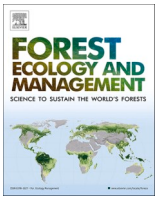
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Perspective: Managing European forests for biodiversity conservation and global change adaptation: An assessment of current management concepts

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ABSTRACT

Integrative forest management (IFM) aims at integrating biodiversity conservation and global change adaptation into forest management for the sustainable provision of multiple ecosystem services. In this paper, and in the context of the European project TRANSFORMIT, we have developed a novel definition of IFM and a framework of guiding principles and attributes directing decision-making and objectives. IFM is structured around eight guiding principles and corresponding attributes, encompassing key ecological and silvicultural elements including the promotion of habitat retention, site-adapted native tree species, natural regeneration, structural diversity, and landscape connectivity, while reducing the ecological impact of forestry operations and enhancing resilience to ecological stress and disturbance.

Based on the definition, we explored the alignment of existing forest management concepts in Europe with IFM. Through content analysis, the review evaluates a set of widely used forest management concepts in Europe, including Continuous Cover Forestry, Close-to-Nature Forest Management, ProSilva, the Stepping Stone Concept, Retention Forestry, TRIAD, Climate-Smart Forestry, and Closer-to-Nature Forest Management. These concepts were compared to IFM through a literature-based assessment of their theoretical foundations and implementation strategies. While most concepts overlapped to different extents at the level of principles, the application of the corresponding elements varied across concepts. We subsequently attributed divergences in terminology, emphasis, and implementation in Europe to differing contexts, including disturbance regimes and management traditions.

By using IFM as a common framework, our study clarified where existing concepts converge or diverge, thereby helping to close gaps between high-level management goals and their practical implementation. Using IFM as a benchmark allowed us to compare the respective strengths and weaknesses of established concepts and to suggest improvements through a transparent dialogue between science, practice, and policy. To illustrate the potential actions necessary to implement IFM, we present an exemplary theoretical transition pathway for the transformation of disturbance-prone Norway spruce monocultures toward more diverse, adaptive and resilient forests. The trajectory underscores that successful implementation of IFM relies on context-specific, multi-level planning and should be tailored to local ecological realities and stakeholder networks.

In conclusion, IFM provides a unifying but non-prescriptive concept that is capable of integrating diverse forest management objectives. However, effective implementation requires context- and region-specific adaptation, coordination across governance levels and sectors (e.g. forestry, conservation, and rural development), and continuous exchange between science and practice.

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1. Introduction

The meaning of sustainable management of forests has been subject to intense debate since Carlowitz (1731) first coined the idea of sustainable wood production in planted forests in Germany. Subsequently, debates across Europe have evolved from an early focus on maximising sustained timber production toward a broader recognition of the importance of managing forests for a wide range of ecosystem services (ES) and functions (Pistorius et al., 2012). Concurrently, European forest management has shifted from focusing solely on timber supply (Carlowitz, 1731) to developing as a scientific discipline aiming to organize "*scattered pieces of knowledge into systems*" and to transform "*all sorts of activities previously left to habit into a science*" (Bechstein 1797, Lowood, 1990). By the late 19th century, in response to widespread clear-cutting and replanting with conifer monocultures, shelterwood and selection systems became more popular and implemented in parts of Europe, bringing a stronger emphasis on mimicking natural structures and processes. The shift from forest management (FM) focused on wood production towards managing forests as complex adaptive systems has gained traction over the last decades (Messier et al., 2013; Puettmann et al., 2016) in response to the risks and uncertainties posed by global changes. Alternative management strategies have emerged, such as close-to-nature forest management (CNFM, Schütz, 1999), Continuous cover forest management/futaie irrégulière (CCF, Bruciamacchie and Turckheim, 2005; Mason, 2003), climate-smart forestry (CSF, Nabuurs et al., 2017), Closer-to-Nature Forest Management (CerNFM, Larsen et al., 2022), and others. Together, these developments illustrate a gradual broadening of forest management objectives from sustained yield to multi-functional, biodiversity-aware and risk-sensitive approaches.

This paper addresses two of the foremost challenges confronting forest management today: the integration of biodiversity conservation and adaptation to global change within everyday management practice. These interacting challenges require management approaches that can maintain ecosystem functioning and resilience in the face of disturbance, while simultaneously securing the long-term provision of diverse ecosystem services. Nowadays, the importance of managing forests for the sustainable provision of multiple ecosystem services is widely recognised in European policy, including recent EU initiatives such as the Nature Restoration Law and the EU Forest Strategy (EU Nature Restoration Law (NRL), 2024), although the understanding of what this means in practice still varies substantially (Winkel and Sotirov, 2016).

In this context, Integrative Forest Management (IFM) which was first conceptualized by Kraus and Krumm (2013), and further expanded by Krumm et al. (2020), is defined as a holistic approach that aims to integrate nature conservation and adaptation to global change into sustainable forest management, for the sustainable provision of multiple ecosystem services, guided by natural and diverse forest structures, compositions, and dynamics, whilst acknowledging the complexity and diversity of forest ecosystems and local management traditions. The working definition used in this paper was developed within the Horizon Europe project TRANSFORMIT (Table 1) to support a structured assessment of IFM implementation across operational scales.

Thus, the aim of this opinion paper is twofold: (i) to clarify and operationalise the IFM concept by specifying its guiding principles and attributes, for meeting these challenges by enabling managers and policymakers to align and balance ecological, social, and economic objectives at multiple scales and (ii) to assess where Europe currently stands with respect to IFM by examining how existing forest management concepts align with, or deviate from, this framework.

1.1. Evolution of forest management concepts in Europe between timber production, naturalness and integration

To understand the role of IFM in this broader development, it is useful to briefly trace how forest management concepts in Europe have evolved between timber production, naturalness and integration. Forest management concepts often originate from practical knowledge applied by forest practitioners and are shaped by local ecological and socio-political contexts. Many have evolved over decades and have been defined and applied flexibly without systematic reporting or specific monitoring (Nocentini et al., 2021). They evolved "gradually" as they increasingly merged local traditions and experience with ideas coming out of academia and policy, to achieve local ecosystem services goals, resulting in a patchwork of strategies in forest management. With the policy shift in FM from timber production to multiple ecosystem services, these early integrative methods have been refined and adapted. Multipurpose silviculture, close-to-nature silviculture (Schütz, 1999), or continuous-cover forestry, all of which generally enhance forest naturalness and explicitly aim to secure specific ecosystem services like protection against natural hazards in mountain forests, spreading through parts of Europe in the last 3–4 decades (Larsen et al., 2022). These approaches marked an important step away from purely wood production-oriented forestry by promoting more complex stand structures and continuous forest cover imitating natural processes aiming at increasing stability and protection functions. Although many of these approaches resulted in an increase of the naturalness of the forests, specific measures to promote and conserve important biodiversity elements such as deadwood, habitat trees, or rare species were, at least initially, not considered (Lachat et al., 2013). In addition, they often overlooked key components such as forest reserves and their connectivity at the landscape scale (Krumm et al., 2020). In recent years, the forest sector has been undergoing profound changes, driven by the increasing importance of climate change, biodiversity decline, and societal interest in a broader spectrum of ecosystem services.

Overarching political strategies, such as the EU's goal for climate neutrality, have brought forest management into the forefront of policy debates (European Commission, 2020). At the same time, the simultaneous goals for biodiversity conservation and the development of a European bioeconomy have increased the conflict between wood harvesting from forests and conservation goals (Hurmekoski et al., 2019). Intensive forest management can reduce forests' adaptive capacity (Pohjanmies et al., 2017; Triviño et al., 2017), for example, by simplifying stand structures or shortening rotation lengths, thereby creating tensions between production and ecological resilience (Brockerhoff et al., 2017; Förster et al., 2019). While higher forest "naturalness" does not automatically equate to greater adaptive capacity, these studies consistently highlight the need for diversified management that balances production goals with ecological integrity (Seidl and Lexer, 2013). Likewise, the delivery of ES and the promotion of biodiversity are sometimes overlooked and are reputed to come at the expense of productivity (Blattert et al., 2023). EU's policies mirror these conflicts: efforts to increase wood biomass supply may challenge biodiversity conservation objectives (Sotirov et al., 2021). Empirical studies indicate

Table 1
The IFM definition was developed within the Horizon Europe project TRANSFORMIT (https://transformforests.eu/) to ensure a structured assessment of IFM implementation across various operational scales.

