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PRODUCTIVE AND BIODIVERSE: MANAGING EUROPE'S FORESTS FOR ECONOMIC AND ECOLOGICAL OUTCOMES

An evidence-based synthesis report

Editors: Nelson Grima, Laura Walther, Frank Krumm

Lead Authors: Frank Krumm, Andreea Spinu, Zuzana Dobšinská, Tommaso Chiti, Nataša Lovric, Maria Nijnik

Contributing Authors (in alphabetical order): Jürgen Bauhus, Denis Dobrynin, Adam Felton, Oliver Frings, Lenka Haluskova, Stefanie Linser, Sandra Lupien, Silvina Manrique, Simone Martino, Mariana Melnykovych, David Miller, Yoan Paillet, Petra Palátová, Chad C. Papa, Ana Rey, Christian Rosset, Patrick O. Waeber, Livia Zapponi, Miguel A. Zavala

IUFRO
Interconnecting Forests, Science and People





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Preface

In the face of climate change, biodiversity loss, geopolitical disruption, and evolving societal expectations, the future management of Europe's forests has become a highly relevant topic for a wide range of stakeholders. European forests are increasingly expected to simultaneously provide biodiversity conservation, climate change mitigation and adaptation, renewable raw materials, and a broad range of ecosystem services. Responding to these multiple and often competing demands requires informed decisions based on robust scientific evidence.

Against this background, a group of internationally renowned experts from a broad range of scientific backgrounds and disciplines carried out this comprehensive study titled Productive and Biodiverse: Managing Europe's Forests for Economic and Ecological Outcomes within the framework of the science-business platform Teaming Up 4 Forests. When analysing the existing scientific evidence and preparing this study, the authors were guided by the questions identified during think tank meetings and discussions with stakeholders convened by the platform. Rather than addressing individual aspects in isolation, this publication provides an integrated perspective on how forest management can simultaneously support biodiversity conservation, climate resilience, sustainable wood production, carbon storage, and broader ecological, economic, and societal objectives through evidence-based and multifunctional approaches. By highlighting both scientific evidence and practical implications, the study aims to support informed decision-making across the forest sector.

Since 2017, IUFRO has fostered dialogue between science, business, policy, and other stakeholders in the forest sector and, together with Mondi, established the official platform Teaming Up 4 Forests in 2021. The platform brings together experts from different disciplines and sectors to address some of the most pressing challenges facing Europe's forests. In line with the principles of Teaming Up 4 Forests, the highest standards of scientific quality, integrity, independence, and transparency have been applied throughout the preparation of this study.

My sincere thanks go to the Chair of the study, Frank Krumm, and to all authors who contributed to this publication, for their outstanding work and collaborative efforts. Each member of the team contributed their specific expertise to address the ecological, economic, and societal dimensions of managing Europe's forests. I would furthermore like to thank the Coordinator of Teaming Up 4 Forests, Nelson Grima, and the Project Manager and coordinator of the study, Laura Walther, for their outstanding guidance and support in the drafting process and for editing the publication. This study demonstrates how scientific cooperation across disciplines is essential for developing integrated solutions to the complex challenges facing Europe's forests. I would also like to sincerely thank Mondi for the funding provided for this study.

It is my sincere hope that the study will contribute to informed dialogue and evidence-based decisions that support forests which are both productive and biodiverse, for the benefit of present and future generations.



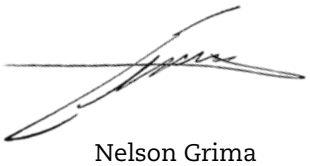
Alexander Buck
IUFRO Executive Director

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This publication is the product of the scientific collaborative work coordinated by Teaming Up 4 Forests. We extend our heartfelt appreciation to all authors and contributors for their valuable work. In particular, we sincerely thank the lead authors for driving the development of each chapter in this study. Their dedication, major efforts and great expertise were essential for the preparation of this publication. We also express our appreciation to the institutions associated with the authors, which facilitated their ability to contribute to this product.

We would like to note that the views expressed in this publication do not necessarily reflect the position of the organisations to which the authors are affiliated. We furthermore express our sincere gratitude to Mondi for the financial support provided and the freedom granted to the team of experts for conducting the study and producing this publication. As a business partner in the Teaming Up 4 Forests platform, the insights of Mondi provided a valuable indication of the information needs of wood-based industries. At the same time, we would like to note that the views expressed within this publication draw on scientific evidence and expert knowledge, and do not necessarily reflect the position of the forest-based industry in general or the funding company in particular.

Our special thanks go to all participants of the 4th Teaming Up 4 Forests Think Tank Meeting – including wood-based businesses, forest owners, public administrations, international organizations, scientists and other stakeholders – that helped us to compile a wide spectrum of different views and stakeholders' perspectives on consequences of potential future developments. We would also like to express our sincere appreciation to the reviewers who provided valuable comments and suggestions during the review process, which helped to further strengthen the quality and clarity of this publication. In addition, we would like to sincerely thank the IUFRO Secretariat for the administrative support and knowledgeable guidance throughout the development of this report and the work of the expert group.



Nelson Grima



Laura Walther



Frank Krumm

List of Acronyms, abbreviations, and units

%	Percentage
°C	Degrees Celsius
ASCC	Adaptive Silviculture for Climate Change
C	Carbon
C&I	Pan-European Criteria and Indicators
CAP	EU's Common Agricultural Policy
CBD	Convention on Biological Diversity
CCF	Continuous Cover Forestry
CCRF	Climate Change Response Framework
CDSE	Copernicus Data Space Ecosystem
CerNFM	Closer-to-Nature Management
CFF	Circularity Footprint Formula
CLT	Cross-laminated Timber
CO_2	Carbon Dioxide
CO_2e	Tonnes of CO_2 Equivalent
CRCF	Carbon Removals and Carbon Farming
CRTC	Composite Recycling Technology Center
CSF	Climate-Smart Forestry
DSS	Decision-Support Systems
EC	European Commission
EO	Earth Observation
EPD	Environmental Product Declarations
EU	European Union
ES	Ecosystem Services
EUDR	Regulation (EU) 2023/1115 on deforestation-free products
FAO	Food and Agriculture Organization of the United Nations
FISE	Forest Information System for Europe
FOKIS	Forest Knowledge and Innovation System
Forest Europe	Ministerial Conference on the Protection of Forests in Europe
FSC	Forest Stewardship Council

GEO-BEN	Group on Earth Observations Biodiversity Observation Network
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GWP	Global Warming Potential
HCV	High Conservation Value
HWP	Harvested Wood Products
IFM	Integrative Forest Management
IUCN	International Union for Conservation of Nature
KMGBF	Kunming-Montreal Global Biodiversity Framework
LCA	Life Cycle Assessment
LiDAR	Light Detection and Ranging
LTER	Long-term Ecological Research
LULUCF	Land Use, Land Use Change, and Forestry
MFF	Multifunctional Forestry
MRV	Monitoring, Reporting, and Verification
NEUFS	New EU Forest Strategy
NFIs	National Forest Inventories
NPV	Net Present Value
NWFP	Non-wood Forest Products
NRR	Nature Restoration
PEF	Product Environmental Footprint
PEFC	Programme for the Endorsement of Forest Certification
PEFCR	Product Environmental Footprint Category Rules
PES	Payments for Ecosystem Services
RED	Renewable Energy Directive
REDD+	Reducing Emissions from Deforestation and Forest Degradation and the Role of Conservation, Sustainable Management of Forests and Enhancement of Forest Carbon Stocks in Developing Countries
RS	Remote Sensing
SES	Socio-ecological Systems
SF	Substitution Factor
SFM	Sustainable Forest Management
SoEF	State of Europe's Forests
SVO	Social Value of Offsets
TU4F	Teaming Up 4 Forests
UAV	Unmanned Aerial Vehicle
UNECE	United Nations Economic Commission for Europe
YFP	Yakama Forest Products

Chapter 1

Introduction

Lead Author: *Frank Krumm*

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1.1 Background

With the continued growth of the global population, the demand for ecosystem services, including those provided by forests, has increased substantially (MEA, 2005). Forests supply a wide range of essential services, such as clean drinking water, recreational opportunities, protection against natural hazards and soil erosion, local climate regulation, and global climate mitigation through carbon storage (FAO, 2020; Zellweger et al., 2020). While both managed and unmanaged forests contribute to these services, targeted forest management is often required to ensure their provision in sufficient quality and quantity.

At the same time, rising demand for forest resources, agricultural land, and other natural resources has intensified the global biodiversity crisis (Díaz et al., 2019). Forest ecosystems represent important biodiversity hotspots (Myers et al., 2000), and protecting these in a sufficient way could mean that not all ecosystem services can be maximized simultaneously within the same area. Consequently, management decisions must prioritise certain services while ideally improving synergies between them. In a globalised economy, however, such decisions often have indirect impacts on forests in other regions. Furthermore, many consumers remain largely unaware of the environmental and social consequences of their consumption choices. Combined with governance failures and the dominance of short-term economic incentives, these dynamics increase the pressure on forest ecosystems. International initiatives such as forest certification schemes and mechanisms like Reducing Emissions from Deforestation and Forest Degradation and the Role of Conservation, Sustainable Management of Forests and Enhancement of Forest Carbon Stocks in Developing Countries (REDD+) aim to improve production standards and mitigate these pressures.

This report focusses on European forests. Political frameworks, governance, and markets are strongly interconnected and influence each other. However, the authors are aware that differences of biomes, management approaches, historical developments, and local policies may be very diverse. This great diversity is characteristic for Europe and provides not only opportunities but certainly also challenges. The gradient from Boreal to Mediterranean forests is striking, and many concepts that are introduced and described in this report have been developed for temperate forest areas in Central Europe. This must be considered as local contexts may require adaptations while applying and interpreting these concepts. A number of publications have tried to reflect on this specific European situation (e.g. Kraus and Krumm, 2013; Krumm et al., 2020; Larsen et al., 2022).

1.2 The importance of biodiversity in managed forests

Biodiversity in forests operates across multiple levels, including genetic diversity, species richness, structural diversity, and landscape heterogeneity. These components are critical for ecosystem stability and resilience in general, but they are of particular importance in the context of managed forests (Hooper et al., 2005; Messier et al., 2019). Maintaining biodiversity is essential not only for conservation purposes but also for sustaining ecosystem services. Diverse forests tend to be more resilient to disturbances such as storms, pests, and climate change. Mixed-species forests, for instance, are often more resistant to environmental stressors than monocultures (Jactel et al., 2018). However, conventional forestry practices, especially monoculture plantations and clearcutting, often simplify forest structure and reduce biodiversity (Brockerhoff et al., 2008). This has led to increasing recognition that biodiversity must be explicitly integrated into forest management planning.

Reconciling forest management with biodiversity conservation has therefore become a central challenge in environmental science and policy. Scientific research increasingly emphasizes that biodiversity conservation is not per se incompatible with forest use, but rather requires a shift towards multifunctional and adaptive management approaches (Krumm et al., 2020; Messier et al., 2015). Forest ecosystems are inherently complex, and management interventions can either enhance or degrade biodiversity depending on their design and implementation. The key question is no longer whether forests should be used or protected, but how both objectives can be achieved simultaneously. This means that forests should be productive and biodiverse; but a very important question is, how much is enough?



Forests are critical for biodiversity, climate regulation, and human well-being © Nelson Grima

1.3 Trade-offs between forest management and biodiversity

A central challenge in combining forest management with biodiversity conservation is the existence of trade-offs. Maximizing timber production or bioenergy supply often leads to intensified management, which can negatively affect species richness and habitat quality (Felton et al., 2016). Climate mitigation strategies relying heavily on forest biomass can further exacerbate biodiversity loss if not carefully managed. However, these trade-offs can be mitigated through biodiversity-sensitive approaches, such as reducing management intensity, increasing protected areas, and optimizing spatial allocation of production forests (Hof et al., 2018). Adaptive management strategies aimed at improving forest resilience may also have unintended ecological consequences. For example, interventions to reduce pest outbreaks can alter forest structure in ways that increase vulnerability to other disturbances (Seidl et al., 2017; Viana-Soto and Senf, 2025). This underscores the need for integrated, multi-objective planning frameworks.

1.4 Clear and robust information

One important precondition for objective evaluation and effective biodiversity conservation consists in robust measures based on monitoring data and indicators. To achieve this, definitions of agreed terms are essential to ensure common language and comparability. Since different countries have developed different traditions, comparisons are complex. For example, national forest inventories still vary across countries despite efforts to harmonize measurements, and national biodiversity monitoring schemes are widely missing or have started only recently. Additionally, monitoring of ecosystem services has not yet been developed at a larger scale, and interactions among services are particularly difficult to evaluate. It is therefore an ongoing task to identify and agree on monitoring, technology, and research needs.

Advances in remote sensing, geographic information systems (GIS), and artificial intelligence have significantly improved our ability to assess forest structure and biodiversity at large scales (Turner et al., 2015). Nevertheless, despite these advances, important knowledge gaps remain. Long-term studies are needed to better understand the interactions between forest management, biodiversity, and climate change. Interdisciplinary research will be critical for developing more effective management strategies in the near future.

1.5 Carbon storage in forest ecosystems

Forests serve as one of the Earth's most significant terrestrial carbon reservoirs, playing a fundamental role in the global carbon cycle by sequestering atmospheric carbon dioxide (CO_2) and storing it in both biomass and soil (IPCC, 2019). This process is critical for climate change mitigation, since terrestrial ecosystems,



Maintaining resilient forest ecosystems is essential for both carbon storage and biodiversity conservation
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dominated by forests, are estimated to absorb approximately 30% of human-induced CO_2 emissions annually (Tian et al., 2016).

The capacity of a forest to act as a carbon sink is determined by a complex interplay of factors, including stand age, health, tree species composition, and site productivity (Nagel et al., 2017). Carbon is primarily stored in two major pools, namely in Above- and Below-ground Biomass. Living trees, including their trunks, branches, and root systems, represent a dynamic pool that actively captures carbon through photosynthesis. Additionally, forest soils often constitute the largest terrestrial carbon pool in the form of soil organic carbon (IPCC, 2019). While biomass carbon sequestration can be relatively rapid, soil carbon accumulation occurs over longer timescales and is heavily influenced by management practices, decomposition rates, and disturbance related processes (Chiti et al., 2024).

The long-term effectiveness of forests as climate mitigation tools depends on the resilience of these carbon pools against natural disturbances such as fires, storms, and pest outbreaks, which are becoming increasingly frequent due to climate change (Forzieri et al., 2021). Consequently, modern forest management strategies prioritize maintaining structural complexity and species diversity to buffer these pools against volatility (Winkel et al., 2022). Furthermore, the climate benefits of forests are extended beyond the stand through the sustainable use of harvested wood products, which retain carbon for decades or centuries in structural timber and furniture, effectively delaying the return of carbon to the atmosphere (Cook-Patton et al., 2021).

1.6 Integrating forest management and biodiversity conservation

Among the approaches developed in European forestry, three broad concepts can be distinguished. Their relevance within the broader landscape of European forest management is explored further in Chapter 2. One strategy to reconcile competing demands for forest resources is spatial segregation, which separates land uses in order to maximise specific ecosystem services. This approach has been used, for example, to reduce conflicts between forestry and agriculture in Central Europe (Suda and Pukall, 2014). Industrial plantations represent an extreme form of segregative land use (Spathelf, 2009), and segregation can also include highly productive forest stands managed for timber production with limited biodiversity elements (Borchers, 2010). Similarly, strictly protected areas established for biodiversity conservation follow a segregative logic. However, the increasing global demand for timber and fuelwood (Bais et al., 2015; Sloan and Sayer, 2015), combined with growing expectations for non-timber ecosystem services such as biodiversity conservation and recreation (Sheppard et al., 2020), means that withdrawing large forest areas from production may intensify pressure on remaining forests worldwide.

An alternative approach is multi-functional forestry, which aims to deliver various ecosystem services simultaneously within the same forest area (Gómez-Baggethun et al., 2010; Wagner et al., 2013).

A third strategy named Integrative Forest Management (IFM) combines elements of segregation and integration (Kraus and Krumm, 2013; Sotirov and Arts, 2018). This approach seeks to reconcile multiple objectives across different spatial and temporal scales, from individual trees and stands to entire landscapes, while allowing for temporary or permanent protection of particular habitats or forest areas. IFM is particularly relevant in Central and Southern European forests, since they are embedded in long-established cultural landscapes shaped by centuries of human use. The situation is different in the boreal forests of Europe, where the use of forests has a long history of non-timber forest products use. Forest-related activities like mushroom picking, hunting and fishing, and reindeer herding are truly integrating different interests of society and mirror the historical multifunctional use of forests in the Nordic countries.

In the European context, high population densities, extensive infrastructure, limited land availability, and strong landscape fragmentation characterize many regions. As a result of historical land use, primary forests have almost disappeared in much of Europe, and near-natural ecosystems are relatively rare (Sabatini et al., 2018, 2020). Protected areas are often small, which restricts the occurrence of natural forest dynamics. Consequently, certain habitat features characteristic of primary forests, such as deadwood, old habitat trees, and structural complexity, must also be maintained within managed forests (Bütler et al., 2013; Gossner et al., 2013; Lachat et al., 2013; Ranius and Jonsson, 2007).

Historically, forest management in parts of Europe was guided by the assumption that timber-oriented management would automatically ensure the provision of other ecosystem services. This idea was expressed in the so-called "wake-water theory" ("*Kielwasser-Theorie*" – in Rupf, 1960). In practice, it was often associated with close-to-nature silviculture, which incorporates natural processes into forest management (Brang et al., 2014; Schütz, 1999). While this approach can support some ecosystem services, such as protection against natural hazards (Brang et al., 2008), it may fail to conserve key biodiversity elements such as deadwood, habitat trees, or rare tree species (Bauhus et al., 2013). Moreover, the concept is often implemented differently depending on the knowledge and attitudes of forest managers.

Public attitudes toward forest management have also changed considerably since the 1980s. Increasing awareness of biodiversity loss and the growing urbanisation of societies have led to greater expectations for nature conservation in forests (Puettmann et al., 2009). International policy frameworks have reinforced these expectations, particularly the Convention on Biological Diversity (CBD) and its Aichi Biodiversity Targets (CBD, 2010). Consequently, forest biodiversity conservation is no longer limited to preventing further loss but increasingly includes efforts to actively restore and enhance biodiversity.

At the same time, biodiversity conservation targets are not static. They vary across regions and change over time depending on historical land use, site conditions, and societal values. Climate change further complicates these dynamics. Shifts in temperature and precipitation regimes are expected to alter vegetation zones and species distributions across Europe (Frehner et al., 2018; Hanewinkel et al., 2013). Extreme climatic events, such as the droughts and heatwaves experienced in Central Europe in recent decades, have increased disturbance regimes, including outbreaks of bark beetles and other pests (Schuldt et al., 2020). These changes may lead to temporary or permanent losses of certain forest habitats. Therefore, promoting structural and species diversity is increasingly viewed as a key strategy for enhancing ecosystem resilience and buffering uncertainties associated with climate change.

Beyond ecological challenges, forest management strategies must also address complex socio-economic and governance contexts. Forest policies and biodiversity regulations vary significantly across Europe due to differences in ownership structures, legal frameworks, and political priorities (Sotirov and Arts, 2018). Forest ownership patterns are particularly diverse: while some public or private owners manage large forest areas, millions of individuals own very small parcels. Urbanisation and changing lifestyles have reduced the economic importance of these small forest holdings, often resulting in declining management interest. However, this diversity in ownership can also stimulate innovation and generate a variety of management approaches across landscapes.

The transition towards a bio-based economy further increases the relevance of sustainable forest management (SFM). Forests play a critical role in climate mitigation through carbon sequestration and through the substitution of fossil-based materials with renewable wood products. Efficient use of wood resources, guided by principles such as cascading use and circular economy concepts, is therefore essential (Jarre et al., 2020). At the same time, increased demand for timber may create additional trade-offs with biodiversity conservation and other ecosystem services.

Additional challenges arise from interactions of forestry, wildlife management, and nature conservation. Changes in predator populations, ungulate densities, and hunting practices have significantly influenced forest dynamics and biodiversity in Europe (Gill, 1992a, 1992b). Therefore, effective forest management requires integrated wildlife management approaches that involve multiple stakeholder groups and address both ecological and socio-economic considerations.

Overall, the increasing complexity of societal demands, ecological uncertainties, dynamics and governance structures makes the integration of biodiversity conservation into forest management more challenging than in the past. By promoting structural diversity, adaptive management, and stakeholder cooperation, integrative approaches can enhance the resilience of forest ecosystems and ensure their capacity to deliver essential services in the face of climate change and evolving societal expectations.

Focusing on Europe, the following five chapters give answers to timely and pressing questions that come along with the question of how productive and biodiverse forests can be maintained or improved. In particular, the following questions are tackled:

- How can biodiversity conservation and active forest management coexist, through defining acceptable levels of use and intervention while effectively meeting conservation goals?
- How can biodiversity in forest systems be defined and measured, with realistic targets and indicators that can be easily communicated, and that reflect both ecological value and societal relevance?
- How can carbon storage in forests be maximized sustainably, while aligning with value chain and policy incentives?
- How can forest management align climate resilience with evolving economic and societal goals?
- How can institutional support, incentives, and science-driven communication enable multifunctional forest management?

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Chapter 2

Integrative Forest Management for coexistence in Europe

Lead Author: *Andreea Spinu*

Contributing Authors: *Adam Felton, Yoan Paillet, Livia Zapponi, Jürgen Bauhus*

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2.1 Introduction

As socio-ecological systems, forests in Europe meet a broad and evolving array of societal demands. For example, they face increasing pressures from competing uses: growing demand for biomass to fulfil renewable-energy targets sits alongside the need to maintain recreational functions, water regulation, and other diverse ecosystem services (Kalaba, 2014). Most European forests are managed for multiple functions that underpin the provision of these services.

Approximately two-thirds of the total forest area in Europe supply timber, although the contribution varies widely according to tree species composition, site potential, market opportunities, ownership type, and conservation value and strategies (Barredo et al., 2024; Scherpenhuijzen et al., 2025). The combined extent of old-growth and strictly protected forest reserves accounts for five percent of the total forest area, which is substantially less than the area targets proclaimed in policies and what may be required to protect certain habitats and species (Forest Europe, 2020; Sabatini et al., 2018, 2020). The EU Biodiversity Strategy aims to protect at least 30% of the land in the EU, with a subset of ten 10 % percent under strict protection (EC, 2021). Consequently, forests outside these strict reserves, covering the vast majority of the landscape, play a crucial role in biodiversity conservation. They act as a surrounding matrix that both harbours habitats and species, and connects patches of high conservation value (Duflot et al., 2022).

In the past, forestry operations have often simplified and homogenised the structure of forest managed for timber supply. As a result, production forests often lack habitats for many forest-dwelling species, especially those dependent on structural elements of old-growth forests, or on other biological legacies formed by natural disturbances (Gustafsson et al., 2020). Biodiversity-friendly practices are therefore essential in production forests to support and complement conservation areas in large-scale managed forest across Europe (Bollmann and Braunisch, 2013). Furthermore, achieving biodiversity promotion relies on employing a variety of forest management strategies that differ across space and time (Duflot et al., 2025; Uhl et al., 2025) (Table 2.1).

Climate change adds further emergency. Forests, both inside and outside protected areas, will experience pronounced climate change-driven shifts in structure and composition (Krüger et al., 2025; Meyer et al., 2022). “Naturalness” (*sensu* Forest Europe; see e.g., Paillet et al. (2024)) alone is not a reliable indicator of resilience or of the adaptive capacity of these forests. Many native species have undergone genetic bottlenecks, and naturally regenerating stands can be monodominant (e.g., beech stands) and vulnerable to rapid climate change or pests and diseases (Hoffmann et al., 2019; Wessely et al., 2024).

The challenge is therefore to develop forest management approaches for Europe that deliver wood production and biodiversity conservation, while addressing risks related to climate change. European landscapes are often characterised by fragmented forests and forest ownership, where forest patches are isolated or separated by other land uses and where larger forest areas are divided in many, often small, properties with diverse objectives. This chapter argues that Integrative Forest Management (IFM) provides a flexible, evidence-based framework to meet this challenge. Drawing on existing European management traditions and emerging evidence on the adaptation of forests to global change, IFM offers principles and operational tools to reconcile wood production and biodiversity conservation across scales.

The following sections examine how IFM relates to existing management approaches (Section 2.2), how it can be coordinated at the landscape level (Section 2.3), how adaptive management can build resilience and restore biodiversity in forests (Section 2.6) and what levels of biodiversity and harvest can be considered acceptable and measurable in the context of global change (Section 2.7).

2.2 Integrative forest management framework

Reconciling the delivery of multiple ecosystem services in European forests while addressing the uncertainty of global change requires a management framework that operates across ecological, spatial, and temporal scales. In recent years, the concept of IFM has been developed, not as a replacement of existing management traditions, but as an umbrella concept that builds on the ideas and strengths of established, alternative forest management approaches

Table 2.1 Theoretical foundations, underlying mechanisms and practical consequences of relationships between forest management approaches and biodiversity promotion. Adapted from Duflot et al. (2022).

Hypothesis	Mechanism	Expected biodiversity consequence	Opportunities for practical actions
Habitat-diversity within a forest stand: management diversity increases landscape-scale habitat and species diversity.	Promotion and retention of large, living trees, coarse woody debris, tree species diversity, etc. creates a vertically and horizontally heterogeneous stand structure (deadwood, canopy gaps, varied bark texture).	Increased **β-diversity*,** overall species richness, and functional complementarity (more niches for specialist species).	▪ Retain **habitat trees and deadwood** (including snags, logs, downed branches). ▪ Manage for a mosaic of canopy gaps of differing characteristics (sizes, age, landscape position) and management intensities to increase the variation in habitats and resources.
Landscape spatio-temporal heterogeneity: asynchrony in and interspersion of management types and timing enhance long-term availability of diverse habitats.	Variable rotation lengths, combined with intermixing of contrasting silvicultural regimes produce a fine-scale mosaic of tree cohorts at various stages, with diverse structures and resource availability.	Continuous provision of resources across multiple forest stages can boost overall diversity and support specialists with limited dispersal. Landscape-level complementarity ensures that edge-adapted and other habitat specific species can find suitable conditions within short distances.	▪ Plan harvests so that older and younger stands remain **continuously interspersed,** and that different silvicultural regimes are applied across the landscape, preventing clustering or synchronised clear-cut blocks.
Temporary corridor: management diversity creates non-permanent connections between protected forests for multiple species.	Timing of harvesting is coordinated so that successional development stages are maintained within forest landscapes, producing a moving series of habitat windows that connect otherwise isolated patches (mosaic cycle).	Provides temporary corridors for low-mobility, habitat-specialist species, reducing the need for permanent linear corridors and lowering connectivity costs.	▪ Synchronise silvicultural activities so that **new gaps** are created before **previous gaps** fully regenerate (e.g., staggered felling across adjacent stands).
Forests with natural dynamics: heterogeneous unmanaged forests are needed for complete biodiversity conservation.	Designation of strictly protected unmanaged old-growth or primary forest blocks that remain free from any harvesting or intensive disturbance.	Conserves the subset of forest-dependent taxa that require long-uninterrupted habitat	▪ Designate parts of the forest in different successional stages as **strict reserves.**

* In forest ecology, **alpha diversity (α-diversity)** is a measure of diversity within homogenous units of a landscape (e.g., forest stands), **whereas beta diversity (β-diversity)** measures its variation between these units (different sites, habitats, or communities in a landscape).

Box 2.1 The concept of IFM

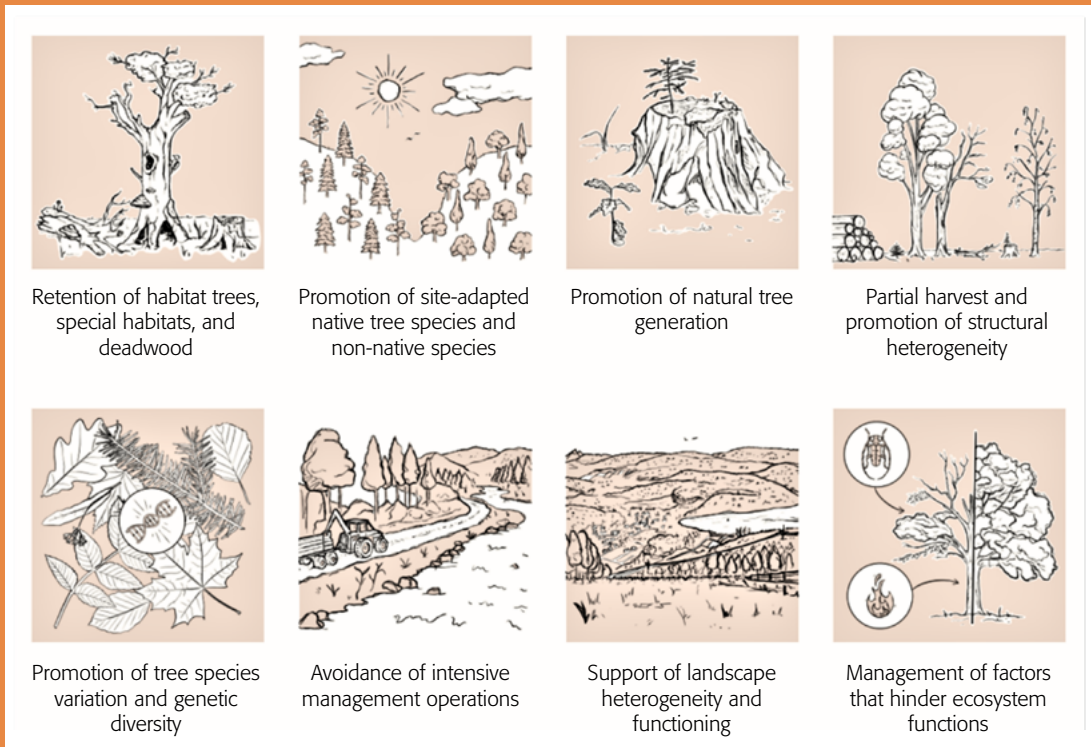
Integrative Forest Management (IFM) aims at integrating biodiversity conservation and global change adaptation into forest management for the sustainable provision of multiple ecosystem services. It is guided by natural and diverse forest structures, compositions, and dynamics to support ecosystem functioning and resilience. Its management practices consistently consider the tree, stand, and landscape scales 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.

(e.g., Puettmann et al., 2015), extending them to address the dual pressures of biodiversity loss and global change. Important additional elements of IFM are multi-scale thinking and stakeholder involvement (TRANSFORMIT, 2024; Vitali et al., 2026).

IFM is organised around **10 principles and 25 practical attributes** that address how biodiversity promotion and global change adaptation may be incorporated in multiple-use forests (Figure 2.1). Teachers of forest sciences in European higher education institutions indicated in a recent survey that they regard the *promotion of natural regeneration with site adapted tree species, partial harvesting, structural heterogeneity, and retention of habitat trees and deadwood as 'highly important'* actions in the practice of IFM (Spinu et al., 2026). These principles may be operationalised through a diverse set of practices, such as implementation of retention strategies, promotion of pioneer and site-adapted species, or avoidance of clearcutting and promotion of selection harvesting.

Retention of habitat trees, special habitats, and deadwood could be translated into practice through the active retention of structural elements, the protection of valuable habitats, and the recognition of forest reserves as an integral part of the area covered by a management plan. Regeneration in many European forests is poorly adapted to projected future climate conditions, as illustrated by the regeneration of former Norway spruce plantations (Potterf et al., 2026). Therefore, to establish **site-adapted tree species, with natural regeneration, tree species variation, and genetic diversity**, a diversity of native, site-adapted species should be promoted. Where non-native species are considered, a clear distinction should be made between assisted migration using regional or continental provenances of congeneric species, and the introduction of intercontinental species that can carry higher risks of invasiveness and novel pests or pathogen establishment under global change. Non-native species should be included in limited proportions, generally not exceeding 20% of stand and landscape composition. Site-adapted species should be promoted through active regeneration management to achieve or maintain levels of natural tree species richness (which often means at least three species per stand). Pioneer species should be promoted and maintained in the landscape, and in order to **avoid intensive management**

Figure 2.1 Core principles of Integrative Forest Management. Drawing by F. Mäling based on Vitali et al. (2026), concept of A. Spinu.



operations and promote structural heterogeneity, selection harvesting should be applied (from a single tree to group selection, including shelterwood systems in accordance with the regeneration requirements of target tree species). **Management strategies coordinated at landscape level** (e.g., through management planning) should be in place to support **heterogeneity**, protection and retention of special habitats (e.g., water bodies), or to **control factors hindering ecosystem function** (e.g., invasive species) (Vitali et al., 2026).

