3], [4][1,3], [5], [11], [14], [24], [31]	○	
	rare tree species	Ø number of rare species per hectare based on the list "rare tree species" (BMEL, 2025)	(n) ha^{-1}	[4][1,3], [24], [31]	●	
	Woodland Bird Index	selection of 10 bird species representative of the forest (based on BMUV, 2023)	N	[11]	○	
	proportion of forest specialists	Ø number typical (indicator) forest plants per hectare based on the forest species lists of ferns and flowering plants, mosses and lichens in Germany (BfN, 2011)	(n) ha^{-1}	[4][1], [31]	○	
tree-specific parameters*[d]				[4][1,2,3,4], [11], [13], [14], [19], [20], [22], [23], [25], [28], [30]	●	○
	tree species (name)	names of tree species occuring in the area	species name	[4][1,2,3,4], [11], [13], [14], [19], [20], [22], [23], [24], [28], [30]	●	
	tree species (number)	Ø number of trees per species per hectare	(n) ha^{-1}	[13], [14], [19], [20], [22], [23], [25], [28],	●	
	tree age	Ø tree age per tree species in stand	Ø in years	[4][3], [23], [30]	●	
	tree height	Ø tree height per tree species in stand	Ø in m	[22], [23], [25], [28], [30]	●	
	diameter breast height (DBH)	Ø DBH per tree species in stand	Ø in cm	[19], [20], [22], [30]	●	
stock-specific parameters *[d]				[4][3], [23], [28], [30]	●	○
	area by tree species	Ø basal area per tree species per hectare	m^2 ha^{-1}	[23]	●*a	
	forest stratification	predominant stratification of the stands		[28]	●	
	stock density	Ø stock density per tree species per hectare	Ø ha^{-1}	[4][3],[30]	●	
endangered species				[2], [4][1,3], [11], [14]	○	●
	red list species	total number of species of the BfN red list	N	[2], [4][1,3], [11], [14]	○	
	protected assets FFH and Birds Directives	habitat types listed in Annex I, animal and plant species listed in Annex II Habitats Directive (COM, 2021a); bird species listed in Annex I Birds Directive (COM, 2020)	N	[4][1], [11]	●	
forest soil				[4][3], [24], [30], [31]	○	○
	soil type	predominant soil type of the total forest area		[24], [30]	●*c	
	humus type	predominant humus type of the total forest area		[4][3], [24], [30], [31]	○	
deadwood and habitat trees				[4][1,4],[14], [16], [17], [19], [20], [22], [25], [28]	○	●
	total amount of deadwood	Ø amount of standing and lying deadwood incl. root shoots (based on Riedel et al., 2020)	m^3 ha^{-1}	[14], [20], [22], [25], [28]	○	
	proportion of standig deadwood	Ø amount of standing dead trees	m^3 ha^{-2}	[19], [20], [28]	○	

(continued on next page)

Table 5 (*continued*)

main indicator	sub-indicator	description	ref.unit	sources	feasibility	suitability
	habitat trees	Ø number of marked habitat trees	(n) ha^{-1}	[4][1,4], [16], [17], [28]	◍	
regeneration					●	◍
	area (total)	total area of regeneration (DBH <7 cm)	ha	[11], [31]	●	
	area (natural)	area on natural regeneration (DBH <7 cm)	ha	[11]	●	
wood increment		Ø wood increment per hectare in the reporting year (less natural mortility)	m^3 ha^{-1} a^{-1}	[4][4]	●	○
logging		total amount of timber felling per hectare in the reporting year (less crop lose or unusable wood)	m^3 ha^{-1} a^{-1}	[4][1]	●	○
designated areas				[4][1,2,4], [11], [14]	●	◍
	name	areas that have a legal protection status, legal restrictions on use, or have been (voluntarily) taken out of use	name	[4][1,2,4], [11]	●	
	percent of total area	areas that have a legal protection status, legal restrictions on use, or have been (voluntarily) taken out of use	% of total	[4][2,4], [11]	●	
	area for genetic conservation or experimental area	used for gene conservation, propagation and breeding, and scientific experimental areas	ha	[11], [14]	●	
area for nesting and foraging		useful for pollinators for foraging and nesting	ha	[3], [14], [21], [31]	●*a	◍
Shannon Index		calculating of tree species diversity (Shannon, 1948)		[17], [23], [25]	●*a,b	◍

[1] Drachenfels, (2012): Waldspezifische Naturschutzkriterien, Indikatoren und Datenlage der Waldbiotopkatierung
[2] Ontrup, (2012): Waldfunktionenplanung in Rheinland-Pfalz: Forstliche Abwägung und planerische Konsequenzen
[3] Bastian et al., (2012): Verfahrensansätze der Landschaftsökologie zur Erfassung und Bewertung von Ökosystemdienstleistungen
[4] Schuck et al., (2012): Kategorien und Indikatoren im Europäischen waldpolitischen Diskurs
*[a] calculable with available data
*[b] derivable from statistics or literature
*[c] easy to collect only with site mapping
*[d] adjusted

● easy high
◍ hard medium
○ not feasible weak

Table 6
Indicators of the FES unit "air pollution control and climate regulation" with description, reference unit (ref.unit), sources and their evaluation by forest enterprises (feasibility) and ES-experts (suitability).

Main indicator	Sub-indicator	Description	Ref.unit	Sources	Feasibility	Suitability
forest area*[d]				[3], [4][1,2], [11], [14], [15], [17], [18], [19], [20], [22], [25], [27], [31]	●	●
	forest area	size of the (usually) stocked forest area	ha	[4][1,2],[14], [15], [18], [19], [20], [27], [31]	●	
	carbon storage capacity	carbon storage capacity of the forest area (by trees)	(t) ha^{-1}	[4][1,2],[14], [15], [18], [19], [20], [27], [31]	*a,b ●	
	rate of change of the carbon (greenhouse gas) storage	annual change in the carbon (greenhouse gas) balance, based on a fixed index value (e.g., first year of participation)	% a^{-1}	[3], [9], [11], [17], [22], [25]	● *a,b	
tree-specific parameters*[d]				[4][1,2], [9], [16], [22], [24]	●	◎
	tree species (name)	names of tree species occuring in the area	species name	[4][2], [9], [22]	●	
	tree species (number)	Ø number of trees per species per hectare	(n) ha^{-1}	[4][2]	●	
	tree age	Ø tree age per tree species in stand	Ø in years	[4][1], [24]	●	
	tree height	Ø tree height per tree species in stand	Ø in m	[16], [24]	●	
	diameter breast height (DBH)	Ø DBH per tree species in stand	Ø in cm	[4][1], [16], [24]	●	
logging		total amount of timber felling per hectare in the reporting year (less crop lose or unusable wood)	m^3 ha^{-1} a^{-1}	[9],[11]	●	●
wood increment		Ø wood increment per hectare in the reporting year (less natural mortality)	m^3 ha^{-1} a^{-1}	[5],[11], [17]	●	●
growing stock		Ø growing stock (total biomass) of living trees per hectare for the reporting year	m^3 ha^{-1}	[4][1], [16], [19]	●	●
deadwood and habitat trees				[16], [17], [22]	◎	◎
	total amount of deadwood	Ø amount of standing and lying deadwood incl. root shoots (based on Riedel et al., 2020)	m^3 ha^{-1}	[16], [17], [22]	◎	
	habitat trees	Ø number of marked habitat trees	(n) ha^{-1}	[16], [17]	◎	
forest soil				[4][2], [5], [24]	◎	◎
	humus type	predominant humus type of the total forest area		[4][2], [5], [24]	◎	

[1] Schuck et al., (2012): Kategorien und Indikatoren im Europäischen waldpolitischen Diskurs
[2] Bastian et al., (2012): Verfahrensansätze der Landschaftsökologie zur Erfassung und Bewertung von Ökosystemdienstleistungen
*[a] calculable with available data
*[b] derivable from statistics or literature

● easy high
◎ hard medium
○ not feasible weak

Table 7
Indicators of the FES unit "protection services of forests" with description, reference units (ref.unit), sources and their evaluation by forest enterprises (feasibility) and ES-experts (suitability).

main indicator	sub-indicator	description	ref.unit	sources	feasibility	suitability
forest area		size of the (usually) stocked forest area	ha	[11]	●	◍
designated areas				[3], [4][2], [10], [11]	●	●
	names	areas that have a legal protection status, legal restrictions on use, or have been (voluntarily) taken out of use	name	[3], [4][2], [11]	●	
	percent of total area	areas that have a legal protection status, legal restrictions on use, or have been (voluntarily) taken out of use	% of total	[3], [4][2], [11]	●	
floodplains		floodplains according to § 76 WHG[4]	% of total	[4][2], [10], [11]	●	●
rockfall (R)/ avalanche (A) protection index				[13], [17], [19], [20], [25]	◍	●
	diameter breast height (DBH) (R)/(A)	Ø DBH for every tree species in stand	Ø in cm	[13], [17], [19], [20], [25]	●	
	tree height (A)	Ø tree height per tree species in stand	Ø in m	[17], [19], [20]	●	
	stock density (R)	Ø stock density per tree species per hectare	Ø ha^{-1}	[13], [17], [19], [20], [25]	●	
	area by tree species (R)/(A)	Ø basal area per tree species per hectare	m^2 ha^{-1}	[13], [17], [19], [20], [25]	●*a	
	slope (R)/(A)	areas with a slope > 30%[5] of the total operating area	% of total	[17], [19], [20], [25]	●*d	
	wooded slope (R)	areas with forest cover on areas with >30%[5] slope	% of toal	[13], [17], [19], [20]	●*d	
	rock diameter (R)	Ø rock diameter on areas with >30%[5] slope and >= 50 cm mean	Ø in cm	[17], [19], [20]	○	
	rock distribution (R)	Ø number of rocks in areas with >30%[5] slope	(n) ha^{-1}	[17], [19], [20]	○	
tree-spezific parameters*[d]				[4][1,2], [11], [17], [19], [20], [25], [30]	●	◍
	tree species (name) (R)/(A)	names of tree species occuring in the area	species name	[4][1,2], [11], [17], [19], [20], [25], [30]	●	
	tree species (number)	Ø number of trees per species per hectare	(n) ha^{-1}	[4][1], [11], [30]	●	
management technique		predominant forest management technique		[4][1], [30]	●	◍
forest soil				[4][1], [30]	◍	◍
	soil type (R)	predominant soil type of the total forest area		[4][1], [19], [20]	●*c	
	humus type	predominant humus type of the total forest area		[30]	◍	
ant colonies		total number of ant colonies on the forest area	N	[11]	◍	○

