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# Untapped treasures of forest biodiversity indicators in the UNECE region

## Unerschlossene Potenziale bei Waldbiodiversitätsindikatoren in der UNECE-Region

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**Keywords:** forest biodiversity monitoring, Pressure-State-Response framework, climate-sensitive indicators, data accessibility, restoration, Austria

**Schlüsselbegriffe:** Waldbiodiversitätsmonitoring, Pressure-State-Response Modell, klimasensitive Indikatoren, Datenverfügbarkeit, Renaturierung, Österreich

## Abstract

Accelerating biodiversity loss under intensifying climate and anthropogenic pressures underscores the urgent need for forest biodiversity indicators than can assess ecosystem status, pressures, and management responses. We reviewed national forest and biodiversity reports from countries of the UNECE region, identifying 106 forest biodiversity indicators, many absent in international and national reporting systems. Classification using the OECD Pressure-State-Response (PSR) framework reveals a clear dominance of State indicators (72%), while Response (18%) and Pressure indicators (10%) are underrepresented. This limits the ability to trace causal chains and assess management effectiveness. We assessed data accessibility using a standardised typology (from reported to deficient), finding relatively better coverage for fragmentation, tree species diversity, native and introduced species, protected areas, deadwood, and natural regeneration, but gaps for old-growth forests, habitat trees,

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and forest birds. High climate sensitivity was identified for 16 indicators responsive to temperature and precipitation shifts, disturbance regimes, and habitat change. To translate findings into practice, we propose a concise workflow for revising indicator sets: identification of priorities of current EU policies, displaying causal-chains with the PSR indicator category assignment to strengthen the Pressure and Response coverage, prioritisation of climate-sensitive indicators, data-availability screening, and stakeholder co-design. Our findings support the Forest Europe indicator revision process and provided a pool of additional and novel indicators for revising Austria's national biodiversity indicators. in Austria, ten of the twelve forest biodiversity indicators were amended to include climate-sensitive sub-indicators, and three new indicators were added (Forest birds, Habitat trees, Structural diversity). Strengthening the coverage of Pressure and Response indicators, prioritising climate-sensitive indicators and feeding predictive modelling with additional State indicators can shift biodiversity monitoring from retrospective reporting to anticipatory, decision-supportive management under accelerating climate change.

## Zusammenfassung

Angesichts des zunehmenden Verlusts der biologischen Vielfalt durch den Klimawandel und anthropogene Einflüsse, ist die Erarbeitung effektiver Indikatoren zur Bewertung des Zustands der biologischen Vielfalt der Wälder sowie der Belastungen, denen sie ausgesetzt sind, sowie der Gegenmaßnahmen, unerlässlich. Wir haben nationale Wald- und Biodiversitätsberichte aus Ländern der UNECE-Region ausgewertet und dabei 106 Indikatoren mit Waldbiodiversitätsbezug identifiziert, von denen viele in internationalen und nationalen Berichtssystemen fehlen. Eine Klassifizierung anhand des OECD-Belastung-Zustand-Reaktions-Ansatzes zeigt eine Dominanz von Zustandsindikatoren (72 %), während Reaktions- (18 %) und Belastungsindikatoren (10 %) weniger häufig vorkommen. Dies schränkt die Möglichkeit ein, Kausalketten nachzuvollziehen und die Wirksamkeit von Bewirtschaftungsmaßnahmen zu bewerten. Anhand einer standardisierten Typologie (von öffentlich zugänglich bis nicht verfügbar) bewerteten wir die Datenverfügbarkeit und stellten eine relativ bessere Abdeckung bei Fragmentierung, Baumartenvielfalt, heimischen und nicht-heimischen Arten, Schutzgebieten, Totholz und Naturverjüngung fest. Lücken bestehen bei Altbeständen, Habitatbäumen und Waldvögeln. Eine hohe Klimasensitivität wurde für 16 Indikatoren festgestellt, die auf Temperatur- und Niederschlagsveränderungen, Schadereignisse und Lebensraumveränderungen reagieren. Zur Umsetzung der Ergebnisse in die Praxis, schlagen wir folgenden Ablauf zur Überarbeitung von Indikatorensystemen vor: Identifizierung von EU- oder nationalen Zielen, Darstellung von Kausalzusammenhängen, um insbesondere die Anteile von Belastungs- und Reaktionsindikatoren zu erhöhen, Priorisierung klimawandelempfindlicher Indikatoren, Überprüfung der Datenverfügbarkeit und partizipative Erarbeitung. Unsere Ergebnisse flossen in den Prozess zur Überarbeitung der Forest Europe Indikatoren

ein und dienten als Grundlage für zusätzliche Indikatoren im Überarbeitungsprozess der österreichischen Waldbiodiversitätsindikatoren. In Österreich wurden zehn der zwölf Biodiversitätsindikatoren um klimawandelempfindliche Parameter ergänzt und es wurden drei neue Indikatoren hinzugefügt (Waldvögel, Habitatbäume, Strukturvielfalt). Insgesamt kann die stärkere Integration von Belastungs- und Reaktionsindikatoren, sowie die Priorisierung klimawandelempfindlicher Indikatoren und die Integration zusätzlicher, neuer Zustandsindikatoren in Modellen dazu beitragen, das Biodiversitätsmonitoring von einer rückblickenden Berichterstattung hin zu einer proaktiven Entscheidungshilfe zu entwickeln.

## 1 Introduction

Biodiversity in forest ecosystems is changing due to a variety of impacts, including climate change, large-scale forest damages, deforestation, reforestation and land-use change (Balvanera *et al*., 2014; Pilotto *et al*., 2020). Through shifts in precipitation patterns and rising temperatures, climate change alters the distribution and abundance of species in forest ecosystems. Some species move to higher elevations and latitudes, while others face population declines or local extinction as they struggle to survive in their current range (Clark *et al*., 2011; Moore & Lauenroth, 2017; Pearce-Higgins *et a*l., 2015). Land use changes and habitat degradation often lead to a decline in habitat quality by reducing and fragmenting habitats (IPBES, 2019). This can disrupt ecosystems and limit the range of species that can succeed in these areas. The introduction of non-native species also alters the composition of forest-dwelling species, contributing to a decline in biodiversity. These impacts are all complex and often interrelated, which impede their monitoring and assessment.

In response to these challenges, forest biodiversity indicators have gained renewed attention in research and policy debates as essential tools for monitoring ecosystem dynamics, assessing pressures, and informing sustainable forest management strategies (Lier *et al*., 2020, 2021; Linser, 2024; Oettel & Lapin, 2021; Paillet *et al*., 2024). Political decision-makers are increasingly requesting improved forest biodiversity indicators to support responses to new and emerging needs, including climate and biodiversity emergencies (CBD, 2020; FAO, 2022; Forest Europe, 2020; IPBES, 2019). The necessity for biodiversity indicators to address the present biodiversity challenges is a central part of global, regional or national biodiversity-related strategies such as the Convention on Biological Diversity post-2020 global biodiversity framework and the European Union Green Deal. The endeavours to develop appropriate biodiversity indicators and alignment to the above-mentioned and other international instruments such as the Paris Agreement, and the UN Decade on Ecosystem Restoration, are major reasons for the renewed interest in forest biodiversity indicators. Coherence with the main international goals, such as the Global Forest Goals, the Sustainable Development Goals, Aichi-Targets, Forest Europe Oslo Goals & Targets, the Global

Core Set of Forest-related Indicators and the EU forest biodiversity-related Strategies and Regulations is likewise needed. For instance, only about two-thirds of all the objectives and commitments identified in the New EU Forest Strategy for 2030 can be monitored at least partially by the Forest Europe indicators. New indicators must be developed for the remaining third. Several of the Forest Europe indicators are not linked to the New EU Forest Strategy for 2030, and some are only weakly linked to the policy issues that it addresses (Lier *et al*., 2021). A comparison of Lier *et al*. (2022) shows significant differences between the vision of sustainable forest management formulated in the Forest Europe indicator set and the scope of the objectives and commitments in the New EU Forest Strategy for 2030. Particularly, the forest policy concerns reflected in the strategy address some biodiversity related issues, which cannot be monitored or only partially by the Forest Europe indicators, for instance protecting EU's last remaining primary and old-growth forests or plant 3 billion additional trees. In other forest-related indicator processes like the Montreal Process or the International Tropical Timber Organization, and in other countries outside Europe like Canada and USA, biodiversity assessment is likewise a major focus. By adapting and amending forest biodiversity indicators, we can align our monitoring and assessment frameworks with related global commitments, fostering accountability and facilitating the implementation of targeted conservation and management strategies.

Biodiversity monitoring in forests is complex and requires the selection of feasible, reliable, and replicable indicators based on the availability of data and the expected environmental changes (Gao *et al*., 2015; Hill *et al*., 2019). Common indicators of forest biodiversity include deadwood, forest structure and tree diversity (Oettel & Lapin, 2021). Data for these indicators rely primarily on national forest inventories, designed to provide comprehensive information about the forest ecosystem, in order to support forest management decisions and resources assessments (Chirici *et al*., 2011; Winter *et al*., 2008). Less frequently applied in national biodiversity monitoring are indicators, which describe the status or richness of taxonomic groups or species (Oettel & Lapin, 2021). Species-driven indicators are used to measure and assess biodiversity, as well as changes in species populations over time. Examples of indicators include species richness, abundance, diversity, rarity, and vulnerability. These indicators provide insights into the impacts of environmental changes on species populations and can inform conservation strategies and management interventions. They also capture responses to management actions (*e.g*., harvesting regimes, habitat restoration, invasive species control, protected areas), allowing evaluation of management effectiveness (Butchart *et al*., 2010; Leung & Gonzalez, 2024; Portaccio *et al*., 2026).

The selection of indicators for forest biodiversity monitoring depends on the objectives of the monitoring program as well as the characteristics of the forest ecosystem being monitored. Previous studies have emphasised the importance of considering the various components of biodiversity and the range of available indicators with which to measure them (Linser, 2024; Linser & Wolfslehner, 2015; Oettel & Lapin, 2021). Furthermore, the selection of indicators should be informed by the available data sources, human and financial resources, and the selection of indicators should be tailored to the specific context of the monitoring program. However, data availability, access to data, and technological know-how are limiting factors for its selection. Forest biodiversity indicators are particularly weak regarding data availability and quality (Lier *et al*., 2020; Linser, 2024).

In parallel, recent advances in scientific knowledge and geospatial technologies have opened up novel opportunities for the assessment and monitoring of forest biodiversity (Pettorelli *et al*., 2024). High-resolution remote sensing and related geospatial data provide more precise, scalable, and timely information on forest composition, structure, and function, enabling improved indicator development, assessment, and reporting (Calders *et al.*, 2020; Latifi & Valbuena, 2019; Phiri *et al*., 2020; Stevenson *et al*., 2024; Tariq *et al*., 2023). Prioritising indicators that can be feasibly assessed with these technologies strengthens evidence-based decision-making and accelerates effective conservation and sustainable management.