As discussed in Chapter 1, European forestry has developed different approaches to reconcile competing demands for timber production, biodiversity conservation and the provision of other ecosystem services. The principles mentioned above are not exclusive to IFM but also guide many other forest management approaches practiced in Europe that were developed over the course of two centuries to address recurring challenges of wood supply, stand stability, and biodiversity loss. These approaches include the following (based on Vitali et al., 2026):

- **Continuous Cover Forestry** (Bruciamacchie and Turckheim, 2005) is rooted in Central European silviculture and motivated initially by soil protection and economic stability, it explicitly avoids clear-felling in favour of selection harvesting, maintaining permanent forest cover while promoting structural diversity and age-class heterogeneity. This approach is a direct precursor to IFM's emphasis on uneven-aged systems.

- **Close-to-Nature Forest Management** (Bauhus et al., 2013) emphasizes the use of natural processes to guide forest development, favouring natural regeneration, mixed-species stands, and continuous cover while supporting sustainable wood production. Its emphasis on ecosystem stability, adaptability and site-specific management laid the groundwork for Closer-to-Nature Forest Management (CerNFM) (Larsen et al., 2022), which extends these principles to include also landscape-level objectives, explicitly sharpening the focus on biodiversity conservation, climate resilience, and ecosystem connectivity, aligning closely with IFM's multi-scale coordination principles.

- **ProSilva** (Pro Silva, 2026) advocates for mixed tree species and continuous cover forestry without clearcuts across European professional forestry networks, promoting resilience, natural regeneration, and multifunctionality with the pragmatic argument that natural processes reduce management costs without sacrificing productivity. It is strongly shaped by practitioner knowledge and experience, and mirrors IFM's focus on stakeholder engagement in designing context-appropriate solutions.

- **The Stepping Stone concept** (Lapin et al., 2024) targets habitat connectivity through the retention of deadwood, habitat trees, and small reserves functioning as dispersal nodes for specialist species; a conservation-biology perspective that complements IFM's spatial matrix.

- **Retention Forestry** (Gustafsson et al., 2012) retains key structural elements such as deadwood, old trees, and intact forest patches at the time of harvest to maintain continuity of forest structure and function. Widely applied across boreal and temperate forests in Europe, it represents one of the most operationally straightforward entry points into IFM retention practices.

- **The TRIAD concept** partitions forest landscapes into strict conservation, ecosystem management, and intensive production zones, spatially separating objectives to optimize both ecological and economic functions. The zoning logic of this approach is reflected in IFM's spatial matrix (Table 2.2), though IFM integrates rather than segregates these functions wherever possible (Duflot et al., 2025; Nagel et al., 2025).

- **Climate-Smart Forestry** explicitly addresses greenhouse gas mitigation, adaptive silviculture, and carbon-efficient wood use in a climate policy context, aligning with IFM's global change adaptation dimension and the EU Green Deal objectives.

The application of other types of alternative forest management, such as **natural disturbance-based ecosystem management,** is being discussed or tested in Europe (Kuuluvainen et al., 2015), but without wide applications in practice yet. This approach proposes that silvicultural systems should emulate the spatial patterns, frequencies, and severities of natural disturbance regimes to maintain the range of forest structures and successional stages that many forest species depend upon. This approach can meet challenges of landscape and political complexities, but its principles (variable retention, gap dynamics, snag creations) align directly with IFM's emphasis on structural heterogeneity and retention of structural elements.

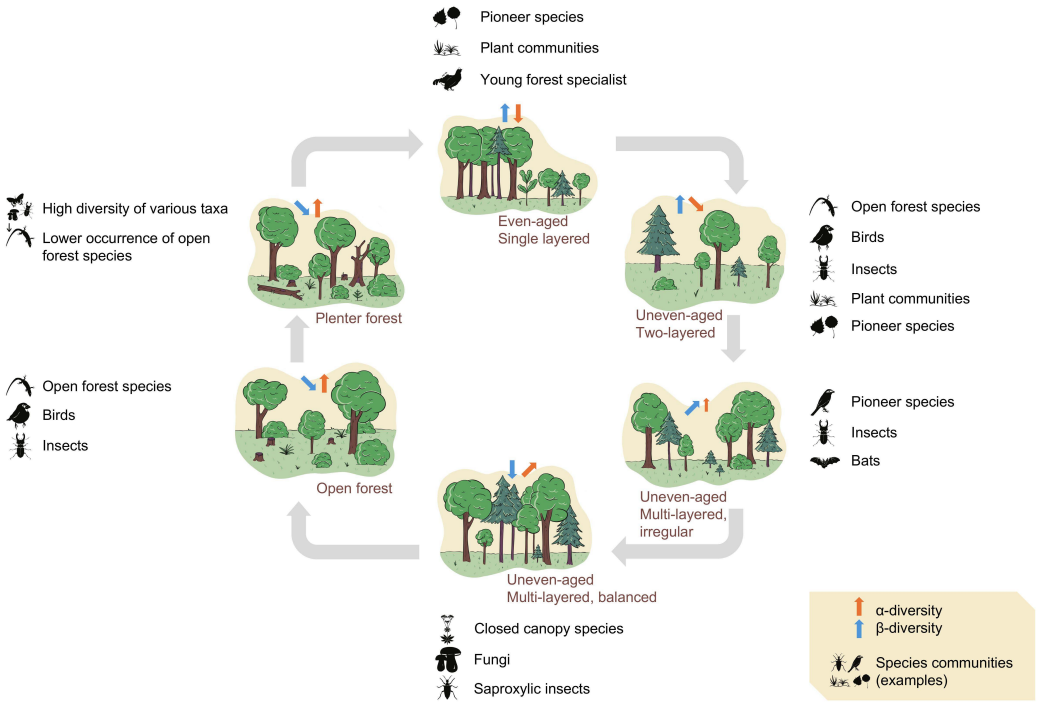
The different approaches listed above employ a diversity of silvicultural regimes, ranging from single tree selection to gap cutting, resulting in different forest structures and compositions, providing a range of habitats for different forest-dwelling species (Figures 2.2). For instance, many forest-dwelling organisms depend on abundant deadwood at various decay stages and on the structural complexity of old-growth stands, whereas species such as the Eurasian capercaillie (*Tetrao urogallus*) require more open, early-successional conditions.

A recent literature-based review compared IFM-related management approaches and revealed that, despite their origin, terminology, and specific management practices, many IFM-related concepts substantially overlap in their core principles and shared goals (Vitali et al., 2026). Their high similarity offers potential opportunities for IFM to:

- Capitalize on the strengths of existing practical experience and political frameworks;
- Close the operational gap by producing clear, detailed management guidelines, robust indicators and user-friendly educational and implementation tools.

The potential to deliver ecosystem services, promote biodiversity through structural complexity, provide compositional diversity, and enhance forest adaptive capacity are promoted by most IFM-related approaches in Europe (Vitali et al., 2026). However, these goals receive different emphases in the application of the different IFM-related approaches (Figure 2.3). For example, forests managed according to a Closer-to-Nature Forest Management or a Stepping Stone concept may show high structural complexity, and thus, **conservation potential** and **adaptive capacity,** but slightly lower **provision of ecosystem services** such as

Figure 2.2 Framework describing how different management regimes might promote different successional stages and forest organisms. Orange arrows represent α-diversity and blue arrows show the levels of β-diversity, reflecting spatial heterogeneity at small scales within a given management regime. β-diversity can be further enhanced by combining different successional stages across the landscape through complementary management regimes. Drawing by F. Mäling based on Schall et al. (2020, 2018) and Uhl et al. (2025). Concept of A. Spinu.



wood production. Retention forestry, depending on the level of retention, may result in a more or less balanced achievement of the three goals. Although these IFM-related approaches share several overarching principles, their different priorities reflect diverse origins, development pathways, and contexts such as ownership or market pressures (Vitali et al., 2026).

The similarities in goals among many of the management approaches in Europe shows a high potential to move towards a shared IFM approach in Europe through the integration of local knowledge and already existing practices. However, the coexistence of wood production and biodiversity conservation while addressing the uncertainties of global change may only be achieved through context-specific solutions, multi-scaled coordination, and long-term commitment. More importantly, there is no single solution to be applied across Europe, as successful IFM must consider local ecological conditions, socio-economic realities, and stakeholder perspectives. At a landscape level, this will likely result in a mosaic of practices, all of them aiming to fulfil the same overall goals (Duflot et al., 2025).

The value of IFM as an overarching framework lies not in the novelty of individual silvicultural practices, but in its integrative vision that other approaches address only partially: **multi-scale coordination** of decisions from stand to landscape level, **global change adaptation** addressing uncertainty, as well as **stakeholder integration** and the acknowledgement of socio-economic realities. These aspects will be discussed in the following sections of this chapter.

Figure 2.3 Coexistence of ecosystem services delivery (including wood supply), promotion of structural complexity for biodiversity promotion, and adaptive capacity for various management approaches in Europe. The conceptual alignment of IFM and the other management approaches was calculated using an averaged point scale based on the 25 IFM attributes (more in Vitali et al., 2026), where "0" indicates that the attribute is present in the management approach, "0.5" indicates partial presence, and "1" indicates presence. Scores were converted into percentages and aggregated into three dimensions: ecosystem services (blue in the figure), structural complexity (green), and adaptive capacity (orange). Adapted from Vitali et al. (2026). Drawing by F. Mäling, concept of A. Spinu.



2.3 IFM across multiple spatial scales

Implementing IFM within individual forest stands is necessary but insufficient. The coexistence of wood production and biodiversity conservation in European forests depends on how the management strategies are coordinated across the landscape. Europe presents a particular challenge in this regard due to its long history of agriculture, prevalent traffic networks, and high-density urban areas, which has resulted in a mosaic of fragmented forest patches. In addition, owing to a diversity of forest owners (public and private) including a large number of small private ownerships, management decisions are decentralised and follow very different goals. Landscape-level coordination, at least at the management planning level, should therefore be a key element in applying IFM in the fragmented forest landscapes of Europe.

Fragmentation is a landscape scale process that subdivides a once-continuous habitat into isolated patches, and has significant effects on biodiversity conservation and forest management in Europe. Together with habitat loss, it compounds negative effects on species persistence. Section 3.5 explores forest fragmentation and connectivity in greater depth, by presenting them as structural, habitat-based indicators for biodiversity assessment.

Fragmentation alters landscape composition and structure, creates edge environments that modify microclimates, and increases vulnerability to invasive species (Fahrig, 2003; McGarigal and Cushman, 2002; Undin et al., 2024; Vandekerkhove et al., 2013). From a management perspective, fragmentation also affects resilience of forests as well as how they are accessed and harvested, including the related operational costs. For example, isolated patches are more susceptible to wind damage and pest outbreaks, which can reduce harvestable volumes and increase salvage logging costs. Edge effects may also affect regeneration dynamics and limit the range of silvicultural options available in small patches. This is often the case for small privately-owned forests, which characterise many parts of Europe (Pulla et al., 2013). The fragmented ownerships, diverse governance systems, and historical developments in Europe challenge the coordination of IFM at larger scales further.

The overall extent of forested land in Europe has increased over the last two decades. Yet, several interacting dynamics continue to challenge biodiversity outcomes and may complicate coordination of IFM. **In Northern Europe and along the alpine treeline,** climate change, cessation of pastoral practices, and agricultural activities have allowed trees to colonise former grasslands and scrublands. This created a mosaic of newly established forest patches that develop at the expense of non-forest habitats and their associated species (Cudlín et al., 2017; Harsch et al., 2009). **In the Mediterranean area,** climate-driven disturbances such as drought or fire impede the succession of secondary stands towards mature, structurally complex forests, prolonging their fragmented state (Cos et al., 2026). Long-running fragmentation experiments have shown that negative impacts of habitat fragmentation on species richness and ecosystem processes can be underestimated because extinction, immigration, and functional responses often lag behind physical landscape changes (Betts et al., 2017). **In northern Fennoscandia,** long-term satellite data reveal that past clear-cutting has significantly reduced intact forest areas, creating a polarised, fragmented landscape that undermines functional green infrastructure and threatens biodiversity (Svensson et al., 2019).

These dynamics are not independent of management, and they interact with silvicultural choices, rotation lengths, and the spatial arrangement of harvesting across the landscape, reinforcing the need for IFM expansion beyond the scale of individual stands. Given the diverse ownership patterns and goals, three approaches appear to be particularly effective to achieve IFM goals at the landscape and higher spatial scales:

- Integration of IFM principles into regulations such as national or sub-national forest laws and certification schemes (e.g., PEFC, FSC).

- Recognition that IFM improves the provision of ecosystem services. Considering that many of those services are public goods, public money should be allocated to incentivise biodiversity-friendly forest management in both state and non-state forests, for example, to promote the retention of habitat trees and deadwood beyond minimum legislated levels. Such incentives may also support climate mitigation and carbon storage objectives, highlighting potential synergies with the financing and incentive mechanisms discussed in Chapter 4 and the enabling conditions explored in Chapter 6.

- Complementary management of state-owned forests to achieve landscape-scale objectives, such as increasing the area under strict protection or developing other green infrastructure, including biotope networks and migration corridors.

2.4 Integrating biodiversity conservation at stand and landscape scales

Forest reserves play a central role in the IFM matrix, and their management depends on size and spatial arrangement. Recent multi-taxa analyses have highlighted the value of such small, protected areas, especially when they represent a variety of forest types and are spatially dispersed across a region (Huber et al., 2025; Riva and Fahrig, 2023). **Small reserves** can, for instance:

- Provide habitat diversity that supports specialists and generalist species alike;
- When placed strategically, reduce travel distance for species with limited dispersal ability.

Nevertheless, **large reserves** with contiguous forests retain unique importance and are necessary to accommodate natural dynamics, including disturbance regimes that shape forest structure and biodiversity at multiple scales. The *Minimum Dynamic Area* threshold refers to the minimum area of forest required to sustain natural disturbance regimes while allowing ecological succession to proceed without external intervention and differs between forest types. Below this threshold, stochastic disturbances (e.g., fires) may exceed the capacity of the system to self-regulate, compromising the natural dynamics that strict forest reserves are intended to protect (Leroux et al., 2007). The Scandinavian Mountains Green Belt is a good example of this, since it encompasses large contiguous forest blocks over 100 km^2 that is simultaneously an intact boreal ecosystem with natural dynamics, a carbon sink, and a reservoir for biodiversity (Svensson et al., 2020). Generally, national parks and extensive reserves protect rare, endangered habitat types and species, and decouple production of wood from other forest services. Small reserves act as stepping stones and temporary refugia, critical for the survival of many forest-dwelling species colonising both production forests and reserves. Whereas the management of larger reserves is rather straightforward for managers, smaller strict reserves are regularly embedded in a managed matrix that often requires buffers from edge effects while still facilitating the movement of species between forest patches. Balancing these requirements and dynamics readily requires more complex decision strategies.

2.5 IFM spatial matrix beyond stand level

Within the European forest landscape, two contrasting paradigms have historically dominated the debate on how to reconcile wood production and biodiversity conservation: segregation vs. integration. **In the segregation approach,** the forest is partitioned into distinct zones, each governed by a dominant management objective (e.g., wood production, protection of habitats, natural dynamics). **The integration approach** seeks to meet several objectives, including biodiversity conservation, simultaneously on the same area (Bollmann and Braunisch, 2013; Konczal et al., 2025; Nagel et al., 2025).

In practice, these categories represent endpoints of a continuous spectrum rather than a binary choice, and their choice depends on spatial scale, forest ownership patterns, ecological context, and policy framework. In sparsely populated regions such as the boreal north or the Carpathians, large, strictly protected reserves can be established, delivering substantial biodiversity benefits. In densely populated Central Europe, the space available for extensive strict reserves is limited and integration becomes dominated by necessity (Bollmann et al., 2020). A multiple-use matrix approach, in which elements of segregation and integration are deliberately blended across multiple spatial spaces, has emerged as the most widely applicable framework for Europe (Jandl et al., 2024; Kraus and Krumm, 2013; Muys et al., 2022). This matrix is built around **core elements** that differ in management strategies and intensity, and in the ecological role they play to meet goals for biodiversity conservation, adaptation, and wood production (Table 2.2).

2.6 Adaptive IFM for resilient forests

2.6.1 Enhancing resilience through adaptive management

Maintaining the desired condition of managed multiple-use forests in the face of climate change is often discussed in terms of enhancing their resilience (Nikinmaa et al., 2020; Seidl et al., 2016). In simple terms, ecological resilience refers to a system's ability to absorb disturbances and

Box 2.2 Natura 2000 network

One comprehensive spatial strategy that has been implemented across Europe is the Natura 2000 network, a foundational element of European conservation architecture established under the EU Birds and Habitats Directives with the aim to safeguard natural habitats and wildlife in the long-term. In 2025, the network contained 27,000 protected sites, making it the world's largest coordinated system of protection. Approximately half of The Natura 2000 areas are spread widely in most European countries, and approximately half of those areas are estimated to be covered by forests (EEA, 2026). The *integration* nature of the Natura 2000 network lies in the continued use of the sites for the delivery of other ecosystem services, including wood production while maintaining conservation obligations for specific habitats and species. The ecological effectiveness of these sites for forest biodiversity depends substantially on their size, quality of the surrounding managed matrix, and the degree to which management within the sites can maintain or promote habitat quality.

reorganise while still maintaining its essential functions, structure, and identity (Walker et al., 2004). In practice, this includes both the ability to withstand disturbances and to recover ecosystem functions once those disturbances pass (Folke et al., 2004). In forests, resilience arises from the many natural processes and feedbacks that shape how ecosystems respond to stress. These mechanisms are often closely linked to biological diversity. Several IFM principles directly target these mechanisms; for example, the promotion of structural heterogeneity, site-adapted and compositionally diverse tree species mixtures, and the retention of habitat trees and deadwood maintain the biological complexity on which resilience depends (Drever et al., 2006; Turner and Seidl, 2023).

However, multiple-use managed forests are not just ecological systems. They are, to a greater or lesser extent, **socio-ecological systems.** Management interventions can play a dominant role, often reducing natural variation in tree species composition and structure to ensure predictable and consistent outputs, such as timber yield. In the most intensive systems, trees are grown as even-aged (planted) monocultures, in which the stand is supposedly set on a fixed developmental path from planting to harvest. The required interventions for those trees to achieve maturity may include planting genetically improved seedlings, applying fertilizers, using chemical or mechanical treatments to control pests and competing vegetation, and removing diseased or malformed trees. Such systems diverge substantially from the structural and compositional diversity that IFM principles prescribe, and in doing so, they trade ecological resilience for short-term production predictability.

Paradoxically, efforts to standardize forests and limit their natural variability in the pursuit of increased production, can instead undermine the ecological resilience that helps secure this production. By suppressing diversity and structural complexity, some management practices may reduce the ability of forests to cope with unexpected disturbances (Drever et al., 2006). Still, while the natural processes that maintain resilience in strict forest reserves are often replaced by human control in production forests, management actions themselves can sometimes serve a similar stabilizing role (Ibáñez et al., 2019). Even highly modified forests can be maintained in a desired condition after disturbance; not through ecological resilience, but through intensive human intervention. Such resilience, sustained by repeated and deliberate management rather than by ecological processes, has been described as "coerced resilience" (Rist et al., 2014, p. 3). Examples include measures to reduce risk exposure (e.g., shorter rotation periods), contain hazards (e.g., sanitary felling of diseased trees), or directly increase tree resistance (e.g., selective breeding). Notably, coerced resilience approaches should be avoided in the practice of IFM, since they can be accompanied by stark trade-offs in terms of i) reduced habitat for biodiversity, ii) limited breadth of ecosystem services delivery, and iii) potential constraints on the range of disturbances the forest is likely to endure (Felton et al., 2024).

2.6.2 Reducing lag effects in forest management

Lag times in adaptive forest management and restoration occur at different stages of the forestry decision-making process, which comprises four main components: **detection** (time needed to recognize a pressure or an

Table 2.2 Typical elements of Integrative Forest Management in the landscape (adapted from Muys et al. (2022) and Vitali et al. (2026).

Element	Primary function	Typical silviculture solutions	Expected biodiversity benefit	Benefits to wood production
Multiple-Use Forest Matrix	▪ A non-hostile matrix that can harbour most-forest dwelling species and facilitate their dispersal. ▪ Provision of most ecosystem services. ▪ Contains habitat trees, deadwood, and other structural elements.	Single tree and group selection systems, irregular shelter-wood, retention of legacy structures, extensive even-aged with retention.	Generates habitat-diversity, spatio-temporal mosaic-cycle heterogeneity, and temporary corridors.	Provision of multiple ecosystem services, including high quality wood.
Large strict forest reserves	Preserve natural forest dynamics, serve as source populations of species with special habitat requirements. May contain primary and/or old-growth forest, and should be large enough to allow natural dynamics and succession to occur.	No harvesting; minimal direct human influence and long-term protection.	Maintains species that require natural forest dynamics, typically old-growth structures.	Maintenance of genetic diversity; reference sites for silvicultural research, early warnings for global change impacts.
Old-growth stands or special habitat patches	Small-scale relics of forests with high-conservation value serving as "source habitats" for specialist organisms.	Typically, no removal of trees.	Maintains rare biotopes and provides habitats for saproxylic insects, cavity-nesting birds; shade-demanding understory plants.	Supply of reproductive material; maintenance of locally adapted tree populations.
Groups of habitat trees and higher deadwood availability	"Stepping stones" that improve the provision of tree-related microhabitats for forest dwelling species and continuity of deadwood and seed resources.	Retained as both groups and single elements in the multiple-use forest matrix.	Increases structural complexity, temporal and spatial continuity within managed forests, providing microhabitats for forest-dwelling species.	Supporting natural regeneration.
Early successional forest habitat	Recently disturbed patches that sustain species requiring open conditions (e.g., butterflies, ground-nesting birds).	All systems that provide large enough canopy gaps. May be temporarily reserved to prevent salvage harvesting following disturbance.	Generates habitat heterogeneity, supports pioneer flora and fauna, and maintains the successional mosaic needed for many taxa.	Reorganisation phase offers opportunities for natural and managed adaptation processes: establishment of new species combinations.
Intensively managed forest for production of wood	Satisfy wood demand, bioenergy, and economic objectives. Focal areas for efficient production and harvesting. Scale can range from individual stands to production forest estates.	Even-aged clear-cut, or short-rotation coppice with retention elements. Mostly artificial regeneration through planting.	Can free up matrix land for biodiversity conservation, if policies embrace these different land-use systems as communicating vessels in the TRIAD approach.	Supplies bulk wood, contributes to local and regional value-adding chains.

opportunity); **decision-making** (interval between detection and the formulation of a plan); **implementation** (period required to translate a decision into on-the-ground actions; and **ecological reaction** (the biological response time until ecosystem services reach desired levels) (Puettmann and Bauhus, 2023).

By increasing the frequency of monitoring and shortening the interval between detection of change and management response, adaptive management under IFM can reduce the lag times that characteristically delay responses in managed forests. However, the effectiveness of increased monitoring frequency depends critically on sampling intensity relative to the variance of the target indicator. More frequent but insufficiently replicated surveys may fail to detect changes and must be weighed against the associated costs.

In **restoration** contexts, the speed of biodiversity recovery is shaped by the regional species pool, dispersal ability, and continuity of suitable habitats. Furthermore, the choice between **passive** (letting natural processes run) and **active** (targeted intervention) management should be evaluated against the combined lag time: passive approaches may entail long ecological lags, especially in compositional changes; whereas active measures can accelerate recovery, at higher economic and operational costs. Long-term passive protection can rebuild structures (e.g., increase basal area or amount of deadwood) relatively quickly, but compositional changes often lag behind (Franzén et al., 2026; Paillet et al., 2015; Spînu et al., 2023).
In **production** forestry with stand-replacing systems, silvicultural and tree species composition decisions are made 60-100 years before harvests, under conditions of deep uncertainty about future climate, market condition, biodiversity targets, and societal demands. This decision horizon makes flexibility a core management prerequisite for IFM that maintains future options through mixed species, uneven-aged structures, and site-adapted regeneration (Felton et al., 2026; Messier et al., 2016, 2015). Frequent, targeted interventions allow managers to respond more swiftly to emerging pressures and opportunities related to global change, whether these are related to a biotic outbreak, a climatic shift, or a rare species colonising a forest stand, without locking forests into trajectories that close future options. IFM, by preserving the ecological processes and diversity that generate resilience, reduces dependence on coercive intervention and expands the adaptive capacity available to managers across temporal and spatial scales. The adaptive capacity, as well as the potential of forests for maintaining biodiversity, are not achieved through one silvicultural pathway, but through the deliberate diversification of management regimes across the landscape. This distributes ecological risks, maintains spatio-temporal heterogeneity, and ensures that no single disturbance agent or climatic shift can uniformly compromise the entire management unit.

2.6.3 Diversification of solutions

A central operational component of IFM is the deliberate diversification of silvicultural solutions across the landscape. By applying context-specific silvicultural options (e.g., selection systems, irregular shelterwood, retention forestry) with different tree species combinations across different parts of the IFM matrix, managers can promote structural and compositional heterogeneity, maintain habitat diversity for a broad range of species, and distribute economic risks. This diversification is a framework through which the IFM landscape matrix achieves the spatio-temporal heterogeneity that neither a single management approach nor a patchwork of uncoordinated decisions could reliably produce. This is strongly tied to the challenges posed by the fragmentation of forests in Europe, and to the potential solutions for coordination (see Box 2.3).

The current distribution of silvicultural systems across Europe illustrates both a potential and a challenge for the management of European forest. Even-aged systems still dominate in Fennoscandia, for instance, while selection and shelterwood systems are more commonly applied in Central Europe. This variation reflects differences in tree species composition and their regeneration dynamics, ownership structure, and historical management traditions, rather than deliberate landscape-scale planning. It indicates potential to enhance the heterogeneity of silvicultural approaches into a functionally coordinated IFM matrix.

2.7 Defining targets for IFM under global change

2.7.1 Normative dimensions of target-setting

Determining what constitutes an acceptable level of forest harvest in relation to biodiversity inevitably involves setting normative goals. Science can inform us, for example, about

Box 2.3 Biodiversity in disturbed forest areas

Consideration for and management of **natural disturbance regimes** contributes an additional dimension to the IFM diversification rationale. Natural disturbances such as fire, windthrows, or insect outbreaks generate a range of structural conditions, from standing dead trees to early-successional openings. As discussed in earlier sections, such components of disturbance can be integrated in managed forests, for example through retention forestry or gap creation of varying sizes. Due to climate change, disturbances are likely to increase in frequency and severity (Grünig et al., 2026). Therefore, post-disturbance areas with significant potential as temporary home for open-habitat specialists should be integrated into the IFM matrix. Salvage logging operations that remove all structural legacies have been shown to suppress forest bird communities for up to two decades, and should be appropriately limited in application (Walesiak et al., 2024).

the minimum population size required for a species to persist over a given period (i.e., its minimum viable population size), and indices such as the Red List Index can reveal trends in average extinction risk across species groups over time. However, none of these scientific metrics inherently define what is or is not acceptable. This reflects the philosophical "is-ought" problem described by David Hume: ethical conclusions cannot be derived solely from factual statements. Nonetheless, value-based goals can achieve broad consensus when justified through reason and evidence, and stakeholder-derived preferences alongside ecological constraints in setting operation targets should be incorporated in the IFM framework (Linser et al., 2025).

Also, in the IFM context, forest management requires both an **ecological floor** (below which biodiversity outcomes deteriorate) and a **normative ceiling** defined by regulatory caps and social demands/negotiations. Within this space, wood extraction or silvicultural intensity should not act as competing goals; in forests with little biodiversity potential and not adapted under climate change, wood production capacities are affected. However, in practice, these objectives are sometimes pursued through separate planning targets and policy instruments. For **biodiversity,** the EU Biodiversity Strategy for 2030 is a normative anchor; it specifies that at least 30% of species and habitats not currently in a favourable conservation status should reach (or should show measurable progress towards) that status by 2030. For **wood production,** the analogue requirement is that harvest rates should not exceed levels at which forest regeneration and carbon stocks are maintained over the long term, recognising that the felling-to-increment ratio varies substantially across Europe. For example, in Bulgaria, average fellings amount to less than half of the net annual increment, whereas Belgium, Denmark, Scotland, Sweden and Switzerland operate at or above 85% (Konczal et al., 2025). Within each country, the ratio fluctuates between the assessment periods, with no consistent trend over the past 25 years (Konczal et al., 2025).

Furthermore, the spatial dimension of target-setting is equally important. The requirement may be that all forests contribute equally to national or regional biodiversity goals. Alternatively, this responsibility may be unequally distributed in forest landscapes, with some forests allocated primarily for production and others allocated primarily for habitat provision (Kneeshaw et al., 2000). IFM aims to accommodate the latter, treating the landscape matrix as the unit within which overall goals are met, rather than imposing uniform standards on every stand.

2.7.2 Quantitative assessment of IFM performance regarding biodiversity

Translating scientific references into management thresholds is conceptually and technically challenging. Within this context, a **threshold** is the inflection (tipping) point in the species-habitat relationship where the system's state shifts markedly; when empirical data are scarce, thresholds may be set by expert judgement or linked to feasible management objectives. Meanwhile, **references** are a sometimes-idealized condition that serves as a directional goal for the system. Typical references are long-unmanaged forests that exemplify close-to-nature dynamics, structures

and functions. Managed stands are not required to duplicate the reference exactly but should approximate its key attributes.

In the case of biodiversity, pronounced variability across temporal, spatial, and management dimensions makes the application of uniform, universal thresholds unattainable. Additionally, scientific references are most of the time based on local case studies. For example, white-backed woodpeckers (*Dendrocopos leucotos*) may require 10 to 20 m^3ha^{-1} of deadwood, while the rare beetle *Pytho kolwensis* or the parasitic fungus *Antrodiella citrinella* do not survive in areas with logging and require over 70 and 120 m^3ha^{-1} of deadwood respectively (Müller and Bütler, 2010). Management thresholds must be grounded in explicit conservation targets, as the ecological and practical implications of retaining 20 versus 120 m^3ha^{-1} differ significantly. Further, sometimes a set of species that are absent from a site, but belong to its regional species pool, can potentially occur given suitable conditions (Pärtel et al., 2011). This phenomenon is known as "dark diversity", and provides a measure of unrealised biodiversity potential, which in forest management can help identify species that are systematically excluded by current management practices or dispersal barriers. These species-specific requirements as well as the biodiversity potentials illustrate why indicator thresholds must be calibrated to the ecological and management goal in question, rather than applied uniformly throughout a set of prescribed targets.

When absolute thresholds are not known (i.e., lack scientific references), approaches that define them relative to natural variability by using reference conditions from unmanaged forest with the same successional stages should be considered. They generally achieve intended outcomes better than strategies tied to poorly defined global absolute values. This is particularly important for indicators capturing social values and ecosystem services, which may shift with changing societal expectations (Harshaw et al., 2007; Kneeshaw et al., 2000). The three target levels relevant to IFM are:

- **baseline target** (sometimes referred to as **benchmark**) shifting from insufficient level for a given species or ecosystem to acceptable (or intermediate) level (e.g., reaching the same volume of deadwood as compared to the national level);
- **target above the threshold** at which the species or ecosystem significantly **improves** (e.g., reaching a deadwood volume 10% higher than the national or regional level);
- an **ambitious target** that reaches the same level as the reference (e.g., having almost the same amount of deadwood in set-asides or woodland key habitats than in unmanaged forests).