[1] Bürger-Arndt, (2012): Kategorien, Indikatoren und Datenlage der Waldfunktionenkartierung
[2] Ontrupt, (2012): Waldfunktionenplanung in Rheinland-Pfalz: Forstliche Abwägung und planerische Konsequenzen
[3] Bastian et al., (2012): Verfahrensansätze der Landschaftsökologie zur Erfassung und Bewertung von Ökosystemdienstleistungen
[4] Water Resources Act of Germany
[5] derived from Dorren et al. (2005) and Irauschek et al. (2017)
[a] calculable with available data
[c] easy to collect only with site mapping

● easy high
◍ hard medium
○ not feasible weak

Table 8
Indicators of the FES unit "drinking water supply" with description, reference unit (ref.unit), sources and their evaluation by forest enterprises (feasibility) and ES-experts (suitability).

main indicator	sub-indicator	description	ref.unit	sources	feasibility	suitability
tree-specific parameters*[d]				[10], [24], [30]	●	*d ●
	tree species (name)	names of tree species occuring in the area	species name	[10], [24], [30]	●	
	tree species (number)	Ø number of trees per species per hectare	(n) ha^{-1}	[10], [24], [30]	●	
	tree age	Ø tree age per tree species in stand	Ø in years	[30]	●	
	tree hight	Ø tree height per tree species in stand	Ø in m	[30]	●	
	diameter breast height (DBH)	Ø DBH per tree species in stand	Ø in cm	[30]	●	
stock-specific parameters*[d]				[8], [30]	●	◍
	stock density	Ø stock density per tree species per hectare	Ø ha^{-1}	[30]	●	
	forest stratification	predominant stratification of the stands		[8]	●	
management technqiue		predominant forest management technique		[30]	●	◍
forest soil				[4][1], [8], [10], [11], [30]	◍	◍
	soil type	predominant soil type of the entire forest area		[4][1], [30]	●*c	
	humus type	predominant humus type on the entire forest area		[4][1], [10], [11], [30]	◍	
	infiltration rate	calculation according to the TUB-BGR method (Wessolek et al., 2008)	mm a^{-1}	[4][1], [8]	●*a,b	
catchment area drinking water production plant		catchment area used for drinking water production	% of total	[4][2], [10]	●	●
drinking water		estimated total available amount of drinking water (ground water) on the forest area	Tsd.m^3 ha^{-1}	[3], [11], [14], [27]	○	●
floodplains		floodplains according to § 76 WHG[5]	% of total	[4][2,3], [10]	●	●
designated areas				[4][2,3], [7][4], [10], [14]	●	●
	names	areas that have a legal protection status, legal restrictions on use, or have been (voluntarily) taken out of use	name	[4][2], [7][4], [10], [14]	●	
	percent of total area	areas that have a legal protection status, legal restrictions on use, or have been (voluntarily) taken out of use	% of total	[4][2], [7][4], [10], [14]	●	

[1] Bastian et al., (2012): Verfahrensansätze der Landschaftsökologie zur Erfassung und Bewertung von Ökosystemdienstleistungen
[2] Bürger-Arndt, (2012): Kategorien, Indikatoren und Datenlage der Waldfunktionkartierung
[3] Ontrup, (2012): Waldfunktionenplanung in Rheinland-Pfalz: Forstliche Abwägung und planerische Konsequenzen
[4] Schäfer (2013): Ökonomische Bewertung von Biodiversität und Ökosystemleistungen in Wäldern
[5] Water Resources Act of Germany
*[a] calculable with available data
*[b] derivable from statistics or literature
*[c] easy to collect only with site mapping
*[d] adjusted

● easy high
◍ hard medium
○ not feasible weak

Table 9
Indicators of the FES unit "culture, health and recreation" with description, reference unit (ref.unit), sources and their evaluation by forest enterprises (feasibility) and ES-experts (suitability).

main indicator	sub-indicator	description	ref.unit	sources	feasibility	suitability
special elements for recreation and tourists		facilities that exist for the purpose of recreation and tourism or natural elements that increase the attractiveness of the area	N	[4][1], [5], [6], [7][2], [10], [12], [29]	●	●
infrastructure for recreational or tourist purpose				[6], [7][2,3], [9], [10], [11], [12], [27], [29]	●	●
	road density	Ø path density that can be used for recreation, hiking, sports, etc.	$m\ ha^{-1}$	[6], [7][2,3], [9], [11], [12], [29]	●	
	parking spaces and bus stops	number of parking spaces and public transport stops within the operating area or directly adjacent	N	[7][3], [10], [12], [29]	●	
forest visitors				[3], [4][1,4], [10], [11], [14], [26], [27], [29]	○	◍
	forest visitors	estimaded number of forest visitors per year	$N\ a^{-1}$	[3], [4][1,4], [10], [11], [14], [26], [27], [29]	○	
	catchment area	distance to the nearest town with over 50.000 inhabitants	km	[4][1], [7][3], [10], [29]	●*b	
designated areas				[4][1,5], [10]	●	◍
	names	areas that have a legal protection status, legal restrictions on use, or have been (voluntarily) taken out of use	name	[4][1,5], [10]	●	
	percent of total area	areas that have a legal protection status, legal restrictions on use, or have been (voluntarily) taken out of use	% of total	[4][1,5], [10]	●	
religious sites		number of places of worship, burial forests, or other sites related to religion	N	[3], [6], [26]	●	●
statements of individuality, beauty, diversity and disruptive elements				[4][1,4,] [5], [6], [10], [11], [12], [17], [29]	●*d	●
	tree species (name)	names of tree species occuring in the area	species name	[4][4], [17]	●	
	tree species (number)	Ø number of trees per species per hectare	$(n)\ ha^{-1}$	[4][4], [17]	●	
	tree age	Ø tree age per tree species in stand	Ø in years	[17]	●	
	tree height	Ø tree height per tree species in stand	Ø in m	[17]	●	
	diameter breast height (DBH)	Ø DBH per tree species in stand	Ø in cm	[17]	●	
	area by tree species	Ø basal area per tree species per hectare	$m^2\ ha^{-1}$	[17]	●*a	
	forest stratification	predominant stratification of the stands		[4][4], [5]	●	
	logging	total amount of timber felling per hectare in the reporting year (less crop lose or unusable wood)	$m^3\ ha^{-1}\ a^{-1}$	[17]	●	
	amount of deadwood	Ø amount of standing and lying deadwood incl. root shoots (based on Riedel et al., 2020)	$m^3\ ha^{-1}$	[17]	◍	
	Shannon Index	calculating of tree species diversity (Shannon, 1948)		[29]	●*a,b	
	Woodland Bird Index	selection of 10 bird species representative of the forest (based on BMUV, 2023)	N	[11]	◍	

(continued on next page)

Table 9 (continued)

main indicator	sub-indicator	description	ref.unit	sources	feasibility	suitability
	number of inteference elements	noise or technical elements that disturb the natural aesthetics	N	[4][1,4], [10], [12], [29]	●	
management technique		predominant forest management technique		[12], [29]	●	◎

[1] Bürger-Arndt, (2012): Kategorien, Indikatoren und Datenlage der Waldfunktionkartierung
[2] Schäfer, (2013): Ökonomische Bewertung von Biodiversität und Ökosystemleistungen in Wäldern
[3] Aicher und Bergdorfer (2013): TEEB-Ansatz in Großstadtwäldern in Nordrhein-Westfahlen
[4] Bastian et al., (2012): Verfahrensansätze der Landschaftsökologie zur Erfassung und Bewertung von Ökosystemdienstleistungen
[5] Ontrupt, (2012): Waldfunktionenplanung in Rheinland-Pfalz: Forstliche Abwägung und planerische Konsequenzen
*[a] calculable with available data
*[b] derivable from statistics or literature
*[c] easy to collect only with site mapping
*[d] adjusted
● easy / high; ◎ hard / medium; ○ not feasible / weak

hectares), only forest enterprises > 50 hectares were considered in this specific case. This exception was applied exclusively to these two indicators, as the difference in response was particularly pronounced, spanning both extremes of the feasibility scale.

The indicators *forest area* and *management technique* are easily feasible but only have a medium suitability. The indicators *forest soil* and *ant colony* are not appropriate for integration into the FAN: forest soil is hard feasible and medium suitable; ant colony is hard feasibly and weakly suitable.