With the increasing threat of climate change leading to increased forest damage, species loss and habitat change, society is placing new and complex demands on forests (Prins *et al*., 2023). Ambitions raised, also because of the Aichi Biodiversity Targets - part of the Convention on Biological Diversity's Strategic Plan for Biodiversity 2011–2020 (CBD, 2010) - which called for, among other goals, reducing habitat loss (Target 5), ensuring sustainable management of all forests (Target 7), expanding effectively managed protected areas (Target 11), preventing extinctions (Target 12), and restoring degraded ecosystems (Target 15). These commitments have sharpened the focus of policy instruments on reversing biodiversity loss and protecting the remaining primary and old-growth forests. Building on this, the Kunming–Montreal Global Biodiversity Framework (CBD, 2022) now succeeds the Aichi Targets and maintains - and in places strengthens - these ambitions through 2030, underscoring the need to further develop forest biodiversity indicators to adequately address these challenges.

The aim of this study is to support high-level decision-making on forest biodiversity in the UNECE region by systematically exploring the breadth of forest biodiversity indicators used in national reporting and identifying those most sensitive to climate change. This work addresses the need for indicators that can monitor biodiversity during climate emergencies, capture rapid ecological responses, and inform time-sensitive conservation decisions under accelerating environmental change.

Our focus aligns with international commitments - including Forest Europe's Vienna Resolution 5, Madrid Ministerial Resolution 2, Bratislava Ministerial Resolution, and Bonn Ministerial Decision - which highlight the twin challenges of biodiversity loss and climate change (Forest Europe, 2021).

The Montréal Process likewise emphasises integrating climate change into biodiversity conservation (Montréal Process Working Group, 2023), by providing strong justifications for prioritizing climate-sensitive biodiversity indicators. Specifically, we address the following research questions:

(1) Can the observation of forest biodiversity status and trends be improved by incorporating novel, so far not widely used indicators identified across UNECE countries?
(2) Which criteria should guide indicator selection to enhance forest biodiversity monitoring under emerging climate change?

## 2 Methods

### 2.1 Study area

The study covers the 56 Member States of the United Nations Economic Commission for Europe (UNECE), which together comprise 1714 million hectares of forest, 42.5% of the global forest area. Spanning the temperate and boreal biomes of North America, Europe, the Caucasus, Central Asia, and the Russian Federation, the region exhibits ecological, climatic, and socio-economic diversity (UNECE, 2025). Forest covers 39% of the region's land area, though forest cover ranges from 74% in Finland, to less than one per cent in Malta, Kazakhstan and Iceland and no forest area in Monaco. Over the past three decades, forest area in the UNECE region increased by 60 million hectares. Boreal forests cover 65% of the region's forest area. Temperate forests account for 28%. Sub-tropical forests account for the remaining 7%. The United States of America, Canada and the Russian Federation together account for 86% of all forest area in the UNECE region.

UNECE countries produce 55% of the world's industrial roundwood and provide 60% of the global export value of wood-based products. 8 % of forest area, or 317 million hectares, are located within legally protected areas (UNECE, 2025).

### 2.2 Compilation of forest biodiversity indicators

We conducted a structured review to identify and document forest biodiversity-related indicators monitored and reported by countries in the UNECE region. Information was compiled through two complementary approaches: we surveyed national correspondents for Forest Europe and for the FAO/UNECE forest data reporting, as well as members of the FAO/UNECE Team of Specialists on Monitoring Sustainable Forest Management, ensuring that we approached at least one contact person in each UNECE country. Monaco was excluded a priori because it has no forest area. Although initiated to inform the revision of the Forest Europe and Austrian forest biodiversity indicators, the scope was expanded to cover all UNECE countries to enhance the comparability of countries with mainly temperate and boreal forest ecosystems in the Northern Hemisphere. The aim was also to capture the recent revisions in North American countries and to include new indicator sets developed in the Caucasus and in Central Asia (Linser & O'Hara, 2019; Otrakcier *et al*., 2023). This ensured a comprehensive, region-wide evidence base. We included national-level documents and data portals that report forest biodiversity indicators, specifically national forest inventory reports, national reports on indicators for sustainable forest management, national forest strategies with indicator sets, forestry statistics yearbooks and official open-data portals, national biodiversity or state-of-environment reports where forest indicators are reported, and internationally coordinated reports. 73% of the national correspondents provided relevant reports and official links to databases. For non-responding countries, we conducted a standardized web search of official government or mandated agency sites (ministries, forest or environment agencies, statistical offices) using English and national-language keywords combining "forest," "biodiversity," "indicator(s)," "sustainable forest management," and "national forest inventory." Because national reporting systems across the UNECE region vary substantially, we applied specific rules to handle differences in language, reporting years, and data completeness:

- Language: Sources in national languages were translated either by the national correspondents themselves or via machine translation by the authors, which was subsequently verified by correspondents where possible. All indicator names were standardised into English.

- Reporting years: To address temporal discrepancies between national reporting cycles, we prioritised the most recent edition whenever multiple editions existed. Where multiple national sources reported overlapping indicators, we prioritized the most authoritative documents (*e.g.*, official NFI reports).

- Completeness: To manage varying levels of detail and gaps in national reporting, we triangulated national data with regional reports, such as the State of Europe's Forests 2020. Data analysis involved a systematic investigation of national databases and open-data portals using R programming. Indicators were then classified into a six-tier data accessibility typology (from ‚reported' to ‚deficient', see Figure 5) to account for varying completeness and accessibility, ultimately identifying monitoring gaps and data needs for future climate scenarios.

We recorded the title, measurement unit and data source for each extracted indicator. In total, we identified 110 indicators (including 4 indices) monitored and reported by UNECE countries (see Supplementary Material A and B for the sources screened and the list of indicators).

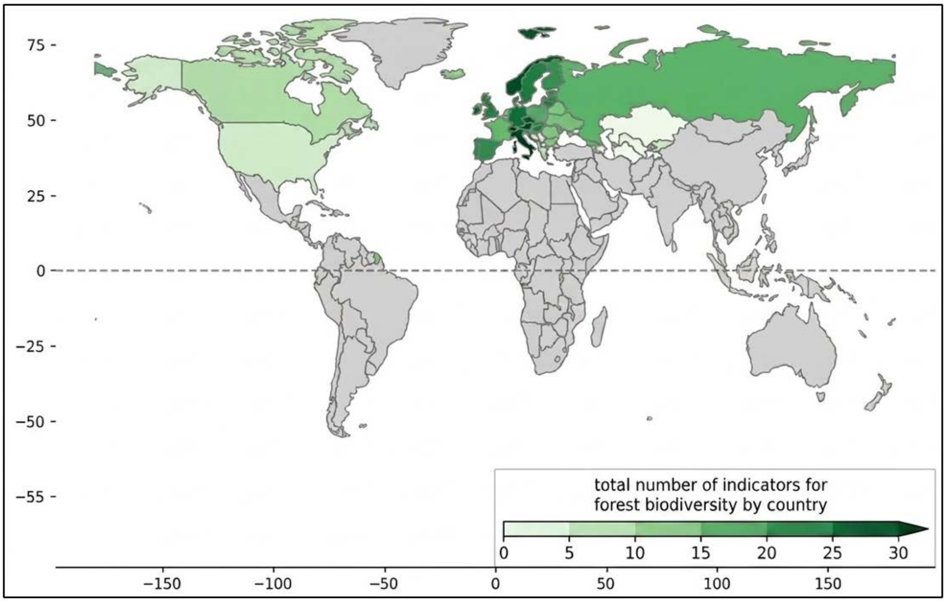


*Figure 1: Number of forest biodiversity indicators reported by each UNECE country. Countries outside the UNECE or without forest cover are shown in grey.*

Abbildung 1: Anzahl der von jedem UNECE-Land berichteten Waldbiodiversitäts-Indikatoren. Länder außerhalb der UNECE oder ohne Waldflächen sind grau dargestellt.

Figure 1 displays the investigated 56 UNECE countries with a gradient from light to dark green representing increasing numbers of biodiversity indicators used for national reporting. The data highlight greater indicator reporting activity in European and Central Asian countries.

## 2.3 Application of the PSR approach

To structure and group the indicators, we applied the OECD Pressure-State-Response (PSR) framework which is suitable to depict the causal chains of forest biodiversity-related issues, and is widely used in environmental policy and sustainability assessments (Hagan & Whitman, 2006). According to Maxim *et al*. (2009) PSR is a relevant tool for structuring communication between scientists and users of biodiversity-related data. We chose the PSR framework due to its simplicity, policy relevance, and compatibility with the available information, though we acknowledge that the DPSIR (Driving forces-Pressures-State-Impacts-Responses) framework could offer additional insights into underlying drivers (broader socio-economic factors that lead to pressures) and impacts (the effects of environmental changes on ecosystems, human health, and society) and may be preferable for exploring the root causes of environmental issues and their broader consequences (Linser, 2002), though it would have required the inclusion of forest indicators beyond the focus on biodiversity, like forest health indicators. PSR category assignment was based on pre-defined decision rules based on the following clear description of the categories. Coding was double-checked by both authors, and data accessibility was reviewed by a data analyst. In more detail, Pressures refer to human activities that directly or indirectly impact the composition, structure, and functioning of forest ecosystems, leading to biodiversity decline or loss (for example fragmentation, invasive species). The State indicators emphasise the condition of forest ecosystems and their associated biodiversity. These include various indicators such as deadwood, tree species diversity or threatened species. However, measuring the state in isolation is of limited value as State indicators only inform us about "how things are" but without Pressure and Response indicators one can't tell "why", "so what", or "what to do next". State indicator thus reflects the outcomes of Pressures exerted on forests and provides a basis for judging the effectiveness of Responses aimed at mitigating these Pressures. We also identified four indices used by some countries (see Figure 4), namely, biodiversity index, stand density index, forest structure index, and species diversity index. These unitless aggregates combine several primarily State indicators. As our main interest is in easily comprehensible single indicators, we classified indices separately to avoid conflating aggregated indices with their constituent indicators. Note that species diversity can be presented as a State indicator (number of species per hectare) or as an Index (e.g. the Shannon diversity index capturing species richness and how evenly individuals are distributed among species).

Response indicators comprise measures, management approaches, and policies implemented to counteract Pressures and maintain or enhance State (for example protected areas, invasive species control, close-to nature or integrative forest management, reforestation, restoration or forest areas managed to produce forest reproductive material.

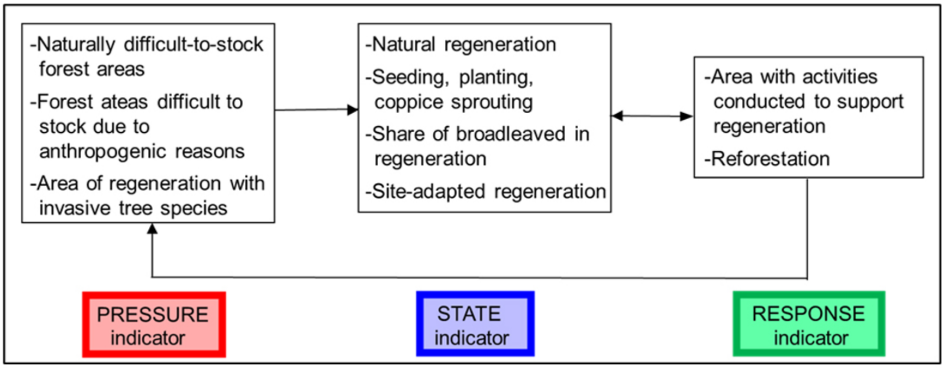


*Figure 2: Indicators used in countries of the UNECE region, clustered by Pressure, State and Response categories: the example of regeneration-related indicators.*

Abbildung 2: In den Ländern der UNECE-Region verwendete Indikatoren, gruppiert nach den Kategorien Belastung, Zustand und Reaktion am Beispiel von Indikatoren zu Verjüngung.