2.8 Monitoring IFM outcomes

Monitoring the outcomes of IFM requires a system designated to track the complex nature of socio-ecological systems that deliver multiple objectives. Current monitoring frameworks in Europe are commonly structured on separate objectives; for instance, biodiversity conservation, achievements of carbon storage, sustained yield, and other sustainability indicators derived from national forest inventories (Burrascano et al., 2025).

Biodiversity monitoring is often challenged by contextual aspects, including demographic effects and taxon-specific responses that are rarely accounted for. A major limitation of current **monitoring schemes** is their reliance on indirect (non-taxonomic) indicators, such as forest structural variables (e.g., canopy cover, deadwood volume, stem density). These are practical because they are based on measurable variables that can be readily derived from conventional forest inventories (Storch et al., 2023). Such indicators can be used to describe the capacity of a forest to deliver most ecosystem services, including habitat provision. However, the relationship between forest structural indicators and biodiversity is scale- and context-dependent. In some cases, species diversity of certain taxa cannot be described by typical forest structural variables, while in others, broad measures of habitat heterogeneity reliably predicted the richness of threatened species in boreal forests (Hekkala et al., 2023). The strength of these relationships depends on the specific indicator used, the range of forest variation, and the taxonomic group of interest. The feasibility of a continental-wide biodiversity monitoring network is also constrained by logistical, methodological, and financial hurdles, as well as by the lack of harmonized field-sampling protocols allowing comparability across countries (Burrascano et al., 2025, 2021; Lier and Parviainen, 2013; Paillet et al., 2024, 2018).



Diverse forest landscapes strengthen ecological resilience © Alexandra (Unsplash)

Beyond biodiversity conservation, ecosystem service provision and global change adaptation represent core objectives of IFM that remain difficult to assess in an integrated way. Indicators capable of measuring not only progress towards each objective individually, but also trade-offs and synergies among them, need to be developed and validated. Such IFM indicators should be scale-sensitive and incorporate stakeholder values through participatory processes (Linser et al., 2025). The topic of indicators is discussed in more depth in Chapter 3 of this report.

2.9 Projected production capacity and conservation scenarios

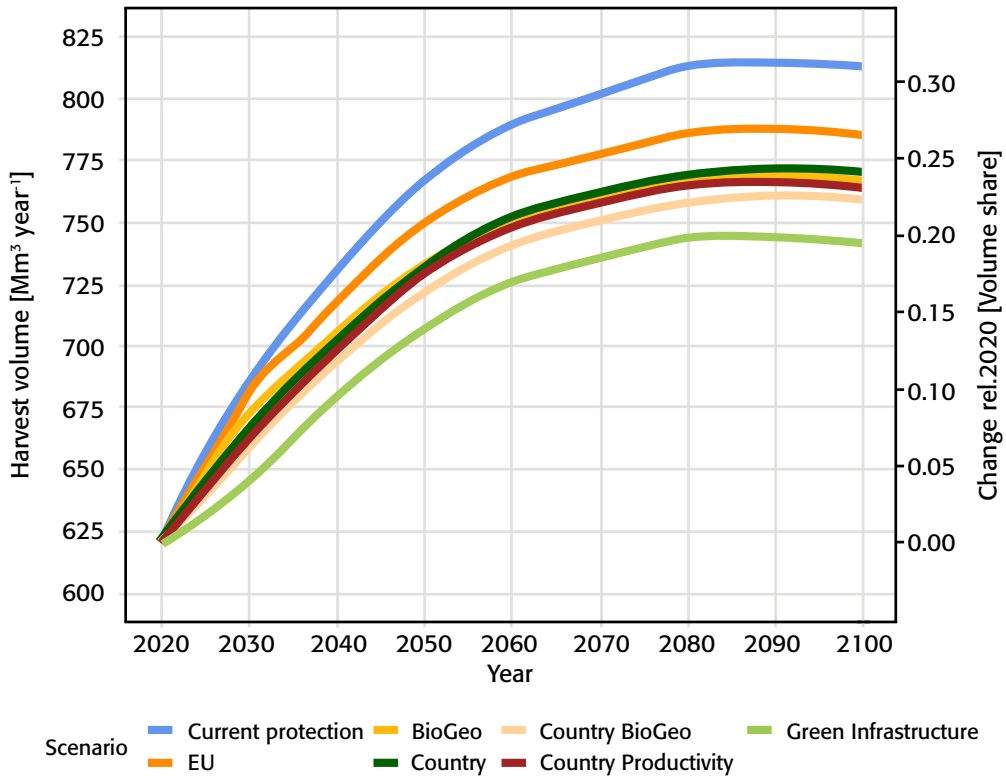
European forests should sustain the long-term provision of a wide suite of ecosystem services, including wood provision, carbon storage, and water regulation, as well as recreation and cultural values (Biber et al., 2020; Winkel et al., 2022). The provision of these services is influenced by accelerated climate change, urban expansion, and growing markets for bioenergy to replace fossil fuels. Therefore, the projection of future production and conservation capacity in Europe is highly sensitive to assumptions about societal responsibility, political priorities, and environmental change. For instance, when the EU Biodiversity Strategy is interpreted under IPCC's SSP2-RCP1.9 scenario demand pathway, the impact on forest harvest is modest. This scenario follows a 1.5 °C warming scenario (RCP1.9) and a socioeconomic development "middle of the road" (SSP2) until the year 2100. Even with the strictest interpretation of conservation measures (30% of area set-aside in reserves), European forests could have the biophysical capacity for substantial production gains under this scenario. In this context, roundwood extraction can still increase by 10% by 2100 (Figure 2.4).

However, accounting for uncertainty in such projections is difficult. For instance, many existing tree species in the regeneration can be considered as maladapted, indicating that substantial shifts in current tree species composition are needed (Thom et al., 2026). Proactive management, favouring adaptive silvicultural practices, and adapted species can steer forests towards a more climate-resilient state.

The scenarios included in Figure 4 include:

- Current protection: Maintains current EU protection areas.
- EU: An economy-driven scenario. Protection is distributed on land where it has the least impact on economy in terms of wood production and harvested wood products within the EU. Areas that are currently least profitable to harvest are progressively moved to strict protection and closer-to-nature management until the 10%-20% target is reached. Forest areas mapped in each grid cell as potential primary forests (7.5 Mha in the EU according to Sabatini et al., 2020) were excluded from future management.
- Biogeographical region (BioGeo): Similar to EU, but objectives are achieved for each EU biogeographical region. This scenario aims to reach representativeness of the EU biogeographical regions in the allocation of protection.
- Country: Similar to EU, but objectives are achieved for each EU country. This scenario aims for equal distribution of protection areas in each EU country, and it is the intended implementation according to the EU Guidelines (EC, 2022).
- Country BioGeo: Similar to EU, but objectives are achieved for both each EU country and EU biogeographical region. This scenario aims to reach representativeness of the EU biogeographical regions in the country-level allocation of protection.
- Country Productivity: Similar to Country BioGeo, but with allocation of protection within countries so that protected and unprotected forests have the same country-level mean productivity (including both new and previous areas protected already in 2020). This scenario aims to distribute protection to not only the least profitable land, but also considers representativeness regarding productivity (affecting biodiversity) and EU habitat types.
- Green Infrastructure: Similar to EU, but with allocation of the 10%-20% protection target within each grid cell. This scenario aims to distribute protection to rebuild the EU green infrastructure and facilitate dispersal and migration of species.

Figure 2.4 Development of the yearly forest biomass harvest volumes in the EU (including roundwood and logging residues) under SSP2-RCP1.9, and the protection scenarios simulated in absolute volumes (left) and as relative changes compared to the year 2020 (right). Modified from *Fulvio et al. (2025)*.



2.10 Conclusion

The question posed in the title of this chapter: "How can Integrative Forest Management reconcile goals for biodiversity conservation and timber production" does not have a single, universal answer. What this chapter has shown is that reconciliation is possible within current ecological and economic constraints and can be delivered through IFM as an organizing framework, providing (sometimes small) efforts to take biodiversity into account and monitor the effects of such management framework.

Biodiversity in European forests is inherently multifaceted, operating across scales, and driven by a suite of interacting factors, including management choices, ecological conditions, and broader global change. Reconciling biodiversity conservation with wood production in European forests requires not only a shift towards a diversified tree-species choice, but also a diversified toolbox of management practices coordinated in a landscape-scale matrix. By retaining structural elements, such as habitat trees, deadwood, and structural heterogeneity across a mosaic of core reserves, stepping stone patches, and production stands, biodiversity can be enhanced while meeting the demands for ecosystem services, including the supply of regional wood. IFM provides a flexible framework that combines the strengths of existing biodiversity-friendly management approaches while taking into consideration future uncertainty and making allowances for tailored regional practices to suit ecological conditions, ownership patterns, and other socio-economic drivers. Effective implementation of strategies promoting the coexistence of wood production and biodiversity promotion hinges on coordination at landscape-levels, robust, scale-sensitive indicators, and rapid decision loops that shorten lag times often characteristic of forest management.

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3

Chapter 3

Defining and measuring forest biodiversity using realistic, socio-ecologically meaningful, and communicable targets and indicators

Lead Author: *Zuzana Dobšinská*

Contributing Authors: *Stefanie Linser, Lenka Haluskova*

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3.1 Introduction

Recognizing the multiple functions of forests, the European Union (EU) has placed them at the core of its environmental and climate strategies (Gregor et al., 2024; Korosuo et al., 2023; Lier et al., 2022; Wolfslehner et al., 2020). The European Green Deal sets the overarching framework for achieving climate neutrality by 2050, emphasizing the role of forests in carbon sequestration and resilience against climate impacts. Enhancing forest biodiversity supports long-term carbon sequestration by increasing ecosystem resilience and stability, thereby contributing directly to the objectives of the EU Biodiversity Strategy for 2030 and the EU's climate neutrality goals. Within this context, the EU Biodiversity Strategy for 2030 includes specific targets for forest habitats, with strict protection of all remaining primary and old-growth forests (Arias-Navarro et al., 2023; Paillet et al., 2024).

The New EU Forest Strategy (NEUFS) for 2030 complements these ambitions by promoting sustainable forest management (SFM), enhancing forest resilience, and ensuring multifunctionality. It introduces measures such as planting three billion additional trees by 2030 and reinforces monitoring obligations to track forest health and biodiversity. Similarly, the EU Bioeconomy Strategy positions forests as renewable resources for a circular economy, balancing economic use with ecological integrity (Lovrić et al., 2019).

Legally binding instruments, such as the Nature Restoration Law, require restoration of at least 20% of EU land and sea areas by 2030, prioritizing forest ecosystems. The Natura 2000 network remains the cornerstone of EU nature conservation, safeguarding habitats of high ecological value and species listed under the Habitats Directive. These commitments are aligned with global frameworks, notably the Kunming-Montreal Global Biodiversity Framework (KMGBF) adopted under the CBD, which calls for continuing monitoring and reporting of biodiversity indicators at national and regional scales.

This policy framework creates a strong mandate for robust biodiversity monitoring systems. Accurate measurement of forest biodiversity is essential for assessing progress towards pan-European and EU targets, informing adaptive management, and ensuring compliance with legal obligations. Measurement is not only about tracking species richness or habitat extent, but also about demonstrating that managed forests can maintain high levels of biodiversity while delivering economic and social benefits. This requires monitoring approaches that capture multiple dimensions of biodiversity, including structural complexity, species composition, genetic diversity, and ecosystem functions, across different management regimes. Advances in remote sensing, integrated field inventories, and harmonized indicators enable scalable and cost-efficient monitoring. By linking monitoring data to management decisions, the forestry sector can play an active role in achieving climate and biodiversity targets.

Recent research underlines that biodiversity has not only an ecological value but is also a foundation for productive and multifunctional forests. This biodiversity-productivity nexus is particularly relevant under climate change, where structured and diverse forests show greater resilience to storms, pests, and droughts, thus securing long-term provisioning functions alongside carbon storage, recreation, and conservation (Brockerhoff et al., 2017; Schütz et al., 2016). Therefore, framing biodiversity indicators in relation to these multiple benefits strengthens their societal relevance and aligns conservation goals with the broader ambition of multifunctional, productive forests.

Biodiversity is inherently multidimensional, encompassing variation at genetic, species, and ecosystem levels, as well as structural and functional attributes that underpin ecological processes. This complexity makes it challenging to define biodiversity in a way that is simultaneously measurable, comparable, and communicable across scales and contexts. While species richness is often used as a proxy, it captures only one facet of biodiversity and may overlook critical aspects such as habitat heterogeneity, genetic variability, and ecosystem functionality. Furthermore, indicators that work well at a local scale may not translate effectively to regional or global assessments, complicating efforts to harmonize monitoring frameworks (e.g., Krumm et al., 2020; Nicholson et al., 2021; O'Connor et al., 2020; Winkel et al., 2022).

Communicating biodiversity status to policymakers, industry, and society adds another layer of difficulty, as technical metrics often lack intuitive meaning for non-specialists. The task, therefore, is to propose indicators that balance scientific rigor with practical applicability, enabling clear communication without oversimplifying the complexity of living systems.



Forest biodiversity spans multiple dimensions, from species and structures to ecological processes
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Without measurable and comparable indicators, it is difficult to evaluate trade-offs between productivity and conservation or to demonstrate progress towards policy targets. Adequate indicators also facilitate communication with stakeholders, from policymakers to industry, ensuring that biodiversity is integrated into decision-making rather than treated as an abstract concept.

The aim of this chapter **is to explore definitions and feasible indicators** of forest biodiversity that can be easily communicated, and balance ecological value with societal relevance.

3.2 Defining forest biodiversity

The CBD defines biological diversity as "the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems" (CBD, 2011, p. 4). This definition emphasises variability at multiple hierarchical levels and scales. It includes genes, species, and ecosystems, reflecting the complexity of living systems. As such, biodiversity can be measured from the national, regional, and local, to the forest unit level, and at different internal and external scales and grains (Nabuurs et al., 2024).

In forest ecosystems, biodiversity emerges from interactions between biological components and ecological processes operating across spatial and temporal scales. European forest science and policy have increasingly adopted this integrative perspective to support SFM, biodiversity monitoring, and policy assessment (Forest Europe, 2020).

Forest biodiversity is increasingly understood as a **hierarchical and multidimensional phenomenon,** covering genetic, species, and ecosystem levels (hierarchy), and expressed through composition, structure, and function (dimensions) (DeLong, 1996; Muys et al., 2022; Nabuurs et al., 2024).

a) **Composition** refers to the identity and variety of living components within a forest ecosystem, covering **genes, species, and ecosystems** (CBD, 2011; Muys et al., 2022). This dimension captures what is present, from genetic variation within populations to species richness and the diversity of habitat types across landscapes.

   Genetic diversity forms the basis for adaptation to environmental change and resilience against disturbances (Fady et al., 2016). It underpins long-term resilience to disturbances such as pests, diseases, and climate variability, and allows species to adapt over time to environmental stresses by making changes (mutations) possible (DeLong, 1996; Fady et al., 2016; Muys et al., 2022; Nabuurs et al., 2024). At the genetic level, composition encompasses genetic variation within and among populations, including allelic diversity

and population differentiation. Forest biodiversity at the genetic level reflects the capacity of forest ecosystems to evolve, adapt, and maintain their ecological functions over time, forming the biological foundation upon which species diversity, ecosystem structure, and forest ecosystem services depend.

Species diversity, often expressed through metrics like alpha, beta, and gamma diversity (also see Section 2.1), represents ecosystem stability and multifunctionality (Gamfeldt et al., 2013; Jucker et al., 2014). It includes the richness and relative abundance of tree species, understory vegetation, fungi, animals, and microorganisms, all of which interact in complex networks (Primicia et al., 2016; Schirkonyer et al., 2013). While species richness has historically dominated biodiversity assessments, literature highlights that species composition, rather than species counts alone, is crucial for ecosystem functioning and stability (Brockerhoff et al., 2017; Carrick and Forsythe, 2020; Swingland, 2013). In Europe, biodiversity monitoring and reporting have historically focused most strongly on this level, for example through indicators on threatened species or forest birds (Forest Europe, 2015; Linser, 2024), although species-based metrics alone provide only a partial representation of biodiversity status (Muys et al., 2022; Oettel and Lapin, 2021).

At the ecosystem level, compositional diversity manifests in the variety of forest types, successional stages, and microhabitats such as wetlands, rocky outcrops, and dendrotelms (tree hollows filled with water), which support specialized species (Bütler et al., 2020). Maintaining compositional diversity is critical because it provides functional redundancy, meaning that having multiple species performing similar roles enhances resilience (van der Plas et al., 2016). However, European forests face challenges such as homogenization due to even-aged monocultures, fragmentation, and the spread of invasive species that reduce compositional complexity (Langmaier and Lapin, 2020; Muys et al., 2022). This includes differences in forest naturalness, disturbance regimes, and spatial configuration across landscapes. European forests range from primary and old-growth ecosystems to intensively managed stands, each contributing differently to biodiversity conservation depending on ecological and socio-economic context (Muys et al., 2022; Wolfslehner and Linser, 2023).

b) **Structural diversity** is the physical organisation and spatial arrangement of forest components, including, among-others, vertical and horizontal stand structure, age-class diversity, deadwood volumes, habitat trees, and landscape connectivity. Structural diversity is critical for maintaining microhabitats and ecological niches and is strongly influenced by both natural disturbances and forest management legacies (Forest Europe, 2015; Linser, 2024).

   At the genetic level, structure can be reflected in the spatial distribution of genetic variation within populations, influencing gene flow and local adaptation. At the species level, structural attributes such as tree size diversity, age heterogeneity, standing and downed deadwood, and the presence of habitat trees create microhabitats that support diverse species assemblages (Muys et al., 2022). At the ecosystem level, landscape structure including forest patch size, connectivity, and fragmentation strongly influences biodiversity patterns and species persistence. Structural simplification associated with intensive forest management has been widely identified as a key driver of biodiversity loss in managed forests, particularly through reductions in deadwood and old-growth features (Forest Europe, 2015; Muys et al., 2022).

c) The **functional dimension** of forest biodiversity refers to ecological processes and interactions that occur within forest systems. These include regeneration dynamics, nutrient cycling, decomposition, trophic interactions, and species dispersal. Functional diversity highlights biodiversity as a driver of ecosystem processes rather than merely a conservation target (DeLong, 1996; Petchey and Gaston, 2006). At the genetic level, functional diversity is linked to trait variability affecting growth, stress tolerance, and reproductive success. At the species level, functional traits influence ecosystem productivity, resistance, and resilience. Meanwhile, at the ecosystem level, functional interactions regulate forest development, stability, and responses to disturbances (Muys et al., 2022). Functional diversity links biodiversity directly to ecosystem services, stability, and resilience,

emphasising that biodiversity is not only a conservation value but also a driver of forest system performance (Oliver et al., 2015; Song et al., 2014).

While based on the CBD definition, forest science emphasises several **forest-specific implications** for forest biodiversity definition:

1. Biodiversity in forests is understood as species richness and as having structural attributes such as deadwood, tree size diversity, vertical canopy layering, and the presence of old-growth forests. These elements form key habitats for numerous forest-dependent species, and therefore constitute integral components of forest biodiversity.

2. Forest biodiversity is influenced by ecological processes and disturbance regimes, including regeneration cycles, natural succession, decomposition, fire, storms, and insect outbreaks. These processes and the resulting spatial heterogeneity are central to forest ecosystem functioning and resilience, making functional diversity particularly important in forest contexts.

3. As most European forests are managed, the definition of forest biodiversity explicitly incorporates the influence of management intensity, historical land use, and landscape configuration. Forest biodiversity is therefore closely linked to human interventions.

4. Forest biodiversity is interpreted across multiple spatial and temporal scales, from microhabitats on individual trees to landscape varieties shaped over centuries. Long life spans of trees and slow ecological responses mean that forest biodiversity includes legacies of past management and requires long-term monitoring to detect meaningful change.

In summary, the definition of biodiversity in forest ecosystems includes the interaction of **composition, structure,** and **function,** the significance of **disturbance and succession,** and the important role of **forest management history.**

3.3 Measuring biodiversity: indicators and data sources

As part of the sustainable forest management concept, forest biodiversity is a prominent topic in international forest policy discussions. In addition to ecological value of biodiversity in forests for the environment, there is evidence that biodiversity contributes to forest ecosystem productivity and stability. The success of biodiversity conservation measures, as well as our ability to understand and enhance biodiversity, depends on effective monitoring systems that provide reliable and comparable information on ecological change (Nabuurs et al., 2024). An overview of indicators, data sources, and related goals and targets, emphasizing forest biodiversity at pan-European and the EU levels is provided below. We consider indicators as a metric that represents the state of a variable or system (Jones et al., 2011).

3.3.1 Pan-European level indicators

The pan-European Criteria and Indicators (C&I) for SFM originated from resolutions adopted at the Helsinki Ministerial Conference of the Forest Europe process (Resolutions H1 and H2). The quantitative indicators were first adopted at the expert level in Geneva in June 1994. The full set of six criteria, associated indicators, and Operational Level Guidelines were formally adopted by the Ministerial Conference on the Protection of Forests in Europe (Forest Europe) in Lisbon in 1998 (Resolution L2). The C&I were subsequently revised in 2003, and further updated in 2015 at the 7th Ministerial Conference in Madrid. These tools are fundamental instruments used for monitoring, assessing, and internationally reporting progress toward SFM in the pan-European region.

The Forest Europe C&I framework defines SFM as the stewardship and use of forests that maintains their biodiversity, productivity, regeneration capacity, vitality, and potential to fulfil relevant ecological, economic, and social functions without causing damage to other ecosystems. Nowadays it consists of six criteria, of which *Criterion 4: Maintenance, conservation, and appropriate enhancement of biological diversity in forest ecosystems* is directly dedicated to biodiversity (Table 3.1). The framework encompasses 45 indicators - 34 of them quantitative and 11 qualitative - (Linser et al., 2015) and it includes one specific goal and one corresponding target dedicated primarily to forest biodiversity conservation, degradation, and restoration (Linser and Wolfslehner, 2015).

Table 3.1 Overview of the biodiversity-related indicators of the Forest Europe process, produced by the authors.

Process	Indicator Number/Type	Indicator	Data Source	Scale of Practical Measurement	Related Goal/ Target
Criteria and Indicators for Sustainable Forest Management	Criterion 4 Maintenance, Conservation and Appropriate Enhancement of Biological Diversity in Forest Ecosystems	4.1 Diversity of tree species	NFIs	Plot level/National	Target 6
		4.2 Regeneration	NFIs	Plot level/National	Goal 5
		4.3 Naturalness	NFIs	Plot level/National	Goal 5
		4.4 Introduced tree species	NFIs	Plot level/National	Target 6
		4.5 Deadwood	NFIs	Plot level/National	Goal 5
		4.6 Genetic resources	NFIs/ EUFORGEN (European Forest Genetic Resources Programme)	National/European	Target 6
		4.7 Forest fragmentation	CORINE Land Cover, Copernicus (JRC/ EEA)	Landscape/ National/European	Goal 5
		4.8 Threatened forest species	National reports (National Red Lists)	Stand level/ National	Target 6
		4.9 Protected forests	National reports; EEA databases;	National	Goal 5
		4.10 Common forest bird species	Pan-European Common Bird Monitoring Scheme (PECBMS)	European	Target 6

The data and information required are collected through questionnaires jointly produced by Forest Europe, United Nations Economic Commission for Europe (UNECE), and Food and Agriculture Organization of the United Nations (FAO). Quantitative data are primarily derived from National Forest Inventories (NFIs), harmonised by Forest Europe, and reported by countries using a common C&I template. These data are then compiled and analysed in the State of Europe's Forests (SoEF) reports. The 2020 report includes ten indicators of forest biological diversity: tree species diversity; regeneration; naturalness; introduced tree species; deadwood; genetic resources; forest fragmentation; threatened forest species; protected forests; and common bird species.

3.3.2 EU level indicators

At the EU level, several initiatives include biodiversity indicators. The selected ones can be divided into strategies or policy documents (EU Biodiversity Strategy and New Forestry Strategy) and EU legislation (EU Nature Restoration Law).

EU Biodiversity Strategy for 2030

The strategy recognises forests as essential for biodiversity, climate and water regulation, carbon

sequestration and storage, and the provision of food, medicines, and materials, and aims to ensure that Europe's biodiversity is on the path to recovery by 2030. To achieve this, the European Commission (EC) committed to establishing an enhanced governance framework. The timeline for key actions started immediately in 2020, with targets such as providing guidance on selecting species and habitats, and the proposal for legally binding EU nature restoration targets set for 2021.

This strategy builds upon and requires coherence with established frameworks, such as the existing pan-European C&I for SFM. However, the EC noted that the existing pan-European indicators for SFM need further development to adequately address the escalated threats posed by climate change, habitat change, and species loss, as well as the new ambitions set by the EU Biodiversity Strategy.

The Goals and Targets of the strategy include:

1. **Strict Protection:** The strategy mandates the strict protection of all remaining EU primary and old-growth forests, emphasising their role as the most biodiversity-rich forest ecosystems and as vital carbon sinks.

2. **Increased Quality and Quantity:** The EU committed to proposing a dedicated EU Forest Strategy in 2021, including a roadmap for planting at least three billion additional trees in the EU by 2030. The goal is to increase the quantity, quality, and resilience of forests against threats like fires and pests.

3. **Sustainable Management:** Guidelines developed on biodiversity-friendly afforestation, reforestation, and closer-to-nature forestry practices.

The New EU Forest Strategy

The NEUFS is anchored in the European Green Deal and the EU Biodiversity Strategy for 2030. It aims to ensure growing, healthy, diverse, and resilient EU forests, serving as the policy framework to deliver on the EU's climate and biodiversity ambitions. The indicator system aims to address the shortcomings of the internationally agreed SFM concept, which provides relevant indicators (such as deadwood and species diversity) but currently lacks defined thresholds or ranges for desirable forest conditions related to biodiversity, ecosystem health, and climate change. The EC committed to identifying additional indicators as well as thresholds or ranges for sustainable forest management. This new work on thresholds and indicators is informed by the development of guidelines on closer-to-nature forestry practices. The strategy prioritizes the protection and restoration of forest biodiversity to reverse negative trends and to ensure that forests can continue providing their multifunctional role. The NEUFS emphasizes biodiversity through two main commitments:

1. **Protection:** It mandates the strict protection of all primary and old-growth forests, urging Member States to urgently complete the mapping and monitoring of these forests.

2. **Management and Restoration:** It promotes the adoption of closer-to-nature forest management practices, which are defined as management that ensures multifunctional forests by combining biodiversity goals, carbon stock preservation, and wood-related revenues, as introduced in more detail in Section 2.2. This approach aims to restore biodiversity and forest resilience by increasing structural complexity and promoting natural forest dynamics. The shift moves away from the historical practices that led to the simplification and homogenization of European forests.

The central platform for harmonized forest data and results is the enhanced Forest Information System for Europe (FISE), a single-entry point for data and information on forests in Europe. FISE brings together data, information, and knowledge gathered or derived through key forest-related policy drivers such as data reported by countries to Forest Europe, Eurostat, the FAO, and the UNECE.

Since it is difficult to monitor all species, biodiversity often is characterised according to its three dimensions as defined above, namely composition, structure, and function. For example, at the European level, there are very few assessments that directly monitor forest biodiversity indicators such as forest birds or threatened plant and animal species. A remaining challenge is that only about two-thirds of the commitments in the NEUFS can be partially monitored by the existing Forest Europe indicators, requiring the creation of new indicators or approaches to fully address the scale and scope of the 2030 Strategy (Table 3.2).

Table 3.2 Overview of potential indicators derived from the EU Biodiversity Strategy and the New EU Forest Strategy. Produced by the authors.

Process	Issues potentially suitable as indicator	Related Goal/Target
EU Biodiversity Strategy for 2030	Legal protection of a minimum of 30% of land area	Key commitment 1
	Strict protection of one third of legally protected areas	Key commitment 2
	Strict protection of EU primary and old-growth forests	Key commitment 2
	Preservation of protection and status of all habitats and species by 2030	2.2.1. Strengthening the EU legal framework for nature restoration
	Three billion additional trees in the EU	2.2.4. Increasing the quantity of forests and improving their health and resilience
	Ecological corridors	Key commitment 1
	Application of biodiversity-friendly practices such as closer-to-nature forestry	2.2.4. Increasing the quantity of forests and improving their health and resilience
	Decrease the number of Red List species by 50%	2.2.10. Addressing invasive alien species
The New EU Forest Strategy	Three billion additional trees in the EU	3.3. Re- and afforestation of biodiverse forests
	Protection of EU primary and old-growth forests	3.1. Protecting EU's last remaining primary and old-growth forests
	Diversity of forest ecosystems and species	3.2 Ensuring forest restoration and reinforced sustainable forest management for climate adaptation and forest resilience
	Well-adapted genetic resources	3.2 Ensuring forest restoration and reinforced sustainable forest management for climate adaptation and forest resilience
	Ecosystem-based approaches to forest management	3.2 Ensuring forest restoration and reinforced sustainable forest management for climate adaptation and forest resilience

EU Nature Restoration Regulation

The indicator set within the framework of Regulation (EU) 2024/1991 on nature restoration (NRR) emerged from the EU's commitment to halt and reverse biodiversity loss, as articulated in the European Green Deal (2019) and the EU Biodiversity Strategy for 2030. The regulation, which was adopted on 24 June 2024, establishes Union-level rules for ecosystem restoration. The indicators themselves represent measurable metrics used to track progress against general obligations to improve biodiversity in ecosystems where common methods for assessing their ecological condition are currently lacking, such as forest ecosystems. The fulfilment of the obligation to improve forest biodiversity should be measured on the basis of the common forest bird index and of a selection of other indicators, such as standing deadwood, lying deadwood, share of forests with uneven-aged structure, forest connectivity, stock of organic carbon, share of forests dominated by native tree species, and tree species diversity.

The regulation requires Member States to implement effective restoration measures covering at least 20% of terrestrial and 20% of marine areas by 2030, and to restore all ecosystems by 2050. By 2030, restoration measures in Natura 2000 areas are to be prioritized. Member States must prepare national nature restoration plans, which will serve to quantify the types of habitats that are not in a good condition, and subsequently adopt measures to restore them to the required levels.

The methodologies used for these structural and compositional forest indicators are based on well-established systems, enhancing the practicality of measurement. They draw on standards developed and used by Forest Europe, the descriptions of national forest inventories (Tomppo et al., 2010), and the methods set out in

line with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (particularly for organic carbon stock). The methodology for Forest Connectivity uses standards developed by FAO.

To ensure practical implementation, the Commission is empowered to adopt implementing acts specifying the methods for monitoring the forest ecosystem indicators listed in Annex VI. Furthermore, Member States' monitoring systems must utilize electronic databases and GIS, as well as maximize the use of remote sensing technologies and Earth observation data (Copernicus services).
In essence, the NRR utilizes a suite of forest indicators (Table 3.3), combining species-based metrics (e.g., Common Forest Bird Index) with structural and compositional metrics (e.g., deadwood, species diversity). By leveraging existing, standardized data collection practices (e.g., national forest inventories, IPCC guidelines), the Regulation aims to make the monitoring of forest biodiversity practical and effective across various scales.

Table 3.3 Overview of the indicators of the Nature Restoration Regulation set to measure the fulfilment of the obligation to improve biodiversity in forest ecosystems, produced by the authors.