'drinking water supply' (table 8) – the only indicators appropriate for integration into the FAN are *tree-specific parameters, catchment areas drinking water production plant, floodplains*, and *designated areas.* All these indicators are both easily feasible and highly suitable. The suitability for the *tree-specific parameters* indicator was adjusted based on qualitative responses from the survey's free text fields, where some ES-experts emphasized tree species as a key indicator here. The remaining sub-indicators of this main indicator were rated only as medium suitable. Apart from the indicator *drinking water* - assessed as not feasible - the other indicators were evaluated as easily feasible but with medium suitability. The sub-indicator infiltration rate could be calculated using the TUB-BGR method based on available information about *forest soil*, the *management type*, and the *tree-specific parameters* supplemented by literature data (Wessolek et al., 2008).

'culture, health and recreation' (table 9) – the indicators most frequently cited in the literature encompasses *statements of individuality, beauty, diversity, and disruptive elements* as well as *infrastructure for recreational and tourist purpose,* and *forest visitors*. Of these 3 main indicators, only the first two are both easily feasible and highly suitable. The feasibility assessment for *statements of individuality, beauty, diversity, and disruptive elements* has been adjusted, as out of 13 sub-indicators, only 2 are regarded as hardly feasible, while the remainder are deemed easily feasible. Furthermore, most of these sub-indicators were only defined by one single article (Blattert et al., 2017); the other sources typically refer to the main indicator and occasionally note the effects of anthropogenic or technical elements as disruptive factors. The indicator *forest visitors* was deemed not feasible, as one corresponding sub-indicator was assessed as not feasible. Additionally, the ES-experts rated the main indicator as only medium suitable. The other sub-indicator *catchment area* could be derived directly from literature.

More indicators that are well adequate for integration into the FAN and frequently cited in the literature are: *special elements for recreation and tourists* (e.g., observation towers, castles, etc.), and *religious sites*.

The remaining indicators *designated areas* and *management technique,* could be integrated. They are easily feasible but rated medium suitable.

'economics, science and education' (table 10) – the indicators *special elements for recreation and tourist* and *infrastructure for recreational and tourists' purpose* were evaluated as both easily feasible and highly suitable. These were also frequently referenced in the literature. The indicator *income* could be derived from literature as a sectoral average. The remaining indicators were assessed as easily feasible and as medium suitable, except for *deadwood and habitat trees*, which was considered as hardly feasible. Thus, integration of these indicators into the FAN – excluding *deadwood and habitat trees* – could be possible.

4. Discussion

ES have been a focal point of scientific and policy discourse for many years, particularly in response to the ongoing impacts of climate change. In the forestry sector, an increasing number of ES have been incorporated into (inter)national strategies and regulations over time. This development reflects a growing prioritization of ES, as evidenced by the expanding range of forest-related ES described in policy strategies and regulations. Frequently addressed ES include those related to biodiversity, air quality regulations, as well as cultural, health and recreation. Moreover, new strategies are being published at increasingly shorter intervals (e.g., table 1). National assessment and monitoring

Table 10
Indicators of the FES unit "economics, science and education" with description, reference unit (ref.unit), sources and their evaluation by forest enterprises (feasibility) and ES-experts (suitability).

main indicator	sub-indicator	description	ref.unit	sources	feasibility	suitability
special elements for recreation and tourists		facilities that exist for the purpose of recreation and tourism or natural elements that increase the attractiveness of the area	N	[5], [6], [12], [14], [29]	●	●
infrastructure for recreational or tourist purpose				[3], [12], [15]	●	●
	road density	Ø path density that can be used for recreation, hiking, sports, etc.	m ha^{-1}	[12], [15]	●	
	parking spaces and bus stops	number of parking spaces and public transport stops within the operating area or directly adjacent	N	[3], [15]	●	
deadwood and habitat trees				[12]	◐	○
	habitat trees	Ø number of marked habitat trees	(n) ha^{-1}	[12]	◐	
designated areas				[4][1]	●	◐
	area for genetic conservation or experimental area	used for gene conservation, propagation and breeding, and scientific experimental areas	ha	[4][1]	●	
educational events		educational events that serves the further education of the population	N	[6], [7][2], [27]	●	◐
logging		total amount of timber felling per hectare in the reporting year (less crop lose or unusable wood)	m^3 ha^{-1} a^{-1}	[4][3]	●	◐
management technique		predominant forest management technique		[12]	●	◐
employees		permanent employees of the enterprise	N	[4][3]	●	◐
income		Ø income of enterprise permanent employees	Ø €	[4][3]	●*b	◐

[1] Ontrupt, (2012): Waldfunktionenplanung in Rheinland-Pfalz: Forstliche Abwägung und planerische Konsequenzen
[2] Schäfer, (2013): Ökonomische Bewertung von Biodiversität und Ökosystemleistungen in Wäldern
[3] Schuck et al., (2012) : Kategorien, Indikatoren und Datenlage der Waldfunktionskartierung
[b] derivable from statistics or literature

●	easy	high
◐	hard	medium•
○	not feasible	weak

programmes serve as an essential foundation for developing and validating strategies and setting policy targets. In parallel, forest enterprises are showing growing interest in highlighting their contributions to society, extending beyond timber production (Winkel et al., 2022). This effort aims to foster greater public understanding and appreciation of the important work they do in managing forests sustainably. However, these efforts are only partially captured by existing national monitoring programs, and their contributions remain largely invisible in the data aggregated at (supra)national levels. This highlights the need within the forestry sector for suitable and well-structured data to accurately represent their own performance.

This study investigates which indicators are applicable for mapping forest-related ES, using the development of FES units as a framework to connect forest-based services with their societal value and enhance the interpretability of ES data for a broad range of stakeholders. This interpretability is further enhanced by considering the terminology employed in the regulations and strategies analyzed. Representing ES in such product-based units also enhances the potential for systematic comparisons between forest enterprises (Castro and Frazzon, 2017; Horváthová et al., 2021; Bürgi, 2023). In contrast, the commonly used classifications – such as MEA categories or the CICES-framework's categories – are often too abstract for this purpose (MEA, 2005; Haines-Young, 2023). An additional advantage of this type of grouping is the potential to reduce the number of indicators required to represent forest enterprise performance. Through the thematically bundling of ES into functional FES units, the requirement to define individual indicator sets for each ES is rendered unnecessary. This simplifies data collection and reduces the operational workload. At the same time, the explanatory power of the results is maintained, as the grouped services still allow for a differentiated and transparent assessment. A potential drawback of such groupings lies in the loss of details and the subjective arrangement of the creator, including the fact that broader social or political factors are not necessarily taken into account (Swift et al., 2004; Corbera et al., 2007; Kull et al., 2015). The perceived importance of individual ES may vary significantly depending on their context, as individual and societal needs shape the extent to which ES contribute to human well-being. Policymakers may prioritize services such as biodiversity conservation or carbon storage, as reflected in strategies and regulations, due to the urgent need to address species extinction and climate change (UNFCCC, 2015). In contrast, the general public tends to prioritize ES that have a more immediate and tangible impact on their daily lives. However, societal preferences are far from uniform; as perceptions of the value of ES are shaped by cultural background, lived experiences, socio-economic conditions, ecological knowledge, and other factors (Daw et al., 2011; Zolyomi et al., 2023). As a result, certain ES that may be relevant for political measures or funding instruments can be overlooked, or the grouping may appear arbitrary when viewed in a different context. Furthermore, this approach may reduce comparability with other studies or established classification systems. Representing ES in clearly defined product groups may also obscure potential synergies and interdependencies between individual services, which are important for integrated ecosystem management (Barnaud and Antona, 2014).

The scoping review was conducted to identify potential indicators for the FES units and proved to be effective in compiling a broad range of relevant indicators. Scoping reviews are particularly well-suited for systematically mapping diverse types of evidence, regardless of source or format, within the context of a specific topic, geographical areas, or research fields (Munn et al., 2022; Khalil et al., 2025). They are especially valuable for addressing topics with overlapping concepts, such as ES. The methodological transparency and the inclusion of grey literature make this approach especially beneficial in national application contexts, as it enables the consideration of sources that may not be internationally published (Munn et al., 2022; Khalil et al., 2025). The resulting overview provided a solid foundation for the selection of appropriate indicators and stakeholder consultations. However, a limitation of scoping reviews lies in the subjectivity of literature selection: different reviewers may arrive at different outcomes despite applying the same methodology, often due to individual value systems influencing the evaluation process (Giegrich, 1995; Mauchline et al., 2012; Latruffe et al., 2016). Furthermore, the outcome is highly dependent on the choice of search criteria, as only studies that meet these criteria are included. Nevertheless, since the indicators were derived from existing literature and have already been applied in the context of ES reporting it can be assumed that they fulfill basic requirements for suitable indicators (Oudenhoven et al., 2018)(. Therefore, the two most important aspects requiring adjustment, concerned the feasibility for forest enterprises, a point emphasized by Oudenhoven et al., (2018), as well as the evaluation of their suitability at the operational level, due to the lack of information regarding the management area as a reference surface.

The survey results indicate that most indicators are suitable for integration into the German FAN and that their implementation is feasible for the majority of forest enterprises. The robustness of both surveys can be considered as high, as no ES-experts classified all indicators the same and only four forest enterprises rated all indicators as not feasible. It is unclear whether this reflects their genuine opinion or a response aimed at influencing outcomes in their particular interests. Furthermore, each participant may interpret the questions within a different context, depending on their professional background. Although pre-tests were conducted to improve the comprehensibility of the questions and ensure consistent wording to minimize potential misinterpretations, a certain degree of interpretive leeway remains inevitable. Consequently, the respective questionnaires should be taken into account when analyzing the results.