IFM Definition
"Integrative Forest Management (IFM) aims at integrating biodiversity conservation and global change adaptation into forest management for the sustainable provision of multiple ecosystem services. It is guided by natural and diverse forest structures, compositions, and dynamics to support ecosystem functioning and resilience. Its management practices consistently consider the tree, stand, and landscape scale and employ different silvicultural intensities, including intentionally unmanaged forest patches. IFM can be applied in any type of forest to achieve integrated environmental, economic, and social outcomes."

that management with reduced intervention intensity and a focus on maintaining structural and compositional diversity fosters recovery and resilience after disturbances (Senf et al., 2019), and ecosystem modelling suggests that multifunctional management that mimics natural processes enhances forest adaptive capacity under climate change scenarios (Dobor et al., 2025). Maintaining and developing structurally diverse and species-rich stands emerges as a key strategy for buffering against novel disturbance regimes (Liu et al., 2024; Messier et al., 2013; Schnabel et al., 2021). These findings are consistent with the assessments of forest management experts, many of whom already consider diversification and adaptation-oriented management to be important responses to global change (Himes et al., 2023)

In this context, the notion of forest naturalness, not only identified by the complete absence of human interventions, rather best defined as forest composition, structure, and dynamics which reflect the regional natural disturbance regime across the full successional mosaic, benchmarked against type-specific reference conditions (historic range of variation) rather than only old-growth endpoints (Aszalós et al., 2022; Franklin et al., 2007), and has gained prominence. Continuous-cover forestry has been shown to support biodiversity, promote natural regeneration, and contribute to long-term ecosystem stability (Pignatti, 2012; Standovár, 2003). Uneven-aged forest stands in Central Europe have been shown to be less vulnerable to disturbances than even-aged stands (Mohr et al., 2024). Yet, continuous cover forestry may disadvantage light-demanding and early successional species (Schall et al., 2018) and make it more difficult to increase resilience to climate change through cultivating climate-adapted but currently absent species through assisted migration. Taken together, these developments show that many European concepts have moved well beyond purely production-oriented forestry and already incorporate elements of naturalness, risk reduction and multifunctionality.

In the past, a variety of integrative forest management approaches have been proposed to address these crucial issues and, whilst upholding other ecosystem services, promote biodiversity and support adaptation to global change. However, although these approaches often emphasized long-term stand development, many proposed measures remained largely at the stand scale, even for ecosystem services that inherently depend on landscape-level processes (Carpenter et al., 2009; Cejudo et al., 2018; Turner et al., 2013). This limitation highlights the need for Integrative Forest Management as a contemporary framework that explicitly links biodiversity conservation and climate-change adaptation with the coordinated management of forests across multiple spatial and temporal scales. Such heterogeneity is precisely what motivates the use of the IFM framework in this paper: it provides a common structure to make these differences transparent and to identify where additional objectives or more detailed management elements might be useful and needed. The new IFM concept joins different, sometimes also older concepts and approaches and results in a process of optimizing and adapting forest management for current and future challenges. Here, we use IFM as such a benchmark to ask which principles and management actions are already realised in current concepts, which remain underrepresented, and what this implies for future forest policy and practice in Europe. Rather than evaluating or ranking individual approaches, our aim is to assess where Europe currently stands with respect to IFM by identifying the degree to which existing concepts already align with the IFM framework and where substantive gaps persist. This perspective provides pointers for forest managers, planners, and policymakers on existing strengths, remaining gaps, and the magnitude of effort and resources that may be needed to further promote IFM across managed forest landscapes.

2. Methods

2.1. Towards a definition of IFM and related principles and attributes

The definition of Integrative Forest Management (Table 1) and the associated set of principles and attributes used in this paper were developed in three steps. First, we traced the evolution of the IFM concept based on existing literature and policy discussions, including recent syntheses of integrative, biodiversity-oriented forest management approaches (e.g. Kraus and Krumm, 2013; Larsen et al., 2022). Second, an expert group within Work Package 3 (WP3) of the TRANSFORMIT project refined this emerging understanding into a working definition of IFM that explicitly links biodiversity conservation and adaptation to global change with the sustainable provision of multiple ecosystem services. Third, we derived a set of guiding principles and related attributes by systematically reviewing IFM-like management concepts (Krumm et al., 2020; Larsen et al., 2022) and adding missing elements identified through expert knowledge. This process resulted in the operative IFM framework summarised in Table 1, which serves in this study as the reference against which existing forest management concepts are interpreted and compared.

The guiding principles (i) emphasise the naturalness of forest ecosystems by mimicking natural processes, (ii) enhance biodiversity, (iii) extend the focus from timber production to a broader range of ecosystem services, including carbon sequestration, water regulation, protection against natural hazards and recreation, (iv) account for landscape connectivity and species-migration pathways by maintaining permanent forest cover in some areas while allowing openings in others, (v) recognise disturbances as integral processes of natural systems, and (vi) integrate climate-adaptive management principles. Each principle is further specified by one or more operational attributes that describe typical management aims or actions at tree, stand, and landscape scales (Table 1), providing the level at which alignment with existing concepts is assessed. IFM employs both integrative and segregative measures, with measures that unfold over different spatial and temporal scales (Bollmann and Braunisch, 2013; Kraus and Krumm, 2013), building on some of the above introduced earlier approaches, including close-to-nature silviculture (Brang et al., 2014; Mason, 2003; Schütz, 1999, 1994), multipurpose silviculture (Díaz-Yáñez et al., 2019; Gustafsson et al., 2012; Messier et al., 2021), and continuous-cover silviculture (Pommerening, 2004; Pukkala and Von Gadow, 2012). A defining feature of IFM addresses the limitations of earlier approaches that failed to conserve critical biodiversity by explicitly including rare species, deadwood, the designation of habitats, trees and old-growth features in management plans, and operates at multiple spatial and temporal scales. By integrating climate-smart forestry principles (Nabuurs et al., 2017), IFM may also be suitable to adapt forests to changing climatic conditions, promoting resilient forest ecosystems capable of delivering multiple services while addressing the dual goals of conservation and socio-economic demands.

2.2. Identified IFM-related concepts

We selected major IFM-related forest management concepts (Table 2) for comparison with IFM guiding Principles and Attributes. These concepts arose from diverse regional, ecological, and historical contexts, reflecting varying interpretations of sustainability and biodiversity integration. While many predate formal IFM, they show partial to substantial overlap in principles and attributes.

Continuous Cover Forestry (CCF) or Futaie Irrégulière is among the oldest forest management concepts and is rooted in Central Europe (Bruciamacchie and Turckheim, 2005). It was initially motivated by soil protection and economic stability. It clearly states the avoidance of clear felling, instead maintaining permanent forest cover via selection harvests. Its focus on structural diversity, age-class heterogeneity, and resilience has made it a key precursor to IFM.

Close-to-Nature Forest Management (CNFM), as defined by Schütz (1999) and expanded by Bauhus et al., (2013), emphasises working with natural processes to guide forest development, maintain species richness, and promote structural complexity. Rooted in central European silvicultural thinking, this approach avoids large-scale canopy

Table 2
List of principles and attributes for assessing the literature to compare IFM-related concepts to IFM, and highlight overlapping or misaligned goals, and quantifiable attributes adapted from Kraus and Krumm (2013); Krumm et al. (2020); Larsen et al. (2022).

	Principles	Attributes
1	Retention of habitat trees, special habitats, and dead wood	**P1-A1** Active actions of the retention concept are applied (i.e. habitat trees, deadwood, high stumps, retained vegetation patches etc.). **P1-A2** Retention in relation to average growing stock across the considered landscape. **P1-A3** Valuable habitats are mapped and protected or managed towards conservation goals beyond regulations. **P1-A4** Forest reserves are an integral part of the area covered by a management plan.
2	Promoting site-adapted native tree species and non-native species	**P2-A1** Native species forest cover is prioritized. **P2-A2** Non-native species are included in minority shares. These should be adapted to site conditions and climate change. **P2-A3** Site-adapted species are prioritized and promoted through natural regeneration, active regeneration management or stand tending.
3	Promoting natural tree regeneration	**P3-A1** Regeneration is obtained naturally, except for areas under active conversion (tree species change towards more adapted ones) **P3-A2** Mature stands to carry advanced regeneration. **P3-A3** Herbivore pressure is monitored and active browsing control is implemented (incl. hunting and physical protection via fences); **P3-A4** Promotion and maintenance of pioneer species in the landscape (e.g. pioneer species along roads, etc.).
4	Partial harvest and promotion of structural heterogeneity	**P4-A1** Most/Main planned harvesting is done by selection harvesting (from a single tree to group selection, including shelterwood systems), **P4-A2** Most/Main planned harvesting is done without clear felling
5	Promoting tree species variation and genetic diversity	**P5-A1** Active regeneration management that promotes the establishment of diverse forests mimicking natural diversity (e.g. with a minimum of three tree species in each stand). **P5-A2** Tending operations aim at keeping or enhancing the diversity of tree species. **P5-A3** Prioritisation of minority tree species
6	Avoidance of intensive management operations	**P6-A1** No application of agrochemicals (some exceptions may be possible, e. g. in the form of integrated pest management) **P6-A2** Machine traffic is constrained to a fixed extraction network **P6-A3** Salvage logging actions retain considerable dead wood volumes **P6-A4** Water courses are protected from disruption from machine traffic
7	Supporting landscape heterogeneity and functioning	**P7-A1** Landscape level strategy for water retention and protection of watercourses in place: **P7-A2** Protection of valuable and rare habitats. **P7-A3** Landscape level strategy to promote connectivity and heterogeneity of habitats between forest stands and non-forested areas in place
8	Management of factors that hinder ecosystem functioning	**P8-A1** Management strategy in place to control invasive species **P8-A2** Management strategy integrates natural processes and disturbances (e.g. fires, pest outbreaks, storm, game control) for increasing the forest resilience and the regeneration and restoration post-disturbances.