Process	Indicator	Data Source	Scale of Practical Measurement	Related Goal/Target
Nature Restoration Law	Standing deadwood	NFIs	Stand/national	Article 12, point 3 Member States shall achieve an increasing trend at national level
	Lying deadwood	NFIs	Stand/national	Article 12, point 3 Member States shall achieve an increasing trend at national level
	Share of forests with uneven-aged structure	NFIs	Stand/national/ landscape	Article 12, point 3 Member States shall achieve an increasing trend at national level
	Forest connectivity	Remote Sensing (e.g., Copernicus)	National/ landscape	Article 12, point 3 Member States shall achieve an increasing trend at national level
	Common forest birds index	Pan-European Common Bird Monitoring Scheme (PECBMS)	National/ landscape/ European	Article 12, point 2 Member States shall achieve an increasing trend at national level of the common forest bird index
	Stock of organic carbon	NFIs	National	Article 12, point 3 Member States shall achieve an increasing trend at national level
	Share of forest dominated by native tree species	NFIs	Stand/national	Article 12, point 3 Member States shall achieve an increasing trend at national level
	Tree species diversity	NFIs	Stand/national	Article 12, point 3 Member States shall achieve an increasing trend at national level

3.3.3 Forest biodiversity monitoring

Forest biodiversity monitoring is important for understanding the status, trends, and drivers of biodiversity change, and for supporting evidence-based decision-making in forest management. In Europe, biodiversity monitoring fulfils multiple interlinked functions: it underpins scientific assessments, supports national and international reporting obligations, enables adaptive forest management, and enhances transparency and accountability of public policy interventions (Burrascano et al., 2023; Forest Europe, 2015; Moersberger et al., 2024; Navarro et al., 2017).

From a scientific perspective, biodiversity monitoring aims to detect long-term changes in forest ecosystems, assess the effects of management practices and natural disturbances, and improve understanding of complex ecological processes. Given the long-life cycles of forest ecosystems and the delayed responses of many biodiversity components, consistent long-term monitoring is essential to distinguish short-term variability from structural trends and regime shifts (DeLong, 1996).

From a policy perspective, forest biodiversity monitoring is central to the implementation and evaluation of international and European

commitments. Monitoring data supports reporting for the CBD, contributes to assessments of progress under the EU Biodiversity Strategy, and forms the empirical basis of Forest Europe's Criterion 4 on the maintenance, conservation, and enhancement of forest biological diversity (Forest Europe, 2015; Linser, 2024). Therefore, reliable monitoring is crucial for evaluating policy effectiveness, identifying emerging risks, and adjusting measures where objectives are not being met.

From a forest management perspective, biodiversity monitoring provides information on the compositional, structural, and functional attributes of forests, allowing decision-makers to assess trade-offs among biodiversity conservation, climate mitigation, wood production, and other ecosystem services.

Biodiversity monitoring also plays an important communication role. Clear and credible indicators help bridge science, policy, and society by making biodiversity change visible, comparable, and understandable. In a context of growing public concern about biodiversity loss and increasing scrutiny of forest management practices, monitoring and reporting contribute to trust-building and to informed dialogue among stakeholders (Moersberger et al., 2024).

To fulfil these functions, forest biodiversity monitoring is commonly framed around the biodiversity triangle of **composition, structure,** and **function,** which provides a unifying conceptual basis for assessing biodiversity change. Monitoring systems that emphasise only one of these dimensions risk producing a partial or misleading picture of biodiversity dynamics, particularly in managed forest landscapes (DeLong, 1996).

Applying this framework to forests presents particular challenges. Forest ecosystems are characterised by long temporal dynamics and strong structural complexity. Many biodiversity responses to management or policy interventions occur slowly, often with long time lags between action and detectable ecological change. As a result, short-term monitoring is insufficient for assessing trends or management effectiveness, highlighting the importance of long-term and consistent observation (Forest Europe, 2015).

The structural complexity of forests also has important implications for indicator selection. Attributes such as age diversity, deadwood availability, canopy layering, and landscape connectivity play a central role in shaping forest biodiversity. These features are often more sensitive to management than species presence alone, making indicators that integrate structural and functional aspects alongside compositional measures an essential complement for biodiversity monitoring (e.g., Lindenmayer and Likens, 2009; Pereira et al., 2013). Consistent with this, recent research has highlighted the limitations of relying solely on species richness. Evidence from global meta-analyses indicates that species composition and functional characteristics are often more closely linked to ecosystem functioning than species counts alone, and that richness-function relationships are frequently non-linear and context dependent (see Carrick and Forsythe, 2020 for an overview).

In Europe, an additional challenge arises from the high degree of human influence on forest ecosystems. Most forests are managed to varying degrees, ranging from strictly protected areas to intensively managed production forests. Monitoring systems should therefore be capable of capturing biodiversity across the full gradient of management intensity and disturbance regimes, which are increasingly shaped by climate change (Pereira et al., 2013).

As a result, forest biodiversity monitoring must also support multiple policy objectives. It is closely linked not only to biodiversity conservation but also to climate change mitigation, wood production, and broader bioeconomy strategies.

3.3.4 Data sources and monitoring approaches

Monitoring forest biodiversity relies on a diverse set of data sources and methodological approaches that together capture the compositional, structural, and functional dimensions of biodiversity across spatial and temporal scales. The reporting relies on proxies and indirect indicators at different level (e.g., deadwood, bird index).

One approach is to structure forest biodiversity monitoring around the essential biodiversity variables globally recognised by the Group on Earth Observations Biodiversity Observation Network (GEO-BON), which allow quantification of the rate and direction of change in complementary aspects of the state of biodiversity over time and across space. These are (i) genetic composition, (ii) species populations, (iii) species traits, (iv) community

composition, (v) ecosystem structure, and (vi) ecosystem functioning (Pereira et al., 2013). This approach was further developed by Muys et al. (2022).

No single data source is sufficient, each provides a partial view, shaped by its sampling design, resolution, and feasibility. Therefore, biodiversity monitoring builds on **complementary systems,** combining national forest inventories, specialised biodiversity networks, remote sensing technologies, targeted ecological surveys, and increasingly, participatory and citizen-science approaches.

The following paragraphs provide a description of the most commonly used data sources, including their specific strengths and weaknesses:

National Forest Inventories

National Forest Inventories (NFIs) are the cornerstone of forest monitoring across Europe. They provide systematic, large-scale information based on statistically representative sampling designs. NFIs traditionally focus on forest resources such as growing stock, increment, and tree species composition, but over the last two decades they have gradually incorporated biodiversity-relevant variables. These include deadwood quantity and type, tree microhabitats, age-class structure, forest naturalness, and indicators of forest health.

NFIs are particularly valuable because they are **long-term, harmonised,** and **repeated,** allowing the detection of trends rather than isolated measurements. However, their ability to capture fine-scale biodiversity elements, such as rare species, functional traits, or microhabitat specialists, is limited by sampling intensity and national methodological differences. For biodiversity monitoring, NFIs serve as a robust backbone, but they require supplementation by more specialised data sources.

Biodiversity monitoring networks and permanent plots

Alongside NFIs, Europe hosts numerous *targeted biodiversity monitoring networks* focusing on specific taxa or ecological functions. These include forest bird monitoring schemes, red-listed species assessments, fungal and lichen plot networks, and long-term ecological research (LTER) stations. Permanent forest plots, some maintained for decades, provide high-resolution data on understory vegetation, tree demography, decomposition processes, and microhabitat dynamics.

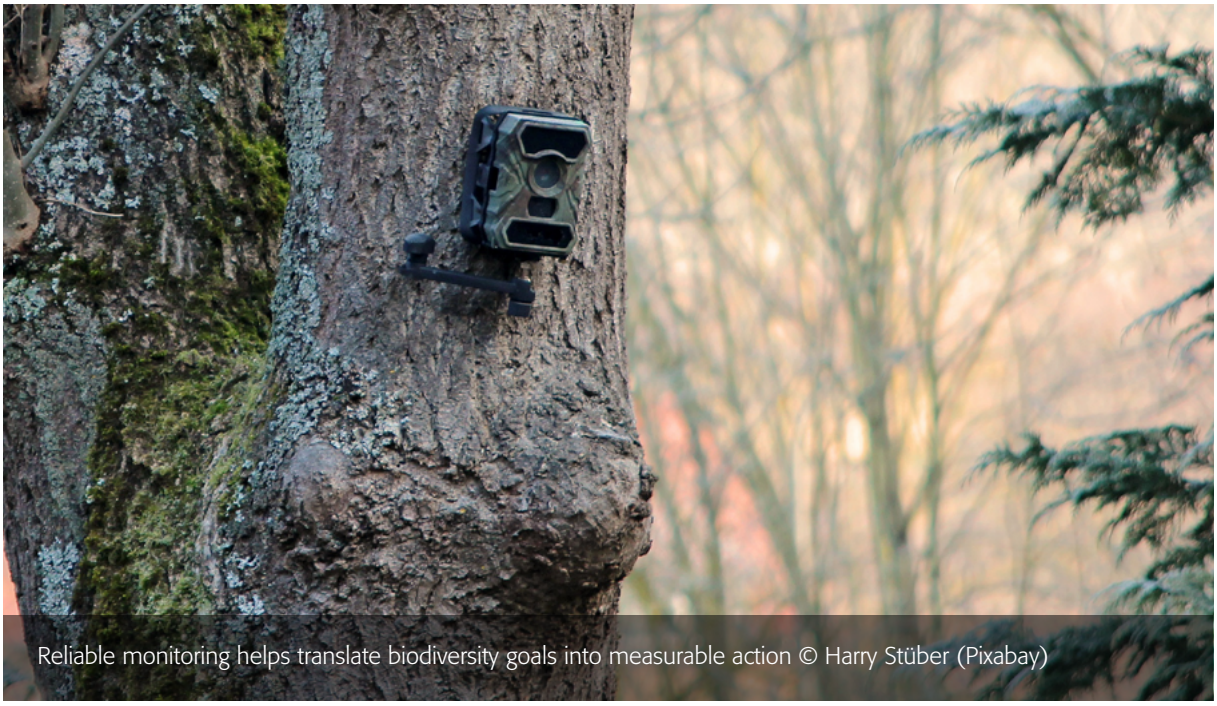
Long-term reference areas representing forests in a relatively natural state are particularly valuable for biodiversity monitoring because they provide baseline conditions against which managed forests can be assessed. Such sites offer unique opportunities to study natural forest dynamics, disturbance responses, and long-term ecological change, while also supporting the development of scientifically grounded conservation and restoration targets. On such forests, the Białowieża Forest at the border between Poland and Belarus, one of Europe's best-preserved forest ecosystems, illustrates the importance of long-term monitoring programmes in generating knowledge on biodiversity, resilience, and ecosystem processes under changing environmental conditions (Broughton et al., 2025).

Such networks provide **high ecological detail** and capture biodiversity elements that NFIs cannot detect, particularly cryptic or functionally important species groups. Their limitations lie in restricted spatial coverage, varying sampling designs across countries, and taxonomic biases. While essential for scientific understanding, they often lack the representativeness required for national-scale reporting.

Remote sensing and Earth observation

Remote sensing technologies are nowadays central to forest biodiversity monitoring, especially for assessing structure and landscape-level patterns. Satellite imagery (e.g., Sentinel, Landsat) enables monitoring of forest cover change, fragmentation, canopy condition, and landscape connectivity. Airborne Light Detection and Ranging (LiDAR) provides detailed three-dimensional information on canopy structure, tree heights, gap dynamics, and biomass, which are key proxies for structural and functional diversity. UAV-based (Unmanned Aerial Vehicle) photogrammetry enables flexible, high-resolution assessments of small areas, particularly for deadwood mapping, forest regeneration, and habitat tree identification.

Remote sensing excels at capturing structural attributes consistently and repeatedly across large areas, making it necessary for harmonised reporting. However, it typically provides indirect measures of biodiversity and must be linked to field data for calibration and interpretation. Thus,



Reliable monitoring helps translate biodiversity goals into measurable action © Harry Stüber (Pixabay)

remote sensing is most powerful when used in combination with ground-based observations.

Recent LiDAR-based approaches enable the detection and monitoring of large habitat trees and other old-growth attributes over large areas, providing valuable biodiversity indicators that can complement conventional forest inventories and monitoring systems (Kane et al., 2023; Ren et al., 2024).

Taxon-specific surveys and ecological field assessments

Certain dimensions of biodiversity, particularly genetic diversity, invertebrate communities, fungi, soil biota, threatened forest species, and understory plant assemblages can only be assessed through direct field surveys. These surveys provide detailed, taxonomically precise information essential for evaluating the status of threatened species, identifying habitat specialists, or assessing ecosystem quality in protected areas.

While taxon-specific surveys supply irreplaceable depth, their main limitations are high financial and human resource needs, limited geographical scope, and low repeat frequency. As a result, they play a complementary role rather than forming the basis of national monitoring systems.

Citizen science and participatory monitoring

Citizen science initiatives ranging from bird and butterfly counts to smartphone-based tree identification or invasive species reporting are increasingly contributing to biodiversity datasets. These initiatives bring significant benefits, as they expand spatial coverage, provide rapid detection of change, and increase societal engagement with forest conservation.

Examples include the Polish initiative *Lasy i Obywatele* (Forests and Citizens) (Lasy i Obywatele, 2026) which engages citizens in documenting ecologically valuable forests and monitoring management interventions; the *LIFE ESC360 programme* (Life 360 ESC, 2026), which mobilizes volunteers to support biodiversity monitoring and conservation activities across Europe, and the *More4Nature* initiative (more4nature, 2026), which aims to strengthen the integration of citizen-generated data into environmental monitoring and decision-making processes.

Citizen-science data often require rigorous validation to address issues of uneven sampling effort, identification errors, and geographic bias. However, when combined with formal monitoring systems, citizen contributions can enrich biodiversity assessments and improve early detection of pests or habitat changes.

Administrative and management data

Forest management plans, harvest records, protected-area designations, Natura 2000 site reports, and forest certification audits provide additional layers of information relevant to biodiversity. These sources help monitor pressures, responses, and management regimes, complementing ecological indicators with contextual data. Although not biodiversity indicators themselves, such datasets are increasingly integrated into monitoring frameworks to interpret ecological trends.

3.4 Challenges and future directions for forest biodiversity monitoring

Forest biodiversity monitoring faces persistent challenges related to scaling, aggregation, data gaps, and evolving policy demands. Biodiversity indicators are often collected at small spatial scales but are expected to inform national, European, and global policy processes. This upscaling is complicated, time-consuming, and expensive; therefore, proxies are used since they are easier to measure (Burrascano et al., 2023).

Many biodiversity components respond slowly to management interventions or disturbance regimes, while policy reporting cycles are comparatively short. Structural attributes such as deadwood availability or tree age diversity often develop over decades, and changes in genetic diversity or adaptation may only become detectable over multiple generations. As a result, short reporting cycles may not adequately reflect ecological trajectories or management impacts (DeLong, 1996; Muys et al., 2022). Major disturbances such as large wildfires, windstorms, or pest outbreaks can rapidly alter forest structure, habitat availability, and species composition. Monitoring frameworks therefore need to be capable of detecting both gradual ecological trends and rapid changes following disturbance events (Gustafsson et al., 2019).

Despite shared frameworks such as the Forest Europe Criteria and Indicators for Sustainable Forest Management, national differences in inventory methods, indicator definitions and data availability limit harmonisation. Even so, aggregated indices that are difficult to comprehend for non-experts are used for communication and high-level reporting, but they are less effective for identifying drivers of biodiversity change, or for guiding management decisions unless uncertainty and context are made explicit (Forest Europe, 2015).

Data gaps also constrain current monitoring systems. Genetic diversity and functional biodiversity remain unrepresented, while monitoring efforts are mainly targeted towards a limited set of forest taxa, particularly trees and birds. Many ecologically important groups, including invertebrates, fungi, and soil organisms, as well as threatened forest species remain under-monitored despite their central role in forest ecosystem functioning and resilience (Moreno-Fernández et al., 2025).

At the same time, expectations placed on forest biodiversity monitoring are expanding. Indicators are increasingly required to inform not only conservation policy, but also climate mitigation and adaptation strategies, adaptive forest management and sustainable finance instruments. Existing monitoring systems were not designed for such multifunctional use (Muys et al., 2022; Nabuurs et al., 2024).

Future forest biodiversity monitoring needs to go beyond just counting species by also tracking the structure of forests (e.g., canopy layers, deadwood) and the functions species perform (e.g., pollination, nutrient cycling). Special attention should be given to under-monitored groups such as fungi, invertebrates, and soil organisms, which are vital for ecosystem health. New tools like remote sensing (e.g., drones, satellites) can help cover large forest areas and detect changes over time on, for example, forest structure, tree species composition, and fragmentation. Monitoring systems should be designed to respond to climate change by tracking shifts in species and disturbance patterns. Communication can help in translating complex biodiversity information into formats accessible to policymakers, forest managers, and the public, without oversimplifying ecological realities.

Another challenge is to balance scientific robustness and policy feasibility. Policy-oriented indicator frameworks require simplicity, comprehensibility, comparability, and cost-effectiveness, while the ecological reality is complex and context-specific. Therefore, indicator systems represent negotiated compromises rather than exhaustive biodiversity status (DeLong, 1996).

Because different indicators capture complementary aspects of biodiversity across compositional, structural, and functional dimensions and hierarchical levels, a portfolio of complementary indicators is required. Each dimension entails specific methodological requirements. Compositional indicators often depend on taxonomic expertise and observation networks, structural indicators require detailed forest inventory data, and functional indicators may rely on proxies related to processes such as regeneration, deadwood dynamics, or disturbance impacts. Furthermore, these indicators respond to drivers at different temporal scales: structural attributes may change slowly, species communities respond at intermediate timescales, and genetic diversity often changes over multiple generations (Moreno-Fernández et al., 2025; Muys et al., 2022).

3.5 Selected indicators to actively maintain and enhance biodiversity

This chapter has shown that forest biodiversity is a multidimensional concept that cannot be adequately captured by single metrics or species counts alone. Instead, biodiversity in forest systems emerges from the interaction of compositional, structural, and functional attributes across genetic, species and ecosystem levels, all of which are strongly influenced by forest management and disturbance regimes. Rather than aiming for an exhaustive representation of all biodiversity components, the criteria chosen to capture key biodiversity dimensions are (i) ecologically relevant, (ii) responsive to forest management, and (iii) measurable through existing monitoring and reporting systems. The indicator set also reflects the fact that most European forests are managed also for conservation. Therefore, the selected criteria allow biodiversity to be assessed in a range from strictly protected forests to multifunctional production forests, supporting adaptive management rather than framing biodiversity solely as a conservation constraint. By relying largely on National Forest Inventories, harmonised European reporting frameworks, and remote sensing the indicators remain operational and scalable from stand to European level.

In addition to ecological relevance, biodiversity indicators should be meaningful and understandable to society, policymakers, and forest managers. Societal relevance refers to the extent to which an indicator is understandable to non-specialist audiences, reflects values and concerns expressed by stakeholders, supports communication and decision-making, and can be linked to tangible ecosystem benefits and management outcomes. The selection of indicators was therefore informed not only by ecological considerations but also by evidence from stakeholder-based indicator development processes. Insights from initiatives such as TRANSFORMIT (2024) and the Index of Biodiversity Potential (CPNF, 2026) demonstrate that stakeholders tend to value indicators that are visible, interpretable, management-relevant, and directly linked to ecosystem condition, resilience, and conservation outcomes.

Indicators such as forest area, deadwood, habitat trees, forest connectivity, forest birds, or protected forest area are included not only because of their ecological significance but also because they facilitate communication, public engagement, and policy implementation. They are scientifically justified, intuitive, and communicable to policymakers, forest managers, and the public. These indicators highlight how active forest management, when guided by biodiversity objectives, can contribute to both ecological integrity and the provision of economic and societal benefits. As mentioned above, **no single indicator can adequately represent forest biodiversity.** Therefore, a set of indicators is proposed that captures biodiversity aspects related to the forest structure and to the forest species while also reflecting socio-ecologic aspects of forest biodiversity (Tables 3.4 and 3.5).

This set of indicators does not claim to represent forest biodiversity in its entirety. Rather, it provides a pragmatic and policy-relevant framework that integrates biodiversity into forest management and monitoring. This approach supports both evidence-based decision-making and clear communication, which are essential for achieving biodiversity and sustainability objectives.

Structural / Habitat-based indicators

Forest area: provides the baseline for biodiversity by defining the spatial extent of forest habitat available for species. The extent and changes in forest area and other wooded land are basic, yet key information for assessing the sustainability of forests management (Korhonen et al., 2020). While not sufficient on its own, it is essential for interpreting all other biodiversity indicators.
Protected forests: safeguard key biodiversity values and natural processes that cannot be maintained through management alone. Protected areas are one of the oldest instruments

for conserving nature and natural resources, and constitute the main pillar of nature conservation laws across Europe (Lier et al., 2020). This criterion directly reflects societal commitment to biodiversity conservation and global protection targets.

Deadwood: is a key indicator for measuring forest biodiversity. Deadwood, consisting of standing or lying dead trees and wood residues of various size and decay stages, is an essential component of forest ecosystems. It provides microhabitats for a broad diversity of animal and plant species. It is also an important factor in nutrient cycles, influences soil development, and reduces soil erosion (Lier et al., 2020). Forest management practices that substantially reduce the quantity or quality of deadwood can lead to biodiversity loss and threaten ecosystem services provision. Conversely, an excessive accumulation of deadwood can increase the risk of forest fires and insect outbreaks and may constrain recreational use and forest operations.

Habitat trees: are defined as standing live or dead trees providing ecological niches (microhabitats) such as cavities, bark pockets, large dead branches, epiphytes, cracks, and sap runs (Bütler et al., 2013). Tree-related microhabitats are defined as "all distinct and well-delineated structures occurring on living or standing dead trees that constitute a particular and essential substrate or life site for species or species communities during at least a part of their life cycle to develop, feed, shelter or breed" (Larrieu et al., 2017, p. 195). They can be regrouped into seven main forms based on morphological characteristics and use by the associated taxa: (i) cavities, (ii) tree injuries and exposed wood, (iii) crown deadwood, (iv) excrescences, (v) fruiting bodies of saproxylic fungi and fungi-like organisms, (vi) epiphytic, epixylic, and parasitic structures (e.g., nests), and (vii) exudates (Martin et al., 2022). This criterion directly links forest structure to species occurrence and is increasingly recognised as a practical and ecologically meaningful biodiversity indicator in managed forests.

Age diversity and the presence of old-growth attributes: reflect long-term ecological continuity and microclimatic stability, which are critical for many forest species. Species diversity is reflected by the 14 pan-European forest categories and 76 corresponding forest types (EEA, 2006). Tree species composition in a forest is affected both by natural factors (climate, edaphic, and hydrological site conditions; stage of stand development) and by present and past human activity (forestry, agroforestry, grazing). Forests composed of several tree species are often richer in biodiversity, more resilient, and more functionally diverse than those of only one tree species (Korhonen et al., 2020). Forest biodiversity is positively affected by an uneven structure of tree age and stem diameter. Including this criterion allows biodiversity monitoring to account for temporal complexity and resilience that cannot be captured by species counts alone.

Tree species composition: influences habitat conditions, trophic interactions and ecosystem functioning. Native species' populations are local populations of species officially recognised as part of the natural flora of the country and may be conserved *in situ* or *ex-situ*. Non-native species' populations, by contrast, are those of either exotic species introduced into Europe or species non-native to the country that can only be conserved *ex-situ* (Lier et al., 2020). Introduced tree species are valued for their species-specific properties, such as yield potential, industrial requirements, carbon sequestration, and erosion prevention. However, introduced species may impact forest ecosystems and negatively affect forest biodiversity.

Forest regeneration: is a prerequisite for maintaining forest area in the long term. Natural regeneration means re-establishment of a forest stand through natural seeding or coppice sprouting. Meanwhile, artificial regeneration takes place by planting or artificial seeding. The type of regeneration in forest management depends on many variables, such as applied management systems, tree species preferences, or the scale of regeneration (Lier et al., 2020). Regeneration patterns determine future forest composition and biodiversity trajectories. Including this criterion links present management decisions to long-term biodiversity effects and adaptive capacity.

Forest naturalness: including Close-to-nature forest management, reflects the intensity and history of human interventions. Different intensities of utilisation are characterised not only by the remaining forest area in the country but also by changes in structures and species composition within the forested areas. Degrees of forest naturalness are: (i) undisturbed by man, (ii) semi-natural, and (iii) plantations (Lier et al., 2020). Forest cover and naturalness reflect the extent and continuity of relatively undisturbed forest ecosystems. This criterion captures long-term biodiversity value that cannot be restored quickly once lost.

Forest fragmentation: is the breaking up of larger, contiguous, forested areas into smaller patches of forest. Typically, these patches are separated by land with uses other than forest such as transport infrastructure, utility corridors, or other human development, although forests may be fragmented also by natural features and processes. Forest fragmentation affects forest ecosystems and forest-dependent flora and fauna (Lier et al., 2020). The Forest Connectivity Index measures the degree of forest coverage within a local, pre-defined neighbourhood area (assessment scale). It provides a general insight into the environment's local habitats without requiring additional knowledge on the type and quality of the forest, or on individual species or species groups demands (Vogt et al., 2009). Connectivity and fragmentation determine species movement, gene flow, and climate-driven range shifts. Including this criterion links biodiversity to spatial configuration and landscape processes that are increasingly important under climate change.

Species-based indicators

Biodiversity loss is often expressed in the **number of species lost**. According to the International Union for Conservation of Nature (IUCN), threatened species are those listed in one of the following Red List categories: vulnerable, endangered, or critically endangered (IUCN, 2019). A forest species is a species that is dependent on the forest for either part or all of its day-to-day living requirements, or for its reproductive requirements. Therefore, a species may be considered a forest species even if it does not live most of its life in a forest (UNEP, 2001). Forest species considered in this indicator are divided into trees, vascular plants, birds, mammals, other vertebrates, invertebrates and cryptogams, and fungi (Lier et al., 2020). The Red List Index provides a standardised, outcome-oriented measure of biodiversity change by tracking extinction risk trends across taxa. Its inclusion links forest monitoring directly to conservation status and global biodiversity targets.

Table 3.4 Selected structural / habitat-based indicators related to forest biodiversity with high ecological value and societal relevance. Produced by the authors.

Indicator	Ecological Value	Societal Relevance	Data Sources	Policy Linkages
Forest area (ha)	Baseline measure of forest ecosystem extent and habitat availability	Simple, intuitive indicator of forest presence and land-use change	NFIs, SoEF, FAO FRA, Copernicus	SDG 15.1, Forest Europe Ind. 1.1, EU Forest Strategy, EU Biodiversity Strategy, EU regulation on deforestation-free products
Area of protected and strictly protected forests (ha, % of forest area)	Safeguards key biodiversity areas	Directly linked to EU Biodiversity Strategy 30% target	National databases, Natura 2000, EEA, SoEF, FAO FRA	EU Biodiversity Strategy 2030, KMGBF Target 3
Deadwood volume and quality (m^3/ha)	Strong proxy for saproxylic beetles, fungi, cavity-nesting birds. Indicates natural processes, nutrient cycling, and forest ecosystem maturity	"Deadwood equals life", well communicable proxy for "living forests". Symbolic for naturalness and ecological health. Contributes to carbon sequestration and soil fertility	NFI, SoEF, FAO FRA	Forest Europe Ind. 4.5, EU Nature Restoration Regulation, EU Biodiversity Strategy 2030, KMGBF Target 2

Table 3.4 Cont. Selected structural / habitat-based indicators related to forest biodiversity with high ecological value and societal relevance. Produced by the authors.

Indicator	Ecological Value	Societal Relevance	Data Sources	Policy Linkages
Habitat trees (number/ha) large and old trees	Captures microhabitat diversity critical for many taxa	Visible and intuitive, increasingly adopted in Europe, "biodiversity lives in tree holes and bark crevices"	Management Plans, NFI pilots in DE, FR, CH	EU Nature Restoration Law (Annex II indicators), Forest Europe Indicator 4.3, close-to-nature forestry guidelines
Stand age and structural diversity (distribution of size classes, presence of old-growth attributes)	A wider spread of tree sizes/ages and multi-layer structure increases vertical and horizontal complexity (light gradients, microclimate, understory variability), which generally supports higher diversity across plants, invertebrates, birds, and mammals	Easy to link to the cultural and recreational value of "old forests" relevant for forestry planning	NFIs (stand structure data), SoEF, Copernicus structural metrics	Forest Europe Indicator 1.3, KMGBF Target 8
Regeneration type (natural, seeded, planted, coppice), incl. site-resilient regeneration (ha, %)	Indicates regeneration success, resilience, and adaptive capacity	Signals sustainability and climate-smart forestry	NFIs, SoEF	Forest Europe Indicator 4.2, EU Forest Strategy, EU Adaptation Strategy
Forest connectivity and fragmentation (patch size, core area, corridors)	Connectivity supports genetic flow, species movement, and assisted migration	Fragmentation resonates with the public (maps, before/after images). Support stable ecosystem services provision, enhance landscape resilience to climate change and natural disturbances, and reduce disaster risks	SoEF, CORINE Land Cover, Copernicus	Forest Europe Ind. 4.7, Nature Restoration Regulation, KMGBF Target 2
Naturalness including **close-to-nature forest management**	Captures long-term ecological continuity, high habitat heterogeneity, and gene conservation value	Clear and intuitive, valued in tourism and culture "how much of our forest is close-to-nature?"	NFIs, SoEF	Forest Europe Ind. 4.3, EU Biodiversity Strategy 2030, KMGBF Target 3

Many naturally occurring forest habitats and forest species in Europe are protected by the EU Habitats Directive and Birds Directive. The **conservation status** is a way to provide an overview of the habitat and biodiversity status and its components (EEA, 2025). Conservation status of forest habitat types and species integrates information on species populations, habitat quality, and pressures, making it a core indicator of biodiversity condition. It also ensures direct alignment between monitoring and legally binding conservation objectives.

Forest birds respond sensitively to changes in forest structure and landscape configuration, making them effective indicators of broader biodiversity trends. This indicator informs about changes in breeding populations of bird species, both common and characteristic for European forests (Lier et al., 2020). Their inclusion adds strong communicative value and long-term comparability.

Table 3.5 Selected species-based indicators related to forest biodiversity with high ecological value and societal relevance. Produced by the authors.

Tree species composition (incl. native and introduced species)	Maintains co-evolved ecological networks and functional complementarity, stands with more diverse tree species composition have enhanced resilience to pests and drought	Higher tree species composition mediates naturalness, diverse species reduce climate change-related risks, socially accepted indicator	NFIs, SoEF, Copernicus, species maps	EU Biodiversity Strategy 2030, Nature Restoration Law, Forest Europe Ind.4.1. and 4.4, EU Invasive Alien Species regulation
Red List Index for forest-dependent species	Tracks extinction risk trends	Used globally as CBD headline indicator "Are forest species getting safer or closer to extinction?"	IUCN Red List; national Red Lists	KMGBF, EU Biodiversity Strategy 2030, Forest Europe Ind. 4.8
Conservation status of forest habitat types & species	Integrates species trends, habitat quality and pressures	Legal reporting obligation directly linked to EU biodiversity strategy easy to frame as "X % of habitats are in favourable condition"	EU Habitats & Birds Directives reporting EEA State of Nature	EU Biodiversity Strategy 2030, Natura 2000
Common forest bird index	Forest birds are sensitive to changes in forest structure and landscape configuration	Birds are charismatic and easy to communicate data collection based on citizen science.	Pan-European Common Bird Monitoring Scheme (PECBMS) SoEF	Forest Europe Ind. 4.10, Nature Restoration Regulation, EU Biodiversity Strategy

3.6 Conclusions

Forest biodiversity is a multidimensional concept encompassing compositional, structural, and functional attributes across genetic, species, and ecosystem levels. Because no single indicator can adequately capture this complexity, biodiversity assessment and monitoring require a portfolio of complementary indicators that reflect different dimensions of forest ecosystems.

European forest policy frameworks, including Forest Europe, the EU Biodiversity Strategy for 2030, the New EU Forest Strategy, and the Nature Restoration Regulation, increasingly recognize the need for harmonised and robust biodiversity monitoring. While significant progress has been made in developing common indicators and reporting systems, important challenges remain, particularly regarding the monitoring of functional and genetic diversity, harmonisation across countries, and the integration of biodiversity objectives with climate and bioeconomy goals.

Biodiversity monitoring should combine field-based observations, National Forest Inventories, long-term ecological research sites, remote sensing technologies, and participatory approaches. Long-term reference forests and monitoring networks are particularly important for understanding natural ecosystem dynamics and for establishing scientifically grounded conservation and restoration targets.