From the perspective of the ES-experts, the evaluation revealed that the majority of main indicators were, on average, assessed as either medium suitable ($n = 30$) or highly suitable ($n = 24$), only a small subset as weakly suitable ($n = 5$). Given that the surveyed ES-experts represented a wide range of thematic backgrounds, it is difficult to determine the precise reasons behind their individual ratings. Despite this, two potential explanations for the low rating can be identified: the indicators were considered ineffective for capturing one or more of the grouped and intended ES, or they were too narrowly defined to allow meaningful evaluation across the entire FES unit. An example for the first explanation is the classification of logging and wood increment as weakly suitable within the biodiversity domain. While the ratio of harvesting to increment is widely recognized as an important indicator for sustainable forest management, it does not directly reflect biodiversity outcomes (Prins et al., 2023). A balanced ratio may indicate ecological sustainability in terms of resource use, but it does not necessarily imply positive or negative effects on species richness or habitat quality (Chaudhary et al., 2016; Duflot et al., 2022). An example for the second explanation is the indicator Christmas trees, which would be too narrowly defined to represent the broad category of non-timber forest products. Other indicators were also rated as moderately suitable and should ideally be interpreted in combination with others: as example, such as those in the field of economics, science and education. Future research could focus on combining different indicators to enhance explanatory power, or on weighting individual indicators, for instance by taking site-specific or climatic conditions into account.

From the perspective of forest enterprises, only a small number of indicators were rated as not feasible ($n = 4$) or hardly feasible ($n = 11$). Most indicators were assessed as easily feasible ($n = 44$). Given that forest enterprises provide key figures for the German FAN voluntarily (Müller et al., 2024), the indicators must be easy feasible. In many cases, feasibility is not reduced by a single factor, but rather by multiple interacting factors. In the following paragraphs, four limiting factors are examined, while acknowledging that additional influences may exist.

The first factor is that forest enterprises regard the indicators as both meaningful and actionable – as variables they are able to influence through their management practice. If an enterprise cannot actively influence the indicators and its outcome, it might be reluctant to collect and report such data, as this could portray their performance unfavorably without simultaneously providing an opportunity for improvement. They may still represent important contextual conditions that shape forest-based ES comparisons. This role warrants further investigation. Indicators such as ant colonies or the Woodland Bird Index, for example, cannot be directly improved or substantiated through forest management. The same applies to endangered species, especially those on Red Lists. Most of them occupy ecological niches and have highly specialized requirements regarding environmental conditions. While forest enterprises can create or maintain suitable habitats, the actual occurrence of these species ultimately depends on natural processes beyond managerial control (Hale et al., 2020; Genes and Dirzo, 2022).

The two further limiting factors are the knowledge and expertise of the personnel responsible, as well as the time required for data collection. Some indicators need specialized expertise or must be collected at specific times: for example, the Woodland Bird Index or endangered species. A similar situation applies to the assessment of plant species richness. These challenges are further exacerbated by the enterprise size, as both the effort and associated costs for data collection increase with larger areas. For indicators not classified as hardly feasible or not feasible, this impact is generally mitigated by data already available within the forest enterprise – such as from forest inventories, site mapping, or similar sources. The same holds when indicators to be collected cover larger spatial extent (e.g., roads) or occur infrequently within the forest enterprise area (e.g., special elements for recreation or tourists). One point to be noticed here is that most of these inventories are only cost-effective if the forest enterprise has exceeded a minimum size, e.g., if tax advantages need a forest management planning (§34b EStG[8]).

The fourth factor is the data currently available. These data generally provide direct operational value, as their presence within forest enterprises reflects their practical relevance. However, where such data are lacking, the collection often proves challenging – as previously discussed – exemplified by the main indicator forest soil. The sub-indicator soil type is of particular importance for forest enterprises when selecting suitable tree species. Where site mapping is available, this information can be relatively easily obtained. Even in the absence of site mapping, forest managers should know at least somewhat about their soil conditions relevant to tree species selection (Walthert and Meier, 2017). If such information is not consistently available, the collection of this indicator becomes difficult – similar to the sub-indicator humus layer. As outlined in the previous section, the acquisition of such information generally requires specialized expertise or the involvement of third parties, as well as significant time and resource investment. An example where a direct benefit for future data collection has been created is the main indicator deadwood and habitat trees. Neither of its sub-indicators is typically available at the operational level – only in national monitoring programs like the national forest inventory or the greenhouse gas inventory; however, various funding programs aimed at preserving or increasing deadwood and habitat trees require corresponding documentation as a condition of funding (ForstBW, 2016; BMUKN, 2024). At least, indicators may be not feasible because of the lack of comparative reference values in the literature, available external data not being specific enough, or because data collection is too dangerous (e.g., rockfall protection index). For example, assessing drinking water is not forest-enterprise-specific and requires high time, expertise, and financial resources, making it impractical. In this context it is noteworthy that certain indicators (Christmas tree production and forest visitors), were rated as not feasible, which is somewhat unexpected. Regarding Christmas tree cultivation, forest enterprises should generally be aware of their production activities. However, if a Christmas tree area exceeds two hectares, it is classified as a special crop and is no longer considered forest land but agricultural land (e.g., §2 Abs.2 Nr.5 BWaldG[9]; §2 Abs.3 SächsWaldG[10]; Art. 2 Abs. 4 BayWaldG[11]). As a result, relevant data is often lacking, as such operations are managed within separate business units. Additionally, there may be reluctance to disclose income figures, as this information is considered commercially sensitive and could provide competitors with strategic advantages. A similar challenge arises with the collection of forest visitor data. The general right of public access to nearly all forest types in Germany (§ 14 BWaldG[9]) makes visitor monitoring particularly difficult. As entry points are virtually ubiquitous, and the effort required to monitor the entire forest edges would be disproportional high, accurate data collection is rarely feasible.

In summary, it can be stated that 20 indicators are unconditionally appropriate for application within the German FAN and should be prioritized accordingly, as they were rated as easily feasible and highly suitable. However, these indicators do not cover all FES units. Therefore, indicators that were assessed as easily feasible and at least medium suitable should also be prioritized for continued application. Their implementation is unlikely to significantly increase the workload for forest enterprises, while their information value is generally considered to be at least moderate. Indicators deemed hardly or not feasible should be excluded from further consideration, as outlined in the previous discussion. The same applies to indicators that were rated as weakly suitable by ES-experts. Since this study focuses exclusively on compiling indicators concerning their measurability and explanatory power at the operational level, no substantive or normative assessment of the indicators is undertaken. Whether, and to what extent, individual indicators are demanded or suitable for specific evaluation purposes depends on their subsequent use and lies outside the scope of this study. Future research could further develop the indicators presented here or consider additional indicators for FES units that were not pursued in the current selection process. Likewise, attention should be given to the combination of different indicators (e.g., those rated as medium suitable) to enhance their overall explanatory power. Moreover, the approach could be adapted to other countries to develop context-specific and appropriate indicator sets tailored to national conditions. Ideally, stakeholder engagement through targeted surveys should be employed to ensure both feasibility and suitability. Future research should aim to establish a set of indicators for each FES unit that is not only accepted by forest enterprises and ES-experts but also endorsed by policymakers and broader public. This would enable transparent communication of the actual performance of forest enterprises across all levels.

5. Conclusion

This study confirms that the topic of ES remains of significant (supra) national relevance, and that Germany possesses a particularly broad spectrum of ES. Most of the assessed indicators for representing these services appear generally acceptable for integration into the German FAN. It becomes evident that, due to the voluntary participation of forest enterprises in the German FAN, more than just the theoretical suitability of an indicator is decisive. To ensure that the required data are collected in a valid and consistent quality, not only sufficient operational feasibility is necessary, but also an intrinsic motivation of forest enterprises to actively engage in the data collection process. Accordingly, this study provides a sound initial basis for further research on how to reflect the actual performance of forest enterprises, taking into account (inter)national reporting, and offers a set of suitable and feasible indicators for practical application.

[8] Einkommenssteuergesetz (Income Tax Act of Germany)

[9] Bundeswaldgesetz (Federal Forest Act in Germnay)

[10] Sächsisches Waldgesetz (Saxon Forest Act)

[11] Bayerisches Waldgesetz (Bavarian Forest Act)

Author statement on funding

This research received funding from the German Federal Ministry of Agriculture, Food and Regional Identity (BMLEH, Project sponsor FNR, FKZ: 221NR071C)

CRediT authorship contribution statement

Niclas Müller: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Kristin Franz:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Matthias Dieter:** Writing – review & editing, Supervision, Conceptualization.

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.

Acknowledgment

We would like to thank all forest enterprises and experts who participated in our surveys and generously shared their knowledge with us.

Appendix A. Selected Literature

Table A1
Selected Literature: corresponding to the sources referenced in tables 3 – 10, chapter 3.2.