Figure 2 illustrates the causal chain linking insufficient regeneration (Pressures), regeneration status (State) and management responses to ease pressures and improve the state (Responses).

## 3 Results

Across all UNECE countries, we identified a total of 106 forest biodiversity indicators and four multi-variable indices currently used in national monitoring and reporting frameworks. These indicators cover a broad range of ecological themes and reflect substantial heterogeneity in how countries monitor and report on forests.

Figure 3 shows that most indicators (24) relate to diversity of species (blue), including abundance of species, endangered species, endemic species, or introduced species among others. One or more of these indicators is used by 48 countries. 18 indicators relate to regeneration (yellow) comprising natural regeneration, planted regeneration, seeded regeneration, natural expansion, site-adapted regeneration, difficult-to-stock areas, areas with competition of tree saplings and herbal plants, among others. One or more of these indicators are used by 51 countries. 46 countries use one or more of the 15 structural diversity indicators (purple), such as old trees, large trees, horizontal layers, and canopy openness. Nearly all investigated countries (49) also report one or more of the 17 different indicators on protected forest areas (dark green). 45 countries report up to five different indicators on aspects of naturalness (light green). Only 12 countries report one or more of the six indicators on diversity of ecosystems (light blue). One or more of the 15 forest management-related indicators (brown) are part of the reporting of ten countries and include close-to-nature forest management, integrative forest management, agroforestry, and forest biodiversity management plans. Furthermore, five countries use one or more of the nine indicators that do not fit into any of the above topics.

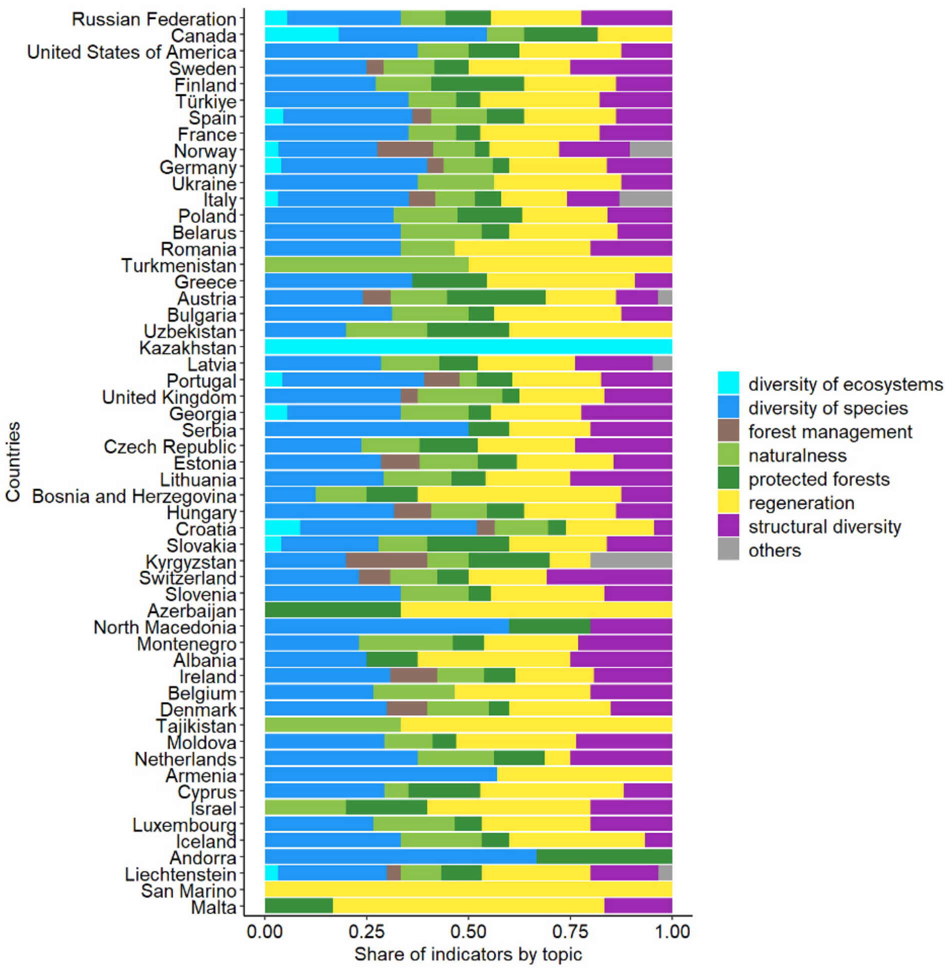


*Figure 3: Share of topics covered by the forest biodiversity-related indicators used in national monitoring and reporting across the UNECE countries. Countries are displayed in descending order of their forest area.*

Abbildung 3: Anteil der Themen, die von den Indikatoren Waldbiodiversität abgedeckt werden, die in den UNECE-Ländern für das nationale Monitoring und Berichterstattung verwendet werden. Die Länder sind in absteigender Reihenfolge ihrer Waldfläche aufgelistet.

### 3.1 Indicator types covered in the PSR framework

The classification of the 106 forest-biodiversity indicators and four indices according to the PSR framework revealed a high emphasis on State indicators (76; 72%), with fewer Response (19; 18%) and Pressure indicators (11; 10%) and only occasional use of aggregated indices (Figure 4).

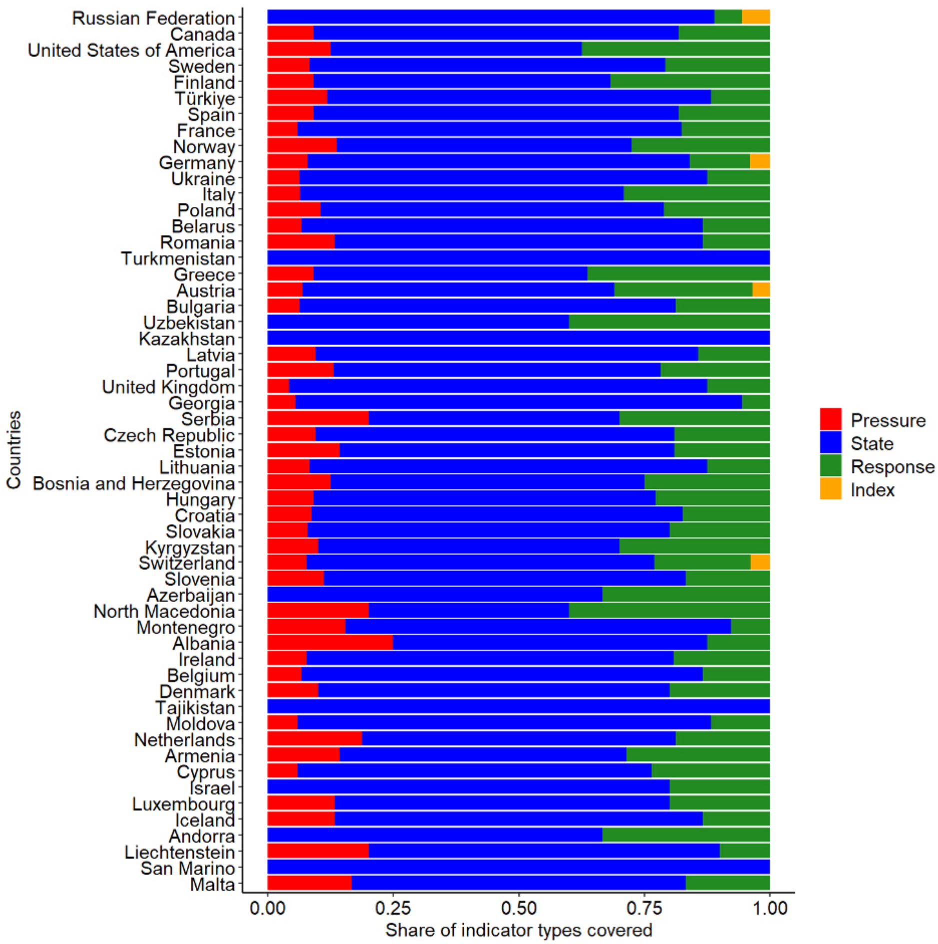


*Figure 4: Share of indicator types (Pressure, State, Response and Indices) within the forest biodiversity-related indicators of each UNECE country. Countries are sorted by decreasing forest area.*

Abbildung 4: Anteil der Indikatortypen (Belastung, Zustand, Reaktion und Indizes) der Indikatoren zur Waldbiodiversität in den UNECE Ländern. Die Länder sind nach absteigender Waldfläche aufgelistet.

Some countries reported no biodiversity-specific Pressure indicators such as invasive species, while Response indicators were more common. The imbalance reflects practical realities. State indicators are more feasible to monitor and report on, but they remain less valuable for forest policy and forest management decision-making. While State indicators describe current conditions, without complementary Pressure and Response indicators it is difficult to attribute changes to specific pressures, anticipate future trends or evaluate the effectiveness of interventions. Consequently, forest managers and decision-makers may overlook emerging risks (*e.g.* non-site-adapted or invasive tree species) or overestimate success when State indicators lag underlying dynamics. While maintaining a set of meaningful State indicators remains essential, strengthening Pressure indicators (*e.g.*, fragmentation, clear-cutting, invasive species) and Response indicators (*e.g.*, close-to-nature or integrative management practices, protected areas, genetic resources management, forest area with site-adapted tree species) would improve monitoring, assessment, and reporting. Rather than striving for equal shares, monitoring should ensure sufficient Pressure and Response indicators. Alongside the higher number of State indicators, these provide causal chains, early warnings and evidence of prevention or countermeasures.

## 3.2 Data review

We conducted a data review and coded data accessibility using six categories (Figure 5). The results revealed an abundance of data-centric indicators as most indicator data is reported in a publicly accessible data source offering previously unexplored insights into forest biodiversity reporting efforts. Almost all countries have some indicators for which data can be derived by using publicly available data and an established process such as the methods used by the European Environment Agency for fragmentation and/or a replicable approach from peer-reviewed data sources. Furthermore, there are a few indicators with potentially derivable data, meaning that although there is publicly available data, no established process is yet in place. This was particularly the case for Natura 2000-related indicators. About 80% of the countries report some indicators for which data are not publicly available but for which there are established processes to obtain the information, *e.g*. for the forest birds indicator. Half of the countries report few indicators with no established data collection process and no publicly available data. In most cases this is refers to old-growth-related indicators. In some cases, we also identified data deficiencies mainly concerning naturalness indicators. This means that the available data is insufficient, incomplete, or lack quality to support reliable analysis, conclusions, or decisions.