openings like clear felling, favouring natural regeneration, mixed species stands, and continuous forest cover. Its core motivation lies in enhancing ecosystem stability and adaptability while still allowing for sustainable timber production. Schütz argued that close-to-nature forest management is not only compatible with biodiversity goals but can actively support species richness when properly implemented. Associated CNFM practices aim to enhance resilience, adaptability, and multifunctionality under global change, emphasizing structural and species diversity, long-term sustainability, site-specific management, and fostering adaptability to environmental uncertainty and disturbance regimes. This concept laid the groundwork for later frameworks such as Closer-to-Nature Forest Management (Larsen et al., 2022), which expanded the scope to include landscape-level and climate resilience objectives.

ProSilva, formalised in 1989 and documented in its 2012 charter, is an European confederation of professional foresters, advocates continuous, close-to-nature forest management without clearcuts, aiming to maintain all forest functions over time (Pro Silva, 2012; Schütz, 2011). It promotes forest resilience, natural regeneration, and multifunctionality. Its motivation was both ecological and economic, aiming to reduce management costs through the use of natural processes and sustaining forests without sacrificing productivity.

The **Stepping Stone Concept** (SSC; Mergner, 2018) targets habitat connectivity via retention of deadwood, habitat trees, and reserves as "stepping stones" for species dispersal. Emerging from conservation biology rather than a timber production objective, it has expanded to include landscape-scale ecological networks (Lapin et al., 2024).

Retention Forestry (RF; Gustafsson et al., 2012) focuses on biodiversity conservation in managed forests by retaining key structures during harvest (e.g., deadwood, old trees and intact forest patches during harvesting) to maintain a continuity of forest structures and function. In Europe, RF is largely applied in boreal and also in temperate forests (Gustafsson et al., 2020).

The **TRIAD** concept (Messier et al., 2009) divides forests into three functional zones: conservation, ecosystem management, and intensive production. Motivated by the need to reconcile timber harvesting with biodiversity protection, it spatially separates objectives to optimise both ecological and economic functions. It reflects a strategic zoning approach popular in North America.

Climate-Smart Forestry (CSF; Nabuurs et al., 2017; Verkerk et al., 2020) emerged recently from climate policy debates. Unlike other approaches, it explicitly addresses greenhouse gas mitigation, resilience, and productivity in a climate change context. It promotes carbon sequestration, adaptive silviculture, provision of other ES and efficient use of wood, aligning well with EU Green Deal objectives.

Finally, **Closer-to-Nature Forest Management** (CerNFM; EU Forest Strategy 2030, Larsen et al., 2022) introduced in EU forest policy under the Green Deal (EU Forest Strategy 2030) as an umbrella term for more biodiversity/nature-oriented forestry approaches, and then defined and substantiated in a publication by Larsen et al., (2022). This concept builds on the latest scientific evidence and proposes a definition of the concept by a set of seven guiding principles and a framework/checklist for flexible European-wide implementation. Building on earlier close-to-nature approaches, CerNFM explicitly sharpens the focus on biodiversity conservation and resilience by formulating scalable strategies that go beyond stand-level silviculture and address landscape-scale challenges such as climate change and ecosystem fragmentation. In this sense, CerNFM operationalises more explicit biodiversity and

landscape-level objectives, in line with proposals for integrative management put forward by Krumm et al. (2020).

2.3. Evaluation of IFM-related concepts – literature-based review

IFM-related management concepts were selected based on the authors' expertise and their expected alignment with the current IFM principles and attributes (Fig. 1). In this paper, we use "concept" to denote overarching forest management approaches or strategies that articulate explicit objectives, guiding principles, and typical sets of measures, rather than individual silvicultural operations. Silvicultural systems, where the focus is on the form of regeneration cutting (e.g., clear-cutting, coppicing with and without standards, plenterforests, group plentering, group shelterwood (Femelschlag), shelterwood, strip cutting) were not treated as separate concepts, because they do not in themselves constitute overarching forest management paradigms, even though they may be applied within different IFM frameworks.

Using the principles and attributes defined in Table 1, similarities and differences between concepts were assessed in a semi-systematic way (Snyder, 2019). We conducted a literature review accessing international databases (Web of Science and Scopus). Searches combined each concept's name with "forest management," applying Boolean operators (Management concept name & forest & management) and alternative keyword variations to optimise retrieval. Filters confined the results to relevant categories such as Environmental Sciences and Forestry, focusing on articles and reviews. Citation trends over time were analysed using Web of Science's "Analyse Results" feature to track frequency and evolution of each concept. Key publications were reviewed to investigate conceptual development and application in forest management. Manual screening excluded non-relevant records to ensure alignment with intended concepts, refining the dataset and clarifying the academic uptake of IFM-related approaches.

2.4. Comparative assessment of IFM-related concepts

The guiding principles and attributes of IFM provided the basis for comparative evaluation of IFM-related concepts. Rather than ranking the concepts, we examined how they position themselves across the different IFM principles and attributes, using IFM as a descriptive reference frame. This allowed us to identify areas of strong correspondence, partial coverage, or absence, without implying that IFM represents a normative "gold standard". Original definitions of each concept were identified by associating them with a "foundational paper", defined as an early publication explicitly outlining the concept's objectives and guiding principles. Successive publications that extended or amended the original concepts were also reviewed to highlight the evolution of specific concepts in time. This selection of papers does not claim to be exhaustive; it was rather intended to show the development of the approaches using examples.

A content analysis methodology was applied to identify key themes, concepts, and terminology related to guiding principles and attributes. A qualitative coding scheme scored the presence (1), absence (0), or partial presence (0.5) of each principle and attribute (Table 1). The scoring was carried out by 3 experts independently, on the basis of the information in the foundation paper. The average between the scores was considered. Descriptive statistics quantified similarities and discrepancies between IFM and IFM-related concepts. To explore broader conceptual dimensions, scores were aggregated into three categories: 1) Structural Complexity (SC): encompassing principles P4 and P7, describing forest complexity in spatial, architectural, and compositional patterns (LaRue et al., 2023; Liu et al., 2024; Puettmann et al., 2012; Seidel and Ammer, 2023), 2) Adaptive Capacity (AC): covering P2, P3, and P5, reflecting the potential of ecosystems to adjust to climate change through climate-adapted and non-native species and through species and genetic diversity, and to respond to disturbances through advance regeneration and presence of seed trees including pioneers (IPCC, Calvin et al., 2023; Yousefpour et al., 2017), 3) Ecosystem Services (ES): involving P1, P6, and P8, targeting actions that explicitly promote ecosystem service provisioning (Brockerhoff et al., 2017). Having quantified the differences between IFM and IFM-related approaches, we discuss examples of potential approaches to implement the different principles along a time scale from short-term to long-term and move towards the implementation of an Integrative Forest Management.

Continuous Cover Forestry CFF Avoids clearcutting; maintains permanent cover via selective harvests; focuses on structural diversity and resilience; central Europe origins.	**Close-to-Nature Forest Management CNFM** Applies natural forest processes; promotes species richness, mixed stands, and continuous cover; balances stability and timber production.
ProSilva Continuous cover, close-to-nature silviculture without clearcuts; emphasizes multifunctionality and natural regeneration.	**Stepping Stone Concept SSC** Conservation-driven; enhances habitat connectivity through retention of deadwood, habitat trees, and forest reserves.
Retention Forestry RF Retains structural elements during harvesting to conserve biodiversity; mainly applied in boreal forests.	**TRIAD** Spatially divides forest into conservation, ecosystem management, and production zones to reconcile ecological and economic goals.
Climate-Smart Forestry CSF Focuses on mitigating climate change impacts; promotes carbon storage, adaptive silviculture, and sustainable wood use aligned with EU policy.	**Closer-to-Nature Forest Management CerNFM** Promotes heterogeneity, native species, resilience, and landscape-level biodiversity connectivity.

Fig. 1. Overview of IFM-related concepts investigated. Each cell presents the concept's abbreviation and a brief description. See Table S1. for the identified "definition paper" and extracted definitions and main objectives or principles, and indicative geographical setting (Table S.2).