Biodiversity indicators should balance scientific robustness, policy, societal relevance, and communicability. A carefully selected set of indicators can support adaptive forest management, demonstrate progress towards biodiversity objectives, and strengthen the integration of biodiversity considerations into broader forest policy and management decisions. In this way, biodiversity monitoring becomes not only a tool for reporting ecological change, but also a foundation for maintaining resilient, multifunctional, and productive forests in Europe.

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Biodiversity indicators help track the health and resilience of forests © Merlin Kraus (Unsplash)

4

Chapter 4

Maximising forest carbon storage while aligning sustainability, value chains and policy

Lead Author: *Tommaso Chiti*

Contributing Authors: *Ana Rey, Miguel A. Zavala, Silvina Manrique, Oliver Frings*

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4.1 Introduction

Forests play a central role in the European Union's climate strategy, acting both as major carbon sinks and as providers of renewable resources. In line with the EU's climate neutrality objective for 2050, the proposed Carbon Removals and Carbon Farming (CRCF) Regulation establishes a harmonised framework for certifying carbon removals while emphasising robust quantification, additionality, permanence, and ecosystem co-benefits.

Forests currently absorb around 30% of global anthropogenic CO_2 emissions. Yet, their mitigation potential is increasingly challenged by ageing stands, intensified harvesting, and climate-driven disturbances. To enhance long-term carbon storage while preserving ecosystem resilience and biodiversity, Europe needs a diversified portfolio of sustainable forest management practices tailored to its varied climates, including afforestation, continuous cover forestry, species diversification, longer rotations, retention forestry, and fire-smart management. Although effective, such measures face barriers linked to local financial costs, long-term commitments, and risk exposure, factors that disproportionately affect smallholders.

Robust Monitoring, Reporting, and Verification (MRV) remains essential for credible carbon accounting, drawing on the integration of field measurements, remote sensing, modelling tools, and independent verification. A crucial component of forest-based mitigation lies in the forest value chain, which extends climate benefits beyond the forest stand. Long-lived harvested wood products, such as engineered timber in buildings, furniture, and durable construction materials, store carbon over extended periods and can substitute for emissions-intensive materials like concrete, steel, and plastics. Strengthening circularity, extending product lifespans, and improving recycling further increase the mitigation impact. Therefore, coupling sustainable forest management with innovation in wood processing, construction, and bio-based materials amplifies carbon benefits while supporting regional economies and green industrial transitions.

Beyond these direct mitigation pathways, increasing attention is also being given to market-based mechanisms that can mobilise additional finance for forest climate action. As demand for forest carbon credits grows, ensuring integrity in carbon markets is essential. Addressing additionality, leakage, temporality, and reversal risks through transparent and conservative crediting approaches will be critical to mobilising finance responsibly and delivering durable, verifiable climate benefits.

4.2 Policy context and incentives

Forests, including soils, represent the planet's largest carbon reservoir (IPCC, 2019) and play a crucial role in delivering ecosystem services related to climate regulation (Paré et al., 2024). Terrestrial ecosystems, largely dominated by forests, absorb around 30% of human-induced CO_2 emissions, around 2 billion tonnes of carbon (C) each year, thereby slowing the accumulation of CO_2 in the atmosphere (Tian et al., 2016). The long-term ability of forests to remove and store atmospheric carbon is controlled by factors such as productivity, age structure, health, and resilience, as well as by management practices and the impacts of natural disturbances (Janowiak et al., 2017).

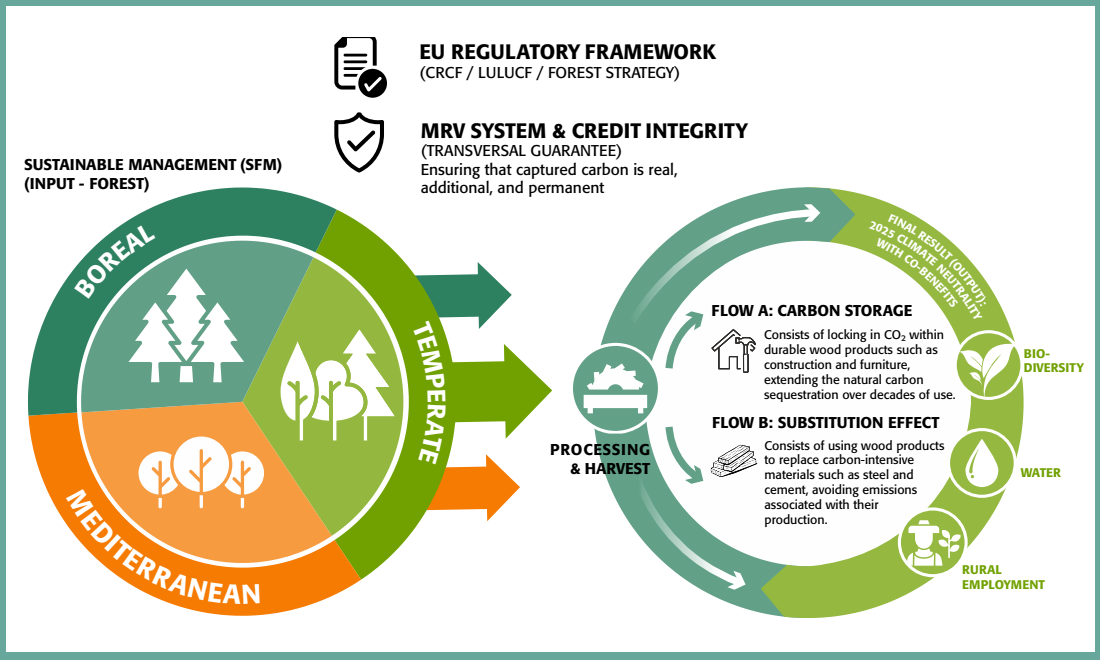
In the European context, forests are central and key to reach the climate neutrality objective, serving as both carbon sinks and providers of renewable resources (Korosuo et al., 2023). The recently proposed EU CRCF Regulation (EU, 2024) seeks to establish a common certification framework for carbon removals, including those achieved by the forestry sector. The challenge is to maximise long-term carbon storage in forests while ensuring sustainability, safeguarding biodiversity, and aligning incentives across value chains. The proposed EU CRCF Regulation represents a central pillar of the European Union's strategy to accelerate climate mitigation and advance the objectives of the European Green Deal (EC, 2019). Its overarching goal is to enhance the capacity of land-based sectors to contribute to the 2050 climate neutrality, primarily by promoting practices that increase carbon sequestration in soils and tree biomass, reduce greenhouse gas emissions, and generate verifiable climate benefits. To achieve this objective, the CRCF Regulation establishes a harmonised MRV framework and an EU-wide certification system for carbon removals, designed to ensure transparency, comparability, and environmental integrity across Member States. The Regulation relies on the so called *Qu.A.L.ity* criteria, which require a robust quantification, the additionality of the implemented measures, the liability of the stored carbon, and the generation of additional ecosystems services that the sustainable practices can generate. In this way, the Regulation aims to build trust in carbon farming

schemes and support the emergence of credible carbon removal markets. The Regulation is closely aligned with wider EU policy frameworks. It supports the EU Forest Strategy (EC, 2021a), which emphasises the dual role of forests in climate mitigation and biodiversity protection, and calls for sustainable forest management that strengthens carbon sinks while enhancing ecosystem resilience. For forest managers, the Regulation introduces new opportunities and incentives. Certified carbon removals may be monetised through emerging carbon credit markets, offering a potential revenue stream for practices such as improved forest management, afforestation, and restoration of degraded forest ecosystems.

The CRCF Regulation also complements the EU's Common Agricultural Policy (CAP), particularly through eco-schemes and rural development measures promoting soil health, agroforestry, and climate-smart land management. Furthermore, the Regulation contributes to the EU's biodiversity targets, including those set out in the EU Biodiversity Strategy for 2030 (EC, 2020), by incentivising practices that restore degraded ecosystems, increase structural diversity in forests, and enhance habitat quality.

Another important aspect of these policies is represented by the possibility of generating carbon credits in relation to the storage of carbon in long-lived wood products, namely the Harvested Wood Products (HWP). A coherent way to connect carbon farming with the credits generated by HWP is to frame forest management and wood use as a continuous carbon cycle that begins in the forest and extends into long-lived materials. Carbon farming practices in forests are aimed at increasing carbon sequestration through practices that enhance biomass growth, soil carbon stocks, and stand resilience. When part of this biomass is harvested sustainably, the carbon stored in the wood does not immediately return to the atmosphere but continues to be retained in long-life HWP, such as construction timber or furniture. By applying recognised accounting rules for HWP, the carbon stored in these products can be quantified and certified, creating an additional stream of carbon credits that complements the removals achieved by a forest. In this way, carbon farming and HWP credits become integrated components of a single mitigation strategy, where improved silviculture enhances the forest sink capacity, while the use of durable wood products extends carbon storage beyond the forest and substitutes more carbon-intensive materials (Figure 4.1).

Figure 4.1 The elements mentioned in this chapter are represented in a cyclical and hierarchical manner. Centre: EU Regulatory Framework as a driving force. Left Block (Input-Forest): SFM in the three climate zones. Right Block: Flow A: Storage in Long-Lived Products; Flow B: Substitution Effect. Linking both Blocks: MRV System and Credit Integrity. "Envelops" the process to ensure carbon capture is real, additional, and permanent. Final Output: Climate Neutrality by 2050 with co-benefits (biodiversity, water, rural employment). AI-generated figure using author's data.





Sustainable forest management can enhance carbon storage while supporting ecosystem health
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4.3 Forest management practices for climate mitigation

Forest management practices include all actions carried out by forest managers to achieve multiple, often competing, objectives. While effective management is crucial for meeting EU policy goals (e.g., climate neutrality in 2050), it also involves navigating complex trade-offs (Luyssaert et al., 2018). For example, biodiversity conservation requires maintaining and enhancing key ecological features and processes, while strengthening the bioeconomy requires a sustainable supply of renewable wood resources (Rybar and Bosela, 2023). Definitions of forest management categories vary widely across Europe, and comprehensive data on forest ownership and management regimes remain scarce. As a result, forest management patterns at the European scale are still not well-documented (Scherpenhuijzen et al., 2025). To help fill this gap, Aszalós et al. (2022) carried out an expert-based survey that classified a broad range of silvicultural systems and their regional variations, including distinctions relevant to boreal and temperate regions. Their study offered valuable insights into management approaches, stand characteristics, and the difficulties in harmonising terminology. However, it did not produce a spatially explicit map of forest management across Europe. For silvicultural practices to enhance forest carbon removal while delivering other essential ecosystem services (in line with CRCF regulation), some important gaps exist, particularly concerning their effect on soils (Chiti et al., 2024). Forest soils contain large amounts of soil organic carbon and constitute the largest terrestrial carbon pool (IPCC, 2019). However, increasing soil carbon takes time, much longer than in living biomass. Nevertheless, a broad set of silvicultural practices can significantly enhance carbon removal in European forests by increasing both above-ground biomass and long-term soil carbon storage (Chiti et al., 2024). Some of the most promising silvicultural practices are presented below according to the main climatic zones of Europe, except for afforestation, the extension of the rotation period, and the shortening of the rotation period, which can be implemented in all the different climatic regions.

4.3.1 Afforestation

This practice is implemented on croplands and grasslands. In addition to capturing carbon in both soil and above-ground biomass, afforestation delivers a range of environmental co-benefits. Carbon sequestration rates from afforestation vary depending on factors such as previous land use, local climate, and tree species, with estimates typically ranging from 2 to ~25 Mg CO_2 ha^{-1} yr^{-1} (Chiti et al., 2024). Sequestration rates in European afforestation projects can occasionally reach even higher values by using fast-growing tree species such as eucalyptus and poplars, known for their high potential for carbon sequestration (Pérez-Cruzado et al., 2012). The effects of these plantations should be carefully assessed at

both landscape and local scales considering socioeconomic factors. Potential trade-offs may arise with other ecosystem services, including, among others, water provision and regulation, soil formation, and biodiversity conservation. The implementation of afforestation at European level is, however, constrained by the availability of suitable land, since agricultural areas are needed for food production due to increasing population demand, and grassland and other open areas support distinct biodiversity values and ecosystem functions that may be lost or altered through conversion to forests. Moreover, the short-term climate benefits of afforestation are modest, since young forests typically sequester carbon at relatively low rates, with higher uptake occurring only after stands mature, depending on the tree species involved (Chen et al., 2020).

4.3.2 Extension of the rotation period

Another promising practice that allows to maximise C storage in the short term is the extension of the rotation period, which further increases above-ground biomass by allowing trees to reach larger sizes before harvest. An example of the potential is presented in the study by Stokland et al. (2012), performed in Norway, which examined the effects of extending rotation lengths from 100 to 120 years in Scots pine and Norway spruce stands, and found that this adjustment increased biomass carbon sequestration by 2.1-8.1 Mg CO_2 ha^{-1} yr^{-1}. Extending rotation periods can provide additional ecosystem co-benefits, including enhanced biodiversity and improved recreational opportunities in forested areas (Başkent and Kašpar, 2023). However, implementing longer rotations requires careful consideration of disturbance risks, as regions prone to storms, pests, or other disturbances may be less suitable (Keesstra et al., 2024), and all of these are forecast to increase as a result of climate change (Forzieri et al., 2021). Longer rotations can also reduce timber yields and revenues of landowners. Therefore, it is essential to balance the ecological and carbon advantages of extended rotations with the environmental risks and the suitability of specific forest sites.

4.3.3 Shortening the rotation length

While extending rotation periods can increase carbon storage within standing biomass, shortening rotation lengths represents an alternative pathway that focuses on carbon storage and substitution effects across the forest value chain. Reducing rotation lengths in productive forests can lead to climate mitigation, when considering the whole wood value chain, by increasing harvest frequency and thereby accelerating the transfer of biogenic carbon into HWP, where it can be stored for decades or used to substitute fossil-intensive materials. Shorter rotations can also reduce the exposure to climate-related disturbances that threaten long-term carbon stocks. Harvesting wood towards the culmination age of mean annual increment decreases the carbon stock of trees but can increase the soil carbon stock due to litter production and an increased amount of harvesting residues (Liski et al., 2001). When combined with sustainable management and allocation of harvested wood to long-lived products, shorter rotations can therefore support a dynamic mitigation strategy that balances forest carbon stocks with durable carbon storage and substitution benefits across the forest value chain.

4.3.4. Climate zone-specific forest management practices

Boreal zones

In boreal forests, the most climate-effective sustainable practices for carbon farming are those that maximise long-term carbon storage while minimising disturbances, given the slow growth rates and the large soil organic carbon pool typical of these regions. Current evidence indicates that diverse non-stand-replacing disturbances are the primary forces shaping forest dynamics and the natural range of variation in northern European boreal forests. These forests are characterised by infrequent severe disturbances, widespread small-scale gap dynamics, and variable- or mixed-severity disturbances that cause partial tree mortality and promote multi-aged forest structures (Berglund and Kuuluvainen, 2021).

In this regard, Continuous Cover Forestry (CCF) helps maintaining a permanent canopy and stable carbon stocks, avoiding the substantial emissions associated with clear-cutting (Peura et al., 2018). CCF can be applied only in forests where ecological conditions support natural regeneration under a partial canopy cover. It is most suitable in uneven-aged or multi-layered conifer forests, such as mixed spruce-pine, where natural gap dynamics already occur. CCF is also effective in sites with moderate moisture and sufficient soil fertility, because these conditions allow seedlings to establish

under shade. Boreal mixed wood forests, where shade-tolerant conifers (i.e., Norway spruce) coexist with lighter-demanding species like birch or aspen, can also support continuous cover systems by enabling selective harvesting while maintaining canopy closure. Old-growth or late-successional conifer stands, which naturally regenerate through small canopy gaps, are among the most compatible forest types for CCF (Gromtsev, 2002). By contrast, CCF is generally unsuitable in very cold, dry or nutrient-poor boreal sites, such as lichen woodlands, or in pure light-demanding pine stands where regeneration fails under shade. It is also limited in high-disturbance systems dominated by stand-replacing fires, and in areas with shallow soils or permafrost, where maintaining canopy cover can inhibit regeneration. Uneven-aged stands created through CCF are generally more resilient to disturbances, pests, and diseases, reducing the risk of unexpected carbon losses (Mohr et al., 2024). CCF also maintains a steady flow of carbon to the forest floor, while clear-cutting disrupts soil inputs and can temporarily turn forests, especially drained peatlands, into net sources of CO_2 (Korkiakoski et al., 2023). Although shifting species composition and transitioning to CCF are long-term processes that may initially reduce carbon stocks (Hilmers et al., 2020), they yield quicker benefits for biodiversity conservation, soil health, and overall forest productivity.

In boreal zones, a key societal force driving changes in forestry practices has been the rise of environmentally conscious markets seeking assurance that wood harvesting does not harm ecosystems or biodiversity. Combined with growing criticism of intensive forestry in many countries, these expectations have encouraged the widespread adoption of **retention forestry** (Simonsson et al., 2015). Retention forestry involves leaving selected trees and structural elements, such as large living trees, snags, fallen logs and damaged trees, to preserve features characteristic of older forests (Gustafsson et al., 2020). This approach aims to mimic the ecological effects of natural disturbances and ultimately balance timber production with the delivery of other ecosystem services while conserving biodiversity (Lindenmayer et al., 2012). However, the extent to which increased levels of retention benefit species with varying ecological requirements remains poorly understood (Basile et al., 2019). In addition, retention forestry enhances forest carbon storage by leaving selected trees, deadwood, and structural elements in place during harvesting. This approach maintains continuous biomass and soil carbon inputs, reduces carbon losses from disturbances, and supports long-term ecosystem stability, making it an effective strategy for increasing both above- and below-ground carbon stocks.

Temperate zones

In temperate forests, the most climate-effective sustainable forestry practices for carbon farming focus on maintaining continuous carbon stocks and increasing ecosystem resilience. Continuous Cover Forestry (see boreal zones sub-section above) and selective harvesting help preserve standing biomass while supporting natural regeneration. Introducing mixed-species stands improves productivity, resilience to pests and climate extremes, and long-term carbon storage.

Adapting **tree species composition** can have variable effects on carbon sequestration in both biomass and soil, with soil carbon responses also being influenced by the associated mycorrhizal symbionts (Mayer et al., 2020). Species-specific carbon sequestration rates may further change over time depending on how individual species respond to global change, including alterations in growth and mortality (Kasper et al., 2022). For example, Vospernik et al. (2024) found that mixing oak and pine can partially offset climate-induced productivity losses, though not entirely. In particular, the establishment of mixed-species stands may simultaneously support adaptation of forests to climate change and an increasing productivity (Augusto and Boča, 2022). More diverse stands generally exhibit greater stability (Pretzsch et al., 2015). In particular, species mixing increases resistance and resilience to extreme drought (Pretzsch et al., 2013) and reduces vulnerability to biotic and abiotic disturbances (Guyot et al., 2016). Additionally, higher tree species richness can positively influence soil carbon through changes in litter quality, nitrogen fixation, and rooting patterns (Díaz-Pinés et al., 2011). However, the benefits of mixing species are context-dependent. Reviews indicate that while it can enhance growth and carbon sequestration in central and southern Europe, the effect is less clear in northern boreal forests (Huuskonen et al., 2021). Therefore, assessing the additional climate mitigation contribution of species mixing is challenging. Nonetheless, converting monocultures into mixed stands remains a recognised climate adaptation measure.

An important aspect to consider particularly in forests in temperate regions is the adoption of **soil protection measures** related to the impact of

logging operations, which are known to represent a potential threat to forest soils, mostly when using ground-based logging systems (Schweier et al., 2019). Soil compaction, often occurring together with rutting, is a common impact of improper use of heavy forestry machinery. The formation of ruts can directly or indirectly damage tree root systems (Stone and Elioff, 2000) and soil fauna (Lindo and Visser, 2004), while the resulting changes in soil structure and microclimatic conditions may even alter plant diversity (Buckley et al., 2003). In general, also the soil gas exchange is hampered, possibly affecting growth and activity of roots (Gaertig et al., 2002). The EU's recent Directive on Soil Monitoring and Resilience (EU, 2023a) highlights both, topsoil and subsoil compaction, as major contributors to soil degradation, one of the main environmental problems in Europe.

Combined, these practices maximise carbon removal while delivering co-benefits for biodiversity, soil health, and forest stability in temperate regions.

Mediterranean zones

In Mediterranean forests, the most climate-effective sustainable forestry practices for carbon farming aim to enhance carbon storage while reducing vulnerability to fire, drought, and soil erosion. Rising temperatures are expected to further increase the frequency and severity of wildfires in the absence of targeted **fire management strategies** (Turco et al., 2014). In highly depopulated areas, abandonment has led to biomass accumulation, making these landscapes highly vulnerable to intense fires (Lecina-Diaz et al., 2014). Forest management remains the most effective strategy to control forest fuel loads while achieving multifunctional objectives, including social benefits (Madrigal-González et al., 2017). For example, since the late 19th century, Spain introduced systematic forest management methods such as shelterwood systems, which have helped stabilise carbon stocks while maintaining multifunctional use of public forests. A priority is the management and treatment of unmanaged pine plantations established during past reforestation programmes. Many of these plantations remain structurally homogeneous and overly dense, which increases their vulnerability to drought, pests, and fire under current climate change scenarios (Vilà-Cabrera et al., 2023). Fuel-reduction thinning and fire-smart management are therefore crucial for preventing catastrophic carbon losses in fire-prone areas.

As forests historically exploited for charcoal were abandoned, coppice stagnation has become a major driver of forest decline. Due to rural abandonment and technical or economic constraints, many coppice forests are now neglected or abandoned, representing a largely underutilized natural resource (Unrau et al., 2018). **Converting traditional coppice systems into high forests** can increase carbon stocks and generate additional ecosystem services. Tree species composition in coppice forests has long been simplified by traditional coppicing, leading to the loss of species with low stump-sprouting ability (Fabbio, 2016). Nevertheless, coppice forests remain important for biodiversity because of their native tree species, continuous forest cover over time, structural diversity, and varied tree ages, which is why this management system is still promoted in some countries (Kirby et al., 2017).

Under certain conditions, gradual conversion of coppices to high forests leads to an increase in the carbon stored in aboveground biomass. Moreover, reducing ramet density through thinning has been shown to significantly improve drought resistance in Mediterranean holm oak coppices by lowering basal area and enhancing water-use efficiency, thereby preventing forest die-off and supporting long-term carbon stock permanence (Domingo et al., 2020). On mesophilic sites, this conversion can enhance long-term carbon sequestration in forest biomass, while coppice systems may remain more productive on drier sites (Bruckman et al., 2011). However, the impact of converting coppice to high forests on soil carbon remains uncertain (Camponi et al., 2022).

4.4 Monitoring, Reporting, and Verification

MRV are essential to ensure that practices leading to increased carbon sequestration in forests can be accurately quantified and assessed in terms of their climate mitigation contribution. **Monitoring** entails applying scientific techniques and modelling tools to quantify the amount of CO_2 removed, using methods tailored to each type of carbon removal activity. **Reporting** involves organising and presenting collected data according to recognised standards, providing clear documentation on the project, the methods used, and the resulting outcomes. **Verification** is conducted by an independent third party, which reviews project information and procedures to confirm compliance with MRV requirements and ensures that the reported carbon removal claims are credible and accurately validated. Accurate

measurements of biomass, soil carbon, and forest dynamics form the basis for estimating carbon removals, while transparent reporting enables forest managers, regulators, and markets to track changes over time. Independent verification strengthens trust by confirming that reported removals meet the requirements of recognised standards, including criteria related to additionality and durability. In this way, MRV provides the scientific and procedural foundation necessary for forest-based carbon credits to be recognised, traded, and integrated into climate policies. The EU Regulation on Land Use, Land Use Change, and Forestry (LULUCF) requires spatially explicit monitoring of land use, mandating that all Member States implement systems incorporating georeferenced data. At the European scale, remote sensing (RS) products have become increasingly accessible, although their spatial and temporal resolutions vary across platforms and datasets. While RS-based estimates are rapidly improving, it remains essential to account for limitations such as processing costs, intrinsic uncertainties, and scale-resolution trade-offs. Hybrid approaches that integrate RS with ground-based observations are currently considered the most reliable for generating robust MRV results (Holvoet et al., 2025). In particular, open-access airborne LiDAR datasets and spaceborne LiDAR missions such as GEDI provide valuable information for characterising forest structure across large regions.

Complementing these observational data, model-based approaches have become indispensable in operational MRV systems. By integrating information from National Forest Inventories (NFIs), remote sensing, and climate data, both process-based and inventory-based models enable the scaling of plot-level measurements to regional and national levels. Models such as the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3 - Kurz et al., 2009) have been widely adapted to simulate carbon dynamics under different forest types and management scenarios.

While these modelling frameworks ensure temporal consistency and support compliance with LULUCF and CRCF requirements, they also introduce uncertainties related to model structure, parameterisation, and assumptions. Robust MRV systems therefore rely on the iterative integration of models and observations, with continuous calibration and validation against field data and independent datasets. Particular attention must be given to microclimate variability, soil carbon dynamics, and fine-scale spatial heterogeneity, which are critical for both carbon stability and ecosystem resilience.

Recent applications in European contexts illustrate the practical implementation of these integrated approaches. For example, high-resolution mapping of canopy height and above-ground biomass across the Iberian Peninsula has been achieved by combining satellite data, LiDAR, and NFI observations with advanced modelling frameworks (Tanase et al., 2024). These approaches enable reliable large-scale estimation of forest structure and carbon stocks, as well as the detection of temporal changes in carbon sink capacity under climate stress (Su et al., 2025).

Key forest inventory variables, such as tree height and diameter, can be derived from airborne and ground-based LiDAR with higher accuracy than traditional inventory methods (Zolkos et al., 2013). LiDAR can provide sub-meter surface height measurements, although accuracy depends on factors such as canopy structure, terrain, and sampling intensity. In complex or heterogeneous forests, limitations in detecting individual trees and understory elements may introduce uncertainties, making LiDAR a complementary tool rather than a replacement for field inventories. The most robust applications therefore arise from its integration within hybrid frameworks combining remote sensing and ground-based measurements.

To ensure the long-term credibility and scalability of forest carbon farming, MRV systems must evolve beyond isolated pilot projects toward a standardised integration of Earth Observation (EO) technologies. In line with the European Union's Carbon Removals and Carbon Farming Regulation, robust MRV frameworks require an optimal combination of field measurements, advanced modelling, and EO data, particularly through infrastructures such as the Copernicus Data Space Ecosystem (CDSE). Strengthening the link between technical monitoring and market transparency is essential to overcome adoption bottlenecks, including methodological fragmentation and uncertainty thresholds.

In this context, emerging best practices frame MRV systems as integrated hybrid frameworks, where field observations, EO data, and modelling approaches are combined in a structured and iterative way. EO provides spatially explicit, wall-to-wall monitoring of forest cover, biomass



Sustainable forest management can create synergies between climate action, biodiversity and broader ecological, economic and societal objectives © Aaron Doucett (Unsplash)

dynamics, and disturbance regimes, while field data remain essential for calibration and validation, and models ensure scalability and temporal consistency.

A key requirement in such systems is the explicit treatment of uncertainty, including its quantification and propagation across all components of the monitoring chain. Uncertainty must be transparently reported, as verification bodies increasingly require clear evidence that results fall within acceptable methodological bounds.

In addition, advanced MRV systems must provide audit-ready and reproducible evidence, including traceable data sources, documented workflows, and version-controlled processing pipelines. EO plays a central role by enabling independent cross-checks of activity data, spatial boundaries, and disturbance events over time, thereby enhancing transparency and comparability across projects and jurisdictions.

The CRCF *Qu.A.L.ity* criteria place MRV systems at the core of carbon credit integrity. MRV provides the technical foundation to demonstrate compliance across these four dimensions, linking monitoring directly to the credibility of carbon accounting. In this sense, MRV design becomes intrinsically connected to carbon crediting mechanisms, as it underpins the quantification of additionality, the management of reversal risk, and the overall integrity of credits, as discussed in the following section.

Finally, MRV outputs are increasingly used not only for compliance and reporting but also for risk assessment and financial decision-making. Spatially explicit indicators of biomass change, disturbance exposure, and associated uncertainty support due diligence by investors, insurers, and carbon credit buyers, linking forest monitoring directly to market confidence and the integrity of forest-based climate mitigation strategies.

4.5 Co-benefits and trade-offs

The **CRCF regulation** emphasises the importance of **co-benefits** alongside carbon removals, recognising that sustainable land management should deliver positive impacts beyond climate mitigation. By integrating co-benefits into the certification process, the CRCF ensures that carbon removal projects contribute to **broader environmental and societal objectives,** increase the credibility and public acceptance of carbon credits, and align climate action with the EU's sustainability and ecosystem restoration goals. Forests deliver a wide array of ecosystem services that go far beyond carbon sequestration and wood supply, but that delivery can be further improved by implementing sustainable forestry measures. Forest management often prioritises specific ecosystem functions, which can lead to both synergies and trade-offs. Many forestry measures can deliver multiple co-benefits for biodiversity, water, soil, air quality, climate adaptation and local communities. However, the extent to which these co-benefits

are achieved depends on ecological conditions, management approaches and the spatial and temporal scale of implementation, as discussed in Chapter 2. When actions focus solely on carbon removal, they may create environmental risks. For example, expanding monocultures of tree species poorly adapted to climate change can heighten vulnerability to fires or pests, undermining carbon permanence. Large-scale afforestation may reduce land availability for agriculture, threaten grassland biodiversity, and affect local livelihoods and food security. Reduced harvesting can also trigger carbon leakage, shifting production, and associated emissions to other regions. For these reasons, aligning forest measures with broader ecosystem service goals and policy needs, including demand-side considerations, is essential. Climate change mitigation policies that fail to consider the conservation of deadwood in forest ecosystems may undermine the achievement of biodiversity conservation targets, as the extraction of deadwood for fuel or wood products can reduce its role in supporting species diversity (Balducci et al., 2026).

Many of the management practices presented in this chapter are cost-effective and widely familiar to land managers, reflecting a high level of technological readiness (ESABCC, 2025). However, their adoption and broader implementation face various barriers and limitations. The financial costs of implementing these measures may include upfront fixed establishment expenses, variable costs associated with changes in management practices (e.g., selective logging), and opportunity costs resulting from foregone income due to reduced biomass production (Kreibiehl et al., 2022). In the case of afforestation, for instance, farmers face costs for purchasing seedlings, installing fencing, and the loss of agricultural crop production, but financial returns may not materialise for several decades. For forest management practice implementation, the long-term commitment (e.g., more than 20 years) is often seen as a financial risk, a concern that may grow given uncertainties related to climate change and natural disturbances. These costs and risks can be substantial, especially for smallholders (EC, 2022).

4.6 Integration with value chains

4.6.1 Strategic context and EU absorption targets

The European forestry sector plays a central role in the regional climate system. Within the European Union, its contribution is structured around three complementary strategies: strengthening the carbon sequestration capacity of forest stands, managing the value chain to maximise carbon storage in HWP, and replacing fossil fuels with bioenergy at the end of the materials' useful life (EU, 2021, 2018). Despite its importance, the net sink of the LULUCF sector has declined by more than 30% over the past decade (2014-2023), reaching 198.4 $MtCO_2e$ (million tonnes of CO_2 equivalent) in 2023 (6% of the EU's annual emissions) due to stand ageing, logging, and natural disturbances (EEA, 2025; Korosuo et al., 2023). To reverse this trend:

- The regulation (EU) 2023/839 sets a binding target of 310 MtCO2e of net removals by 2030 (EU, 2023b).
- The Climate Law (Regulation (EU) 2021/1119) requires a 55% reduction in net emissions by 2030, although it caps the LULUCF contribution at 225 $MtCO_2e$ to ensure that other industrial sectors do not scale back their mitigation efforts (EU, 2021).
- In 2023, HWP already accounted for more than 10% of the EU's total net sink, underscoring its role as a critical sink by retaining captured biogenic carbon, which constitutes up to 50% of the weight of dry wood (EEA, 2025).