Nb.	Title	Source
1	Indicators of biodiversity and ecosystem services: a synthesis across ecosystems and spatial scales	(Feld et al., 2009)
2	Mapping Biodiversity Indicators and Assessing Biodiversity Values in Global Forests	(Ojea et al., 2010)
3	Indikatoren für Ökosystemleistungen	(Staub et al., 2011)
4	Ökosystemdienstleistungen von Wäldern	(Bürger-Arndt et al., 2012)
5	Integrating Expert Knowledge into Mapping Ecosystem Services Trade-offs for Sustainable Forest Management	(Gret-Regamey et al., 2013)
6	An empirical review of cultural ecosystem service indicators	(Hernandez-Morcillo et al., 2013)
7	Der Nutzen von Ökonomie und Ökosystemleistungen für die Naturschutzpraxis	(Ring and Schniewind, 2013)
8	Mapping and assessing ecosystem services	(Marzelli et al., 2014)
9	Accounting for capacity and flow of ecosystem services: A conceptual model and a case study for Telemark, Norway	(Schröter et al., 2014)
10	Empfehlung zur Entwicklung bundesweiter Indikatoren zur Erfassung von Ökosystemleistungen	(Albert et al., 2015)
11	Ökosystemleistungen des Waldes	(Götzl et al., 2015)
12	Assessment and illustration of cultural ecosystem services at the local scale – A retrospective trend analysis	(Szücs et al., 2015)
13	The protective effect of forest against rockfalls across the French Alps: Influence of forest diversity	(Dupire et al., 2016)
14	Ecosystem services in Swedish forests	(Hansen and Malmaeus, 2016)
15	National ecosystem services indicators: Measure of social-ecological sustainability	(Mononen et al., 2016)
16	Seeing the forest for its multiple ecosystem services: Indicators for cultural services in heterogeneous forests	(Sutherland et al., 2016)
17	Management of ecosystem services in mountain forests: Review of indicators and value functions for model based multi-criteria decision analysis	(Blattert et al., 2017)
18	Preliminary Biophysical Assessment of Forest	(Jürmalis et al., 2017)
19	Value-based ecosystem service trade-offs in multi-objective management in European mountain forests	(Langner et al., 2017)
20	Future ecosystem services from European mountain forests under climate change	(Mina et al., 2017)
21	Indicators of ecosystem potential for pollination and honey production	(Affek, 2018)
22	Forest Biodiversity, Carbon Sequestration and Wood Production: Modeling Synergies and Trade-Offs for Ten Forest Landscapes across Europe	(Biber et al., 2020)
23	Utilising forest inventory data for biodiversity assessment	(Heym et al., 2021)
24	Methodology for classifying the ecosystem integrity of forests in Germany using quantified indicators	(Jenssen et al., 2021)
25	Waldleistung und Störungsanfälligkeit: eine modellbasierte Multikriterienanalyse	(Temperli and Blattert, 2021)
26	Exploring evolving spiritual values of forests in Europe and Asia: a transition hypothesis toward re-spiritualizing forests	(Roux et al., 2022)
27	Towards ecosystem service assessment: Developing biophysical indicators for forest ecosystem services	(Tiemann and Ring, 2022)
28	Index of biodiversity potential (IBP) versus direct species monitoring in temperate forests	(Zeller et al., 2022)
29	Erfassung und Bewertung kultureller Ökosystemleistungen in Deutschland	(Hermes et al., 2023)

(*continued on next page*)

Table A1 (*continued*)

Nb.	Title	Source
30	Analyse der waldspezifischen Ökosystemleistungen im Hinblick auf die Wasserhaushaltskomponente	(Müller, 2024)
31	Trade-offs in biodiversity and ecosystem services between edges and interiors in European forests	(Vanneste et al., 2024)

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2026.114701.

Data availability

Data will be made available on request.

References

Affek, A.N., 2018. Indicators of ecosystem potential for pollination and honey production. Ecol. Ind. 94, 33–45. https://doi.org/10.1016/j.ecolind.2017.04.001.

Albert, C., Burkhard, B., Daube, S., Dietrich, K., Engels, B., Frommer, J., Götzl, M., Grêt-Regamey, A., Job-Hobeb, B., Keller, R., Marzelli, S., Moning, C., Müller, F., Rabe, S.-E., Ring, I., Schwaiger, E., Schweppe-Kraft, B., Wüstemann, H., 2015. Empfehlung zur Entwicklung bundesweiter Indikatoren zur Erfassung von Ökosystemleistungen: Diskussionspapier. BfN-Skripten 410.

Barnaud, C., Antona, M., 2014. Deconstructing ecosystem services: Uncertainties and controversies around socially constructed concepts. Geoforum 56, 113–123.

Bergen, V., Löwenstein, W., Olschewski, R., 2013. Forstökonomie: Volkswirtschaftliche Ansätze für eine vernünftige Umwelt- und Landnutzung, second ed. Franz Vahlen GmbH, Munich.

BfN, 2011. Waldartenlisten der Farn- und Blütenpflanzen, Moose und Flechten Deutschlands. *BfN-Skripten* 299. Bonn.

Biber, P., Felton, A., Nieuwenhuis, M., Lindbladh, M., Black, K., Bahyl, J., Bingöl, Ö., Borges, J.G., Botequim, B., Brukas, V., Bugalho, M.N., Corradini, G., Eriksson, L.O., Forsell, N., Hengeveld, G.M., Hoogstra-Klein, M.A., Kadıogulları, A.I., Karahalil, U., Lodin, I., Tucek, J., 2020. Forest Biodiversity, Carbon Sequestration, and Wood Production: Modeling Synergies and Trade-Offs for Ten Forest Landscapes Across Europe. Ecol. Evol. 8, 1–21. https://doi.org/10.3389/fevo.2020.547696.

Blattert, C., Lemm, R., Thees, O., Lexer, M.J., Hanewinkel, M., 2017. Management of ecosystem services in mountain forests: Review of indicators and value functions for model based multi-criteria decision analysis. Ecol. Indic. 79, 391–409. https://doi.org/10.1016/j.ecolind.2017.04.025.

BMEL, 2021. Waldstrategie 2050: Nachhaltige Waldbewirtschaftung - Herausforderung und Chancen für Mensch, Natur und Klima. Bonn, German Federal Ministry of Food and Agriculture (BMEL).

BMEL, 2023. Den Wandel gestalten! Zusammenfassung GAP-Strategieplan 2023 – 2027. Version 20.3.2023. German Federal Ministry of Food and Agriculture. Bonn.

BMEL, 2024. Die wirtschaftliche Lage der forstwirtschaftlichen Betriebe: Buchführungsergebnisse 2022. German Federal Ministry of Food and Agriculture, Bonn.

BMEL, 2025. Seltene Baumarten. German Federal Ministry of Food and Agriculture. Online. https://www.genres.de/fachportale/baeume-und-straeucher/seltene-baumarten/verborgene-vielfalt-erhalten. Last accessed: 02.03.2025.

BMELV, 2011. Waldstrategie 2020: Nachhaltige Bewirtschaftung - eine gesellschaftliche Chance und Herausforderung. Bonn, German Federal Ministry of Food, Agriculture and Consumer Protection.

BMUB, 2016. Klimaschutzplan 2050: Klimaschutzpolitische Grundsätze und Ziele der Bundesregierung. German Federal Ministry for the Environment, Nature Conversation, Construction and Reactor Safety. Bonn.

BMUKN, 2024. Richtlinien für Zuwendungen zu einem Klimaangepassten Waldmanagement PLUS. German Federal Ministry for the Environment, Climate Action, Nature Conversation and Nuclear Safety. Bonn.

BMUV, 2023. Indikatorenbericht 2023: der Bundesregierung zur Nationalen Strategie zur biologischen Vielfalt. German Federal Ministry for the Environment, Nature Conversation, Nuclear Safety and Consumer Protection. Bonn.

Boyd, J., Banzhaf, S., 2007. What are ecosystem services? The need for standardized environmental accounting units. Ecol. Econ. 63, 616–626. https://doi.org/10.1016/j.ecolecon.2007.01.002.

Brinkord, M., Elsasser, P., Seintsch, B., 2024. Hilfstabellen zu Abschätzung der Kohlenstoffspeicherung in Waldbeständen ("Kohlenstoff-Ertragstafeln"), *Thünen Working Paper* 239. Brunswick.

Burdekin, D.A., Buttoud, G., Csoka, P., Efthymiou, P.N., Krott, M., Kulikova Elena, G., Rojas-Briales, E., Seppälä, R., Spiecker, H., Tome, M., 2001. Guidelines for establishing Farm Forestry Accountancy Networks: MOSEFA (monitoring the Socio-Economic Situation of European Farm Forestry). European Commission Concerted Action. European Forestry Institute Res, Rep, p. 12.

Bürger-Arndt, R., Ohse, B., Meyer, K., Höltermann, A., 2012. Ökosystemdienstleistungen von Wäldern: Workshopbericht. BfN-Skripten 320.

Bürgi, P., 2023. Benchmarking in der Forstwirtschaft: Eine Methode für forstbetriebliches Benchmarking in der DACH-Region mit Fokus auf die Holzernte [Dissertation]. Georg August Universität, Göttingen.

Bürgi, P., Müller, A., Pauli, B., Rosset, C., 2024. Forstwirtschaftliches Testbetriebsnetz der Schweiz: Ergebnisse der Jahre 2020 – 2022. Statistik der Schweiz. Bundesamt für Statistik, Neuchâtel.

Burkhard, B., Kroll, F., Müller, F., Windhorst, W., 2009. Landscapes Capacities to Provide Ecosystem Services - a Concept for Land-Cover Based Assessments. Landsc. Onl. 15, 1–22. https://doi.org/10.3097/LO.200915.