3. Results & discussion

3.1. Evolution of IFM-related concepts in literature

Analysis of Web of Science (WoS) data reveals growing but divergent scientific interest in IFM and related concepts over time (Fig. 2). Although some IFM-related approaches have existed in practice for decades, their presence in scholarly literature varies widely. IFM itself was practically not covered in the scientific literature until the early 2000s, followed by a steady increase in publications and citations, with a notable surge in the last decade, highlighting its rising importance in the forest management discourse. This trajectory marks IFM's rise from a niche idea to a widely recognized framework balancing ecological, economic, and social dimensions in sustainable forest management.

Newer concepts, namely TRIAD and RF, display the steepest citation growth, exceeding 1500 citations, indicating strong importance in academic discourse. Also, CCF, despite its origins in forest praxis, was cited similarly frequently in scientific literature, and it might even further increase as the newest publications (e.g. Pommerening, 2024; Pommerening et al., 2025) will boost its visibility. In contrast, CerNFM shows slower uptake. Although written for policy and application, the relative citation frequency of CerNFM demonstrates the growing interest of academia in 'grey literature' that is consistent with strategic narratives. Recent increases in citation numbers for the SSC and CNFM reflect renewed scholarly and policy interest. This rise corresponds with heightened concerns about biodiversity loss, climate adaptation, and ecosystem service multifunctionality. Conversely, ProSilva, despite its practical relevance, remains underrepresented in scientific literature, highlighting a gap between applied forestry networks and academic dissemination. This may in part reflect the fact that ProSilva primarily functions as a practitioner network promoting Close-to-Nature Forest Management, so many activities and documents remain within member organisations and are not published as peer-reviewed scientific outputs. It is also noteworthy that language barriers may contribute to this pattern, as many ProSilva discussions likely take place in European languages other than English, which are typically not represented in citation databases. Overall, citation trends suggest parallel but regionally contextualized development of specific IFM-related approaches rather than conceptual consolidation. Academic interest is linked to the importance of forest management in environmental policy discourse. Hence, European-level networks and initiatives (e.g., COST Actions, Horizon Europe projects) accelerate concept dissemination by aligning forestry research with policy priorities such as biodiversity conservation, climate resilience, and multifunctionality. Peaks in citation numbers often coincide with policy shifts, or wider scientific debates on sustainable forest management. Thus, citation patterns reflect not only scholarly interest but also broader socio-political processes and funding dynamics influencing IFM adoption.

3.2. Alignment of IFM-related concepts to the IFM-principles and attributes

The spider-grams in Fig. 3 (principles) and Fig. 4 (attributes) illustrate the alignment of each IFM-related management concept with the guiding principles and attributes of IFM (Table 1). All concepts show some degree of adherence to IFM-Principles, although the extent varies notably. ProSilva and CerNFM exhibit broader and more consistent alignment across the principles, while TRIAD demonstrates a more selective pattern. Most concepts align with at least half of the IFM-Principles; CSF aligns strongly only with principle 2 promoting site-adapted native tree species (P2). When assessing the attributes, which specify concrete strategies within each principle (e.g., P1-A1; Table 1, Fig. 4), greater variability emerges. While principles tend to be generally acknowledged, the translation into detailed attributes is limited, with IFM-related concepts covering less than 40% of the desired attributes overall.

ProSilva and CerNFM stand out by demonstrating more comprehensive coverage across multiple attribute-based strategies. TRIAD's focus is narrower, with fewer attributes addressed. This variation underlines that existing concepts emphasise different subsets of IFM

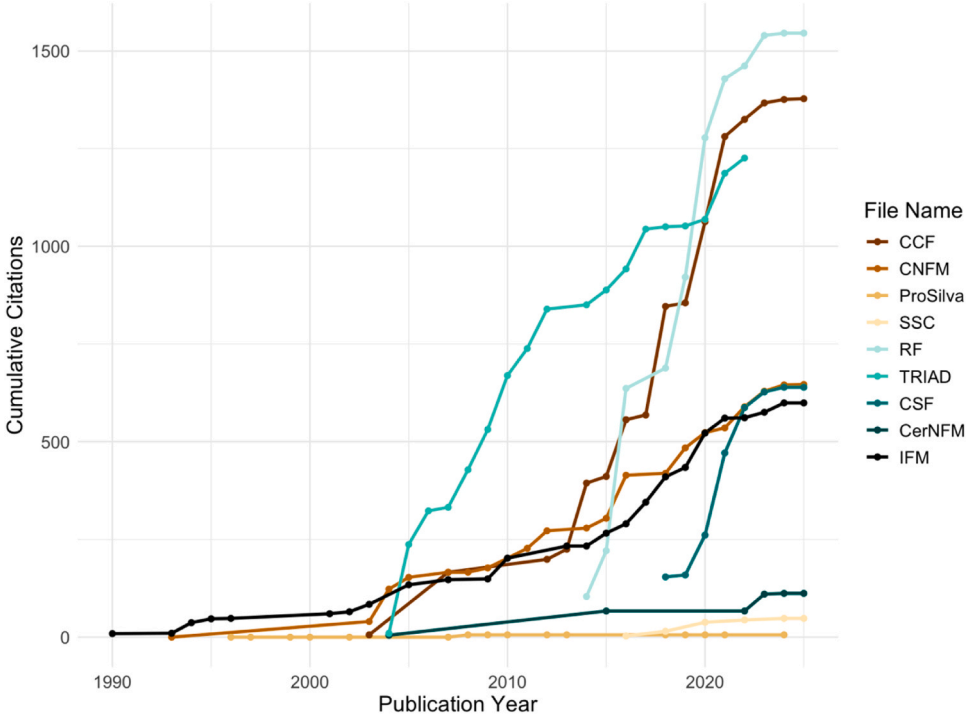


Figure 2. Comparison of the cumulative total citations since 1990 for each IFM-related concept (Fig. 1) per year based on Web of Science. The search is based on the management concept + forest management. Continuous cover forest management (CCF), Close to nature forest management (CNFM), ProSilva, Stepping Stone concept (SSC), Retention forestry (RF), TRIAD, Climate-smart forestry (CSF), Closer to nature forest management (CerNFM); Integrated forest management (IFM).