The EU is restructuring the forest value chain under the framework of Regulation (EU) 2024/3012 to prioritise climate mitigation (EU, 2024). Within this framework:

1. **Long-lived forest products:** These are essential due to their dual role in physical carbon storage and as substitutes for materials in the construction sector, which accounts for 5-12% of national greenhouse gas (GHG) emissions (EC, 2025a).
2. **Short-lived forest products and residues:** These contribute primarily through the substitution of fossil fuels.
3. **Bioenergy:** It is integrated exclusively as the final link in the chain, in accordance with the Renewable Energy Directive (RED III), ensuring that biomass is used first for higher-value material purposes (EU, 2023c).

4.6.2 Cascade use strategy and resource efficiency

The growing need to replace energy-intensive and fossil fuel-dependent materials is driving a demand for wood that could compromise

the net carbon sequestration potential of European forests. To manage this pressure, the EU Bioeconomy Strategy (EC, 2025b) establishes a framework for balancing biomass production with the restoration and protection of ecosystems. The operational core of this transition is the "cascading use strategy", which establishes a hierarchy of priorities geared towards circularity (Dammer et al., 2016):

1. Material priority: Wood should first be used for long-life applications (e.g., construction, furniture).

2. Circularity: Reuse and recycling should be encouraged as many times as possible before disposal.

3. Energy recovery: Bioenergy is reserved as the final link, once material options have been exhausted.

The economic rationale for this hierarchy is sound: the material use (cascade) scenario generates 2.68 times more added value and 3.5 times more employment than direct energy use (EC, 2016). This difference stems from the fact that material pathways (plywood, engineered wood, furniture) require longer supply chains, complex industrial processes, and high labour intensity, which also promotes the sustainability of local industries (Carus and Raschka, 2011). Cascading use presents numerous opportunities and examples already explored in the forestry sector (Bais-Moleman et al., 2018). Despite these benefits, the use of biomass for energy has grown by 14% over the past decade, compared with an 11% increase in material use, due to financial incentives that allow power plants to pay prices for raw materials that exceed the processing industry's capacity (Camia et al., 2025).

To align the value chain with climate goals, the EU applies three key regulatory frameworks:

- Renewable Energy Directive (RED III): establishes targets and criteria that Member States must transpose into national law, including restrictions on financial support for energy production from industrial-grade wood (such as sawmill chips or veneer), limiting incentives to waste and by-products with no other viable uses (EU, 2023c).

- EU Regulation on Deforestation-free products (EUDR - Regulation 2023/1115): establishes due diligence requirements to ensure that wood placed on the market or exported (including solid wood, panels, pulp, and paper) is free from deforestation and forest degradation, requiring legal compliance regarding its origin (EU, 2023d).

- Bioeconomy Strategy Framework (Table 4.1): structures actions ranging from sustainable forest management (upstream), through investment in biorefineries for advanced materials like wood-based textile fibres (midstream), to the prioritisation of cascading use (downstream), alongside environmental footprint accounting using the Product Environmental Footprint (PEF) method (EC, 2021b) throughout the product's life cycle.

This framework seeks to transform the forest bioeconomy into a resilient system that harmonizes the mobilisation of wood with the integrity of carbon sinks and the protection of biodiversity.

Table 4.1 The Impact of the Bioeconomy Strategy (Com EU 960/2025) on the Forest Value Chain (EC, 2025b).

Value Chain Link	Strategy Focus
Resources and Management (Upstream)	Encourages Sustainable Forest Management (SFM), reforestation, and increasing carbon absorption in forests as producers of sustainable biomass. It aligns with the DNSH (Do No Significant Harm) principle, seeking co-benefits for biodiversity, soil health, and ecosystem resilience.
Transformation and Industry (Midstream)	Promotes investment in biorefineries and technologies to convert wood (including byproducts and residues) into new advanced materials, such as textile fibres (viscose, lyocell), bio-chemicals, and high-quality cellulose.
Products and Uses (Downstream)	Drives the cascading use principle: prioritising the use of wood for long-lived products (such as construction and furniture) before dedicating it to energy (bioenergy). This maximises carbon storage.
Circularity and End-of-Life (EoL)	Regulates the collection and recycling of paper, cardboard, and wood products (furniture, pallets). Promotes the recovery of wood residues that cannot be recycled, for controlled bioenergy production (closing the loop). Promotes the use of the Product Environmental Footprint (PEF) methodology and the refinement of circularity assessment.

4.6.3 Industrial opportunities and new wood markets

Wood is one of the most strategically important renewable raw materials globally, with growing use in innovative fields that is blurring traditional industrial boundaries and forcing forestry companies to adopt new business models (Antikainen et al., 2017). In the UNECE region (56 countries), exports exceeded EUR 140 million in 2019, with consumption concentrated at 50% in roundwood and 39% in wood for energy (UNECE, 2019).

The forestry sector and its related wood-based industries serve as a central and irreplaceable pillar of the European bioeconomy (EC, 2013). This importance is underscored by the region's high level of self-sufficiency, as more than 95% of the roundwood processed within the EU is sourced directly from European forests. Beyond material supply, the sector's economic weight is significant, accounting for approximately 8% of the total value produced by the EU manufacturing industry (Kallio et al., 2022). This industrial strength translates into a substantial social impact. In 2021 alone, the sector provided jobs for 3.6 million people (Eurostat, 2025), representing 21% of the total employment within the bioeconomy (Lasarte-López and M'Barek, 2025). Within this workforce, furniture manufacturing stands as the largest employer with 1.1 million workers, closely followed by wood and cork manufacturing with 1 million, while forestry and harvesting activities maintain the smallest labour base (Eurostat, 2025). Furthermore, the growth potential for the sector is vast, with projections suggesting that even a modest 1% increase in the market share of wood products across the construction, textile, and chemical sectors could generate between EUR 10-60 billion in additional revenues (EC, 2013; Hetemäki et al., 2017). Such an increase would represent a transformative impact, accounting for between 3-20% of the EU forestry industry's total current earnings.

The Bioeconomy Strategy promotes the commercialisation of products currently in the early stages of development (wood foam, bioplastics, lignin-based adhesives) and fosters key markets (FAO, 2022; UNECE and FAO, 2025):

- **Advanced Construction Systems:** Engineered wood products, such as cross-laminated timber (CLT), and panels including plywood, particleboard, and fibreboard, along with glued laminated timber (glulam), enable wood construction to be extended to mid- and high-rise buildings thanks to their strength and design flexibility (Svatoš-Ražnjević et al., 2025). These solutions, often prefabricated off-site (Lobos Calquin et al., 2024), help reduce material waste and have the potential to lower a building's embodied carbon and energy requirements by up to 40% (Amarasinghe et al., 2025).

- **Textile Bioeconomy:** Man-made cellulosic fibres, derived from wood pulp, represent a strategic opportunity. Although their role in carbon sequestration is limited by their short lifespan (approx. 5 years), their climate contribution is significant, replacing synthetic fibres in a global market of 100 million tonnes annually (Leskinen et al., 2018).

- **Biorefineries and Biochemistry:** It is estimated that 300 new biorefineries will need to be established by 2030 to meet the demand for advanced materials (EC, 2021b). These facilities achieve an efficiency of up to 85.3% (Rödsrud, 2014) converting byproducts and waste into specialty cellulose, lignin, and ethanol, with process emissions that are 30-50% lower than those of conventional petrochemical production (EC, 2025b).

The expansion of wood-based bioeconomy applications will, however, require appropriate regulatory frameworks and adaptations within existing value chains. Trade in products such as solid wood, panels, pulp, and paper, is subject to the EUDR (Regulation 2023/1115), which establishes due diligence requirements to ensure that they are free from deforestation and forest degradation. However, industrial processing faces structural challenges: most current machinery is designed to process softwoods rather than hardwoods. Furthermore, there is asymmetric substitutability in the market: while an increase in the production of sawlogs boosts the availability of wood for pulp, an increase in the latter tends to reduce the availability of high-quality sawlogs, requiring a profound reconfiguration of the existing infrastructure (Bolkesjø et al., 2005).

4.6.4 Carbon mitigation mechanisms in wood products

Harvested wood products offer a dual benefit for greenhouse gas mitigation: they act as physical sinks by storing carbon and prevent industrial emissions through the substitution effect. The net climate benefit of wood products is only realised when the sum of embedded

carbon reduction and long-term storage exceeds production emissions and losses from forest stocks. The first dimension of this mitigation strategy focuses on the physical sequestration of biogenic carbon within the wood fibres, effectively extending the forest's role as a carbon sink into the built environment:

A. Biogenic Carbon Storage

Harvested wood becomes a sink that keeps carbon out of the atmosphere for decades or centuries (Schmid et al., 2021). One cubic metre of wood stores approximately 0.9 to 1 tonne of biogenic carbon (Steel, 2021), which is equivalent to an absorption of between -730 and -1,000 kg CO_2e in the Global Warming Potential (GWP) calculation (EPD Stora, 2025). Under the CRCF Regulations, storage is classified into two categories (EU, 2024):

1. **Permanent sequestration:** Chemically bound carbon that is not released after the end of the product's useful life (several centuries). This includes biogenic carbon in biopolymers and bioplastics, carbon captured for synthetic fuels, and mineralised carbon in stable construction materials such as certain types of cement (EU, 2023e).

2. **Temporary storage in products:** Requires a minimum threshold of 35 years of *in situ* retention and monitoring to be certified. This category includes:

    - Sawn timber: Historically having the longest default useful life, including glulam and conventional structures (EU, 2018).

    - Engineered wood panels: Cross-laminated timber, plywood, and particleboard.

    - Wood buildings: Mid- and high-rise structures that represent the greatest potential for biogenic carbon sequestration in the built environment.

While physical storage addresses the carbon already captured, the second dimension of the wood products' benefit (the substitution strategy) focuses on avoiding future fossil fuel emissions by displacing carbon-intensive materials.

B. Substitution strategy and embodied carbon

This mechanism prevents the release of embodied fossil carbon, which accounts for emissions generated during the procurement, transportation, and processing of alternative materials (steel, concrete, glass) excluding operational emissions (Hemmati et al., 2024). In multi-storey buildings, the structural frame alone can account for 60% of embodied carbon (Al-Najjar and Malmqvist, 2025). The use of wood mitigates the risk of "carbon lock-in" (Orfanidou et al., 2023; Pomponi et al., 2020), a phenomenon where high emissions generated during construction (often through carbon-intensive energy) remain locked into physical structures for centuries, thereby perpetuating a long-term dependence on fossil resources and highly emissive processes. Replacing these intensive materials with wood reduces embedded carbon and avoids the risk of carbon lock-in. The efficiency of this mechanism is measured by the Substitution Factor (SF), which quantifies the emissions avoided per unit of carbon contained in the wood product (Wedajo et al., 2025). Although the average SF is 1.2 kg C/kg C (Leskinen et al., 2018), values vary significantly by sector (see Table 4.2).

Table 4.2 Average Substitution Factors by sector and application (SF in kgC/kgC) (adapted from Leskinen et al. (2018).

Application	Average SF	Value Range (95%)
Construction (structural)	1.3	-0.9 to +5.5
Construction (non-structural)	1.6	+0.2 to +4.7
Textiles	2.8	2.5 to 3.1
Other Materials (chemicals, packaging)	1.0 to 1.5	(Not specified)

It is estimated that using one cubic metre of wood in construction instead of traditional materials reduces emissions by between 2 and 4 tCO_2e (Verkerk et al., 2022), depending on the regional energy mix and the material being replaced (e.g., replacing one tonne of concrete reduces CO_2 emissions by 2.1 tonnes - Hurmekoski, 2017). To achieve a truly comprehensive understanding of these dual benefits, these factors must be viewed within a broader systemic framework that accounts for energy efficiency and long-term planning.

C. Strategic considerations and energy efficiency

Replacing fossil fuels with biomass (bioenergy) also yields significant mitigation benefits, although its efficiency varies drastically depending on the resource being replaced and the quality of the wood used. The greatest efficiency is achieved by displacing coal, the fuel with the highest emissions, while the use of high-quality wood for heating is inefficient from a strategic climate perspective (see Table 4.3).

However, for an accurate assessment of this impact, it is essential to integrate substitution factors with dynamic changes in both forest carbon and wood products stocks (Werner et al., 2010). Strategic planning must adopt long-term horizons, as short-term analyses (e.g., up to 2048) indicate that carbon storage in products only partially offsets forest sequestration, with the mitigation effects on forest stocks typically remaining more dominant in the near term (Bösch et al., 2017). Ultimately, the positive net benefit of wood products is only confirmed when evaluating the entire life cycle and accounting for the material substitution effect (Bösch et al., 2019). This assessment is particularly complex in the construction sector due to the vast combinations of wood types and fossil alternatives. For instance, the manufacture of engineered products (e.g., laminated beams) requires significantly more energy (63-83% more) than sawn wood, which can reduce the environmental benefit if the efficiency of industrial processes is not managed (Harmon, 2019).

Table 4.3 Average Substitution Factors by fuel (SF in tC/tC) (adapted from Schmid et al., 2021).

Substituting biomass source	Fossil fuel substituted	Substitution factor (tC/tC)
Forest biomass	Coal	0.8 - 1.27
Forest biomass	Oil	0.6 - 0.79
Forest biomass	Natural gas	0.4 - 0.56
Sawnwood (for heating)	Fossil fuels	0.34

4.6.5 Product carbon accounting: PEF method

To ensure climate integrity, the EU distinguishes between macroeconomic accounting (at the national level) and microeconomic accounting (at the product level). Regarding the macro level, the transition of the LULUCF sector towards simplified rules in 2026 will integrate wood products directly into National GHG Inventories (EU, 2023b, 2018). Simultaneously, at the micro level, accounting is governed by the PEF method developed by the European Commission (EC, 2021b). This framework allows for conducting Life Cycle Assessments (LCA) in full alignment with ISO 14040/14044 standards to quantify the impact of specific timber products (ISO, 2006a, 2006b). For practical application, standardisation is required through Product Environmental Footprint Category Rules (PEFCR), which enable comparisons between products and serve as the basis for Environmental Product Declarations (EPD) in accordance with ISO 14025 (ISO, 2006c). EPDs are voluntary, third-party verified reports that communicate environmental information based on a product's LCA. They are prepared using specific PEFCRs to ensure that declarations of competing products are directly comparable. The development of PEFCR rules remains active in key sectors of the forest bioeconomy:

- **Construction:** Governed by Technical Rule UNE-EN 16485 and standard UNE-EN 15804 (A2:2019), which harmonise indicators with EPD requirements (CEN, 2019, 2014a). This regulation requires mandatory declaration of biogenic carbon content in both the product (beams, panels) and its packaging, based on the harmonised standard EN 16449 (CEN, 2014b).

- **Textiles and Biochemistry:** Specific rules for wood-based textile fibres (viscose, lyocell), biochemicals, and bioplastics are currently in the development and adoption phase.

- **Bioenergy:** Although PEF rules exist for biofuels, this sector operates primarily under the criteria of the Renewable Energy Directive (RED III).

The quantification of emissions and removals under the PEF method is broken down into three subcategories of GWP: a) Fossil GWP: emissions from fossil fuels; b) Biogenic GWP: carbon exchanges from above-ground biomass; and c) LULUCF GWP: exchanges resulting from deforestation and native forests. Methodologically, the PEF applies a zero-sum accounting approach (-1/+1) for biogenic carbon, and assumes that carbon uptake during growth (-1) is offset by emissions at the end of the product's life cycle (+1), provided that the wood comes from sustainably managed forests (UNECE and FAO, 2025). It is important to note that direct benefits from storage in wood products or offset credits should not be included in the calculation of the product's total GWP indicator, nor is the deduction of emissions from temporary storage permitted within this metric. Finally, it is worth mentioning that the PEF method incorporates the Circularity Footprint Formula (CFF), which assesses the end-of-life environmental profile by considering three factors: R1 = Recycled content at the input stage; R2 = Recyclability of the product at the end of its life and R3 = Benefits derived from energy recovery. For intermediate products, the formula excludes end-of-life stages (R2 and R3 are set to zero) but maintains the requirement to report physical biogenic carbon as additional technical information before the material leaves the factory. This structure ensures that, while national reporting is simplified, voluntary certification under the CRCF Regulation maintains climate integrity through continuous monitoring and compliance with the 35-year retention threshold.

4.6.6 Regional challenges and outlook for the forest bioeconomy

The expansion of the European forest bioeconomy depends not only on technical advances but also on its ability to integrate into resilient territorial models. This requires overcoming structural barriers ranging from land fragmentation to disparities in regional innovation. To navigate these complexities, the following sections analyse the four critical dimensions that define the future roadmap for the sector's expansion: territorial, administrative, socio-environmental, and strategic.

1. Local value chains and territorial development

The EU Bioeconomy Strategy prioritises decentralised and circular production models, focused on development at the local, rural, and coastal levels (Schipfer et al., 2022). This decentralised approach is rooted in the essential interdependence between economic well-being and environmental health, effectively positioning the local level as a 'testing ground' for replicable, small-scale bio-based solutions (Doloreux and Parto, 2005). To successfully implement this vision, several operational and social dimensions must be prioritised:

- **Logistical efficiency:** Since forest residues are bulky and costly to transport, the proximity of processing facilities (such as new biorefineries) to primary production sites is critical for economic viability.

- **Rural revitalisation:** Models where the first transformation of biomass occurs close to the source support the livelihoods of the EU's approximately 16 million forest owners, creating specialized green jobs in rural areas (Asheim and Coenen, 2005).

- **Governance debate:** While regulatory frameworks drive a cascading use hierarchy, scientific discourse suggests that rigid hierarchies may have unintended consequences, advocating for a more flexible "bottom-up" approach tailored to specific territorial needs.

2. Barriers for smallholders and the CRCF framework

Despite the opportunities offered by the CRCF Regulation to mobilise private financing, its implementation presents specific challenges for small-scale forest managers:

- **Administrative burden:** The regulation aims to reduce the financial burden through simplified certification standards and group audits, but compliance with the *Qu.A.L.itY* criteria remains complex.

- **Knowledge and monitoring gaps:** Certification requires demonstrating tangible co-benefits for biodiversity and soil health. This poses a significant hurdle due to a lack of technical knowledge regarding the impact of certain bio-based solutions and the high costs associated with small-scale monitoring studies.

- **Regional disparities:** Currently, the development of bio-innovations is uneven; while countries such as Germany, France, and Italy lead the sector, other regions lack the infrastructure and funding needed to scale up their capabilities (EEA, 2025).

3. Scalability challenges: Socio-environmental and economic factors

The forest sector faces increasing pressure that could compromise its ecological integrity:

- **Biocapacity vulnerability:** A recent analysis indicates that the 32 member countries of the European Environmental Agency (EEA-32) already consume more resources than their ecosystems can provide, currently supplying only half of the necessary biocapacity.

- **Waste and the construction sector:** The transition to a wood-based bioeconomy is urgent because conventional construction is responsible for more than 35% of the waste generated in the EU, and approximately 10% of the total carbon footprint of the EEA-32 region.

- **The risk of leakage:** Strict local conservation policies without corresponding increases in efficiency may lead to "leakage", where harvesting is displaced to unregulated external regions. This is critical given that the current harvest rate of 65% of the annual net increment may be underestimated by up to 20% (EC, 2018).

- **Technical and social barriers:** Obstacles persist; for example, the lack of standardized wood waste classification and the need for updated building codes and fire safety standards for the widespread use of Engineered Wood Products. Additionally, cultural resistance toward materials derived from bio-waste remains a hurdle for market expansion.

4. Critical factors for the success of expansion

To ensure a sustainable transition, the expansion of the bioeconomy must be guided by several fundamental pillars:

1. **Robust evidence:** The use of transparent, in-depth LCAs to inform policy and industrial decisions.

2. **Policy coherence:** Aligning the bioeconomy with the EU Forest and Biodiversity Strategies to ensure that incentives do not create cross-sectoral contradictions.

3. **Scenario analysis:** Evaluating long-term risks, specifically focusing on the strategic competition for biomass created by bioenergy incentives, which could elevate supply risks for the material industry.

4. **Integrity and risk mitigation:** Ensuring that large-scale bio-based innovation does not compromise the integrity of forest carbon sinks or regional food security.

4.7 Incentives and credits: mobilising finance while ensuring integrity

4.7.1 Purpose and context

Forest carbon crediting has been promoted as a relatively low-cost route to climate mitigation, capable of mobilising substantial private finance for land-based sequestration. Recent evidence has put that promise under strain. Low-cost expectations often assume four core integrity requirements that are rarely fully priced in: additionality, the time-bound nature of biological storage, reversal risk, and leakage. A portfolio-scale review of approximately one billion credits across project types found that schemes overestimate climate impact by 5-10 times, with fewer than one in six credits representing genuine reductions (Romm et al., 2025); baseline inflation undermines additionality claims (Probst et al., 2024; West et al., 2023, 2020); methodologies have been shown to substantially underestimate both leakage and reversal risk (Anderegg et al., 2025); and transparency in standards and registries remains inadequate (Delacote et al., 2024). Markets have responded, though not uniformly. Forest-based avoidance credits (REDD+ and similar projects where credits represent projected deforestation that did not occur) have seen prices fall sharply and trading volumes contract between 2021 and 2024, as buyers withdrew over reputational concerns (Bloomberg, 2023; Xpansiv, 2023),

with many credits now trading at single-digit prices (Ecosystem Marketplace, 2025). This is the classic 'market for lemons' problem (Akerlof, 1970), familiar from used cars: when buyers cannot tell good products from bad, they pay an average price too low to cover the cost of the good version; high-quality sellers exit and only low quality remains, which unravels the market. At the same time, credits with stronger quality signals (typically removals where each credit corresponds to measurable biomass, often under newer methodologies, and increasingly screened by independent labels) command a five- to ten-fold price premium over the avoidance pool (Ecosystem Marketplace, 2025; ICVCM, 2024). This is partial evidence that where credible quality signals exist, markets can begin to sort rather than unravel.

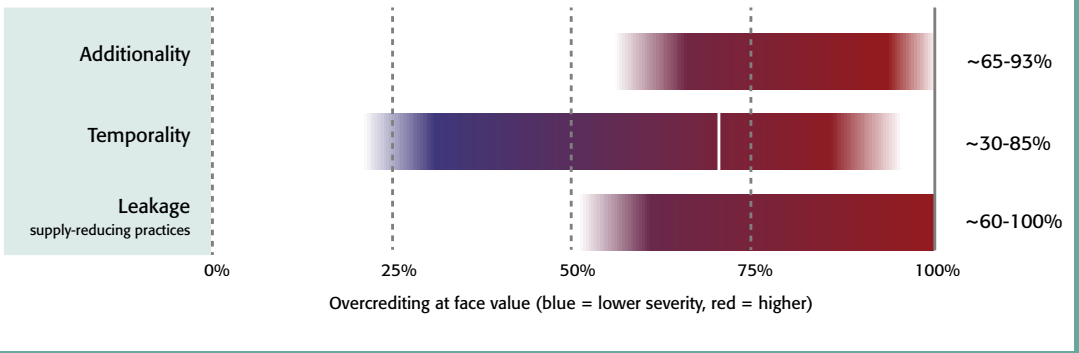
Most crediting frameworks in Europe and abroad address additionality in their methodologies, though often imperfectly. Systematic accounting for temporality, jurisdiction-level leakage, and adaptive reversal risk remains largely absent. Where these dimensions are addressed, deductions are typically fixed and modest (Badgley et al., 2022; Chiti et al., 2024). Forest carbon credits used for carbon-neutrality claims can therefore mask real increases in atmospheric CO_2 if storage is temporary or if protection in one area merely shifts pressure elsewhere. This frames two design questions: how integrity gaps are closed within crediting systems, and how those systems are then linked to compliance markets. The remainder of this section addresses each in turn.

4.7.2 Crediting integrity: four issues that must be addressed

Crediting delivers real mitigation only if four issues are addressed: additionality, temporality, reversal risk, and leakage. Three of these correspond to elements of the CRCF's *Qu.A.L.ity* criteria introduced in Section 4.1 (additionality, temporality, and reversal), while leakage is not separately defined in CRCF but is well-established in the wider integrity literature. Each can be handled at issuance through ex-ante adjustments, after the fact through ex-post verification, or by combining both. The literature offers several methodological families for each issue, with distinct trade-offs in accuracy, complexity, and data demands. Figure 4.2 anchors three of these gaps empirically with documented overcrediting at face value; reversal is measured separately through buffer-pool solvency and discussed in its subsection. What follows characterises what each issue requires. In practice, most systems combine elements of several families.

Additionality: ensuring genuine change. Perhaps the most direct integrity failure in recent years has been the overstatement of additionality. Investigations across multiple offset programmes

Figure 4.2 Overcrediting at face value for three of the four integrity gaps. Produced by the authors. Solid bar bodies show documented ranges; soft edges indicate that the bounds are approximate, varying across studies for additionality and leakage and across practice types and valuation methods for temporality. Bar colour runs from blue (lower severity) to red (higher severity)[NG31.1]. The central tick on temporality marks the tonne-year estimate (~70%, 30-year storage against a 100-year benchmark). The leakage range applies to supply-reducing practices; harvest-neutral and supply-positive practices show lower or negative leakage. Reversal is measured by buffer-pool solvency rather than face-value overcrediting.



have shown that many credited projects would have proceeded without carbon finance (Romm et al., 2025; West et al., 2023, 2020), with REDD+ baselines in particular found inflated by 65-93% (Tang et al., 2025; West et al., 2020). Closing this gap requires that uncertainty about whether projects would have proceeded without carbon finance be explicitly handled in the baseline against which credits are issued, whether by conservatism in its construction, by verification against observed outcomes, or both. Available approaches range from conservative up-front baseline deductions (ICVCM, 2024) to ex-post verification through control plots or matched counterfactuals (Delacote et al., 2025), with hybrid arrangements that issue a portion of credits provisionally and release the remainder against observed performance.

Temporality: valuing the duration of storage. Forest carbon storage is inherently finite; even without unexpected loss, biological carbon cycles back to the atmosphere over decades or centuries. This is distinct from reversal risk, which concerns unplanned disturbance. The design problem is how to value storage that delays but does not eliminate emissions. Forest carbon contributes to mitigation by deferring atmospheric release, yet cannot be credited one-for-one with permanent removal. The asymmetry is grounded in atmospheric physics: a CO_2 pulse follows a multi-exponential decay in which roughly 20-35% of the perturbation persists beyond 1,000 years (Archer et al., 2009; Joos et al., 2013), so decades-long storage is genuinely fractional relative to the emission it offsets. The horizon against which storage is benchmarked is itself a design choice; the 100-year convention used in GWP accounting (Fearnside, 2002) is one such positioning. Any credible system must therefore make storage duration explicit in the registry and reflect it in the unit traded. Established methodological families include tonne-year accounting, which measures cumulative storage over time (Matthews et al., 2023). A 30-year storage contract evaluated against a 100-year permanence benchmark yields 30 tonne-years, equivalent to roughly 0.30 permanent-tonne equivalents, meaning that a credit taken at face value overstates climate value by about 70% (Fearnside et al., 2000). This is a central estimate; practices where biological accumulation continues well beyond the contractual horizon (notably afforestation and assisted regeneration) imply lower overcrediting, while pessimistic valuation assumptions push it higher. Temporal crediting issues smaller credits periodically against realised years of storage (Galik et al., 2022); Net Present Value (NPV) methods discount the climate damages avoided by temporary storage and express them as a fraction of those avoided by a permanent tonne. Within this family, the Social Value of Offsets (SVO) formulation defines that fraction using the social cost of carbon (Groom and Venmans, 2023). Under moderate discount-rate assumptions SVO typically yields equivalence ratios at or below simple tonne-year accounting, so implied overcrediting at face value is comparable or larger. A related applied framework issues credits against deliberately pessimistic release forecasts and corrects them through post-credit monitoring (Balmford et al., 2023).

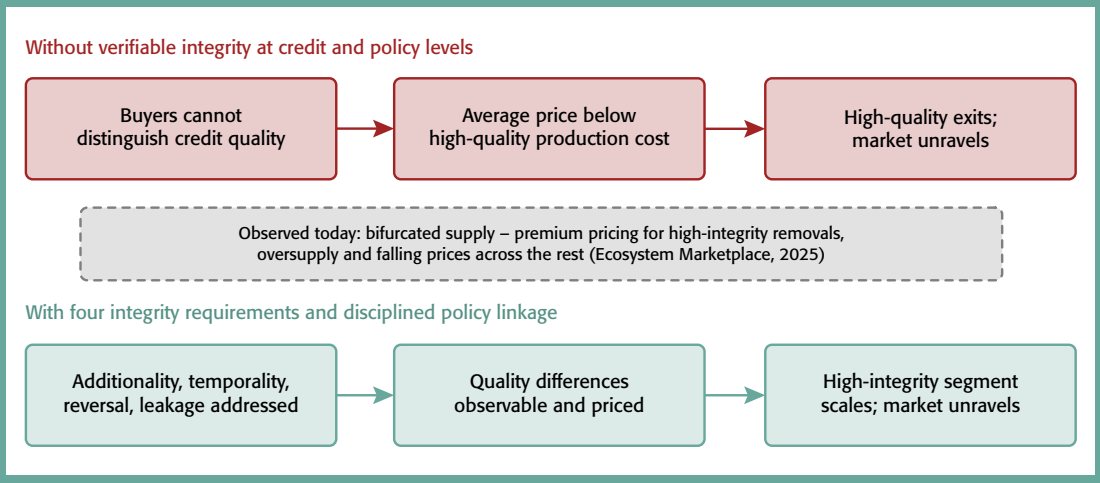
Reversal risk: preparing for loss events. Forest carbon is inherently reversible; storms, fires, pests, droughts, and management decisions can undo decades of accumulation through immediate combustion in fires or gradual decomposition of deadwood over subsequent years. Disturbance frequencies in European forests have risen since the 1980s, with substantial variation across biomes and disturbance agents (Patacca et al., 2023; Viana-Soto and Senf, 2025), and projections indicate further increases (Grünig et al., 2026). Older temperate forests face drought and pest outbreaks (Senf and Seidl, 2021); boreal forests face rising windthrow and insect risk (Forzieri et al., 2021; Seidl et al., 2017); dense Mediterranean stands face acute fire exposure, with up to a tenfold rise in extreme fires projected under warming (El Garroussi et al., 2024). Most crediting frameworks manage reversal through pooled buffer reserves. Yet, flat contributions of 10-20% cannot reflect this variation. California's experience illustrates the stakes: the 2020-2021 wildfire seasons depleted roughly 95% of California's fire-specific buffer allocation within a decade of the programme's launch (Badgley et al., 2022). Reversal arrangements must therefore scale to the underlying disturbance risk; uniform deductions can be defensible where risks are themselves uniform, while differentiated contributions are needed where they vary substantially. Available approaches include flat buffer contributions, which apply a single deduction across projects, and adaptive arrangements that vary contributions according to measurable risk indicators such as stand structure, species diversity, disturbance history, and projected climate exposure. Differentiated arrangements can create incentives for risk-reducing management but place higher demands on assessment. Standardised risk metrics for carbon removals are also emerging; the Carbon

at Risk measure (Lee et al., 2025), inspired by value-at-risk concepts in finance, could make reversal risk directly comparable across projects and removal pathways.