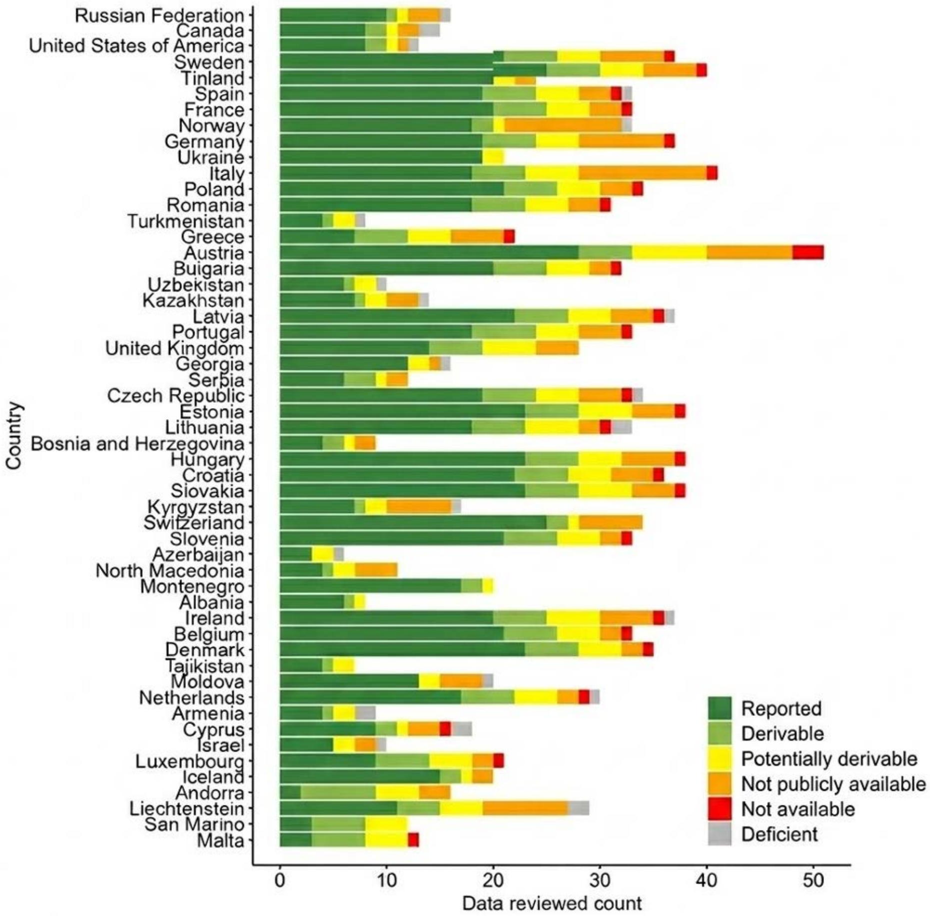


*Figure 5: Accessibility of national data for the forest-biodiversity indicators. Countries are sorted by decreasing forest area (Reported: Data is reported on a publicly accessible data source; Derivable: Data can be derived by using publicly accessible data and an established process; Potentially derivable: Data is potentially derivable and publicly available but no established process exists; Not publicly available: Data is not publicly available but established process exists, Not available: No established process and no publicly available data; Deficient: Data is deficient).*

Abbildung 5: Verfügbarkeit nationaler Daten für die Indikatoren zur Waldbiodiversität. Die Länder sind nach absteigender Waldfläche aufgelistet (Reported: Die Daten sind öffentlich zugänglich; Derivable: Die Daten lassen sich anhand öffentlich zugänglicher Daten und eines etablierten Verfahrens ableiten; Potentially derivable: Die Daten sind potenziell ableitbar und öffentlich verfügbar, es gibt jedoch kein etabliertes Verfahren; Not publicly available: Die Daten sind nicht öffentlich verfügbar, es gibt jedoch ein etabliertes Verfahren; Not available: Es gibt weder ein etabliertes Verfahren noch öffentlich verfügbare Daten; Deficient: Ungenügende Datenlage).

### 3.3 Climate change sensitivity of the indicators

Although one of several direct drivers of biodiversity loss, climate change serves in this study as a demonstrative lens through which the sensitivity and responsiveness of indicators can be assessed. Climate change-induced threats to forest ecosystems include rising temperatures, shifts in precipitation patterns leading to more frequent droughts, floods or pest outbreaks, and increased intensity of extreme events such as heat waves, severe storms, and devastating forest fires (Seidl *et al*., 2017; Seidl & Turner, 2022). Some forest biodiversity indicators are particularly sensitive to climate change impacts. Based on scholarly literature we categorised 16 of our investigated indicators as sensitive to climate change, either through direct effects, such as drought-induced mortality, altered regeneration success, or shifts in tree species composition, or as indirect effects, including changes in forest structure, habitat availability, and species interactions (Table 1). State indicators like diversity of tree species, abundance of habitat trees or structural attributes like deadwood and vertical structure, were found to be highly sensitive to both temperature and precipitation shifts (Allen *et al*., 2010; Coomes *et al*., 2014; Dyderski *et al*., 2018). Regeneration indicators are vulnerable because climate change influences the success of natural regeneration and site-adapted seeding or planting, particularly under increased drought frequencies. Naturalness indicators, such as native tree species, are sensitive to climatic changes that affect habitat suitability and competitive dynamics, triggering the replacement of native tree species by introduced tree species (Thom *et al*., 2023; Vacek et al., 2023; Walck *et al*., 2011). Forest birds indicators show strong indirect climate sensitivity, as changes in forest composition and structure are expected to affect avian habitat availability and food resources (Huntley *et al*., 2008; Labadie *et al*., 2025). Response indicators such as protected areas or adoption of close-to-nature forestry practices are designed to mitigate risks, but their effectiveness may be challenged if conservation targets and management strategies do not adapt to changes in species suitability and disturbance regimes (Araújo *et al*., 2011; Hoveka *et al*., 2022). Pressure indicators such as invasive species and forest fragmentation are likewise climate sensitive, as changing environmental conditions can facilitate the spread of non-native species and exacerbate habitat fragmentation (Ma *et al*., 2023; Puchałka *et al*., 2023). Table 1 presents indicators that are already impacted by climate change and will be affected further in the future. These indicators could therefore add value to forest biodiversity indicator sets that also address climate change issues. However, our findings regarding data accessibility for these indicators are less promising (Figure 5). Regarding data that is reported or that can be derived with an established process, only a few indicators stand out. A wealth of data is available for fragmentation. Further indicators with mixed but rather promising data accessibility include Diversity of tree species, Forests with native tree species, Introduced tree species, Protected forest areas, Deadwood, and Forest area by natural regeneration. By contrast, data accessibility is poor for Abundance of habitat trees, Naturally difficult-to-stock forest areas, Native tree species - of which site adapted, Forest birds, Planting of native broadleaved tree species, Structure of forest stands by layers, Forest area deviating from potential natural vegetation, Area and share of close-to-nature forestry, and Old growth forests (Table 1, Figure 5). However, such information is high on the political agenda, for instance, of the European Commission (O'Brien *et al*., 2021).

*Table 1: Climate change sensitivity of selected indicators and their data accessibility in 55 UNECE countries (except Monaco). Reported: Data is reported on a publicly accessible data source; Derivable: Data can be derived by using publicly accessible data and an established process; Potentially derivable: Data is potentially derivable and publicly available but no established process exists; Not publicly available: Data is not publicly available but established process exists, Not available: No established process and no publicly available data; Deficient: Data is deficient.*

Tabelle 1: Klimasensitivität ausgewählter Indikatoren und Verfügbarkeit der entsprechenden Daten in 55 UNECE-Ländern (außer Monaco). Reported: Die Daten sind öffentlich zugänglich; Derivable: Die Daten lassen sich anhand öffentlich zugänglicher Daten und eines etablierten Verfahrens ableiten; Potentially derivable: Die Daten sind potenziell ableitbar und öffentlich verfügbar, es gibt jedoch kein etabliertes Verfahren; Not publicly available: Die Daten sind nicht öffentlich verfügbar, es gibt jedoch ein etabliertes Verfahren; Not available: Es gibt weder ein etabliertes Verfahren noch öffentlich verfügbare Daten; Deficient: Ungenügende Datenlage.

| **PSR** | **Indicator and measurement unit(s)** | **Data accessibility by number of countries** | **Climate change sensitivity** | **References** |
|---|---|---|---|---|
| Pressure | Fragmentation size of a continuous forest area (km²) | 1 Reported<br>37 Derivable<br>17 Deficient | Climate change can exacerbate forest fragmentation through disturbances. Larger continuous areas are more resilient to the impacts of climate change. | Corlett, 2014; Ma et al., 2023; Opdam & Wascher, 2004 |
| Pressure | Introduced tree species (ha)<br>-of which invasive | 28 Reported<br>27 Deficient | Climate change can facilitate the spread of introduced tree species, which may become invasive and outcompete native tree species. | Dale et al., 2001; Langmaier & Lapin, 2020; Muys et al., 2022; Puchałka et al., 2023; Simberloff, 2000; Vacek et al., 2023 |
| Pressure | Naturally difficult-to-stock forest areas (ha, %) | 1 Not publicly available<br>54 Deficient | Climate change can make it more difficult to regenerate certain forest areas, resulting in an increase in the size of forest areas without forest cover. | Domevscik, 2024; Vacek et al., 2023 |
| State | Abundance of habitat trees (number per ha) | 55 Deficient | Habitat trees are sensitive to climate change (rising temperatures, altered precipitation patterns) which can affect their growth and survival. | Allen et al., 2010; Linser et al., 2026 |
| State | Diversity of tree species (Area with 1, 2-3, 4-5, 6+ tree species occurring) | 29 Reported<br>1 Derivable<br>2 Not publicly available<br>23 Deficient | Climate change can influence the number of tree species that can thrive in an area. It can further alter tree species composition. | Allen et al., 2010; Dyderski et al., 2018; Morin et al., 2018 |
| State | Forests with native tree species (ha, %) | 28 Reported<br>1 Not publicly available<br>1 Not available<br>25 Deficient | Changes in climate can alter the suitability of forest habitats for native tree species, impacting the naturalness of forests. | Dyderski et al., 2018; Lexer et al., 2000; Linser et al., 2026 |
| State | Native tree species (ha, %)<br>-of which site adapted | 6 Not available<br>49 Deficient | Native tree species may be more vulnerable to climate change as they often have specific habitat requirements. The promotion of native site-adapted tree species is becoming increasingly important to face climate change. | Allen et al., 2010; Attorre et al., 2011; Dyderski et al., 2018; Linser et al., 2026; Millar et al., 2007; Vacek et al., 2023 |