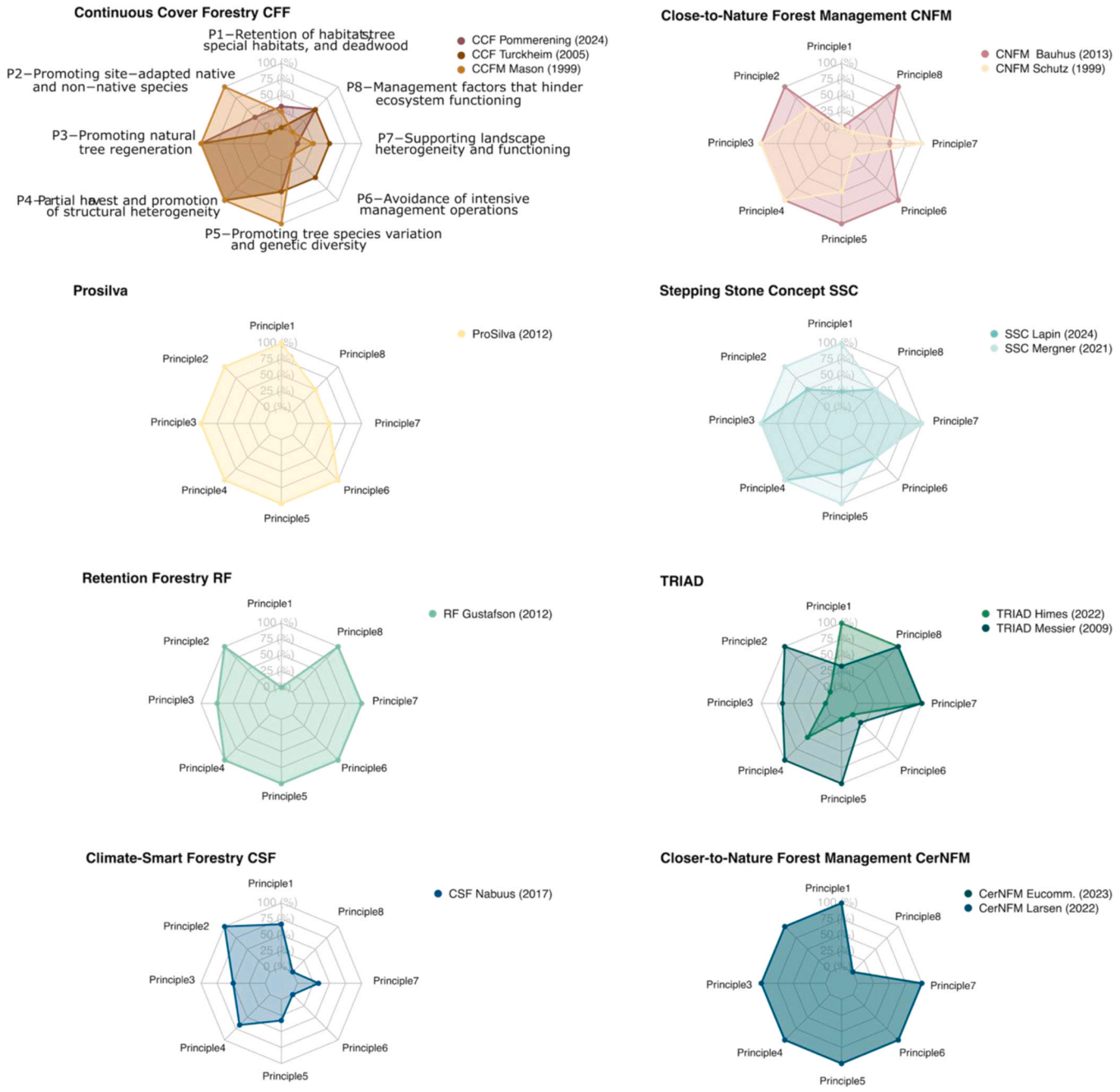


Fig. 3. Spider-grams showing how each management concept aligns with the principles of IFM. A full score indicates a clear alignment between the IFM and IFM-related concepts, while a partial score is just a mention of the principle. When multiple relevant citations were used for one concept, multiple colours overlap (i.e., for CCF, CNFM, SSC, and TRIAD). Continuous Cover Forest management (CCF), Close to Nature Forest Management (CNFM), ProSilva, Stepping Stone concept (SSC), Retention Forestry (RF), TRIAD, Climate-smart Forestry (CSF), Closer to Nature Forest Management (CerNFM). Principle 1: Retention of habitat trees, special habitats, and dead wood; Principle 2: Promoting site-adapted native tree species and non-native species; Principle 3: Promoting natural tree regeneration; Principle 4: Partial harvest and promotion of structural heterogeneity; Principle 5: Promoting tree species variation and genetic diversity; Principle 6: Avoidance of intensive management operations; Principle 7: Supporting landscape heterogeneity and functioning; Principle 8: Management of factors that hinder ecosystem functioning.

objectives and management levers, and that their descriptions of concrete attributes are often incomplete or uneven.

Aggregating the principles and attributes into three broad categories —Structural Complexity (SC), Adaptive Capacity (AC), and Ecosystem Services (ES)—reveals the relative emphasis of each IFM-related concept (Fig. 5). No single IFM-related concept achieved consistently highest scores across all three categories. CerNFM and SSC scored highly in Structural Complexity and Adaptive Capacity, with moderate to good Ecosystem Services performance, indicating strong alignment with IFM's multidimensional goals. ProSilva also performed well, with high SC and AC scores and solid ES representation. In contrast, CSF and CCF generally ranked lowest across these categories. Despite CSF's orientation toward climate adaptation, it scored relatively low in SC and ES, according to its narrower focus. Concepts such as RF, TRIAD, and CNFM showed intermediate or mixed scores. RF maintained moderate scores across all categories, TRIAD excelled in SC and AC but lagged in ES, while CNFM exhibited moderate SC and AC but lower ES scores. This heterogeneity exemplifies the individual orientation, complementary strengths, and resulting gaps among IFM-related concepts.

Although the reviewed concepts share overarching objectives, their

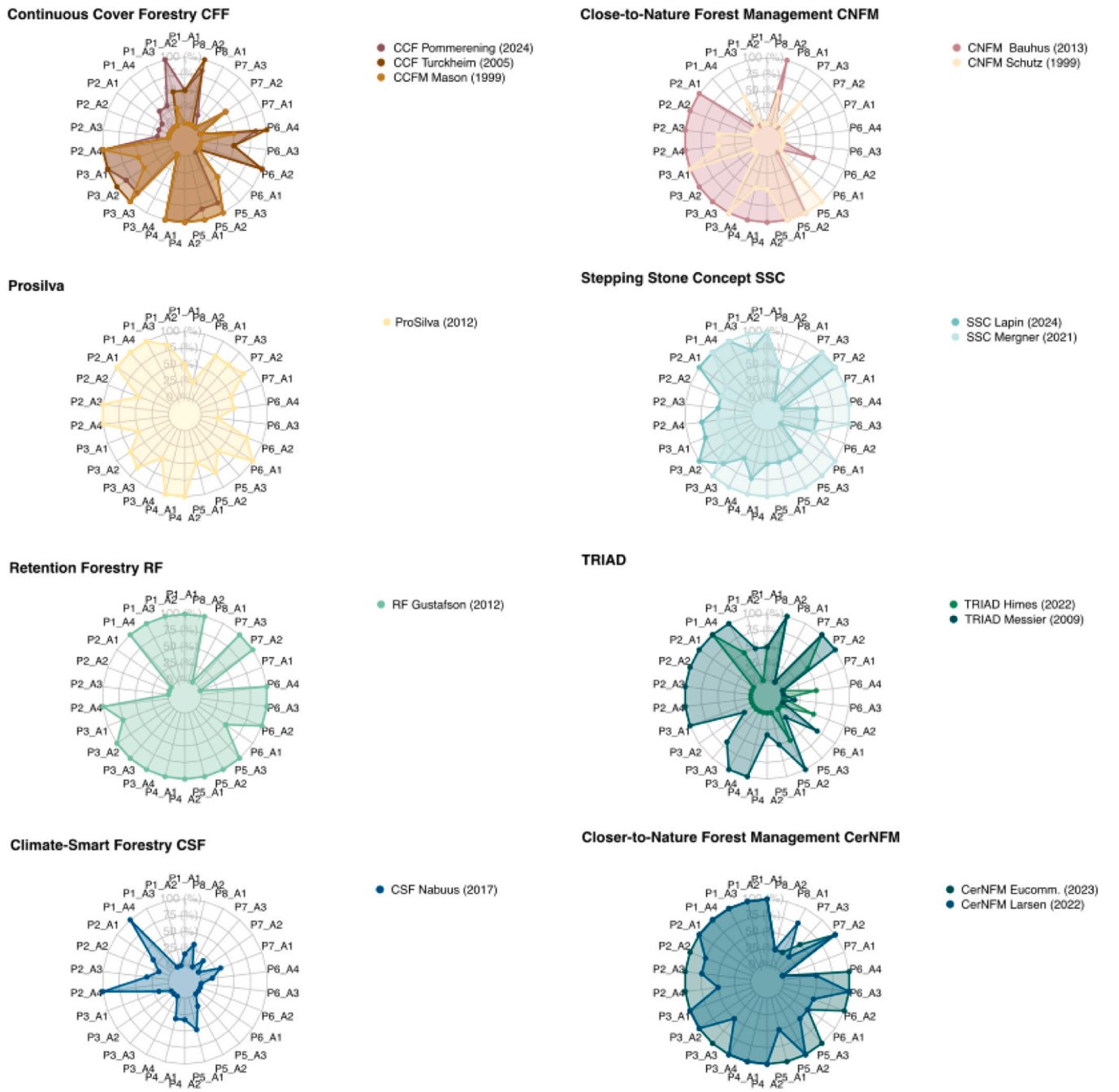


Fig. 4. Spider-grams showing how each management concept aligns with the attributes of IFM. A full score indicates a clear alignment between the IFM and IFM-related concepts, and a partial score is just a mention of the attribute. When multiple relevant citations were used for one concept, multiple colours overlap (e.g. for CCF, CNFM, SSC, and TRIAD). Continuous Cover Forest Management (CCF), Close to Nature Forest Management (CNFM), ProSilva, Stepping Stone concept (SSC), Retention Forestry (RF), TRIAD, Climate-smart Forestry (CSF), Closer to Nature Forest Management (CerNFM).

differing priorities reflect diverse origins, development pathways, and strategic orientations. This diversity enriches the spectrum of biodiversity-oriented, climate-smart, and multifunctional management practices, and the IFM framework helps to make this diversity visible by mapping how each concept addresses different principles and attributes, rather than serving as a "benchmark to beat". Hence, the IFM framework supports the region-specific alignment and adaptation of forest management practice and corresponding strategic policy development.