Leakage: recognising system boundaries. Leakage occurs when reduced emissions or increased carbon stocks in one place trigger compensating increases elsewhere, through operational shifts, adjustments in wood markets, changes in land-use profitability, or substitution with more emission-intensive materials. Empirical studies consistently document substantial leakage from forest carbon programmes, with estimates for the United States ranging from under 10 to over 90% depending on activity and region (Murray et al., 2004), and general equilibrium models suggesting 75-78% when transnational effects are included (Gan and McCarl, 2007). In Europe, Kallio and Solberg (2018) estimated 60-100% leakage from Norwegian harvest reduction projects. Similar displacement effects appear across land-use contexts globally (Meyfroidt et al., 2020). These magnitudes apply primarily to supply-reducing practices. Harvest-neutral practices (e.g., species diversification, structural diversification) show lower leakage, while supply-positive practices such as productive afforestation can show slightly negative leakage by adding to overall timber supply (Daigneault et al., 2025). In current practice, leakage is frequently addressed only at the project boundary, on the basis that displaced harvest will be captured in the receiving jurisdiction's national inventory. This logic holds only where national inventory coverage is comprehensive and double-counting is prevented. Where either condition fails, documented leakage effects go unreflected anywhere in the accounting chain. Beyond accounting, this is partly a distributional question about exporting harvest pressure to other jurisdictions, and partly a strategic choice between maintaining timber supply (and accepting displacement) or reducing it (and accepting material substitution). Either way, leakage must be addressed beyond the project boundary alone, whether prevented at source by restricting crediting to low-leakage activities, or quantified at the system scale where substitution occurs (typically the jurisdiction or broader trade region). Available approaches include deduction-based methods, which apply factors calibrated from harvest data, trade elasticities, or product-substitution studies, and eligibility-based methods, which restrict crediting to activities with inherently low leakage risk such as improved silviculture, species diversification, or afforestation on land not competing with existing production.

These requirements make credit quality observable to buyers, which is one of the two conditions for resolving the market-for-lemons dynamic introduced earlier (Figure 4.3). Whether that observable quality then translates into actual reductions in fossil emissions depends on the second condition: how credits interact with compliance markets, the next design question.

Figure 4.3 Two paths for forest carbon crediting and their consequences in market permanence. Produced by the authors.



4.7.3 Policy use cases: pathways for integration

Linking forest credits to compliance markets can unlock larger private finance, but the same linkage can also flatten the carbon price and blunt abatement incentives if not designed carefully. The outcome hinges on how credits interact with the cap and whether integrity is made explicit. Three configurations are available, each with characteristic effects:

Additive use. Credits are recognised as additional compliance units on top of the allowance cap, so the effective constraint on fossil emissions is lower than under a pure cap-and-trade system (Schneider and La Hoz Theuer, 2019). Each offset surrendered allows one extra tonne of fossil emissions under the cap, reallocating carbon from geological reserves into the coupled atmosphere-biosphere system. Even with high-integrity credits, this loosens the constraint; with low-integrity credits, a larger share ends up in the atmosphere. The EU ETS experience illustrates these risks: integrity failures in Joint Implementation credits alone may have undermined the system's emission reduction target by approximately 400 million tCO_2e (Kollmuss et al., 2015). The added supply of compliance units also tends to lower the carbon price.

Substitutive use (with cancellation). Each credit used for compliance cancels an allowance one-for-one (or at a higher ratio), so the overall limit on fossil emissions remains the original cap. This prevents credits from loosening the emissions constraint. However, if credits are abundant and cheaper than marginal abatement in capped sectors, the carbon price will track credit generation costs, potentially compressing permit prices. Hard limits on the share of compliance that can be met with credits can mitigate this effect. The EU ETS allowed substantial offset use in Phase 2 (around 1.06 $GtCO_2e$ of international credits were surrendered) before phasing them out entirely from Phase 4 over additionality concerns (ICAP, 2025).

Contribution use (non-compliance). Credits are purchased as climate contributions rather than for compliance (VCMI, 2024). Mobilised capital is lower in the near term, but the ETS price signal is untouched. Coupling with public co-funding or procurement standards can raise volumes while keeping separation from the cap.

The choice among these configurations depends on the market setting. In contribution use, capital mobilisation depends on credit-level integrity (the lemons dynamic described above): without verifiable integrity, demand collapses. In compliance use, demand can be created by regulation, but the additive-versus-substitutive choice then determines whether the resulting flows preserve or dilute the cap.

For EU forest carbon specifically, the compliance pathway is not imminent. The CRCF Regulation requires the Commission to assess EU ETS integration by July 2026, but this assessment is limited to permanent industrial removals. Forest carbon, classified under the regulation's carbon farming pillar, is expected to remain in contribution use for the foreseeable future (EU, 2024). For European forest credits today, credit-level integrity is therefore the principal lever for capital mobilisation, supported, where available, by public co-funding and procurement standards.

4.7.4 Implementation and inclusion

A high-integrity system must remain accessible to the full range of forest owners, including the smallholders who manage a substantial share of Europe's forest area. Transaction costs of verification, certification, and monitoring can be prohibitively high for individual landowners (Markowski-Lindsay et al., 2011), so accessibility depends on mechanisms that aggregate or simplify these costs. These two requirements (integrity and accessibility) are not a trade-off in which one is sacrificed for the other; both must hold simultaneously. If monitoring becomes too complex, only large players participate; if standards are simplified by dropping integrity elements, the system drifts towards over-crediting.

Several mechanisms can reduce participation barriers without weakening the integrity requirements set out above. Group certification allows small farmers and foresters to undergo joint audits, spreading fixed costs across multiple participants; an approach now explicitly enabled under the EU CRCF Regulation (EU, 2024). Aggregation programmes, where a certified intermediary manages contracts with multiple landowners, can lower both baseline-establishment and ongoing verification costs (Kerchner and Keeton, 2015). These arrangements work best when value flows are transparent, since intermediation costs can otherwise erode the share of credit revenue reaching landowners. Remote sensing, including satellite-based monitoring through systems such as Copernicus, further reduces field-measurement burdens by providing standardised, low-cost data on forest cover and biomass change.

Crediting systems must also manage the trade-off between standardisation and project-specific accuracy. Default values calibrated to project characteristics, an approach with precedent in the CDM's standardised baselines framework (UNFCCC, 2011), offer one route. Defaults can be derived from regional data on disturbance regimes, climate projections, forest types, and typical management, then linked to project inputs such as species group, stand density, and site productivity. A spruce plantation in a high-risk zone might face a higher buffer contribution and a shorter assumed storage horizon than a mixed stand in a less exposed area. This differentiation maintains integrity without requiring each project to generate bespoke evidence. Developers can depart from defaults when stronger evidence is available, though they have incentives to do so mainly when the credits increase; setting defaults conservatively and accepting deviations only when supported by verifiable data limits this bias. Where systematic deviations emerge, defaults can be revised for future vintages.

Transparent region- and practice-based defaults, combined with group certification, aggregation, and remote sensing, can maintain rigour while keeping crediting accessible to the diverse actors who manage Europe's forests. Without accessibility, the high-integrity segment of the market remains concentrated among large, well-resourced projects.

4.7.5 Strategic outlook

The EU climate strategy depends on forests closing a substantial gap toward the 2030 LULUCF target (Section 4.6.5). The integrity requirements set out above extend beyond the forest stand into the broader value chain: the CRCF Regulation treats long-lived harvested wood products as a distinct certification category, with a minimum 35-year monitoring period (EU, 2024). The four integrity issues apply downstream too; harvested wood product storage has its own duration, reversal risk (decay, fire, end-of-life emissions), and substitution dynamics relative to non-wood materials. Crediting frameworks that integrate standing-forest carbon with downstream retention in durable products can align incentives across the supply chain and support cascading use.

These EU developments are increasingly embedded in international frameworks. Article 6 of the Paris Agreement provides accounting infrastructure for cross-border credit transfers, with corresponding adjustments preventing double-counting against national inventories (UNFCCC, 2021). The COP30 Belém decisions (November 2025) operationalised the Article 6.4 Paris Agreement Crediting Mechanism by adopting standards on baselines and additionality, building on the rulebook agreed at COP29 (UNFCCC, 2025, 2024). For forest carbon specifically, key methodological questions (particularly permanence and reversal management) were deferred to subsequent sessions, mirroring at the international level the integrity gaps this section has addressed. Looking further ahead, the Commission's Roadmap towards Nature Credits signals an extension of EU crediting infrastructure beyond carbon to broader nature-based assets (EC, 2025c).

Two requirements emerge from this section. First, credit-level integrity (addressing additionality, temporality, reversal, and leakage) must be made observable to buyers. Second, the policy linkage between credits and compliance markets must be designed for the operative market setting rather than assumed equivalent across configurations. Meeting both will likely reduce credited volumes relative to systems that treat integrity as background, but the resulting credits (fewer nominal tonnes, demonstrable integrity) can support higher prices, more stable demand, and durable integration with compliance markets and international accounting frameworks. Without both, the lemons dynamic continues and the market remains exposed to further contraction; with both, the high-integrity segment can scale.

4.8 Conclusions and recommendations

Across the sections of this chapter, several recommendations emerge for maximising sustainable carbon storage in European forests while ensuring policy alignment and market integrity. Policy and incentives should prioritise harmonised certification under the CRCF Regulation, strengthen coherence with the EU Forest Strategy, CAP, and Biodiversity Strategy, and ensure that carbon farming schemes reward long-term, verifiable climate benefits. Forest management practices should be tailored to regional ecological conditions, favouring measures such as afforestation on suitable land, continuous cover forestry in shade-tolerant systems, extended rotations where disturbance risks are manageable, species diversification, soil-protective harvesting, and fire-smart management in Mediterranean forests. Practitioners should avoid maladaptive approaches, such as expanding vulnerable

monocultures, and give priority to strategies that enhance resilience and soil carbon. Monitoring, Reporting, and Verification systems should combine ground measurements, remote sensing, and modelling to improve accuracy while maintaining transparent reporting and independent verification to ensure comparability. Co-benefits and trade-offs must be explicitly considered: carbon-oriented interventions should be assessed for their impacts on biodiversity, water, soil, and local livelihoods, with priority given to interventions that deliver multifunctional benefits and minimize risks such as carbon leakage or ecological degradation. Value-chain integration should promote the cascading use of wood, increase the share of long-lived harvested wood products, develop regional bioeconomy clusters, and ensure that supply chains follow sustainable forest management principles. Finally, finance and crediting integrity require adopting risk-priced issuance that accounts for additionality, temporality, leakage, and reversal risk, ensuring that forest carbon credits reflect real atmospheric benefits. Strengthening transparency, developing adaptive buffers, improving baselines, and limiting low-integrity credit use in compliance markets are essential for restoring trust and enabling carbon finance to support genuinely sustainable forest mitigation.

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Chapter 5

Aligning forest management with climate resilience and evolving socioeconomic goals

Lead Author: *Nataša Lovrić*

Contributing Authors: *Denis Dobrynin, Sandra Lupien, Petra Palátová, Chad C. Papa*

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5.1 Introduction

Forest ecosystems are vital for climate regulation, biodiversity, and socio-economic well-being. However, their sustainable management faces increasing pressure from climate change and competing demands, necessitating integrated approaches that balance ecological resilience with economic and societal goals. Integrative forest management in Europe must reconcile climate resilience, biodiversity goals, and economic objectives within an increasingly complex variety of policy frameworks, but systemic barriers such as policy fragmentation, short-term mechanisms, and weak stakeholder alignment impede this integration.

The loss of biodiversity worsens human well-being, influencing life and earnings, and requires adaptive strategies (Stein et al., 2013; Watson et al., 2018). Biodiversity is not restricted to national boundaries, and therefore, cross border cooperation matters. Multifunctional forest management helps to provide and enhance socio-economic benefits, which are linked to job creation, rural development, lower costs for restoration, reduction of risks derived from biodiversity, and new markets (e.g., value-added wood products, carbon credits, and biodiversity offsets).

As demand for wood products continues to grow, so does the need to develop and implement forest management practices that prioritise biodiversity and resilience. Balancing the need to produce wood with these priorities presents both opportunities and challenges, and it requires careful, context-specific management practices. Smart policies and practices can leverage wood-based value-added products as an incentive and revenue source to support forest health, biodiversity, and resilience, while weak or poorly enforced policies can lead to overharvesting, and poor management could undermine forest health. To address those issues, this chapter examines three interconnected pathways for achieving integrated forest management: **i)** voluntary market-based certification schemes that set biodiversity and management standards; **ii)** value-added wood products, particularly mass timber, that can enhance carbon storage and material substitution while generating economic returns; and **iii)** evolving governance frameworks and management strategies that align forest policy and management with binding climate and biodiversity targets.

Drawing on recent empirical evidence and insights from the Teaming Up 4 Forests (TU4F) platform (TU4F, 2026), this chapter identifies persistent barriers in the forest-based sector, including policy fragmentation, short-term economic instruments that undermine long-term ecological goals, and insufficient coordination among stakeholders. Furthermore, it explores challenges and opportunities to deliver climate mitigation, biodiversity conservation, and economic value, examining the role of forest certification, delving into how leveraging value-added wood products can advance forest resilience, analysing the drivers and policy instruments influencing forest governance, and discussing pathways for aligning climate resilience with broader ecological, economic, and societal objectives. The chapter concludes by proposing evidence-based solutions. The combination of scientific evidence with practical implementation pathways offers actionable recommendations for policymakers, forest managers, and industry stakeholders seeking to reconcile climate resilience with biodiversity conservation and sustainable economic development.

5.2 Conceptual framework: Three interconnected pathways

To address the question of how European forests can simultaneously deliver climate resilience, biodiversity conservation, and economic value in a constantly evolving policy context, three interconnected pathways are examined. Together they form a comprehensive approach for an integrative forest management:

1. **Market-based certification as a quality assurance mechanism:** Voluntary forest certification schemes emerged in the early 1990s as market-based mechanisms to promote environmentally appropriate, socially beneficial, and economically viable forest management. Certification sets standards for biodiversity protection, sustainable harvesting, and stakeholder engagement, creating a quality signal for consumers and investors. However, whether certification effectively delivers biodiversity outcomes and economic viability remains contested, with systematic reviews reporting mixed results across regions and contexts (Wolff and Schweinle, 2022).

2. **Value-added wood products as a climate and economic strategy:** This pathway leverages value-added wood products (e.g., mass timber, engineered wood products) to advance



Forests must adapt to changing climates while continuing to deliver essential ecosystem services
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both climate mitigation and rural economic development. Mass timber (including products like glue-laminated timber) enables the construction of taller wood buildings, potentially substituting for steel and concrete, thereby reducing embodied carbon in the built environment. This pathway requires careful assessment of trade-offs between material substitution benefits and potential risks to forest resilience.

3. **Evolving governance frameworks:** This pathway examines the policy instruments and governance reforms that shape forest management decisions; exploring the drivers of policy adoption, including policymakers' beliefs, receptiveness to experiential evidence, and deliberation about "what works" in practice for translating European-level priorities into effective national and local implementation.

These three pathways are not independent, but form a mutually reinforcing system where i) certification provides a framework to ensure that value-added wood products come from sustainably managed and biodiverse forests, addressing concerns about forest degradation from increased harvesting; ii) value-added products generate economic returns that can finance the higher management costs associated with certification and biodiversity-centred practices while providing carbon storage and substitution benefits that align with climate policy goals; and iii) governance frameworks set the enabling conditions through subsidies, regulatory standards, and market incentives that determine whether certification and value-added product strategies can scale effectively across diverse ownership structures and regional contexts.

5.3 Is forest certification effective for biodiversity conservation?

5.3.1 Forest certification as a private governance instrument

The EU Bioeconomy Strategy, published in 2025, frames the bioeconomy to replace fossil-based materials and products with bio-based alternatives, including those made from wood. The proposed large-scale substitution of materials and the development of bio-based products could have a greater impact on European forest ecosystems, requiring careful attention to the sustainability of forestry. It also demands proper consideration of other values linked to forests and stakeholders' interests, such as biodiversity, ecosystem services, and local communities. One approach to support this is through forest certification schemes, which can complement national regulations and international treaties.

Forest certification schemes emerged in the 1990s to promote sustainable forest management after governments and intergovernmental organisations failed to establish a global,

legally binding treaty on forest issues. They have gained significant traction since their emergence, offering market-driven approaches to integrate environmental safeguards. Generally, major forest certification schemes aim to promote environmentally sustainable, socially responsible, and economically viable forest management. Two popular and widely adopted forest certification schemes are the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC). They both underpin market access for certified products and encourage improved governance and sustainable forest management (SFM). These forest certification schemes represent market-driven mechanisms designed to promote sustainable forest management, including biodiversity safeguards. They are non-legally binding forest governance tools that co-exist with other tools, such as national and supranational (e.g., EU level) forest regulation.

Forest certification can be critically examined through two contrasting worldviews: "Hydra", a critical and sceptical evaluation of the ability to change existing unsustainable forestry practices; and "Chloris", emphasising achievements, positive impacts, and best practices (Arts, 2021). This section identifies examples of both "Hydra" and "Chloris" that reflect not different situations with the impact of forest certification on European forests, but rather different perspectives on the same issue. The "Hydra" of forest certification concerns its market orientation (emphasising growth and profit), which raises doubts about its capacity to promote SFM. The example of "Hydra" presents claims regarding overexploitation and biodiversity decline in certified forests in Nordic countries, while the "Chloris" of forest certification signifies active involvement of environmental stakeholders and a strong conservation agenda in the negotiation forums.

In other words, forest certification may act as a 'carrot' by providing market access to some forest owners and corporations, while at the same time, it may function as a 'stick' due to the additional costs and requirements it places on forest management, which need to be added to the government regulations already in place (Angelstam et al., 2021).

5.3.2 The impact of forest certification on biodiversity

Although forest certification has existed since the 1990s, limited scientific research has examined its impacts on biodiversity. Furthermore, efforts to assess the impact of certification on biodiversity in existing studies are hampered by the variability of ecosystem conditions across certified areas, as well as by differences in certification standards and their implementation approaches. As such, there is no clear consensus yet on the general effects of forest certification on biodiversity. For example, the cases reviewed by Kadam and Dwivedi (2025) linked the increase in certified forest area with a decrease in the percentage of threatened species, though this relationship varies widely across regions. Meanwhile, the cases reviewed by Matias et al. (2024) did not reveal any clear impact of forest certification on biodiversity conservation. A review by Tange et al. (2024) on boreal forests showed that although certification-linked conservation measures may reduce the negative impacts of wood harvesting on species richness and abundance compared to non-certified forests, those measures do not achieve to maintain the same biodiversity levels seen in unlogged forests.

In Europe, according to a review by Wolff and Schweinle (2022), the impact of forest certification on biodiversity and forest degradation prevention varies. Approximately 53% of the studies analysed in that review reported positive effects, while the rest showed either neutral or mixed results. In **Southern Europe**, some studies have shown a positive impact of certified forest management on the conservation of biodiversity (e.g., Mexia et al., 2022; Sánchez-Almendro et al., 2018), although those results have proven to be context-dependent and it is worth to emphasise that the implementation of forest certification standards is not sufficient to address all forest management issues in a region (Malovrh et al., 2019).

In general, in the **Nordic and Baltic countries**, the biodiversity-relevant conditions required by certification are overall more stringent and specific than national legislation (Lehtonen et al., 2021; McDermott et al., 2023; Tange et al., 2024). Those conditions include higher retention of deadwood and retention trees, as well as enhanced protection of riparian zones, wetlands, and woodland key habitats. However, despite the positive effects that these conditions might have, structural and functional habitat connectivity remains insufficient for many forest species, particularly those requiring large and old-growth forest stands (Elbakidze et al., 2016).

Certification-driven set-asides complement traditional legally designated nature reserves and improve habitat connectivity, which has shown positive effects in some instances (e.g., Simonsson et al., 2016), helping to address the previously mentioned shortcomings. However, certification standards also allow for clear-cutting practices (Wolff and Schweinle, 2022), which leads some critics of these practices to argue that certification impedes biodiversity conservation (Sahlin, 2013).

Overall, echoing Simonsson et al. (2016)'s findings, scientific evidence remains inconclusive regarding the effectiveness of certification-based forestry measures in meeting biodiversity conservation objectives, despite a number of cases of certified areas showing positive biodiversity outcomes when compared to non-certified areas. Additionally, as a private, market-led mechanism, forest certification complements, but does not replace, other levels of forest governance and policymaking, including national, supranational, and global institutions. Therefore, the capacity of forest certification to resolve existing issues in forest management is limited.

5.4 Leveraging value-added products to advance forest resilience and biodiversity

Carbon and climate policies increasingly call on industry sectors, notably the building construction sector, to substitute non-renewable, fossil-based products for renewable, bio-based ones to reduce greenhouse gas emissions and store biogenic carbon. Such policies raise an array of key questions. Will increased demand for wood and biomass undermine biodiversity and resilience in forests? Will substituting materials like mass timber for steel or concrete lead to over-harvest or even deforestation? Can prioritising wood over other materials in construction create revenue or incentives to manage forests for long-term health, biodiversity, and resilience? This section highlights potential synergies and challenges presented by the simultaneously increasing demand for wood construction materials and the need to optimize forest biodiversity and resilience (Hetemäki et al., 2024).

Globally, buildings account for 39% of carbon emissions, with 11% attributable to building materials, especially steel, concrete, and glass. Twenty eight percent of global carbon emissions are attributable to operational carbon, which is outside the scope of this study. Mass timber, large, engineered wood construction materials are gaining market share globally as a substitute for high-carbon footprint steel and concrete in large buildings. If widely adopted, mass timber products, a uniquely renewable resource that itself stores carbon, can play a valuable role in decarbonising buildings. For example, recent research highlights that, comparing the combined embodied and stored carbon of structural systems in otherwise identical buildings, mass timber's global warming potential is 81-94% lower than that of concrete, and 76-91% lower than that of steel (Kumar et al., 2024). In addition to these carbon and climate benefits, many see mass timber as an opportunity to increase the economic value of harvested wood, thereby creating added incentives to keep forests as forests rather than converting them to other uses, and generating new and diversified revenue to invest in forest management practices that promote health, biodiversity, and resilience (Franklin et al., 2018).

Recognising such opportunities, governments around the world have, in recent years, enacted an array of policies leveraging them. For example, the U.S. Forest Service, through the Wood Innovations Program, invested at least USD 247 million between 2015 and 2025 in projects and initiatives to increase demand for wood harvested from forestlands in the United States (U.S. Forest Service, n.d.). Many of the programmes funded supported mass timber construction and production. Meanwhile, through the CO_2 Bonus Fund, Austria invested at least EUR 28 million to pay one euro per kilogram of structural wood used in eligible buildings, supporting nearly 200 projects between 2021 and 2025 (BMLUK, 2024). At the European Union level, initiatives like the New European Bauhaus (EC, 2021a) and an emerging pair of carbon-reduction policies, the revised Construction Products Regulation (EU, 2024a) and the revised Energy Performance of Buildings Directive (EU, 2024b), could, if implemented effectively, significantly increase demand for wood construction in EU member states. In its Global Forest Sector Outlook for 2050, the Food and Agriculture Organization of the United Nations projects that demand for primary processed wood products will increase by 37% from 2020 levels by 2050, and demand for mass timber in construction alone will increase by between 5-12% during that same period (FAO, 2022).

Balancing the potential carbon, climate, and forest benefits of increased demand for timber, including mass timber products, requires

prioritization and enforcement of policies and practices that avoid overharvesting and deforestation, and that enhance forest health, biodiversity, and resilience. For forest managers, it is common practice to evaluate trade-offs between approaches that maximize yield versus those that focus on species diversity, habitat, and other ecological goals; the combination of the increasing demand for timber with the hastening of climate change makes more pressing the need to develop and implement the types of balanced, context-specific approaches discussed in other sections of this chapter (Betts et al., 2021).

5.5 Drivers, as seen through the lenses of governance, stakeholders, and policy instruments

The effectiveness of a pathway depends fundamentally on the governance frameworks that shape forest management decisions: the policies, regulations, incentives, and institutional arrangements that determine what forest owners and managers do on the ground. European policy frameworks directly incorporate ecosystem services to promote protection and restoration of natural systems as essential infrastructure supporting climate adaptation, biodiversity, and sustainable development.

Recreation is among the broad range of services that forests provide. The coronavirus pandemic period brought unprecedented changes in forest visitor numbers, and consequently, unprecedented pressure on forests and the functions they provide. The increase in forest visits was recorded in case study regions in the Czech Republic in 2020 (Jarský et al., 2022). Similar results confirming increase in the forest visits were indicated also in other European countries such as Germany (Derks et al, 2020), Slovakia (Pichlerová et al., 2021), and Poland (Ciesielski and Tkaczyk, 2023). This increase in forest visits included also visitors that previously did not or rarely attend forests but suddenly found their way to enjoy being out there, which also lead to a change in their perception of and requirements from forests (Grima et al., 2020). This connection critically evaluates the role of ecosystem services and, in the case of forest ecosystem services, it leads to a fragile balance between the different ecosystem services that different target groups demand from forests. To encourage forest owners to manage forests in ways that benefit visitors and society, Payments for Ecosystem Services (PES) have emerged as an important incentive mechanism.

Biodiversity conservation has a large social dimension, and the effective implementation and enforcement of biodiversity-related measures requires global cooperation and multi-stakeholder interactions, and is deeply dependent on social aspects, including global cooperation and diplomacy, multi-stakeholder interactions, cross-sectoral coherence, and close relations between legal and policy frameworks with science. The European biodiversity governance can be defined as a complex interplay between regulation, planning, funding, and monitoring. It brings together European institutions and governing bodies, agencies, knowledge platforms, national and regional institutions and authorities, scientific organisations, funding institutions, local communities, and civil society among others. There are different European projects that can be taken as examples of how to bring different stakeholders and viewpoints together, aiming to increase the knowledge base and prepare relevant materials for informed-decision making (Box 5.1).

5.6 Pathways to aligning climate resilience with ecological, economic, and societal goals

5.6.1 Linking climate resilience across scales

Forests stand at the forefront of addressing climate change through their contributions to both climate adaptation and mitigation while providing other essential ecosystem services, including biodiversity and economic prosperity, key components of sustainable development goals (UN, 2015). As forests face parallel threats from climate change (McDowell et al., 2020) and human pressures (Pendrill et al., 2022), there is a growing need to better integrate and operationalize climate resilience concepts into forest policies and management strategies addressing climate change impacts on biodiversity and subsequent environmental degradation (Stein et al., 2013). This underscores the urgency to better align climate resilience efforts across sectors and policy levels to support ecological, economic, and societal goals. The term ‘resilience’ has been increasingly promoted in forest management to address both the foreseen and unforeseen consequences of climate change (Flores et al., 2024; Johnstone et al., 2016; Thompson et al., 2009), including supporting biodiversity, an important mechanism that fosters resilience and long-term productivity (Watson et al., 2018).

Box 5.1 Examples of European projects bringing together biodiversity stakeholders

BIOCONSENT: One of the BIOCONSENT project activities focused on integrating biophysical, social, economic, and policy drivers, while another one explored forest owners' and managers' behaviour in a case study region. The uncovered societal drivers for biodiversity conservation in the project's region included changes in consumption towards sustainable resource use, increasing demand for environmental protection and recreation services due to urbanization and aging population. Conflicts were observed arising from trade-offs between forest conservation and economic use, which created tension among stakeholders (BIOCONSENT, 2026). The project exemplifies how multi-partner research can shed light on the complex interplay of biophysical, social, and economic factors influencing forest biodiversity, providing critical insights for decision-makers.

BioAgora: An ongoing initiative with 22 partners from 13 countries aimed at bridging the gap between biodiversity research and policymakers within the EU by connecting scientists with key decision-makers. The project has identified 215 organizations at various levels working at the interface of science, policy, and society (D'Amato et al., 2025). The project's focus on connecting knowledge to action is crucial for translating scientific understanding into effective biodiversity strategies at various governance levels.

RESONATE: The project (RESONATE, n.d.) aimed to conduct activities that would help in advising towards more resilient European forests and value chains through extensive research and stakeholder engagement across multiple case studies. Targeted stakeholders were actors in research and education, forest owners and practitioners, forest industry, policymakers, and civil society and media. Stakeholder involvement was an important part of the project, especially through raising awareness about vulnerability of forest systems to climate change, biodiversity loss, and the importance of adaptive forest management.

EuropaBON: The project (EuropaBON, n.d.) was designed to integrate various data streams to support biodiversity and ecosystem services policy by establishing permanent biodiversity monitoring across Europe. One of the key objectives was to mobilize relevant national and European key players. The applicability in practice of the methods used proved to be dependent on the data connection and stakeholder involvement to provide reliable and up-to-date information to decrease the science-to-policy gap, and utilize the data in decision-making.

Climate policies and actions often treat the dual concepts of mitigation and adaptation separately (Di Gregorio et al., 2017; Spencer et al., 2016), but current scientific evidence emphasises the fundamental role of forest adaptation in supporting both climate resilience and mitigation (Falk et al., 2022). This current misalignment between adaptation and mitigation impedes compatibility and policy coherence in integrating climate policies into forest policies and management strategies to support biodiversity and forest resilience (Hogl et al., 2016; Ludvig et al., 2024). Complicating matters further are how climate adaptation and mitigation concepts manifest in forest policy from international to national and sub-national levels, and how these concepts influence and interact with on-the-ground management strategies and decision-making. To date, climate change policies in Europe oftentimes conflict with biodiversity conservation (Balducci et al., 2026). Proper alignment of climate resilience into forest policies should increase the adaptive capacity of forests to withstand, recover from, or adapt to climate change threats and vulnerabilities while disincentivising adverse outcomes for local populations. While there are still significant disagreements on what constitutes 'win-win' or 'win-lose' scenarios for biodiversity, forest adaptation, and mitigation, concurrent implementation offers opportunities to rethink how both concepts can be better integrated across the forestry sector more holistically (Peterson St-Laurent et al., 2021).

5.6.2 Models for integrating climate resilience into policy and management

Forestry policymaking is increasingly fragmented and interconnected with other sectors, including agriculture, energy, regional and rural development, water management, and, notably, climate policy. Additionally, forestry policymaking is increasingly embedded in

international, national, transnational, and sub-national policy frameworks covering topics on deforestation, climate, biodiversity, and land-use. As a result, this increasingly fragmented landscape of forest policies and governance has led to a lack of both policy coherence and integration auguring potential adverse impacts on forests and the communities that rely upon them. Policy coherence generally refers to the consistency of policy objectives and implementation across scales of government, whereas policy integration refers to the policy-making process itself and the governance arrangement including administrative and organisational structures both vertically (integration across government levels but within a sector) and horizontally (integration between sectors).

Various models exist for integrating climate objectives vertically into both forest policy and management, and horizontally across sectors. Most commonly, adaptation and mitigation are divided and treated independent of one another (Locatelli et al., 2015). Mitigation-only models emphasise reducing greenhouse gas emissions and increasing carbon sequestration (Canadell and Raupach, 2008; Griscom et al., 2017). Inversely, adaptation-only models emphasise increasing forest resilience to climate change vulnerability and threats to increase the adaptive capacity of forests, ensuring a continued provision of ecosystem services (Millar et al., 2007). Interaction models consider both climate adaptation and mitigation concurrently during the design of forest policies and implementation of forest management actions (Locatelli et al, 2016). Interaction models can either seek to reduce trade-offs between adaptation and mitigation, or prioritise the most important objectives when trade-offs are unavoidable (Locatelli et al., 2015). This means that some areas such as fast-growing plantation forests can be prioritised for mitigation (Paquette and Messier, 2009), while other areas such as mature or old-growth forests or areas of high conservation value can be prioritized for adaptation (Jandl et al., 2019).

Adaptation-first models seek to prioritise adaptation as the core principle of forest management actions and policies. The focus is on delivering ecosystem services, including climate mitigation, as well as other forest benefits, including biodiversity, wood, recreation, cultural values, and clean air and water. What separates this model from the previous two is that adaptation is considered an integral component for forest management, and without it, other benefits such as mitigation would be hindered (Peterson St-Laurent et al., 2021). More recently, there has been an increasing emphasis on horizontally integrating climate policies into forest policy and management, with a focus on the resilience of the forest bioeconomy (Ludvig et al., 2024) and its growing role in climate resilience (Luhas et al., 2021). Despite pledges made in global forums (EC, 2021b), finance for climate resilience remains fragmented and insufficient to address the challenges at hand (Pauw et al., 2024). In lieu of these financial challenges, there has been growing recognition of traditional markets for timber and bioenergy as well as emerging markets for carbon and biodiversity to serve as key funding mechanisms to support climate adaptation actions (Zhou et al., 2024) beyond more traditional forms of climate finance (Newell, 2024).

Frameworks such as Climate-Smart Forestry (CSF) offer potential points to further align climate resilience into forest policy and management by explicitly linking increasing carbon removals, enhancing forest resilience, and balancing wood production with biodiversity protection and other ecosystem service provisioning (Verkerk et al., 2020). Recent contributions to dialogues on CSF have rightfully pointed out the risks of overly simplifying these relationships and potential unintended societal effects, as well as the need to expand the definition to CSF to better understand the broader impacts of implementation.