| PSR | Indicator and measurement unit(s) | Data accessibility by number of countries | Climate change sensitivity | References |
|---|---|---|---|---|
| State | Forest bird species (number, %) | 3 Reported<br>1 Potentially derivable<br>6 Not publicly available<br>45 Deficient | Climate change induced changes in forest composition and structure can impact the availability of suitable habitats for forest birds. For example, there may be fewer coniferous stands and food sources, which can influence their populations. | Huntley et al., 2008; Labadie et al., 2025; Linser et al., 2026; Virkkala, 2016 |
| State | Forest area by natural regeneration (ha) | 23 Reported<br>32 Deficient | The success of natural forest regeneration which is not site-adapted can be negatively influenced, in particular by higher temperatures, reduced soil moisture, competition through invasive species or forest fires. | Langmaier & Lapin, 2020; Linser et al., 2026; Splawinski et al., 2019; Stevens-Rumann et al., 2022; Thom et al., 2023; Walck et al., 2011 |
| State | Planting of broadleaved tree species (ha) | 2 Not publicly available<br>53 Deficient | Broadleaved tree species regeneration in former conifer-dominated stands can potentially counteract the negative effects of climate change, particularly if they are site-adapted. | Götmark et al., 2005; Harmer & Morgan, 2009 |
| State | Structure of forest stands classified according to number of layers (ha) | 4 Not available<br>51 Deficient | Climate change can alter the vertical and horizontal forest stand structure by altering species composition, slowing growth, and increasing disturbances. Forest stands with rich structural diversity are generally more resilient, while single-layer stands are more vulnerable to the impacts of climate change. | Allen et al., 2010; Coomes et al., 2014; Dobor et al., 2020 |
| State | Area and share of old growth forests by forest types (ha, %) | 27 Not available<br>28 Deficient | Large, old trees, which are typically found for in old growth forests, often appear to be more prone to drought-induced mortality, which can affect their stability and their role for biodiversity. As these forests have specific microclimates, stand structures and species compositions, disruptions caused by climate change can severely impact their health and survival. | Floyd et al., 2009; Mueller et al., 2005; Thom et al., 2019 |
| State | Deadwood -Standing and lying deadwood ($m^3$/ha) | 24 Reported<br>31 Deficient | Increased storm intensities and severe droughts, will raise tree mortality and impact deadwood dynamics, altering decomposition rates, deadwood accumulation, and saproxylic habitats. | Allen et al., 2010; Augustynczik et al., 2024; Chagnon et al., 2022; Muys et al., 2022; Linser et al., 2026 |
| State | Forest area deviating from the potential natural vegetation (ha) | 3 Not publicly available<br>52 Deficient | Climate change can cause shifts in species composition towards other provenances or more site-adapted introduced species, impacting forest naturalness. | Enríquez-de-Salamanca, 2025; Lexer et al., 2000; Lindner et al., 1997; Millar et al., 2007; Simberloff, 2000 |

| PSR | Indicator and measurement unit(s) | Data accessibility by number of countries | Climate change sensitivity | References |
|---|---|---|---|---|
| Response | Protected forest areas (ha) | 27 Reported<br>1 Not publicly available<br>27 Deficient | Protected forest areas are at risk of losing those tree species and other species they were originally established to protect. Climate change may cause many species to shift their ranges, which will often not be possible within the boundaries of these protected areas. | Andrew et al., 2014; Araújo et al., 2011; Hoffmann et al., 2019; Hoveka et al., 2022; Linser et al., 2026 |
| Response | Area and share of close-to-nature forestry (ha, %) | 2 Not publicly available<br>53 Deficient | Close-to-nature forest management systems will be less affected by climate change-induced extreme weather events, pests and diseases. | Blattert et al., 2024; Dobor et al., 2020 |

## 3.4 Revision of existing indicator sets based on our investigations

This subsection demonstrates how the indicator pool and analyses (PSR typology, data accessibility, climate sensitivity) were used to revise the existing sets of forest biodiversity indicators of the Forest Europe process and that of Austria. In both cases the focus was not on revising the entire set of indicators, but rather on revising the forest biodiversity indicators that were weak with respect to feasible data collection procedures. We applied the following workflow:

(i) identification of current EU policy priorities (*e.g.*, halting biodiversity loss, increasing resilience against climate change, and protecting old-growth forests),
(ii) displaying causal chains with the PSR indicator category assignment to strengthen the Pressure and Response coverage,
(iii) prioritising climate-sensitive indicators,
(iv) screening for data accessibility and feasibility, and
(v) participatory stakeholder co-design to ensure ownership and uptake.

Our findings were used to initiate the revision of the forest biodiversity-related indicators of the Forest Europe process. This resulted in a Forest Europe background paper on the potential for revision of the biodiversity-related indicators of the pan-European set of indicators for sustainable forest management (Linser, 2024). The indicator revision process is ongoing. Our results also supported the recently completed revision of Austria's national forest biodiversity indicators within the sustainable forest management indicator set. This revision was conducted as part of a broad participatory stakeholder process (Linser *et al*., 2026). To facilitate the selection of indicators for improved forest biodiversity monitoring under future biodiversity scenarios, the following selection criteria were applied:

- Climate change sensitivity: prioritise indicators with demonstrated responsiveness to temperature, precipitation, drought, disturbances.

- Causal-chain coverage: ensure that the indicators cover Pressure, State, and Response indicators.

- Sensitivity to forest management: select indicators that are directly actionable (*e.g.*, site-adapted species, genetic resource management).

- Policy relevance: select indicators that are aligned with current policy goals and instruments (*e.g.* old-growth protection, restoration, secure genetic resources).

- Early-warning indicators: include indicators which allow to observe considerable climate change impacts (*e.g.* invasive species expansion).

- Data accessibility and scalability: favour indicators with feasible, reproducible methods and the potential to scale down from national to local or regional level.

- Spatial connectivity and landscape context: include indicators of habitat connectivity or stepping stones to consider species migration possibilities.

In the case of Austria, ten of twelve already existing forest biodiversity indicators were amended with climate-sensitive sub-indicators and three additional indicators (Table 1 and 2). Monitoring and reporting of the Austrian forest biodiversity indicators is based on a combination of national forest inventory and remote sensing. Only indicators and sub-indicators for which a feasible data collection procedure is already in place or can be established in the near future, were amended. This approach demonstrates how climate-sensitive and data-feasible revisions can translate scientific insights into actionable monitoring under future biodiversity scenarios. Our workflow can also be transferred to other UNECE countries or regional indicator processes like Forest Europe or the Montréal Process.

*Table 2: Austrian forest biodiversity-related indicators and sub-indicators and the complemented indicators and sub-indicators.*

Tabelle 2: Indikatoren und Sub-Indikatoren zur biologischen Vielfalt in österreichischen Wäldern sowie die ergänzten Indikatoren und Sub-Indikatoren.

| **Indicators** | **Sub-indicators** | **Complemented indicators and sub-indicators** |
|---|---|---|
| Tree species composition | Tree species (ha, %)<br>Shrub species (ha, %) | Native tree species (ha, %)<br>Non-native tree species (ha, %)<br>Site-adapted tree species (ha, %) |
| Regeneration | Natural regeneration (ha, %)<br>Regeneration by seeding (ha, %)<br>Regeneration by planting (ha, %) | Coppice (ha, %)<br>Afforestation (ha, %)<br>Natural extension (ha, %)<br>Number of regenerated tree species<br>Regeneration with site-adapted tree species (ha, %) |
| Naturalness | Undisturbed by man (ha, %)<br>Plantations (ha, %) | Semi-natura forests (ha, %)<br>Primary forests (ha, %)<br>Old-growth forests (ha, %) |

| Indicators | Sub-indicators | Complemented indicators and sub-indicators |
|---|---|---|
| Introduced tree species | Invasive tree species (ha, %)<br>Invasive herb species (ha, %)<br>Uptake of funding to prevent the spread of invasive species (%) | Invasive species in protected forest areas (ha, %) |
| Deadwood | Standing deadwood ($m^3$/ha)<br>Lying deadwood ($m^3$/ha) | Standing or lying deadwood, broken down by:<br>-in forests available for wood supply ($m^3$/ha)<br>-in protective forests ($m^3$/ha)<br>-by forest types ($m^3$/ha)<br>-broadleaved deadwood ($m^3$/ha)<br>-conifer deadwood ($m^3$/ha) |
| Genetic resources | Area managed for conservation and utilisation of forest tree genetic resources (in situ and ex situ) (ha) | Effective size of populations, broken down by:<br>-estimated total census population size (No adult individuals)<br>-registered harvesting stands (No)<br>-populations protected in gene conservation forests (No)<br>- clones in seed orchards (No)<br>-sites for genetic monitoring (No) |
| Fragmentation/ Connectivity | Connected forest areas (ha) | Forest area density (%)<br>Stepping stone habitats (ha, %) |
| Threatened forest species | Trees (No)<br>Vascular plants (including trees) (No)<br>Cryptogams (No) | |
| Protected forest areas (PFA) | PFA broken down by:<br>-no active intervention (ha, %)<br>-Minimal intervention (ha, %)<br>-protection through active management (ha, %)<br>-protection of landscapes/ natural features (ha, %) | Protection through active management (ha, %), broken down by:<br>-protection through active management with specifically defined measures that clearly enhance biodiversity conservation<br>-protection through specific objectives, but without specifically defined measures |
| | | Common forest birds (Index, %) |
| Natura 2000 | Implementation of conservation measures in Natura 2000 sites<br>Uptake of the Natura 2000 funding (%)<br>Conservation status of forest habitats (%) | Conservation status of forest species (%) |
| Contract-based nature conservation | | Contract-based nature conservation, broken down by:<br>-Natural forest reserves (ha, %)<br>-Nature conservation areas (ha, %)<br>-Natural forest areas (only in Styria) (ha, %)<br>-Stepping-stone habitats (ha, %) |
| Natural forest reserves (No, ha) | | |
| | | Habitat trees (No/ha) |
| | | Structural complexity and tree species diversity (Index, %) |

## 4 Discussion

This study provides the first comprehensive synthesis of forest biodiversity indicators used across the UNECE region, revealing substantial thematic breadth but persistent structural weaknesses in indicator portfolios. The large number of State indicators reported by most countries reflects the long-standing reliance on national forest inventories and established monitoring traditions. While State indicators are essential for tracking ecosystem conditions, their dominance limits the ability to interpret causality, detect emerging ecological risks, or evaluate management effectiveness. The comparatively low representation of Pressure and Response indicators is particularly concerning in the context of accelerating climate change and biodiversity loss, where understanding the drivers of change and assessing the effectiveness of management interventions are central to adaptive forest policy and practice. Current policy discussions highlight the need for new, policy-relevant data on management approaches and their measurable impacts on forest biodiversity, underscoring the importance of expanding the coverage of management-related Response indicators. Strengthening Pressure indicators (*e.g.*, fragmentation, invasive species, failed regeneration) and Response indicators (*e.g.*, adoption of close-to-nature or integrated forest management, genetic resources management) would move monitoring beyond description towards measures to prevent or mitigate biodiversity risks and to better adapt forests to climate change. Also, within the framework of the UN Decade on Ecosystem Restoration, the relevance of Response indicators has gained renewed importance. Response indicators are essential for tracking conservation and restoration efforts, including the designation of protected areas or the implementation of biodiversity-friendly forestry practices. Moreover, when linked to ecological outcomes, such as species recovery or habitat restoration, these indicators can serve not only to measure management actions but also to evaluate success. This dual role enhances their value in designing, implementing, and assessing conservation or restoration policies aligned with global biodiversity and climate commitments.