Castro, V.F., Frazzon, E.M., 2017. Benchmarking of best practices: an overview of the academic literature. Benchmarking Int.J. 24 (3), 750–774. https://doi.org/10.1108/BIJ-03-2016-0031.

Chaudhary, A., Burivalova, Z., Koh, L.P., Hellweg, S., 2016. Impact of Forest Management on Species Richness: Global Meta-Analysis and Economic Trade-Offs. Nature Sci. Rep. 6, 23954. https://doi.org/10.1038/srep23954.

COM, 2019. European Green Deal. In: European Commission (COM). 640 final. Brussels.

COM, 2020. Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds: The Birds Directive (L 20). In: European Parliament; Council of the European Communities; European Commission (COM). Brussels.

COM, 2020b. EU Biodiversity Strategy for 2030: Bringing nature back into our lives. European Commission (COM). 380 final. Brussels.

COM, 2021a. Guidance document: The strict protection of animal species of Community interest under the Habitats Directive. A summary. European Commission (COM). 16 final. Brussels.

COM, 2021b. New EU Forest Strategy for 2030. European Commission (COM). 572 final. Brussels.

COM, 2021c. REGULATION (EU) 2021/2115 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 2 December 2021establishing rules on support for strategic plans to be drawn up by Member States under the common agricultural policy (CAP Strategic Plans) and financed by the European Agricultural Guarantee Fund (EAGF) and by the European Agricultural Fund for Rural Development (EAFRD) and repealing Regulations (EU) No 1305/2013 and (EU) No 1307/2013. European Commission (COM). 186 final. Brussels.

COM, 2024. Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society. European Commission (COM). 63 final. Strasbourg.

Corbera, E., Brown, K., Adger, N.W., 2007. The Equity and Legitimacy of Markets for Ecosystem Services. Dev. Change 38 (4), 587–613. https://doi.org/10.1111/j.1467-7660.2007.00425.x.

Costanza, R., 2008. Ecosystem services: multiple classification systems are needed. Biol. Conserv. 2 (141), 30–352. https://doi.org/10.1016/j.biocon.2007.12.020.

Costanza, R., dArge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260. https://doi.org/10.1038/387253a0.

Costanza, R., De Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., Grasso, M., 2017. Twenty years of ecosystem services: How far have we come and how far do we still need to go? Ecosyst. Serv. 28, 1–16. https://doi.org/10.1016/j.ecoser.2017.09.008.

Danley, B., Widmark, C., 2016. Evaluating conceptual definitions of ecosystem services and their implications. Ecol. Econ. 126, 132–138. https://doi.org/10.1016/j.ecolecon.2016.04.003.

Daw, T., Brown, K., Rosendo, S., Pomeroy, R., 2011. Applying the ecosystem services concept to poverty alleviation: the need to disaggregate human well-being. Environ. Conserv. 38 (4), 370–379. https://doi.org/10.1017/S0376892911000506.

De Groot, R., 2006. Function-analysis and valuation as a tool to assess land use conflicts in planning for sustainable, multi-functional landscapes. Landsc. Urban Plann. 75, 175–186 https://doi:10.1016/j.landurbplan.2005.02.016.

De Groot, R., Wilson, M.A., Boumans, R.M., 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecol. Econ. 41 (3), 393–408. https://doi.org/10.1016/S0921-8009(02)00089-7.

De Groot, R., Alkemade, R., Braat, L.C., Hein, L.G., Willemen, L., 2009. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecol. Complex. 7, 260–272 https://doi:10.1016/j.ecocom.2009.10.006.

Doran, G.T., 1981. There's a S.M.A.R.T. way to write management's goals and objectives. AMA 70, 35–36.

Dorren, L.K., Berger, F., Le Hir, C., Mermin, E., Tardif, P., 2005. Mechanisms, effects and management implications of rockfall in forests. For. Ecol. Manage. 215 (1–3), 183–195. https://doi.org/10.1016/j.foreco.2005.05.012.

Duflot, R., Fahrig, L., Mönkkönen, M., 2022. Management diversity begets biodiversity in production forest landscapes. Biol. Conserv. 268, 109514. https://doi.org/10.1016/j.biocon.2022.109514.

Dupire, S., Bourrier, F., Monnet, J.M., Bigot, S., Borgniet, L., Berger, F., Curt, T., 2016. The protective effect of forests against rockfalls across the French Alps: Influence of forest diversity. For. Ecol. Mange. 382, 269–279. https://doi.org/10.1016/j.foreco.2016.10.020.

Elmqvist, T., Maltby, E., Barker, T., Mortimer, M., Perrings, C., 2010. Biodiversity, Ecosystems and Ecosystem Services. In: Kumar, P. (Ed.), The Economics of Ecosystem and Biodiversity: Ecological and Economic Foundations. Routledge, London.

Elsasser, P., Köthke, M., Dieter, M., 2020. Ein Konzept zur Honorierung der Ökosystemleistungen der Wälder. *Thünen Working Paper 152*. Brunswick.

Feld, K.C., Da Silva, P.M., Sousa, J.P., de Bello, F., Bugter, R., Grandin, U., Hering, D., Lavorel, S., Mountford, O., Pardo, I., Pärtel, M., Römbke, J., Sandin, L., Jones, K.B., Harrison, P., 2009. Indicators of biodiversity and ecosystem services: a synthesis across ecosystem and spatial areas. Oikos 118 (12), 1862–1871. https://doi.org/10.1111/j.1600-0706.2009.17860.x.

Ferraro, K.M., Ferraro, A.L., Lundgren, E., Sommer, N.R., 2025. The use and abuse of ecosystem service concepts and terms. Biol. Conserv. 308, 111218. https://doi.org/10.1016/j.biocon.2025.111218.

Fisher, B., Turner, R.K., 2008. Ecosystem services: Classification for valuation. Biol. Conserv. 141 (5), 1167–1169. https://doi.org/10.1016/j.biocon.2008.02.019.

Fisher, B., Turner, R.K., Morling, P., 2009. Defining and classifying ecosystem services for decision making. Ecol. Econ. 68, 643–653. https://doi.org/10.1016/j.ecolecon.2008.09.014.

Forest Europe, 2016. Expert Group and Workshop on a pan-European approach to valuation of forest ecosystem services: Group of Expert 2012-2014 & Belgrade Workshop (Republic of Serbia), 24-25 September 2014. Final Report, Forest Europe.

ForstBW, 2016. Alt- und Totholzkonzept Baden-Württemberg. Tübingen-Bebenhausen, Forst Baden-Württemberg (ForstBW).

Genes, L., Dirzo, R., 2022. Restoration of plant-animal interactions in terrestrial ecosystems. Biol. Conserv. 265, 109393. https://oi.org/10.1016/j.biocon.2021.109393.

Giegrich, J., 1995. Die Bilanzbewertung in produktbezogenen Ökobilanzen. In: Schorb, A., Schmidt, M. (Eds.), Stoffstromanalysen in Ökobilanzen und Öko-Audits. Springer. Berlin/ Heidelberg, pp. 255–279.

Götzl, M., Schwaiger, E., Schwarzl, B., Sonderegger, G., 2015. Ökosystemleistungen des Waldes: Erstellung eines Inventars für Österreich. *Report Rep-0544.*. Austrian Federal Ministry of Environment. Vienna.

Gret-Regamey, A., Brunner, Sybil, H., Altwegg, J., Christen, M., & Bebi, P., 2013. Integrating Expert Knowledge into Mapping Ecosystem Services Trade-offs for Sustainable Forest Management. Ecol. Soc. 18 (3), 34. https://doi.org/10.5751/ES-05800-180334.

Haines-Young, R., 2023. Common International Classification of Ecosystem Services (CICES) V5.2 and Guidance on the Application of the Revised Structure. Nottingham. https://cices.eu.

Haines-Young, R., Potschin, M., 2018. Common International Classification of Ecosystem Services (CICES). V5.1 and Guidance on the Application of the Revised Structure. Nottingham. https://cices.eu.

Hale, R., Blumstein, D.T., Mac Nally, R., Swearer, S.E., 2020. Harnessing knowledge of animal behavior to improve habitat restoration outcomes. Ecosphere 11 (4), 1–14. https://doi.org/10.1002/ecs2.3104.

Hansen, K., Malmaeus, M., 2016. Ecosystem services in Swedish forests. Scand. J. For. Res. 31 (6), 626–640. https://doi.org/10.1080/02827581.2016.1164888.

Harger, J., Meyer, F.-M., 1996. Definition of Indicators for Environmentally Sustainable Development. Chemosphere 33 (9), 1749–1775. https://doi.org/10.1016/0045-6535(96)00194-4.

Hermelingmeier, V., Nicholas, K.A., 2017. Identifying Five Different Perspectives on the Ecosystem Services Concept Using Q Methodology. Ecol. Econ. 136, 255–265. https://doi.org/10.1016/j.ecolecon.2017.01.006.

Hermes, J., Albert, C., Schmücker, D., Bredemeier, B., Barkmann, J., von Haaren, C., 2023. Erfassung und Bewertung kultureller Ökosystemleistungen in Deutschland: Die Qualität der Landschaft für Freizeit- und Wochenenderholung in Deutschland: Potenzial, Dargebot, Präferenz, Nutzung. *BfN-Schriften 659*. Bonn.

Hernandez-Morcillo, M., Plieninger, T., Bieling, C., 2013. An empirical review of cultural ecosystem service indicators. Ecol. Indic. 29, 434–444. https://doi.org/10.1016/j.ecolind.2013.01.013.