A critical challenge is the persistent implementation gap: many IFM-related concepts articulate clear aspirations and guiding principles but lack fully developed, standardized operational guidelines. While high-level principles are essential for framing integrative forest management, they alone do not suffice. Without such operational clarity, these integrative concepts risk remaining theoretical ideals, limiting their practical uptake and tangible impact on forest conditions. Addressing this gap requires forest managers, policymakers, and researchers to prioritize the development and dissemination of comprehensive implementation frameworks. Leveraging these complementary strengths demands multi-scalar and cross-sectoral coordination, engaging a broad spectrum of stakeholders, including public agencies, private forest owners, scientific institutions, and civil society. Based on our review, we argue that future work on IFM should move towards more standardised indicators, shared good practices, and context-adapted interventions that translate principles into concrete

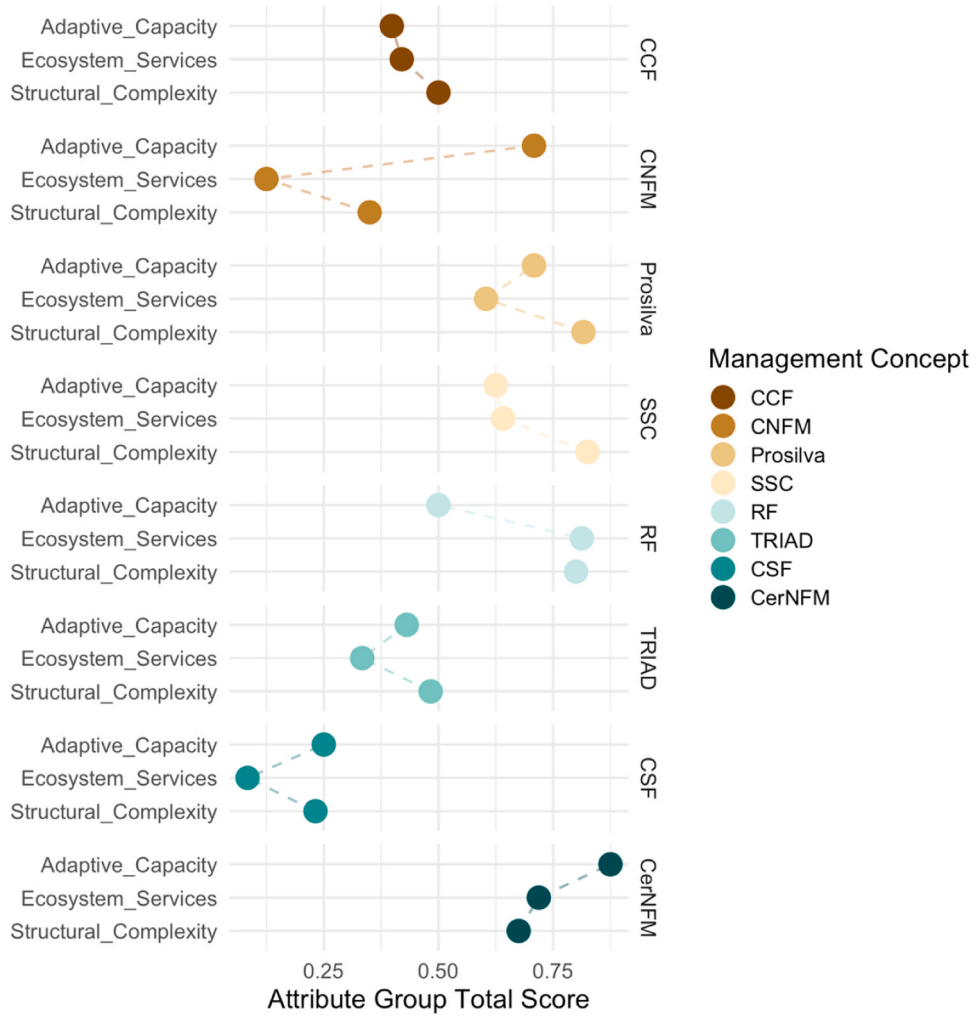


Fig. 5. IFM-related concepts cumulative scores for three aggregation categories of Structural Complexity, Adaptive Capacity, and Ecosystem Services provision. The scores are averaged for all evaluated publications shown in Figs. 3, and 4.

management actions, while remaining flexible enough to fit diverse ecological and socio-economic settings. Rather than claiming that IFM already provides such a toolset, we see this as a key next step for keeping the IFM framework meaningful and useful in guiding implementation. The diversity observed among IFM-related concepts, each excelling across different dimensions of Structural Complexity, Adaptive Capacity, and Ecosystem Services, presents valuable opportunities for synergistic integration. For instance, ProSilva's strengths in promoting structural complexity can complement Climate-Smart Forestry's focus on climate adaptation, while the Stepping Stone Concept's emphasis on connectivity enriches landscape-scale management under frameworks such as Closer-to-Nature Forest Management. Although there might be cases when contrasting options are available, for example, while CSF calls for reducing standing volumes/rotation periods, this may be antagonistic vis-à-vis ProSilva or CerNFM.

A major strength of IFM, is its capacity to be tailored to different contexts. Regional ecological conditions, management traditions, forest history, ownership patterns, market pressures, and governance regimes all shape possible management trajectories and priorities, which can accommodate actions to improve the integration of biodiversity and other ecosystem services (see e.g. Krumm et al., 2020). Successful adaptation, therefore, hinges on flexible strategies tailored to specific social-ecological realities, and adaptive management capable of responding dynamically to evolving environmental challenges and expanding scientific knowledge. In this regard, policy frameworks play a pivotal role. Instruments that incentivize collaborative governance, landscape-level planning, and cross-sectoral coordination are essential to foster coherent strategies that maximize synergies and reconcile potentially conflicting objectives. Policy mechanisms should explicitly support experimentation, participatory planning, co-learning platforms, and adaptive regulatory environments, and have a crucial role in mediating tensions between production and conservation goals (Winkel et al., 2022).

In summary, the findings highlight a dual imperative: 1) to capitalize on the unique strengths of existing IFM-related concepts via synergistic integration and the need for a common framework, and 2) to address the significant operationalization gap by shared principles and attributes resulting in integrative implementation tools. Together, these steps are essential to bridge the divide between conceptual promise and practical forest management transformation. Thus, moving beyond conceptual alignment towards thriving operationalization of IFM requires a concerted, collaborative effort, grounded in scientific rigor, clear and practical management guidelines, coherent and flexible policy frameworks, and incorporation of local knowledge. Ultimately, such integration will support the stewardship of resilient, multifunctional forests capable of meeting ecological imperatives and societal needs amidst the uncertainties of global change.

3.3. Trajectories to implementing IFM in practice: from current practice to future biodiversity-oriented forest management

In practice, improving forest management to better promote biodiversity and global change adaptation requires the targeted application of specific IFM principles. The path of transition depends strongly on initial forest conditions, capacities and constraints of the forest enterprise, regional policy frameworks, and long-term management vision. Multiple transition trajectories may be viable, shaped by starting points, pace of change, and the impact of individual actions. Importantly, even immediate interventions often take years or decades to yield measurable outcomes, particularly for biodiversity enhancement or structural complexity. The success of the implementation of management attributes in delivering IFM goals hinges on their timely and context-appropriate application, making a thorough analysis of site-specific conditions essential for realistic and efficient transitions. This includes recognizing trade-offs and boundary conditions. Thus, a landscape-level perspective, coordinated planning, and strong awareness and support from decision-makers are crucial to mediate these trade-offs and ensure that biodiversity is not sidelined.

When translating IFM principles into practice, context-specific guiding questions arise:

- Which aspects of biodiversity require priority enhancement within the managed forest?
- Over what temporal scale are desired outcomes expected — years, decades, or longer?
- Do objectives require active interventions, or can they be met through using natural dynamics (e.g. natural regeneration)?
- How can climate change adaptation be considered (e.g., how can the current species composition be diversified or adapted to increase climate resilience)?

Effective IFM implementation necessitates strategic planning across short-, medium-, and long-term objectives (Fig. 5), aligned with relevant principles and attributes. For example, in forests currently managed as conifer monocultures for timber, a combination of active measures (targeted planting, thinning) and passive strategies (natural regeneration) can be initiated. While these changes may reduce timber yields in the long term, after the intensive cutting of conifers, they will foster greater species diversity, enhancing biodiversity, structural complexity, and climate resilience over time.