Data accessibility varies substantially. Several frequently occurring indicators - such as diversity of tree species, forests with native species, introduced species, protected areas, deadwood, and natural regeneration - have comparatively better publicly available data or established data derivation methods. In contrast, indicators high on the political agenda, particularly old-growth forests, habitat trees or forest birds often lack publicly available data or standardised collection protocols, creating a critical gap between policy demand and monitoring capacity.

The sensitivity of forest biodiversity indicators to climate change cuts across indicator categories. State indicators related to tree species composition, structural attributes (deadwood, vertical/horizontal structure), and regeneration are responsive to temperature and precipitation shifts, disturbance regimes, and indirect habitat change. Importantly, climate-driven changes can be positive or negative depending on local context and ecosystem resilience: some species may expand or thrive under new conditions while others may decline, and forest structure may become more complex or simplified as disturbance regimes change. Species diversity and the composition of tree species are expected to undergo significant shifts under climate change (Leidinger *et al*., 2021; Mundra *et al*., 2022; Puchałka *et al*., 2023), as altered temperature and precipitation regimes modify the climate envelopes suitable for different species. This may lead to local extinctions of less adaptable species and range shifts of more resilient ones. As a result, forests may become less diverse, or the composition of tree species may change. This challenges traditional conservation or management strategies based on species that were favoured in the past. Currently, many indicators derived from forest inventories offer only a coarse view of these dynamics. They are typically limited to structural or compositional features and often lack the taxonomic resolution needed to detect species-specific trends or climate-sensitive responses. One potential improvement is the inclusion of multi-taxa indicators, which could better capture the nuanced ecological shifts expected over the coming decades (Burrascano *et al*., 2021). However, the practical application of such indicators is constrained by the limitations of traditional forest inventory data, which are usually collected on multi-year cycles and not timed to capture seasonally dependent taxa such as fungi, birds, or herbaceous plants. Notably, deadwood illustrates the need to move beyond monitoring only its volume: climate-driven changes in decomposition and moisture regimes can reduce saproxylic biodiversity even when volumes rise (Seibold *et al*., 2021), underscoring the importance of deadwood quality and species-specific responses to climate-driven changes (Oettel *et al*., 2020). Similarly, indicators linked to naturalness (native species presence, site-adapted species) and species groups (forest birds) capture indirect climate impacts through altered habitat suitability and food webs.

To address feasibility constraints national monitoring systems should integrate cost-efficient, scalable methods alongside traditional National Forest Inventories: remote sensing for species diversity and forest structure, geospatial analytics for connectivity, environmental DNA for multi-taxa detection, and automated bioacoustics for birds and bats (Dyson *et al*., 2024; Ladin *et al*., 2021; Mutanu *et al*., 2022; Teixeira *et al*., 2022). These emerging technologies hold significant promise for providing near-real-time, species-specific data that are essential for understanding climate change impacts and informing timely conservation and restoration strategies. By further developing indicators and integrating these novel technologies, monitoring can better support evidence-based decision-making and catalyse effective conservation and management for present and future generations. However, while these approaches are promising, their widespread implementation faces challenges. Those include technical validation, standardization, and integration into national forest monitoring frameworks. Continued research and applied pilot studies are needed to bridge this gap and facilitate their uptake into policy-relevant biodiversity assessments. Overall, our study shows that novel, not yet widely used indicators can significantly improve the monitoring of forest biodiversity status and change. Specifically, indicators derived from environmental DNA, automated bioacoustics, and advanced remote sensing enhance taxonomic resolution, temporal sensitivity, and spatial coverage compared to measures of traditional forest inventories. Early-warning indicators, such as regeneration failure under drought, invasive species expansion or declines in saproxylic biodiversity, provide signals of change. While validation and standardisation are required, these indicators offer demonstrable advantages in detecting trends, attributing pressures, and guiding timely management responses.

Forest management indicators are pivotal across PSR categories as they provide critical insights on the interactions between human activities and forest ecosystems. Their classification depends on context: clearcutting and afforestation with single tree species or non-site adapted tree species serve Pressure indicators, highlighting anthropogenic stressors that degrade habitat quality. Structural characteristics of management (*e.g.*, Mixed stands, Old or Habitat trees) describe the current state of biodiversity linked to past management practices; biodiversity-oriented practices (Close-to-nature forestry, Integrative forest management, Management plans) constitute Response indicators tracking societal efforts to mitigate pressures and maintain or restore ecological functions. Through targeted, standardised data collection the evidence base can be expanded on how specific management approaches influence biodiversity outcomes and thus support addressing identified policy need for management-impact information. More systematic integration of management indicators across PSR would better reflect socio-ecological dynamics and support the evaluation of management effectiveness under climate change.

Finally, the abundant State indicators and accessible datasets present an untapped opportunity for predictive modelling. Using State indicators as training information for models simulating different future forest management or climate adaptation scenarios would support early warning systems and targeted decision-making. Coupling such models with improved Pressure and Response coverage - and with climate-sensitive prioritization - aligns monitoring with policy needs and enhances the utility of indicators for adaptive management.

## 4.1 Limitations and future research needs

Although this study provides the most comprehensive synthesis of forest biodiversity indicators across the UNECE region, several limitations must be noted. National reporting systems differ widely in scope, definitions, and data accessibility, with gaps for indicators such as old-growth forests, habitat trees, naturalness, and species groups. The PSR classification and climate-sensitivity assessment are likewise constrained by uneven data accessibility, limiting causal inference and full comparability across countries. Moreover, emerging indicators based on remote sensing (*e.g.* forest structure, composition, connectivity), environmental DNA (*e.g.* forest species, genetic material), or automated bioacoustics (forest birds) are not yet systematically integrated into national monitoring systems and thus remain underrepresented. Future work should therefore prioritise improving methodological comparability and validating novel data sources to support more coordinated and climate-sensitive biodiversity monitoring.

## 5 Conclusions

Forest biodiversity monitoring in the UNECE region is based on a large pool of indicators. State indicators dominate, while Pressure and Response indicators are less applied, limiting causal interpretation and proactive management. Closing this gap, particularly by using climate-sensitive Pressure and Response indicators will align monitoring with policy needs and improve the capacity to anticipate and mitigate climate change risks. Data accessibility remains a key bottleneck for indicators that are high on the political agenda such as old-growth forests. Establishing standardised monitoring protocols and publicly available reporting pathways are essential to bridge the policy-monitoring divide. Prioritising climate-sensitive indicators and refining measurement frameworks, for example, moving beyond deadwood volume to include decomposition rates, will better capture ecological change. Integrating remote sensing, environmental DNA, and automated bioacoustics in traditional National Forest Inventories can deliver scalable, timely insights. By harnessing the predictive potential of indicators through scenario modelling, forest biodiversity monitoring can shift from retrospective reporting to proactive decision support, improving adaptation outcomes under accelerating environmental change. Our study demonstrates that the uptake of untapped treasures of forest biodiversity indicators which are novel and have not yet been widely applied, can substantially improve reporting on forest biodiversity in the face of accelerating climate change.

## Author contributions: CRediT

Stefanie Linser: Conceptualization, Methodology, Data curation, Formal analysis, Writing- Original draft, Writing- Reviewing and Editing, Funding acquisition; Katharina Lapin: Formal analysis, Writing- Original draft, Writing- Reviewing and Editing, Funding acquisition.

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## Declaration of generative AI in scientific writing

The authors declare that they did not use generative AI to analyse the data or to write the manuscript. Generative AI tools were used solely for linguistic editing of the manuscript.

## Declaration of competing interests

Both authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the study.

## Supplementary Material

Supplementary A: Survey results. Available on Zenodo at: https://doi.org/10.5281/zenodo.20615365

Supplementary B: Indicator Matrix. Available on Zenodo at: https://doi.org/10.5281/zenodo.20615566

## References

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E.H. (Ted), Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.-H., Allard, G., Running, S.W., Semerci, A., & Cobb, N. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management, 259(4), 660–684. https://doi.org/10.1016/j.foreco.2009.09.001

Andrew, M.E., Wulder, M.A., & Cardille, J.A. (2014). Protected areas in boreal Canada: A baseline and considerations for the continued development of a representative and effective reserve network. Environmental Reviews, 22(2), 135–160. https://doi.org/10.1139/er-2013-0056

Araújo, M.B., Alagador, D., Cabeza, M., Nogués-Bravo, D., & Thuiller, W. (2011). Climate change threatens European conservation areas: Climate change threatens conservation areas. Ecology Letters, 14(5), 484–492. https://doi.org/10.1111/j.1461-0248.2011.01610.x

Attorre, F., Alfò, M., De Sanctis, M., Francesconi, F., Valenti, R., Vitale, M., & Bruno, F. (2011). Evaluating the effects of climate change on tree species abundance and distribution in the Italian peninsula: Evaluating the effects of climate change on tree species abundance and distribution. Applied Vegetation Science, 14(2), 242–255. https://doi.org/10.1111/j.1654-109X.2010.01114.x

Augustynczik, A.L.D., Gusti, M., Di Fulvio, F., Lauri, P., Forsell, N., & Havlík, P. (2024). Modelling the effects of climate and management on the distribution of deadwood in European forests. Journal of Environmental Management, 354, 120382. https://doi.org/10.1016/j.jenvman.2024.120382

Balvanera, P., Siddique, I., Dee, L., Paquette, A., Isbell, F., Gonzalez, A., Byrnes, J., O'Connor, M.I., Hungate, B.A., & Griffin, J.N. (2014). Linking Biodiversity and Ecosystem Services: Current Uncertainties and the Necessary Next Steps. BioScience, 64(1), 49–57. https://doi.org/10.1093/biosci/bit003

Blattert, C., Mutterer, S., Thrippleton, T., Diaci, J., Fidej, G., Bont, L.G., & Schweier, J. (2024). Managing European Alpine forests with close-to-nature forestry to improve climate change mitigation and multifunctionality. Ecological Indicators, 165, 112154. https://doi.org/10.1016/j.ecolind.2024.112154

Burrascano, S., Trentanovi, G., Paillet, Y., Heilmann-Clausen, J., Giordani, P., Bagella, S., Bravo-Oviedo, I., … Ódor, P. (2021). Handbook of field sampling for multi-taxon biodiversity studies in European forests. Ecological Indicators, 132, 108266. https://doi.org/10.1016/j.ecolind.2021.108266

Butchart, S.H.M., Walpole, M., Collen, B., Van Strien, A., Scharlemann, J.P.W., Almond, R.E.A., Baillie, … Watson, R. (2010). Global Biodiversity: Indicators of Recent Declines. Science, 328(5982), 1164–1168. https://doi.org/10.1126/science.1187512

Calders, K., Jonckheere, I., Nightingale, J., & Vastaranta, M. (2020). Remote Sensing Technology Applications in Forestry and REDD+. Forests, 11(2), 188. https://doi.org/10.3390/f11020188

CBD (2010). Strategic Plan for Biodiversity 2011–2020, including Aichi Biodiversity Targets. Secretariat of the Convention on Biological Diversity. https://www.cbd.int/sp/

CBD (2020). Global Biodiversity Outlook 5. https://www.cbd.int/gbo/gbo5/publication/gbo-5-en.pdf

CBD (2022). Monitoring framework for the Kunming-Montreal Global Biodiversity Framework, CBD/COP/DEC/15/5. UN, Montreal, Canada. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-05-en.pdf

Chagnon, C., Moreau, G., Bombardier-Cauffopé, C., Barrette, J., Havreljuk, F., & Achim, A. (2022). Broad-scale wood degradation dynamics in the face of climate change: A meta-analysis. GCB Bioenergy, 14(8), 941–958. https://doi.org/10.1111/gcbb.12951

Chirici, G., Winter, S., & McRobert, R.E. (2011). National forest inventories: Contributions to forest biodiversity assessments. Springer Science & Business Media.