Heym, M., Uhl, E., Moshammer, R., Dieler, J., Stimm, K., Pretzsch, H., 2021. Utilising forest inventory data for biodiversity assessment. Ecol. Indic. 121, 1–11. https://doi.org/10.1016/j.ecolind.2020.107196.

Horváthová, J., Mokrišová, M., Vrábliková, M., 2021. Benchmarking—A Way of Finding Risk Factors in Business Performance. JRFM 14 (5), 221–238 https://10.3390/jrfm14050221.

Irauschek, F., Rammer, W., Lexer, M.J., 2017. Can current management maintain forest landscape multifunctionality in the Eastern Alps in Austria under climate change? Reg. Environ. Change 17, 33–38. https://doi.org/10.1007/s10113-015-0908-9.

Jenssen, M., Nickel, S., Schröder, W., 2021. Methodology for classifying the ecosystem integrity of forests in Germany using quantified indicators. Environ. Sci. Eur. 33 (46), 1–28. https://doi.org/10.1186/s12302-021-00478-y.

Jūrmalis, E., Lībiete, Z., Bārdule, A., 2017. Preliminary Biophysical Assessment of Forest Ecosystem Services: Two Model Area Examples. Acta Biol. Univ. Daugavp. 17 (1), 59–66.

Khalil, H., Jia, R., Moraes, E.B., Munn, Z., Alexander, L., Peters, M.D.J., Asran, A., Godfrey, C.M., Tricco, A.C., Pollock, D., Evans, C., 2025. Scoping reviews and their role in identifying research priorities. JCE 181, 111712. https://doi.org/10.1016/j.jclinepi.2025.111712.

Knoke, T., Kindu, M., Schneider, T., Gobakken, T., 2021. Inventory of Forest Attributes to Support the Integration of Non-provisioning Ecosystem Services and Biodiversity into Forest Planning—from Collecting Data to Providing Information. Cur. Forest. Rep. 7, 38–58. https://doi.org/10.1007/s40725-021-00138-7.

Kull, C.A., de X.A., Sartre, Castro-Larranaga, M., 2015. The political ecology of ecosystem services. Geoforum 61, 122–134. https://doi.org/10.1016/j.geoforum.2015.03.004.

Langner, A., Irauschek, F., Perez, S., Pardos, M., Zlatanov, T., Öhman, K., Nordström, E.-M., Lexer, M.J., 2017. Value-based ecosystem service trade-offs in multi-objective management in European mountain forests. Ecosyst. Serv. 26, 245–257. https://doi.org/10.1016/j.ecoser.2017.03.001.

La Notte, A., DAmato, D., Mäkinen, H., Paracchini, M.L., Liquete, C., Egoh, B., Geneletti, D., Crossmann, N.D., 2017. Ecosystem services classification: A systems ecology perspective of the cascade framework. Ecol. Indic. 74, 392–402. https://doi.org/10.1016/j.ecolind.2016.11.030.

Latruffe, L., Diazabakana, A., Bockstaller, C., Desjeux, Y., Finn, J., Kelly, E., Ryan, M., Uthes, S., 2016. Measurement of sustainability in agriculture: a review of indicators. Stud. Agric. Econ. 118 (3), 123–130. https://doi.org/10.7896/j.1624.

Lebacq, T., Baret, P., Stilmant, D., 2013. Sustainability indicators for livestock farming.: A review. Agron. Sustain. Dev. 33, 311–327. https://doi.org/10.1007/s13593-012-0121-x.

LUKE, 2025. Statistics database: Forest statistics. Natural Resources Institute Finland (LUKE). https://statdb.luke.fi/PxWeb/pxweb/en/LUKE/. Last accessed: 13.11.2024.

Maes, J., Liquete, C., Teller, A., Erhard, M., Paracchini, M.L., Barredo, J.I., Grizetti, B., Cardoso, A., Somma, F., Petersen, J.-E., Meiner, A., Gelabert, E.R., Zal, N., Kristensen, P., Bastrup-Birk, A., Biala, K., Piroddi, C., Egoh, B., Degeorges, P., Lavalle, C., 2016. An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy 2020. Ecosyst. Serv. 17, 14–23. https://doi.org/10.1016/j.ecoser.2015.10.023.

Marzelli, S., Grêt-Regamey, A., Moning, C., Rabe, S.-E., Koellner, T., Daube, S., 2014. Mapping and assessing ecosystem services: Initial step towards employing the concept of ecosystem services at national level in Germany. Natur u. Landschaft 89 (2), 66–73. https://doi.org/10.17433/2.2014.50153256.66-73.

Mauchline, A.L., Mortimer, S.R., Park, J.R., Finn, J.A., Haysom, K., Westbury, D.B., Purvis, G., Louwagie, G., Northey, G., Primdahl, J., Vejre, H., Kristensen, Lone Soderkvist, Teilmann, Kasper Vind, Vesterager, J.P., Knickel, K., Kasperczyk, N., Balazs, K., Laszlo, Podmaniczky, Vlahos, G., Yli-Viikari, A., 2012. Environmental evaluation of agri-environment schemes using participatory approaches: Experiences of testing the Agri-Environmental Footprint Index. Land Use Policy 29, 317–328. https://doi.org/10.1016/j.landusepol.2011.07.002.

MEA, 2005. Millennium Ecosystem Assessment. Synthesis. Island Press. Washington D.C, Ecosystems and Human Well-being.

Mina, M., Bugmann, H., Cordonnier, T., Irauschek, F., Klopcic, M., Pardos, M., Cailleret, M., 2017. Future ecosystem services from European mountain forests under climate change. J. Appl. Ecol. 54 (2), 389–401. https://doi.org/10.1111/1365-2664.12772.

Mononen, L., Auvinen, A.P., Ahokumpu, A.-L., Rönkä, M.T., Aarras, N., Tolvanen Harri, T., Kamppinnen, M., Viirret, E., Kumpula, T., Vihervaara, P., 2016. National ecosystem services indicators: Measures of social-ecological sustainability. Ecol. Indic. 61, 27–37. https://doi.org/10.1016/j.ecolind.2015.03.041.

Moser, T., Zimmermann, W., 2011. Ökosystemleistungen im politischen Kontext: Bedeutung und Argumenttypen. Schweiz. Z. Forstw. 162 (11), 405–411. https://doi.org/10.3188/szf.2011.0405.

Müller, E.V., 2024. Analyse der waldspezifischen Ökosystemleistungen im Hinblick auf die Wasserhaushaltskomponenten: Abfluss und Grundwasserneubildung im Wald. *Mitteilungen aus der Forschungsanstalt für Waldökologie und Forstwirtschaft Rheinland-Pfalz 90/23*. Forschungsanstalt für Waldökologie und Forstwirtschaft Rheinland-Pfalz (FAWF). Trippstadt.

Müller, N., Franz, K., Seintsch, B., 2024. Testbetriebsnetz Forst des BMEL: Grundlagen, Status Quo und zukünftiger Informationsbedarf. *Thünen Working Paper 254*. Brunswick.

Munn, Z., Pollock, D., Khalil, H., Alexander, L., McInerney, P., Godfrey, C.M., Peters, M., [M.], & Tricco, A. C., 2022. What are scoping reviews? Providing a formal definition of scoping reviews as a type of evidence synthesis. JBI Evid. 20 (4), 950–952. https://doi.org/10.11124/JBIES-21-00483.

Ojea, E., Nunes, P.A., Loureiro, M.L., 2010. Mapping Biodiversity Indicators and Assessing Biodiversity Values in Global Forests. Environ. Resour. Econ. 47, 329–347. https://doi.org/10.1007/s10640-010-9381-6.

Plummer, M.L., 2009. Assessing benefit transfer for the valuation of ecosystem services. Front. Ecol. Environ. 7 (1), 38–45. https://doi.org/10.1890/080091.

Poppe, K., Vrolijk, H., Dolman, M., Silvis, H., 2016. FLINT – Farm-level Indicators for New Topics in policy evaluation: an introduction. Stud. Agric. Econ. 118 (3), 116–122. https://doi.org/10.7896/j.1627.

Posner, S.M., McKenzie, E., Ricketts, T.H., 2016. Policy impacts on ecosystem service knowledges. PNAS 113 (7), 1760–1765. https://doi.org/10.1073/pnas.1502452113.

Potschin, M., Haines-Young, R., 2016. Defining and measuring ecosystem services. In: Potschin, M., Haines-Young, R., Fish, R., Turner, R.K. (Eds.), Routledge Handbook of Ecosystem Services. Routledge, London/ New York.

Prins, K., Köhl, M., Linser, S., 2023. Is the concept of sustainable forest management still fit for purpose? For. Policy Econ. 157, 103072. https://doi.org/10.1016/j.forpol.2023.103072.

Rice, J., 2003. Environmental health indicators. *Ocean*. Coast. Manag. 46, 25–259. https://doi.org/10.1016/S0964-5691(03)00006-1.

Riedel, T., Hennig, P., Polley, H., Schwitzgebel, F., 2020. Aufnahmeanweisung (BWI 2022) (2021-2022). First ed., November 2020. Version 1.11. German Federel Ministry of Food and Agriculture. Bonn.

Ring, I., Schniewind, I., 2013. Der Nutzen von Ökonomie und Ökosystemleistungen für die Naturschutzpraxis: Workshop III: Wälder. *BfN-Skripten 334*. Bonn.