Let's consider, for instance, a Central European forest enterprise long managing spruce (*Picea abies,* Fig. 6) monocultures outside their natural range, recently impacted by drought and bark beetle outbreaks, leading to widespread mortality and salvage logging (a quite widespread pattern in Central Europe currently). Natural regeneration remains dominated by spruce with a few pioneer tree species. The enterprise now commits to transitioning toward IFM, aiming to sustain timber production while promoting biodiversity and resilience. Within the IFM framework, corresponding actions illustrate temporal progressions linked to each principle:

- **Principle 1 – Retention of habitat trees and deadwood:** Existing deadwood from dieback provides immediate habitat retention (short-term), whereas development of new habitat trees will take decades (long-term).
- **Principle 2 – Promote site-adapted native tree species:** Due to spruce vulnerability and limited natural alternatives, planting climate-adapted species must begin promptly, with structurally mixed stands maturing over decades (short- to mid-term).
- **Principle 3 – Promote natural regeneration:** Natural regeneration following disturbance may already contain a diverse mix of pioneer and late-successional species; management therefore focuses on steering this cohort by favoring site-adapted individuals and, where important species are missing, supplementing natural regeneration

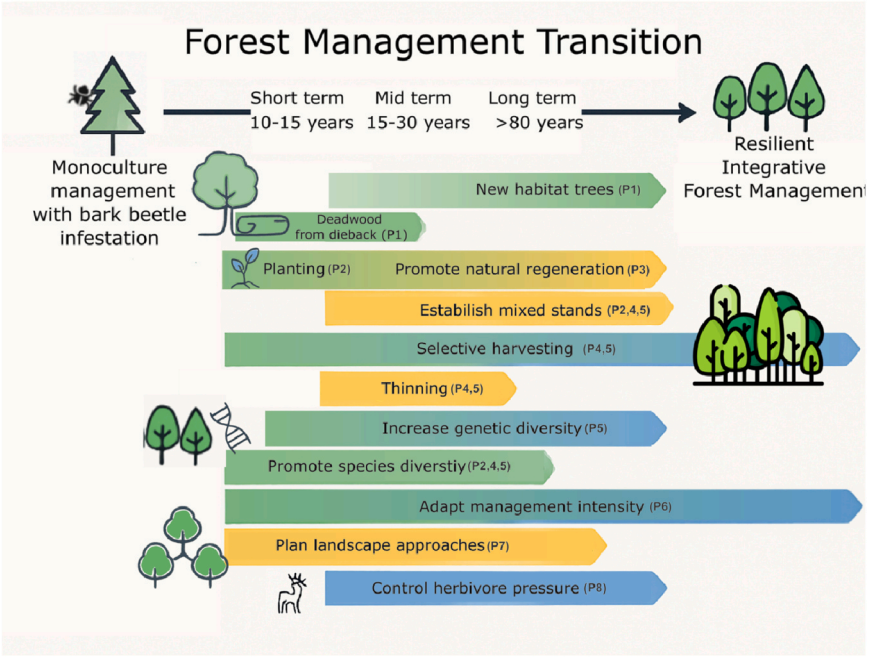


Fig. 6. Timeline figure illustrates the phased transition of a Central European Forest enterprise from spruce monoculture management subject to bark beetle infestation toward Integrative Forest Management (IFM). It maps eight core IFM principles as distinct horizontal layers, showing the temporal initiation and expected duration of key interventions across short-term (0–10 years, green), mid-term (10–30 years, yellow), and long-term (>80 years, blue) horizons. Each action is aimed at contributing to achieving or often multiple principles. Early actions focus on retaining existing habitat trees and deadwood, initiating planting of climate-adapted native species, and revising harvesting practices to reduce intensity. Mid-term efforts promote structural heterogeneity through partial harvesting, natural regeneration maturation, species and genetic diversity, and landscape-scale collaboration. Long-term management consolidates new habitat tree development, heterogeneity maintenance, adaptive ecological stressor control, and sustained ecosystem function. The figure highlights the adaptive, multi-scalar, and multi-decade nature of IFM implementation, underlining the balance between ecological restoration, biodiversity conservation, and forest production goals.

through targeted planting (short-term), with reproductive maturity and regenerative cycles developing over decades (mid-term).

- **Principle 4 – Partial harvests for structural heterogeneity:** Depending on site conditions, post-disturbance regrowth can evolve towards relatively homogeneous cohorts. Targeted planting and subsequent thinning or selection harvests can gradually increase heterogeneity (short- to long-term).
- **Principle 5 – Promote species and genetic diversity:** Selection of species and provenances adapted to future climates and the promotion of species-diverse mixtures is essential during regeneration phases (short- to mid-term).
- **Principle 6 – Avoid intensive management:** Monitor the impact on salvage logging areas, and transition towards less intensive operations may require revising harvesting techniques, investment in equipment, and workforce training (short-term).
- **Principle 7 – Support landscape heterogeneity and function:** Achieving this requires collaboration beyond individual ownership, including joint planning and coordinated management (short- to mid-term).
- **Principle 8 – Manage ecological stressors:** Biodiversity and resilience enhancement depend on effective game management in the absence of regulating carnivores to facilitate regeneration of diverse tree species and mitigate browsing pressures, which is often a long-term challenge (short- to long-term).

Clearly, these principles and attributes work in synergy with each other to encompass the whole ecosystem and key aims of IFM (Table 2). Together, Principles 1–3 primarily shape the regeneration trajectory at the tree and stand level, while Principles 4–8 create the structural, landscape, and governance conditions that enable this regeneration to translate into long-term biodiversity and resilience gains.

This example underscores the layered complexity and temporal scales involved in transitioning to IFM, emphasizing that no single intervention suffices. Instead, a multiscalar, adaptive approach is needed that aligns immediate actions with long-term ecological objectives, all adapted to evolving environmental and social contexts. Place-based knowledge and ecosystem understanding are paramount. While comparing outcomes remains challenging due to the conceptual nature of IFM principles and attributes, the framework offers significant benefits by promoting biodiversity and global adaptation in managed forests. The transition pathways illustrated serve as a practical example of how a forest enterprise managing monocultures can strategically shift toward IFM over short-, medium-, and long-term horizons. These pathways are not prescriptive but function as interpretative tools to guide strategic decision-making within the broader IFM framework. By emphasizing staged implementation, beginning with habitat retention and native species promotion, progressing through structural and tree species diversification, and culminating in landscape-scale adaptation, this approach demonstrates how practitioners need to sequence interventions to align with local ecological and socio-economic realities. Such pathways underscore the importance of long-term, adaptive planning and highlight the potential for operationalizing IFM principles in diverse forest management settings.

3.4. IFM for restoration of naturalness? — The next complexity level and emerging challenges

Balancing ecosystem service provisioning with aims to increase "naturalness," alongside the urgent need to enhance forest resilience, represents a central challenge in contemporary forest management (Barredo et al., 2024). Achieving this balance requires innovative, adaptive management strategies that embrace the complex interplay of forest functions, climate dynamics, disturbance regimes, and socio-economic realities (Seidl et al., 2016). In debates on naturalness, a key tension lies between viewing it as an idealised "pre-human" reference state and recognising that, especially in Europe, such states are largely unattainable; instead, naturalness is more usefully conceived in relation to type-specific reference conditions shaped by regional disturbance regimes, as outlined in our introduction. Here we distinguish between actively managed stands, where naturalness is approximated by restoring or maintaining key compositional and structural features or processes (e.g., regeneration dynamics, deadwood, heterogeneity), and intentionally unmanaged areas (e.g., strict reserves, set-aside patches), which contribute reference conditions, long-term structural legacies, and source populations, and can also function as connectivity elements within managed landscapes.

From this perspective, it is less about returning forests to a pristine state and more about re-creating forest composition, structure, and dynamics that approximate the historic range of variation, including features such as species diversity, age-class heterogeneity, deadwood presence, and spatial patterns. Natural processes remain fundamental drivers of ecosystem functioning and adaptive capacity, but they can be deliberately harnessed and complemented through management, for example, by using natural regeneration, fostering disturbance-created heterogeneity, or actively restoring missing structures and species. Thus, while fully "undisturbed" systems are very rare in Europe, the structural and compositional aspects of naturalness can, to a significant extent, be supported, restored and accelerated through well-designed management interventions (Gossner et al., 2013; Krumm et al., 2020; Messier et al., 2013).

Traditionally, a high degree of naturalness has been linked with minimizing human disturbance, enabling forests to develop into stable, biodiverse, and resilient ecosystems over centennial timescales (Barredo et al., 2024; Schütz et al., 2016). This passive approach utilizes ecosystems' innate adaptive capacity (Angeler, 2019), which can lead to mature, diverse forests. Nonetheless, the increasing pace of climate change increasingly surpasses the capacity of many forest ecosystems to adapt through natural processes alone, resulting in novel ecosystems with different species compositions and functions (Frietsch et al., 2023), aided by assisted migration strategies (Leech et al., 2011, Bower et al., 2024). These ecosystems differ significantly from historical baselines, making a purely "without humans" reference problematic and necessitating a more functional and dynamic perspective centered on processes and structural–compositional features that can be restored or supported through management. The very concept of naturalness is fluid and contested, without a universally agreed-upon baseline or reference condition (Winter, 2012). Resolving this conceptual plurality is beyond the scope of this work; however, it is essential to recognize that IFM, as a framework, relates to and implicitly incorporates the concept of naturalness, while remaining adaptable to multiple interpretations.