Clark, J.S., Bell, D.M., Hersh, M.H., & Nichols, L. (2011). Climate change vulnerability of forest biodiversity: Climate and competition tracking of demographic rates: FORESTS, CLIMATE CHANGE, AND COMPETITION. Global Change Biology, 17(5), 1834–1849. https://doi.org/10.1111/j.1365-2486.2010.02380.x

Coomes, D.A., Flores, O., Holdaway, R., Jucker, T., Lines, E.R., & Vanderwel, M. C. (2014). Wood production response to climate change will depend critically on forest composition and structure. Global Change Biology, 20(12), 3632–3645. https://doi.org/10.1111/gcb.12622

Corlett, R.T. (2014). Forest fragmentation and climate change. In Global forest fragmentation (pp. 69–78). Wallingford.

Dale, V.H., Joyce, L.A., Mcnulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J., Irland, L.C., …& Wotton, B.M. (2001). Climate Change and Forest Disturbances. BioScience, 51(9), 723. https://doi.org/10.1641/0006-3568(2001)051[0723:CCAFD]2.0.CO;2

Dobor, L., Hlásny, T., & Zimová, S. (2020). Contrasting vulnerability of monospecific and species-diverse forests to wind and bark beetle disturbance: The role of management. Ecology and Evolution, 10(21), 12233–12245. https://doi.org/10.1002/ece3.6854

Domevscik, M. (2024). Adapting forest regeneration to a changing climate: 2024:75. Swedish University of Agricultural Sciences. https://doi.org/10.54612/a.7edllms851

Dyderski, M.K., Paź, S., Frelich, L.E., & Jagodziński, A.M. (2018). How much does climate change threaten European forest tree species distributions? Global Change Biology, 24(3), 1150–1163. https://doi.org/10.1111/gcb.13925

Dyson, K., Nicolau, A.P., Tenneson, K., Francesconi, W., Daniels, A., Andrich, G., Caldas, B., Castaño, S., … Saah, D. (2024). Coupling remote sensing and eDNA to monitor environmental impact: A pilot to quantify the environmental benefits of sustainable agriculture in the Brazilian Amazon. PLOS ONE, 19(2), e0289437. https://doi.org/10.1371/journal.pone.0289437

Enríquez-de-Salamanca, Á. (2025). Expected Impacts on Mediterranean Forest Species Under Climate Change. Climate, 13(2), 41. https://doi.org/10.3390/cli13020041

FAO (2022). The State of the World's Forests 2022. Forest pathways for green recovery and building inclusive, resilient and sustainable economies. FAO. https://doi.org/10.4060/cb9360en

Floyd, M.L., Clifford, M., Cobb, N.S., Hanna, D., Delph, R., Ford, P., & Turner, D. (2009). Relationship of stand characteristics to drought-induced mortality in three Southwestern piiion- juniper woodlands. Ecological Applications, 19(5), 1223–1230.

Forest Europe (2020). State of Europe's Forests 2020. Edited by M. Köhl, S. Linser, K. Prins. Forest Europe Liaison Unit Bratislava. https://foresteurope.org/wp-content/uploads/2016/08/SoEF_2020.pdf

Forest Europe (2021). All Forest Europe Commitments until 2021 (p. 176). Liaison Unit Bratislava. https://foresteurope.org/wp-content/uploads/2017/08/ALL_COMMITMENTS.pdf

Gao, T., Nielsen, A.B., & Hedblom, M. (2015). Reviewing the strength of evidence of biodiversity indicators for forest ecosystems in Europe. Ecological Indicators, 57, 420–434. https://doi.org/10.1016/j.ecolind.2015.05.028

Götmark, F., Fridman, J., Kempe, G., & Norden, B. (2005). Broadleaved tree species in conifer-dominated forestry: Regeneration and limitation of saplings in southern Sweden. Forest Ecology and Management, 214(1–3), 142–157. https://doi.org/10.1016/j.foreco.2005.04.001

Hagan, J.M., & Whitman, A.A. (2006). Biodiversity indicators for sustainable forestry: Simplifying complexity. Journal of Forestry, 104, 203–210.

Harmer, R., & Morgan, G. (2009). Storm damage and the conversion of conifer plantations to native broadleaved woodland. Forest Ecology and Management, 258(5), 879–886. https://doi.org/10.1016/j.foreco.2009.03.023

Hill, S.L.L., Arnell, A., Maney, C., Butchart, S.H.M., Hilton-Taylor, C., Ciciarelli, C., Davis, C., Dinerstein, E., Purvis, A., & Burgess, N. D. (2019). Measuring Forest Biodiversity Status and Changes Globally. Frontiers in Forests and Global Change, 2, 70. https://doi.org/10.3389/ffgc.2019.00070

Hoffmann, S., Irl, S.D.H., & Beierkuhnlein, C. (2019). Predicted climate shifts within terrestrial protected areas worldwide. Nature Communications, 10(1), 4787. https://doi.org/10.1038/s41467-019-12603-w

Hoveka, L.N., Van Der Bank, M., & Davies, T. . (2022). Winners and losers in a changing climate: How will protected areas conserve red list species under climate change? Diversity and Distributions, 28(4), 782–792. https://doi.org/10.1111/ddi.13488

Huntley, B., Collingham, Y.C., Willis, S.G., & Green, R.E. (2008). Potential Impacts of Climatic Change on European Breeding Birds. PLoS ONE, 3(1), e1439. https://doi.org/10.1371/journal.pone.0001439

IPBES (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. https://doi.org/10.5281/ZENODO.3831673

Labadie, G., Boulanger, Y., Drapeau, P., Stralberg, D., & Tremblay, J.A. (2025). Projecting bird assemblage responses to climate-driven changes in managed boreal forest landscapes of Québec. Biological Conservation, 302, 110956. https://doi.org/10.1016/j.biocon.2024.110956

Ladin, Z.S., Ferrell, B., Dums, J.T., Moore, R.M., Levia, D.F., Shriver, W.G., D'Amico, V., Trammell, T.L.E., Setubal, J.C., & Wommack, K.E. (2021). Assessing the efficacy of eDNA metabarcoding for measuring microbial biodiversity within forest ecosystems. Scientific Reports, 11(1), 1629. https://doi.org/10.1038/s41598-020-80602-9

Langmaier, M., & Lapin, K. (2020). A Systematic Review of the Impact of Invasive Alien Plants on Forest Regeneration in European Temperate Forests. Frontiers in Plant Science, 11, 524969. https://doi.org/10.3389/fpls.2020.524969

Latifi, H., & Valbuena, R. (2019). Current Trends in Forest Ecological Applications of Three-Dimensional Remote Sensing: Transition from Experimental to Operational Solutions? Forests, 10(10), 891. https://doi.org/10.3390/f10100891

Leidinger, J., Blaschke, M., Ehrhardt, M., Fischer, A., Gossner, M.M., Jung, K., Kienlein, S., Kózak, J., Michler, B., Mosandl, R., Seibold, S., Wehner, K., & Weisser, W.W. (2021). Shifting tree species composition affects biodiversity of multiple taxa in Central European forests. Forest Ecology and Management, 498, 119552. https://doi.org/10.1016/j.foreco.2021.119552

Leung, B., & Gonzalez, A. (2024). Global monitoring for biodiversity: Uncertainty, risk, and power analyses to support trend change detection. Science Advances, 10(7), eadj1448. https://doi.org/10.1126/sciadv.adj1448

Lexer, M., Hönninger, K., Scheifinger, H., Matulla, C., Groll, N., & Kromp-Kolb, H. (2000). The sensitivity of central European mountain forests to scenarios of climatic change: Methodological frame for a large-scale risk assessment. Silva Fennica, 34(2). https://doi.org/10.14214/sf.635

Lier, M., Köhl, M., Korhonen, K.T., Linser, S., & Prins, K. (2021). Forest relevant targets in EU policy instruments—Can progress be measured by the pan-European criteria and indicators for sustainable forest management? Forest Policy and Economics, 128, 102481. https://doi.org/10.1016/j.forpol.2021.102481

Lier, M., Köhl, M., Korhonen, K.T., Linser, S., Prins, K., & Talarczyk, A. (2022). The New EU Forest Strategy for 2030: A New Understanding of Sustainable Forest Management? Forests, 13(2), 245. https://doi.org/10.3390/f13020245

Lier, M., Schuck, A., Van Brusselen, J., Derks, J., Parviainen, J., Bastrup-Birk, A., Gasparini, P., Bozzano, M., Oggioni, S. D., Raši, R., Vogt, P., Biala, K., Köhl, M., Konczal, A., de Konig, J., Alberdi, I., Voříšek, P., Schwarz, M., & Linser, S. (2020). Criterion 4: Maintenance, Conservation and Appropriate Enhancement of Biological Diversity in Forest

Ecosystems. In State of Europe's Forests 2020. Forest Europe Liaison Unit Bratislava. https://foresteurope.org/wp-content/uploads/2016/08/SoEF_2020.pdf

Lindner, M., Bugmann, H., Lasch, P., Flechsig, M., & Cramer, W. (1997). Regional impacts of climatic change on forests in the state of Brandenburg, Germany. Agricultural and Forest Meteorology, 84(1–2), 123–135. https://doi.org/10.1016/S0168-1923(96)02381-7

Linser, S. (2002). Critical Analysis of the Basics for the Assessment of Sustainable Development by Indicators. Schr. Freibg. Forstl. Forsch.

Linser, S. (2024). Potential for Revision of Forest Europe Indicators under Criterion 4 "Maintenance, Conservation and Appropriate Enhancement of Biological Diversity in Forest Ecosystems". European Forest Institute. https://foresteurope.org/wp-content/uploads/2024/03/Background-paper-Potential-for-Revision-of-Forest-Europe-Indicators-under-Criterion-4-Maintenance-Conservation-and-Appropriate-Enhancement-of-Biological-Diversity-in-Forest-Ecosystems.

Linser, S., Lapin, K., Bradley, O., Gschwantner, T., & Russ, W. (2026). Waldbiodiversitätsbericht. Basierend auf den Indikatoren für nachhaltige Waldbewirtschaftung des Österreichischen Walddialogs. BFW-Bericht 155/2026. BFW.

Linser, S., & O'Hara, P. (2019). Guidelines for the Development of a Criteria and Indicator Set for Sustainable Forest Management. United Nations Publications.