Roux, J.-L., Konczal, A.A., Bernasconi, A., Bhagwat, S.A., de Vreese, R., Doimo, I., Govigli, V.M., Kaspar, J., Kohsaka, R., Pettenella, D., Plieninger, T., Shakeri, Z., Shibata, S., Stara, K., Takahashi, T., Torralba, M., Tyrvainen, L., Weiss, G., Winkel, G., 2022. Exploring evolving spiritual values of forests in Europe and Asia: a transition hypothesis toward re-spiritualizing forests. Ecol. Soc. 27 (4), 1–56. https://doi.org/10.5751/ES-13509-270420.

Saarikoski, H., Jax, K., Harrison, P.A., Primmer, E., Barton, D.N., Mononen, L., Vihervaara, P., Furman, E., 2015. Exploring operational ecosystem service definitions: The case of boreal forests. Ecosyst. Serv. 14, 144–157. https://doi.org/10.1016/j.ecoser.2015.03.006.

Schliep, R., Bartz, R., Dröschmeister, R., Dziock, F., Dziock, S., Kowarik, I., Radtke, L., Schäffler, L., Siedentop, S., Sudfeldt, C., Sukopp, U., Trautmann, S., Heiland, S., 2014. Entwicklung eines Indikatorensystems zur Darstellung direkter und indirekter Auswirkungen des Klimawandels auf die biologische Vielfalt in Deutschland. *BfN-Skripten 357*. Bonn.

Schliep, R., Bartz, R., Dröschmeister, R., Dziock, F., Dziock, S., Fina, S., Kowarik, I., Radtke, L., Schäffler, L., Siedentop, S., Sudfeldt, C., Trautmann, S., Sukopp, U., Heiland, S., 2017. Indikatorensystem zur Darstellung direkter und indirekter Auswirkungen des Klimawandels auf die biologische Vielfalt. *BfN-Skripten 470*. Bonn.

Schmithüsen, F., 2007. Multifunctional Forestry Practices as a Land Use Strategy to Meet Increasing Private and Public Demands in Modern Societies. J. For. Sci. 6 (53), 290–298 https://doi.org/10.17221/2016-JFS.

Schröter, M., Barton, D.N., Remme, R.P., Hein, L., 2014. Accounting for capacity and flow of ecosystem services: A conceptual model and a case study for Telemark. Norway. Ecol. Indic. 36, 539–551. https://doi.org/10.1016/j.ecolind.2013.09.018.

Schwaiger, E., Berthold, A., Gaugitsch, H., Götzl, M., Milota, E., Mirtl, M., Peterseil, J., Sonderegger, G., Stix, S., 2015. Wirtschaftliche Bedeutung von Ökosystemdienstleistungen. In: Austrian Federal Ministry of Agriculture and Forestry, Climate and Environmental Protection, Regions and Water Management. Vienna.

Shannon, C.E., 1948. A Mathematical Theory of Communication. Bell Syst. Tech. J. 27, 379–423.

Shvidenko, A., Barber, C.V., Persson, R., Gonzalez, P., Hassan, R., Lakyda, P., McCallum, I., Nilsson, S., Pulhin, J., van Rosenburg, B., Scholes, B., 2005. Forest and Woodland Systems: Chapter 21. In MA (Ed.). In: Ecosystem and Human Well-being: Current State and Trends, Volume 1. Island Press, Washington D.C.

Staub, C., Ott, W., Heusi, F., Klingler, G., Jenny, A., Häcki, M., Hauser, A., 2011. Indikatoren für Ökosystemleistungen: Systematik, Methodik und Umsetzungsempfehlungen für eine wohlfahrtsbezogene Umweltberichtserstattung. In: *Umwelt-Wissen 1102*. Suisse Federal Department of the Environment, Transport, Energy and Communications. Bern.

Sutherland, I.J., Gergel, S.E., Bennett, E.M., 2016. Seeing the forest for its multiple ecosystem services: Indicators for cultural services in heterogeneous forests. Ecol. Indic. 71, 123–133. https://doi.org/10.1016/j.ecolind.2016.06.037.

Swift, M.J., Izac, A.-M.N., Noordwijk, M., 2004. Biodiversity and ecosystem services in agricultural landscapes - are we asking the right questions? Agric. Ecosyst. Environ. 104, 113–134 https://doi:10.1016/j.agee.2004.01.013.

Szücs, L., Anders, U., Bürger-Arndt, R., 2015. Assessments and illustration of cultural ecosystem services at the local scale - A retrospective trend analysis. Ecol. Ind. 50, 120–134. https://doi.org/10.1016/j.ecolind.2014.09.015.

TEEB, 2010. The Economics of Ecosystem and Biodiversity. In: Kumar, P. (Ed.), The Economics of Ecosystem and Biodiversity. Ecological and Economic Foundations. Routledge, New York.

Temperli, C., Blattert, C., 2021. Waldleistungen und Störungsanfälligkeit: eine modellbasierte Multikriterienanalyse. Schweiz. Z. Forstw. 172 (5), 300–309. Doi: 10.3188szf.2021.0300.

Tiemann, A., Ring, I., 2022. Towards ecosystem service assessment: Developing biophysical indicators for forest ecosystem services. Ecol. Indic. 137, 1–13. https://doi.org/10.1016/j.ecolind.2022.108704.

UNFCCC, 2015. Paris Agreement. United Nations Framework Convention on Climate Change (UNFCC), Paris.

UN General Assembly, 1992. Report of the United Nations Conference on Environment and Development: Rio de Janeiro, 3 -14 June 1992. Volume 1 - Resolutions Adopted by the Conference (A/CONF.151/26/Rev.1 (Vol.1)).

UN General Assembly, 2015. Transforming our world: the 2030 Agenda for Sustainable Development (A/RES/70/1)..

Vanneste, T., Depauw, L., de Lombaerde, E., Meeussen, C., Govaert, S., de Pauw, K., Sankzuc, P., Bollmann, K., Brunet, J., Calders, K., Cousins, S.A., Diekmann, M., Gasperini, C., Graae, B.J., Hedwall, P.-O., Iacopetti, G., Lenoir, J., Lindmo, S., Orczewska, A., de P., Frenne, 2024. Trade-offs in biodiversity and ecosystem services between edges and interiors in European forests. Nat. Ecol. Evol. 8, 880–894. https://doi.org/10.1038/s41559-024-02335-6.

van Oudenhoven, A.P., Schröter, M., Drakou, E.G., Geijzendorffer, I.R., Jacobs, S., van Bodegom, P.M., Chazee, L., Czucz, B., Grunewald, K., Lillebo, A.I., Mononen, L., Nogueira, A.J., Pacheco-Romero, M., Perennou, C., Remme, R.P., Rova, S., Syrbe, R.-U., Tratalos, J.A., Vallejos, M., Albert, C., 2018. Key criteria for developing ecosystem service indicators to inform decision making. Ecol. Indic. 95, 417–426. https://doi.org/10.1016/j.ecolind.2018.06.020.

von Elm, E., Schreiber, G., Haupt, C.C., 2019. Methodische Anleitung für Scoping Reviews (JBI-Methodologie). ZEFQ 143, 1–7. https://doi.org/10.1016/j.zefq.2019.05.004.

Wallace, K.J., 2007. Classification of ecosystem services: Problems and solutions. Biol. Conserv. 139 (3–4), 235–246. https://doi.org/10.1016/j.biocon.2007.07.015.

Walthert, L., Meier, E.S., 2017. Tree species distribution in temperate forests is more influenced by soil than by climate. Ecol. Evol. 7 (22), 9473–9484. https://doi.org/10.1002/ece3.3436.

Wessolek, G., Duijnisveld, W., Trinks, S., 2008. Hydro-pedotransfer functions (HPTFs) for predicting annual percolation rate on a regional scale. J. Hydrol. 356, 17–27. https://doi.org/10.1016/j.jhydrol.2008.03.007.

Winkel, G., Lovrić, M., Muys, B., Katila, P., Lundhede, T., Pecurul, M., Pettenella, D., Pipart, N., Plieninger, T., Prokofieva, I., Parra, C., Pülzl, H., Roitsch, D., Roux, J.-L., Thorsen, B.J., Tyrväinen, L., Torralba, M., Vacik, H., Weiss, G., Wunder, S., 2022. Governing Europe's forests for multiple ecosystem services: Opportunities, challenges, and policy options. For. Policy Econ. 145, 102849. https://doi.org/10.1016/j.forpol.2022.102849.

Woltjer, P.J., Voskuilen, M.J., Horsting, A., 2024. Bedrijfsuitkomsten in de Nederlandse particuliere bosbouw over 2022. Rapport 2024-103. Wageningen, Wageningen Economic Research.

Zeller, L., Baumann, C., Gonin, P., Heidrich, L., Keye, C., Konrad, F., Larrieu, L., Meyer, P., Sennhenn-Reulen, H., Müller, J., Schall, P., Ammer, C., 2022. Index of biodiversity potential (IBP) versus direct species monitoring in temperate forests. Ecol. Indic. 136, 1–15. https://doi.org/10.1016/j.ecolind.2022.108692.

Zolyomi, A., Franklin, A., Smith, B., Soliev, I., 2023. Ecosystem services as the silver bullet? A systematic review of how ecosystem services assessments impact biodiversity prioritisation in policy. Earth Syst. Gov. 16, 100178. https://doi.org/10.1016/j.esg.2023.100178.