Restoration ecology has advanced the discourse by integrating notions of novel ecosystems, rewilding processes, and multifunctional landscapes (Perino et al., 2019). Within European contexts, rewilding actions have stressed the importance of keystone species, trophic interactions, and landscape connectivity for restoring naturalistic functions (Carver et al., 2021), concepts directly relevant to IFM's objectives of biodiversity conservation and ecosystem resilience. Newer restoration-oriented paradigms, such as Conceptual Ecological Restoration and rewilding promoted by initiatives like the Horizon Europe WILDCARD project, emphasise dynamic, process-based forest development and self-regulating ecosystems aimed at long-term resilience (Moomaw et al., 2019). However, these approaches can involve trade-offs, including less predictable ecosystem-service trajectories, economic returns that are often uncertain or insufficiently quantified, and disturbance-related risks that, in some contexts, may complicate planning in adjacent managed forests (Faure et al., 2024, Hart et al., 2023). These conflicting demands reflect broader societal debates about how forests should look, function, and contribute to both ecological integrity and human well-being.

Strictly passive management approaches, though ecologically idealized, are often impractical or insufficient to ensure the continuity of desired ecosystem services and forest functions within current societal

timelines (Lecina-Diaz et al., 2024; Messier et al., 2021). Additionally, natural adaptation processes might be too slow in responding to fast changes in climate. Especially in intensively managed forest landscapes, characterized by fragmentation, species impoverishment, and altered disturbance regimes, simply ceasing intervention often fails to restore natural structures and processes within relevant time frames; thus, active management is necessary to bring these forests to desired conditions of high biodiversity and resilience (Senf et al., 2019). Climate-induced shifts in disturbance regimes further complicate assumptions about natural ecosystem dynamics and resilience (Forzieri et al., 2021).

Within this context, integrative forest management (IFM) plays a vital role by providing a conceptual and operational approach that explicitly aims to restore and maintain structural and compositional naturalness through active management measures. IFM supports ecosystem functioning from early successional stages, such as afforestation and the development of new forests, through transitional phases, up to complex, old-growth structures. It does so by promoting species and genetic diversity, facilitating natural regeneration, retaining habitat structures, and enhancing landscape connectivity. In practice, IFM acknowledges that naturalness is not a static target but a dynamic characteristic that changes over time and space, influenced by climate, disturbance regimes, and human interventions. Its principles and attributes are designed to guide the restoration and maintenance of forest elements that approximate natural variability and complexity, while balancing production and protection goals. Rather than prescribing a fixed notion of naturalness, IFM positions itself as a framework that acknowledges multiple legitimate interpretations, supports the restoration of natural forest structures and processes through a combination of passive and active measures, and adapts to evolving ecological and societal realities.

3.5. *Practical implications and the missing link between data and reality*

A recurring challenge when assessing IFM-related concepts is the lack of information on the extent to which they are actually implemented on the ground. While some public forest owners may declare their approach to forest management, there is no harmonised reporting across forest ownerships on where, and to what degree, forest managers apply different IFM concepts (or label their practice accordingly). IFM may be applied in parts of an enterprise only and in combination with other approaches, or it can take place informally and without documentation. Thus, the literature on IFM rarely provides robust quantitative estimates of the spatial coverage of the implementation of concepts at the enterprise, regional, or even national level. Existing figures on European coverage of IFM-related approaches such as continuous cover forestry are thus based on expert estimates (e. g. Mason et al., 2022).

Where formal organisations or networks exist (e.g., Pro Silva and national member organisations), membership lists may indicate a country-level presence and sometimes provide coarse information on where practices are promoted, but they do not necessarily translate into quantifiable implementation on the ground. For example, Pro Silva Europa currently comprises 25 national branches and represents ~5500 members, with the German ANW (Arbeitsgemeinschaft Naturgemässe Waldwirtschaft) as the largest national branch. However, the organisation currently lacks consolidated data on the total forest area actively managed by its members under Pro Silva principles. This illustrates both the value and the limitation of membership-based proxies, which remain useful for demonstrating geographical presence and distribution, but are insufficient for quantifying the extent of implementation of different IFM-related approaches.

Where concepts primarily function as policy framings (e.g., Climate-Smart Forestry or EU closer-to-nature forest management guidance), there is typically no membership-based structure that could provide data on spatial coverage. In a few contexts, elements of concepts are embedded in legal or regulatory frameworks, which allows reporting at the level of rules and intended practice. One of these cases is Switzerland, where close-to-nature forestry is embedded in national governance (Strauss and Fischer, 2025). However, legal coverage is still only a proxy for actual practice: implementation varies by canton, forest enterprise, and local objectives, so “managed under close-to-nature regulations” does not translate into consistent, mappable on-the-ground practice. This absence of comparable implementation data is therefore a crucial gap. Currently, proxy indicators are relied upon based on expert opinions or a rough model-based representation of forest management regimes across Europe, which are neither verified on the ground nor quantifiable, rather than on direct observation and reporting (Hengeveld et al., 2012; Scherpenhuijzen et al., 2025).

Importantly, this data gap also limits the possibility of analysing the “effectiveness” of the application of concepts. If one aims to quantify outcomes and compare concepts, there is a need for meaningful indicators, applied consistently across enterprises and regions and monitored over at least one inventory period. The available indicator systems, which were originally designed to capture forest growing stock and productivity, have not been developed sufficiently to assess the achievement of IFM goals, particularly those related to biodiversity, non-timber related ecosystem services such as recreational and health benefits, resilience and adaptive capacity. For example, most current enterprise-level data or national forest inventories provide only structural proxies for the provision of diverse habitats (e. g. Storch et al., 2018) but little to no information about occurrences of forest-dwelling species beyond trees. Therefore, concept-to-concept comparisons of outcomes remain largely inferential. Developing harmonised indicators and monitoring frameworks that can be applied across operational scales is therefore a prerequisite for future, evidence-based evaluation and is one of the motivations of ongoing efforts within the Horizon Project TRANSFORMIT(Linser et al., 2025). Thus, this conceptual synthesis also highlights the importance of future indicator development to facilitate standardized monitoring approaches as well as cooperation and dialogue between practice and research.

4. Conclusion

This perspective compares prominent IFM-related forest management concepts through a common set of IFM-based principles and attributes. Despite their varied origins, terminology, and management practices, these concepts reveal substantial overlap in their fundamental principles and shared goals, mainly the promotion of biodiversity, climate resilience, structural complexity, and multifunctional ecosystem service provision. However, this convergence at the level of principles does not necessarily extend to the implementation of concepts on the ground. By critically comparing these concepts using a coherent operational framework for IFM and by identifying existing alignments and gaps, this study examines which principles and management actions are currently integrated into European forest concepts, and which are underrepresented. This offers guidance for forest managers, planners, and policymakers on strengths, gaps, and efforts required to promote IFM landscapes.

Owing to the lack of data on the spatial extent and effectiveness of the application of different IFM concepts, our analysis focused on a theoretical level. It showed that none of the reviewed IFM concepts fully achieves the multidimensional objectives of IFM in terms of structural complexity, adaptive capacity, and ecosystem service provision—each concept has particular strengths and weaknesses. While ProSilva, CerNFM, and the SSC, for example, take a relatively comprehensive approach, others, such as CSF and CCF, tend to focus on more limited aspects. Recognising and combining these complementary strengths of the concepts could contribute to the development of more robust, flexible management frameworks capable of addressing the complex socio-ecological challenges facing forests today.

The practical value of this Perspective lies in offering a structured way to translate context-specificity into operational planning, without

assuming that one label fits all contexts. The exemplary IFM trajectory we present in chapter 3.3 highlights how transformations demand a context-specific decision-making process, followed by a selection of feasible attributes, which are multi-scaled and have long-term implications, with the final step being the call for monitoring systems based on indicator sets capable of assessing the achievement of IFM principles. At the policy and research interface, our findings emphasize the catalytic role of institutional support, strategic networking, and policy-aligned initiatives in accelerating the dissemination and evolution of IFM-related concepts. The interplay of scientific discourse, practical application, and policy frameworks will remain key in fostering integrative, evidence-based forest management approaches.

CRediT authorship contribution statement

V. Vitali: Conceptualization; Methodology; Investigation; Formal analysis; Data curation; Visualization; Writing – original draft; Project administration. **F. Krumm:** Conceptualization; Methodology; Resources; Writing – review & editing; Supervision. **A. P. Spinu:** Investigation; Formal analysis; Data curation; Writing – review & editing; Visualization. **F. Schnabel:** Investigation; Formal analysis; Writing – review & editing; Visualization. **J. Bauhus:** Conceptualization; Methodology; Writing – review & editing; Supervision. **A. Konczal:** Conceptualization; Writing – review & editing. **L. Schimetka:** Investigation; Writing – review & editing. **S. Schwegmann:** Investigation; Writing – review & editing. **G. Winkel:** Conceptualization; Writing – review & editing. **A. Rigling:** Conceptualization; Supervision; Funding acquisition; Writing – review & editing.

Declaration of Competing Interest

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2026.123698.

Data availability

Data will be made available on request.

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