Linser, S., & Wolfslehner, B. (2015). Meeting the Goals for European Forests and the European 2020 Targets for Forests. Report on the Mid-term Evaluation of the Goals for European Forests and the European 2020 Targets for Forests. Forest Europe Liaison Unit Madrid. https://foresteurope.org/wp-content/uploads/2016/08/MID-TERM-EvaluatG2020T-2015.pdf

Ma, J., Li, J., Wu, W., & Liu, J. (2023). Global forest fragmentation change from 2000 to 2020. Nature Communications, 14(1), 3752. https://doi.org/10.1038/s41467-023-39221-x

Maxim, L., Spangenberg, J.H., & O'Connor, M. (2009). An analysis of risks for biodiversity under the DPSIR framework. Ecological Economics, 69(1), 12–23. https://doi.org/10.1016/j.ecolecon.2009.03.017

Millar, C.I., Stephenson, N.L., & Stephens, S.L. (2007). CLIMATE CHANGE AND FORESTS OF THE FUTURE: MANAGING IN THE FACE OF UNCERTAINTY. Ecological Applications, 17(8), 2145–2151. https://doi.org/10.1890/06-1715.1

Montréal Process Working Group (2023). Montreal Process: Synthesis of indicator trends 1990 to 2020 and future outlooks. Scion. https://www.montreal-process.org/documents/publications/techreports/MontrealProcessSynthesisReport2023EnglishONLINE.pdf

Moore, L.M., & Lauenroth, W.K. (2017). Differential effects of temperature and precipitation on early- vs. Late-flowering species. Ecosphere, 8(5), e01819. https://doi.org/10.1002/ecs2.1819

Morin, X., Fahse, L., Jactel, H., Scherer-Lorenzen, M., García-Valdés, R., & Bugmann, H. (2018). Long-term response of forest productivity to climate change is mostly driven by change in tree species composition. Scientific Reports, 8(1), 5627. https://doi.org/10.1038/s41598-018-23763-y

Mueller, R.C., Scudder, C.M., Porter, M.E., Trotter, R.T., Gehring, C.A., & Whitham, T.G. (2005). Differential tree mortality in response to severe drought: Evidence for long-term vegetation shifts. Journal of Ecology, 93, 1085–1093.

Mundra, S., Kauserud, H., Økland, T., Nordbakken, J., Ransedokken, Y., & Kjønaas, O. J. (2022). Shift in tree species changes the belowground biota of boreal forests. New Phytologist, 234(6), 2073–2087. https://doi.org/10.1111/nph.18109

Mutanu, L., Gohil, J., Gupta, K., Wagio, P., & Kotonya, G. (2022). A Review of Automated Bioacoustics and General Acoustics Classification Research. Sensors, 22(21), 8361. https://doi.org/10.3390/s22218361

Muys, B., Angelstam, P., Bauhus, J., Bouriaud, L., Jactel, H., Kraigher, H., Müller, J., Pettorelli, N., Pötzelsberger, E., Primmer, E., Svoboda, M., Thorsen, B. J., Van Meerbeek, K. (2022). Forest Biodiversity in Europe. From Science to Policy. European Forest Institute. https://doi.org/10.36333/fs13

O'Brien, L., Schuck, A., Fraccaroli, C., Pötzelsberger, E., Winkel, G., & Lindner, M. (2021). Protecting old-growth forests in Europe A review of scientific evidence to inform policy implementation. https://doi.org/10.36333/rs1

Oettel, J., & Lapin, K. (2021). Linking forest management and biodiversity indicators to strengthen sustainable forest management in Europe. Ecological Indicators, 122, 107275. https://doi.org/10.1016/j.ecolind.2020.107275

Oettel, J., Lapin, K., Kindermann, G., Steiner, H., Schweinzer, K.-M., Frank, G., & Essl, F. (2020). Patterns and drivers of deadwood volume and composition in different forest types of the Austrian natural forest reserves. Forest Ecology and Management, 463, 118016. https://doi.org/10.1016/j.foreco.2020.118016

Opdam, P., & Wascher, D. (2004). Climate change meets habitat fragmentation: Linking landscape and biogeographical scale levels in research and conservation. Biological Conservation, 117(3), 285–297. https://doi.org/10.1016/j.biocon.2003.12.008

Otrakcier, T., Linser, S., Bastrup-Birk, A., Gaworska, M., Köhl, M., Korhonen, K.T., & Talarczyk, A. (2023). Reporting on Forests and Sustainable Forest Management in the Caucasus and Central Asia: Focus on Criteria and Indicators. United Nations. https://doi.org/10.18356/9789210023825

Paillet, Y., Zapponi, L., Schall, P., Monnet, J.-M., Ammer, C., Balducci, L., Boch, S., Brazaitis, G., … Burrascano, S. (2024). One to rule them all? Assessing the performance of sustainable forest management indicators against multitaxonomic data for biodiversity conservation. Biological Conservation, 300, 110874. https://doi.org/10.1016/j.biocon.2024.110874

Pearce-Higgins, J.W., Ockendon, N., Baker, D.J., Carr, J., White, E.C., Almond, R.E.A., Amano, T., … Tanner, E.V.J. (2015). Geographical variation in species' population responses to changes in temperature and precipitation. Proceedings of the Royal Society B: Biological Sciences, 282(1818), 20151561. https://doi.org/10.1098/rspb.2015.1561

Pettorelli, N., Williams, J., Schulte to Bühne, H., & Crowson, M. (2024). Deep learning and satellite remote sensing for biodiversity monitoring and conservation. Remote Sensing in Ecology and Conservation, rse2.415. https://doi.org/10.1002/rse2.415

Phiri, D., Simwanda, M., Salekin, S., Nyirenda, V., Murayama, Y., & Ranagalage, M. (2020). Sentinel-2 Data for Land Cover/Use Mapping: A Review. Remote Sensing, 12(14), 2291. https://doi.org/10.3390/rs12142291

Pilotto, F., Kühn, I., Adrian, R., Alber, R., Alignier, A., Andrews, C., Bäck, J., Barbaro, L., Beaumont, D., … Haase, P. (2020). Meta-analysis of multidecadal biodiversity trends in Europe. Nature Communications, 11(1), 3486. https://doi.org/10.1038/s41467-020-17171-y

Portaccio, A., Paillet, Y., Chojnacki, L., Trentanovi, G., Campagnaro, T., Burrascano, S., & Sitzia, T. (2026). Bird response to forest structure and composition and implications for sustainable mountain forest management. iForest - Biogeosciences and Forestry, 19(1), 18–27. https://doi.org/10.3832/ifor4921-018

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

Puchałka, R., Paź-Dyderska, S., Jagodziński, A.M., Sádlo, J., Vítková, M., Klisz, M., Koniakin, S., … Dyderski, M.K. (2023). Predicted range shifts of alien tree species in Europe. Agricultural and Forest Meteorology, 341, 109650. https://doi.org/10.1016/j.agrformet.2023.109650

Seibold, S., Rammer, W., Hothorn, T., Seidl, R., Ulyshen, M. D., Lorz, J., Cadotte, M. W., Lindenmayer, D.B., … Müller, J. (2021). The contribution of insects to global forest deadwood decomposition. Nature, 597(7874), 77–81. https://doi.org/10.1038/s41586-021-03740-8

Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D., … Reyer, C.P.O. (2017). Forest disturbances under climate change. Nature Climate Change, 7(6), 395–402. https://doi.org/10.1038/nclimate3303

Seidl, R., & Turner, M.G. (2022). Post-disturbance reorganization of forest ecosystems in a changing world. Proceedings of the National Academy of Sciences, 119(28), e2202190119. https://doi.org/10.1073/pnas.2202190119

Simberloff, D. (2000). Global climate change and introduced species in United States forests. Science of The Total Environment, 262(3), 253–261. https://doi.org/10.1016/S0048-9697(00)00527-1

Splawinski, T.B., Cyr, D., Gauthier, S., Jetté, J.-P., & Bergeron, Y. (2019). Analyzing risk of regeneration failure in the managed boreal forest of northwestern Quebec. Canadian Journal of Forest Research, 49(6), 680–691. https://doi.org/10.1139/cjfr-2018-0278

Stevenson, S.L., Watermeyer, K., Ferrier, S., Fulton, E.A., Xiao, H., & Nicholson, E. (2024). Corroboration and contradictions in global biodiversity indicators. Biological Conservation, 290, 110451. https://doi.org/10.1016/j.biocon.2024.110451

Stevens-Rumann, C.S., Prichard, S.J., Whitman, E., Parisien, M.-A., & Meddens, A.J.H. (2022). Considering regeneration failure in the context of changing climate and disturbance regimes in western North America. Canadian Journal of Forest Research, 52(10), 1281–1302. https://doi.org/10.1139/cjfr-2022-0054

Tariq, A., Jiango, Y., Li, Q., Gao, J., Lu, L., Soufan, W., Almutairi, K.F., & Habib-ur-Rahman, M. (2023). Modelling, mapping and monitoring of forest cover changes, using support vector machine, kernel logistic regression and naive bayes tree models with optical remote sensing data. Heliyon, 9(2), e13212. https://doi.org/10.1016/j.heliyon.2023.e13212

Teixeira, D., Linke, S., Hill, R., Maron, M., & Van Rensburg, B.J. (2022). Fledge or fail: Nest monitoring of endangered black-cockatoos using bioacoustics and open-source call recognition. Ecological Informatics, 69, 101656. https://doi.org/10.1016/j.ecoinf.2022.101656

Thom, D., Ammer, C., Annighöfer, P., Aszalós, R., Dittrich, S., Hagge, J., Keeton, W.S., Kovacs, B., Krautkrämer, O., Müller, J., Von Oheimb, G., & Seidl, R. (2023). Regeneration in European beech forests after drought: The effects of microclimate, deadwood and browsing. European Journal of Forest Research, 142(2), 259–273. https://doi.org/10.1007/s10342-022-01520-1

Thom, D., Golivets, M., Edling, L., Meigs, G.W., Gourevitch, J.D., Sonter, L.J., Galford, G.L., & Keeton, W.S. (2019). The climate sensitivity of carbon, timber, and species richness covaries with forest age in boreal–temperate North America. Global Change Biology, 25(7), 2446–2458. https://doi.org/10.1111/gcb.14656

UNECE (Ed.) (2025). 2025 Forest Profile for Europe, North America, Caucasus and Central Asia. United Nations.

Vacek, Z., Vacek, S., & Cukor, J. (2023). European forests under global climate change: Review of tree growth processes, crises and management strategies. Journal of Environmental Management, 332, 117353. https://doi.org/10.1016/j.jenvman.2023.117353

Virkkala, R. (2016). Long-term decline of southern boreal forest birds: Consequence of habitat alteration or climate change? Biodiversity and Conservation, 25(1), 151–167. https://doi.org/10.1007/s10531-015-1043-0

Walck, J.L., Hidayati, S.N., Dixon, K.W., Thompson, K., & Poschlod, P. (2011). Climate change and plant regeneration from seed: CLIMATE CHANGE AND PLANT REGENERATION. Global Change Biology, 17(6), 2145–2161. https://doi.org/10.1111/j.1365-2486.2010.02368.x

Winter, S., Chirici, G., McRoberts, R.E., Hauk, E., & Tomppo, E. (2008). Possibilities for harmonizing national forest inventory data for use in forest biodiversity assessments. Forestry, 81(1), 33–44. https://doi.org/10.1093/forestry/cpm042