Aligning climate resilience with the broader forestry and forest products sectors requires a holistic perspective, flexible policy structures, transformation of the forest-based bioeconomy, and a concerted effort to operationalise these principles to advance economic and social sustainability (Hetemäki and Kangas, 2022). This requires multiple forms of knowledge and expertise including practical management experience and academic and indigenous forms of knowledge. Furthermore, public perception and acceptance are keys to success. The public must understand the value of forests and biodiversity and the role forest and the forest bioeconomy play in climate resilience (Mauser, 2021; Ranacher et al., 2020). Science has a role

in contributing to increasing climate resilience through informing policymaking and on-the-ground implementation (Papa et al., 2025), but significant challenges remain in reducing science-practice gaps, operationalising actions, and aligning climate resilience policies to bolster ecological, economic, and societal goals concurrently. Box 5.2 presents an example of Climate-Smart Forestry focusing on wildfire management in western North America, highlighting the crucial role of the bioeconomy in financing these efforts.

Box 5.2 Climate-Smart Forestry: wildfire management in western North America and the role of the bioeconomy

Increases in wildfire risk in western North America are driven in part by changing climate trends and the overstocking of forest stands from conifer encroachment caused by legacies of fire exclusion and suppression. Climate-Smart Forestry management strategies to address wildfire risk include forest thinning, the reintroduction of prescribed burning, purposeful wildlife prescriptions, other fuel reduction tactics, and hazard mitigation. However, a significant challenge in the region is the lack of markets for low-value and low-quality timber resources being produced from forest resilience treatments. Pairing biomass from wildfire resilience treatments with markets for bioenergy, adhesives, or aviation fuel offer both economic opportunities and a reduction of wildfire risk. Successful examples such as clearing biomass from wildland-urban interfaces and thinning treatments to supplement biomass sources for wood and coal cofiring plants showed potential (Nicholls et al., 2006). Another notable success story was the Fuels for Schools program that paired mechanical thinnings with wood heating systems in public schools, a university, a landfill, and two prisons in Montana, reducing energy costs and wildfire risk (Bergman and Maker, 2007) while simultaneously providing benefits across a wide variety of energy users. Nascent industries for aviation fuels, bio-based adhesives, and mobile pyrolysis systems require technological innovation but provide alternative future supply chain pathways to deliver cost-effective wildfire and value-added products supporting the forest bioeconomy (Nicholls et al., 2018).

5.6.3 Operationalising pathways to foster climate resilience in forests

Reducing science-practice gaps between policymakers, scientists, and practitioners to increase policy coherence and better align policy integration requires thoughtful holistic approaches, especially as the forest policy landscape has become fragmented across jurisdictions, ownerships, and levels of government. There are no clear and simple answers to aligning climate resilience within forest policy and management, but there are flexible, thoughtful perspectives on conditions that can foster a more equitable future, empowering landowners and managers with the necessary tools. Translating climate adaptation theory into effective on-the-ground action requires strong collaboration between research and practice. Box 5.3 details an exemplary model of scientist-manager collaboration, the Climate Change Response Framework and Adaptive Silviculture for Climate Change network, which fosters knowledge co-production for climate-resilient forest management.

5.7 Conclusions and outlook

The challenges of and opportunities in achieving integrative forest management that balances ecological, economic, and societal outcomes is complex and multidimensional. Forest certification may play a role in biodiversity conservation, albeit with context-dependent impacts and limitations. Furthermore, leveraging value-added wood products, such as mass timber, presents considerable potential to incentivise forest health and generate revenues for sustainable practices. The analysis also highlighted the complex interplay of governance, stakeholder engagement, and policy instruments as crucial drivers for effective biodiversity management. As a result, there is a wide variety of potential pathways to align biodiversity conservation with broader forest objectives, emphasising the need for coherent policy integration and multi-scale approaches. Building upon these insights, the conclusions below offer a strategic outlook and actionable recommendations for policymakers and practitioners to foster more productive and biodiverse forests:

Box 5.3 Scientist-manager collaboration: Lessons from a knowledge coproduction adaptation-first network

The climate change response framework (CCRF) was developed as a cross-boundary collaboration to help forest owners and managers cope with climate change issues that span borders, discipline, and perspectives. The framework utilises an iterative approach meant to be paired with menus of adaptation and mitigation strategies (Ontl et al., 2020), adaptation workbooks (Swanston et al., 2016), and regional ecosystem vulnerability assessments (Handler et al., 2014), where managers and landowners: (1) identify location, ecosystems, time frame, goals, and objectives; (2) assess ecosystem vulnerabilities and climate change impacts; (3) evaluate goals and objectives given project impacts and vulnerabilities, (4) identify and compile adaptation strategies, approaches, and tactics; (5) Plan and implement actions at appropriate scales; and (6) integrate monitoring and evaluate effectiveness of actions to inform future planning. Building on the CCRF, the Adaptive Silviculture for Climate Change (ASCC) network was established as a long-term research network addressing barriers while bringing together scientists and managers (Nagel et al., 2026) using three active management approaches (resistance, resilience, and transition) and a no-action control. The network has focused on operationalising adaptive management techniques (Muller et al., 2019) by translating climate adaptation theory into practice. Nevertheless, it has the potential to serve as a model for knowledge coproduction of adaptation science (Nagel et al., 2025).

There is a need to **define robust quality criteria** that consider the socio-economic context of the intervention strategy, including the scale and type of interventions, local capacity, land tenure stability, social trust, and the durability of institutions, including social, economic, and political institutions. The implementation of top-down and jurisdictional approaches should encourage broader social engagement through bottom-up approaches focused on justice-oriented actions and equitable benefit-sharing. On-the-ground decision-making needs to be rooted at the local level, prioritising local community acceptance and incorporating place-based values.

Developing and fostering partnerships, since climate change is a too big and too complex issue for any single entity. Diverse partnerships that span jurisdictional and cultural boundaries can increase the capacity of organisations and individuals to cope with the overwhelming nature of climate change and the subsequent biodiversity crisis. Public-private partnerships can facilitate broader-scale adoption of innovative technologies contributing to sustainability outcomes at multiple levels.

Climate resilient **management should be inclusive of different approaches**, including conservation, preservation, active management, nature-based solutions, and ecological restoration. Market drivers should be designed to avoid perverse incentives and encourage holistic approaches that do not necessarily elevate singular goals such as mitigation or adaptation, as complex ecosystem services can rarely be disentangled. Addressing the sectoral issues properly requires the explicit connection of forest management to human systems and the built environment.

Build capacity and training among local people to empower communities with an emphasis on self-determination, as well as developing more robust and culturally inclusive indicators of biodiversity and forest resilience with a focus on monitoring both ecological and socio-economic outcomes. Address landowner constraints to proactive management, including lack of information, lack of funding, forest legacy planning, and transparency in contracts and markets.

Developing stronger socio-economic safeguards across all levels of governance, rooted in environmental justice and equitable benefit sharing. Safeguards should be designed to protect the most vulnerable populations across both urban and rural landscapes. The capacity of forest certification systems is limited and cannot address all existing forest-related problems. As private, market-driven mechanisms, they complement, but do not replace, other levels of forest governance and policymaking, including national, supranational (e.g., European Union institutions), and global (e.g., United Nations structures) levels.

In addition, it is important to acknowledge that the **cascading use of wood** and **wood reuse** in a circular economy are also key factors in promoting sustainable forest management, since they may help reducing demand for virgin wood.

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Chapter 6

Enabling multifunctional forestry through institutional support, incentives, and science-driven knowledge sharing

Lead Author: *Maria Nijnik*

Contributing Authors: *Simone Martino, Patrick O. Waeber, David Miller, Christian Rosset, Mariana Melnykovych*

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6.1 Introduction

This chapter focuses on **institutional support, incentives,** and **science-driven knowledge sharing** with the purpose of analysing and synthesising the current state of the art in science, EU policy debates, and practical experience to identify how these enabling conditions can empower the development of multifunctional forestry (MFF) in Europe.

Institutional support determines the rules, responsibilities, tenure clarity and security, governance, and cross-sector coordination to align actors and to develop and scale MFF. Institutions shape interactions between policy, markets, and civil society. However, formal public institutions may sometimes fail to adequately address multiple interests of stakeholders and multiple challenges facing forest socio-ecological systems (SES).

Incentives empower MFF. They enhance motivation and risk-sharing required for forest owners, managers, and beneficiaries to adopt sustainable practices and environmentally friendly behaviours aligned with multifunctional forest management and use. These may include financial and market incentives (e.g., subsidies, PES, green finance) and non-financial incentives (e.g., recognition, tenure security, social benefits). In parallel, with direct influence on forestry, incentives act as triggers for innovations, which are built upon science-driven knowledge sharing.

Science-driven knowledge sharing ranges from global efforts to local knowledge co-production and advisory services. It ensures that MFF decisions reflect stakeholder perspectives and are grounded in empirical evidence and social learning. The importance of credibility and clarity of communication in sharing scientific knowledge with policy makers and civil society is extensively recognised (Hermanowicz et al., 2024). This chapter broadens this perspective by moving towards the co-production of knowledge with stakeholders, including communities of places, practices, and interests. It highlights the role of participatory learning and awareness raising, and offers examples of communication platforms.

6.2 Multifunctional forestry: why enabling conditions are important

MFF recognizes that forests provide multiple ecosystem services (ES) (Nijnik et al., 2026; Winkel et al., 2022). However, the MFF concept has been the subject of scientific debates for decades (Nijnik et al., 2010) with the differentiation between i) vertical multifunctionality, where each forest provides a number of benefits, some of which are complementary (integration), and ii) horizontal multifunctionality, where different forest areas are dedicated to different functions (segregation according to Blattert et al. (2018), or specialization, according to Sedjo (2004). The 'vertical' understanding of MFF (dominant since the late 20th century) is the origin of the integrative forest management concept (INFORMAR (INFORMAR, n.d.), which aims at incorporating wider societal requirements into a wood production-oriented forestry (see Section 2.2). This approach seeks to capitalize on synergies of MFF and make forests more resilient, the delivery of ES more sustainable, and the use of resources more efficient (Borrass et al., 2017).

Bončina et al. (2019) briefly address the debate between integrative and segregative approaches to MFF. The integrative approach has long been the guiding forestry paradigm in much of Central Europe and is reflected in the forest legislation of countries such as Germany, Slovenia, and Switzerland. Although the concept of MFF is firmly rooted in this tradition, management in practice has often placed greater emphasis on wood production. Increasing demands for biodiversity conservation, climate adaptation, and other ES have therefore renewed interest in strengthening integrative management approaches. At the same time, some researchers have suggested that incorporating certain elements of segregation may improve management effectiveness, particularly where trade-offs between functions, conflicts of use, or economic efficiency constraints make the simultaneous provision of productive, protective, and social forest functions difficult (Bollmann and Braunisch, 2013). Thus, both basic approaches to MFF have their supporters, and both are associated with the transfer of emphasis from commodity to non-commodity outputs: from the production and consumption of material goods (e.g., wood) to broader ES provision.

These multifunctional considerations concern both the demand side (reflected in public and stakeholder attitudes, perceptions and needs towards forests) and the supply side. However, there is no single classification of MFF systems (some examples are presented in Table 6.1 and in Chapter 2), and none of the MFF paradigms

put in practice can simultaneously maximise the delivery of all ES (Brockerhoff et al., 2017). Implementing MFF requires technical expertise and science-driven knowledge. It also requires a shared understanding amongst stakeholders, which depends on institutional capacity, incentives, communication, collaboration, and social learning.

The diversity of forest types, ownership/tenure structures, and cultural traditions, among others, means that MFF cannot be standardised. For example, mountain forests require different interventions than lowland forests, and forests with fragmented private ownership generally face different operational constraints than large public forests. Thus, practices must be tailored to local conditions and contexts and be flexible and adaptive.

Table 6.1 Classification of multifunctional forest management systems. Source: Adapted from *Scherpenhuijzen et al. (2025), Krumm et al. (2023), and Freer-Smith et al. (2019).*

Forest Management Class	Definition
Unmanaged forest	Forests with limited or no anthropogenic disturbance and little-to-no management in place.
Close-to-nature forestry	Forests where management activities mostly aim to support biodiversity, resilience, and climate adaptation while providing relevant forest ecosystem services, including wood production.
Continuous cover forestry	An approach to sustainable forest management (SFM) in which the forest canopy is maintained at all times, avoiding large-scale clear-felling.
Combined objective forestry	Forests where multiple functions (e.g., protection, recreation, production) are promoted and no single objective dominates.
Intensive forestry	Forests managed for wood production. Management activities include repeated and often large-scale felling.
Very intensive forestry	Forests that may consist of fast-growing tree species and are intensively used for wood production, including short-rotation forestry. Management activities include frequent and/or large-scale felling.

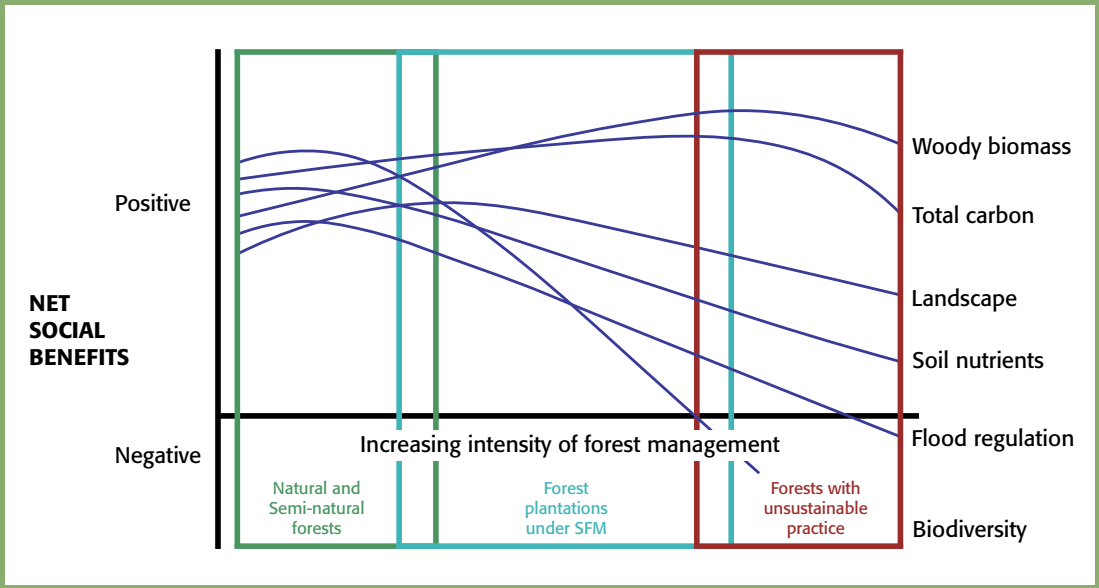
In Figure 6.1, the curves reflect a slight increase in values of most ES as forest management intensity increases, but up to a point beyond which the curves decline. The shapes and positions of the curves are case and context specific. However, an increased intensity of wood production is commonly linked with a diminution of other ES.

Scherpenhuijzen et al. (2025) produced a map of IFM based on datasets that depict various characteristics that can be attributed to spatial differences in MFF regimes. The evidence obtained from their maps implies that Northern Europe exhibits the highest share of unmanaged forests, along with the highest proportion of forests under intensive management regimes. In Eastern and Southern Europe, with some exceptions, the prevalent management method is close-to-nature forestry, while Western Europe is dominated by a combined forestry and close-to-nature forestry, with the latter prevalent in mountainous regions.

It is essential for sustainable MFF to enhance the resilience of forests and improve human livelihoods, for example by increasing household income, employment, and the health and vitality of people. A lack of understanding of what people value, want, and need may be one reason why the implementation of MFF faces difficulties (Nijnik et al., 2026).

Hernández-Morcillo et al. (2022) identified the following pathways to support a balanced supply of ES from forests in order to meet societal expectations: 1) shift towards MFF; 2) consider IFM; 3) strive to increase forest resilience; 4) coordinate actions between stakeholders; 5) increase their participation; 6) promote

Figure 6.1 Generalised relationships between forest management intensity and the delivery of ES. Source: Adapted from *Nijnik and Nijnik (2014).*



continuous, open, and transparent knowledge sharing/integration; and 7) use more incentives, especially in support of regulating and cultural ES.

Nevertheless, implementing MFF is a challenge due to variations in the drivers of change and their impacts, and due to numerous complexities and uncertainties. The uncertainties concern: i) current and future demand and supply of ES; ii) natural assets' stock, flow, and reproduction; iii) adaptation capacities of SES; iv) interrelationships, causalities, trade-offs (e.g., between ES); v) ecological, environmental, technological, economic, social/institutional aspects of forest ES (e.g., property rights, cultural preferences); and vi) the data, models, and scenarios available to use (Nijnik and Pajot, 2014).

Additional complexities may emerge linked to increased joint production and consumption of multiple ES, and to externalities and associated market failures. The scale and multiplicity of complexities is also linked to interactions among the multilevel politico-normative, socio-ecological, and economic contexts. These contexts are complex, dynamic, and intricately intertwined with a range of dimensions that foster or hinder MFF changes and shape their trajectories.

Approaches that have received attention for addressing complexities, take up uncertainties, overcome challenges, and enlarge opportunities for MFF are: institutional back up, supportive policies, efficient instruments, adequate incentives, and science-driven knowledge sharing. These considerations are consistent with Hernández-Morcillo et al. (2022) and are analysed in the next sections.

6.3 Institutional support

The institutional environment can be formal and strictly specified, or informal and manifested in unwritten conventions and codes of conduct shared by people. Formal institutions are of policy, economy, and administrative orders, rules, and instructions that comprise value judgements and are largely self-enforcing. Institutions shape the patterns of political, economic, and social interactions, and can be supportive, non-supportive, or neutral. As forestry becomes more multifunctional (Mather et al., 2006), and pressures on forest SES increase, institutions should provide more clarity, coordination, capacity, and legitimacy in support of MFF. Key policy frameworks empowering MFF development are presented in Table 6.2. Support rests on a multi-layered system in which forest-related laws, norms and strategies interact with regional, national and local institutions.

Table 6.2 Key European policy frameworks relevant for MFF enabling conditions, produced by the authors.

Framework	Main objectives related to MFF	Key implications	Timeframe / legal force	Notes on political debate / conflict
EU Forest Strategy 2030	Promote climate-resilience, MFF, monitoring	Calls for integrated info system; contested sovereignty	2021-2030, non-binding	Commodity vs amenity; forest SES resilience of Member States
EU Nature Restoration Law	Binding restoration targets for degraded ecosystems	Requires national restoration plans & indicators	EU Regulation 2024/1991	Tension with production; some restoration may reduce forest area
EU Biodiversity Strategy 2030	30% protected land, 10% strictly protected	Strengthens conservation constraints in managed forests	Strategy	Debate about strict vs multi-use areas
Green Deal & Climate Law	Climate neutrality by 2050, role of LULUCF	Increases pressure to use forests as carbon sinks	Legally binding climate law	Risk of carbon-centric management
Forest Europe	Pan-European SFM criteria & indicators	Provide monitoring backbone, but voluntary	Continuous ministerial process	Platform for MFF debate

Institutional arrangements, both formal and informal, are the mechanisms for co-ordination of societal interactions within the institutional environment. As forestry requires long-term considerations, the commitments must rely on secure tenure rights. Institutional arrangements (governance structures) can be based on markets, authority/hierarchy, collective actions, or take hybrid forms. MFF development has led to the advancement of hybrid forms of arrangements, with complex polycentric, multi-scale, and cross-sectoral governance (Nagendra and Ostrom, 2012).

The provision and consumption of timber and other commodities are primarily determined by markets. MFF development does not mean that productivity assets become less important, but that their position may be complemented by an increase in the importance of intrinsic and relational values of woodlands. An authority type of governance can play a formative role in safeguarding non-marketed ES, and in the creation and implementation of innovative rules for forestry to overcome a dependency on wood production. Where public policies and governance structures are well-functioning, supportive, transparent, and participatory (Lawrence et al., 2021), they can provide stakeholders with informed bases for communication, co-operation, and fruitful collaboration.

Regarding the **support for MFF**, in Europe, funding is primarily channelled through the Common Agricultural Policy Strategic Plans, the source of EU funding aimed at protecting forests, making them more resilient, promoting the provisioning of ES, and supporting investment, including on innovation and education (EC, 2026). The focal organisations that aim at balancing societal benefits from forests and addressing manifold challenges of MFF are presented in Box 6.1.

Public bodies, governmental agencies, and NGOs contribute to setting and implementing relevant strategies, providing funds, raising awareness, and promoting SFM practices to balance biodiversity conservation, timber production, and community needs. Among supporting organisations are public agencies of advocacy and representation, and organizations of research, education, knowledge sharing, forest stewardship, and certification. MFF outcomes are stronger when there is institutional support for: i) national forest inventories; ii) monitoring; iii) participatory planning; iv) advisory networks; v) multi-actor collaboration; vi) experimentation; vii) social learning; and viii) transparent and continuous reporting (Mann et al., 2022).

To a large extent success in MFF implementation depends upon forestry actors with their

Box 6.1 Key institutional bodies supporting MFF at European level

- **The European Commission Standing Forestry Committee:** The main agency with responsibility for advising on forestry measures and on the development of forest-related initiatives in the framework of EU policies, and it encourages the exchange of information.
- **Forest Europe:** A pan-European political process for dialogue and cooperation involving 46 signatories and developing common strategies for SFM on a voluntary basis.
- **Confederation of European Forest Owners:** An umbrella organisation representing national private forest owner associations, advocating for the interests of the 60% of EU forests that are privately owned.
- **European Investment Bank:** provides financing for public and private sector projects across the forest value chain, including for sustainable MFF.

capabilities to operationalise underpinning knowledge, and to assimilate, advance, and apply it as appropriate. There is also a dependence on the reconfiguration of social practices through institutional and social innovations, driven by bottom-up actions in response to societal demands, to enhance MFF outcomes, provide solutions to challenges, and empower the communities that depend upon forests (Nijnik et al., 2019).

Capacities vary, as success requires robust information systems, transparent communication, and evidence-based decision-making. Competencies include knowledge, social learning, experience, participation, reciprocity, motivation, commitment, and trust. Trust promotes co-operation, crucial for capability development that leads to progressive changes in the belief systems and cultural precepts, which is important for making institutions supportive of MFF changes (Primmer et al., 2021).

Participation, openness, accountability, effectiveness, and coherence are the key principles of supportive institutions (EC, 2001). Based on Nijnik and Slee (2008), the following institutional factors for enabling MFF can be proposed: reconciliation of MFF forestry objectives with all the dimensions of sustainability; flexibility of SFM plans to incorporate additional decisions or involve more or different actors where required; horizontal tuning of SFM plans through their correlation with other relevant plans; vertical tuning of the plans where their executive structure aligns with the policy design and responds to its objectives; feasibility concerning targets and implementation; task orientation with clear definition and allocation of responsibilities among the actors involved; acceptability of decisions by the public; and active stakeholder involvement in decision-making.

6.4 Policy instruments for forest multifunctionality

Policy instruments strive to either dissuade and prevent, or promote and enable certain behaviours for providers and consumers to implement socially desirable actions that they may not do otherwise. Instruments, addressing MFF can be non-economic (e.g., securing tenure rights, planning) or economic (Table 6.3). In Norway, for example, subsidies and tax relief have successfully targeted timber production and carbon sequestration through forest planting, thinning, infrastructure, etc., with annual government expenditure for these measures of approximately EUR 38.17 million for timber and EUR 2.53 million for carbon sequestration (Helseth et al., 2024). Subsidies, taxes, fees, and charges are adopted to correct externalities when no market can be established, or to correct the imperfection of markets.

Direct payments made by governments (e.g., subsidies) are available to individuals, private landowners, firms, and authorities. Importantly, in some regimes, forestry actors can exchange credits in developed markets and trade via cap-and-trade schemes. The markets include credits of carbon and biodiversity, mitigation credits, endangered species protection credits, etc. (Wunder et al., 2025). MFF could be managed more sustainably through utilising direct payments or by trading, for example, enabling private companies to purchase credits from those who plant trees. The role of government is important for operationalising the public/

Table 6.3 Grouping of selected policy instruments enabling MFF. Source: Authors' elaboration based on Thorsen et al. (2014) and Weiss et al. (2011).

Category	Type	Essence	Focus
Public/ Authority	Legislation, top-down regulation	Law; prescription; standard; permit/ license; ban/ prohibition; quota/ benchmark/ limitation/	Tenure/property rights; timber harvesting (e.g., annual allowable cut, clear-cut, illegal logging, wood removal); forest regeneration, reforestation; management operations (e.g., intensity, frequency, quality, timing); regulation of recreation (access) and other activities; endangered species and wildlife protection
	Government control	Public ownership; state/government planning; investment; provisioning	Regional, land use, and SFM plans; development of roads, infrastructure, etc.; research and innovation; procurement; biodiversity and nature protection areas
Economic	Fiscal/ Financial	Direct payments: price-based (primarily public)	Investments; subsidies; grants; taxes; charges; fees; exemptions/rebates; incentives/rewards; environmental funds; soft loans; impact bonds
	Market	Markets for ES (where possible); leveraging private investment	Green financing; private capital attraction; forest resilience bonds and green bonds; tradable permits; market-based payment schemes for ES; biodiversity and carbon offsetting and trading (e.g., cap-and-trade schemes); auctions
	Other	Environmental and user benefits	Public-private contracts; non-market (e.g., government-driven) PES-like schemes; dedicated funds; crowd sourcing
Capability, Capacity Building	Market Cooperation, collaboration	Markets for ES (where possible); leveraging private investment Green financing; private capital attraction; forest resilience bonds and green bonds; tradable permits; market-based payment scheme Dialogues; networking; cooperatives; partnerships; social institutional/governance innovations s for ES; biodiversity and carbon offsetting and trading (e.g., cap-and-trade schemes); auctions	
	Other Education	Environmental and user benefits Professional training; knowledge co-creation and sharing; research and development; social learning; advisory and consultancy; awareness campaigns	
	Information, communication	Correcting information asymmetry; awareness campaigns; recognition; demonstration sites; sharing good practices and lessons learnt	
	Ecolabelling, certification	Audit and monitoring; labelling; certification	

authority category of policy instruments and for enabling other categories, including through leveraging private finance and market-based mechanisms (EC, 2023).

Instruments supporting the provisioning of ES from forests have evolved rapidly, particularly concerning economic instruments. The EU Forest Strategy backs up an increase in subsidies for more ecological MFF and encourages forest-based initiatives, including of ecosystems restoration, through the generation of carbon certificates that can be traded (zu Ermgassen et al., 2025), a topic discussed in greater detail in Chapter 4. The EU Biodiversity Strategy promotes the use of economic instruments for governing forests. It highlights the need to upscale private investment, mobilising at least EUR 20 billion annually through blended (public-private) finance, with an expectation that instruments for MFF should be efficient, well implemented, fair, practical, effective, and affordable (EC, 2026).

Different stakeholders are involved in MFF. They face different decision-making situations, have their distinctive attitudes, perceptions, preferences, needs, information-processing capabilities, and selection criteria. They interact, learn, make decisions on allocations of power and resources, set up agencies and distribute responsibilities. Clarity of rights, roles, and responsibilities is essential for building stewardship and reducing possible conflicts. Deliberative processes, learning, integration of knowledge, and social innovations are crucial in this regard.

Some current European and national policies aim to devolve control to communities (Brnkalakova et al., 2022). In Scotland (Barlagne et al., 2021), the Land Reform Acts 2003, 2016, and 2025 (The Scottish Parliament, 2026) and the Community Empowerment Act (Scottish Government, 2017) set out the regulatory framework for communities to access, acquire, and use public

assets. As a result of this supportive institutional framework, and the motivation and capabilities of innovators, community forestry has expanded. For example, in north-west Scotland, the Lochcarron community developed social innovations to manage and use a community woodland for multiple purposes.

Such bottom-up initiatives fall under the capability and capacity building category of policy instruments that enable MFF. Social innovations pertaining to MFF were analysed in the project "Social Innovation in Marginalised Rural Areas" (EU CAP Network, 2026). The project built a unique database of 243 validated examples of social innovation, more than 20% of which were associated with forests.

The selection of policy instruments to assist in achieving MFF depends on the goals, the context, locality, nature of ES, societal values, institutional settings, land tenure, market effectiveness, funding, and other factors. Forest multifunctionality can be promoted by: i) fully integrating MFF principles into national forest laws, regional land use, and SFM plans; ii) creating cross-sector policy platforms; iii) mainstreaming ES into planning and management procedures; and iv) ensuring that incentives (addressed in the next section) align with case-specific MFF objectives.

6.5 Incentives for multifunctional forestry

Incentives for MFF can: i) compensate forest owners for income foregone due to harvesting restrictions; ii) share risks associated with long-term adaptive forest management or nature-based solutions; iii) co-finance forest restoration, diversification, and biodiversity conservation; iv) reward ecological contributions from MFF, such as increased habitat quality or carbon capture and storage; v) align private decision-making with public policy objectives, enabling forest owners to deliver societal benefits without bearing disproportionate burdens. According to Weiss et al. (2011), at the time of their study, public and authority category mechanisms and direct payments were most commonly used in Europe for directing forest manager's behaviours. The EU Forest Strategy for 2030 and the EU Biodiversity Strategy for 2030 call for the expansion of results-based schemes, PES, and blended financing models. This signals a shift from regulatory to innovative policy instruments and incentives. In some countries, public levies, charges, and taxes have contributed to the establishment of National Forest Funds, supporting SFM under public rules (Liagre et al., 2021).

PES translate the external, non-market values of ES into incentives for their provision by local actors through systems of payments designed to increase the quantity and quality of desired services. An example of a PES scheme operating in the UK is the Woodland Carbon Code, a national voluntary carbon offsetting scheme that legitimises the sale of carbon credits to businesses and individuals seeking to compensate their emissions (Forest Research, 2026).

PES schemes differ along several dimensions, including the type of ES provided, the nature of buyers and sellers, the role of intermediaries, and the structure of payments and bundling arrangements. Contract design, conditionality and choice of intermediaries shape the effectiveness and social legitimacy of PES (Schomers et al., 2021).

Payment schemes for forest ES in Europe are increasingly framed as policy and financing instruments to reward forest owners and managers for providing ES beyond timber, including biodiversity conservation, climate regulation, water regulation, risk reduction, and recreation (EC, 2023). Such schemes are particularly relevant for advancing MFF because they can help align forest-based income with the public benefits generated by forests. However, recent EU guidance stresses that effective PES design requires clear objectives, reliable baselines, long-term financing, monitoring, attention to trade-offs among ES, and integration with public-private funding mechanisms (EC, 2023). This is especially important in contexts where forests face multiple and interacting pressures, such as in Ukraine within its post-war forest recovery context (Melnykovych et al., 2026).

Pagiola et al. (2002) reviewed forest-related PES schemes focused on carbon sequestration and biodiversity protection and concluded that they are promising. However, their success is conditional on demonstrating additional benefits beyond established baselines and building trust with service providers. PES are criticised for commodification risks, equity concerns, and a narrow focus on single ES, particularly when schemes are designed in isolation from wider policy mixes (Kaiser et al., 2023).

Box 6.2 Examples of PES-like schemes in Europe

Norway: PES schemes are offered by the state for voluntary forest conservation strategies and paid according to the opportunity cost of forgone timber revenues (Helseth et al., 2024).

Croatia: A 'user pays' principle applies to economic entities to raise funds for forest protection against fires and pests, with approximately 0.025% of income paid by commercial entities (Hrvatski Sabor, 2018). These payments enable non-voluntary transfers from multiple beneficiaries to local ES providers through the state as intermediary (Vuletić et al., 2020).

Slovakia: Tax allowances provide an additional funding for ES provision, whereby productive forests are taxed and revenues from land taxes are channelled into forest conservation through a PES-like arrangement in which the state acts as the buyer (Giertliová et al., 2019).

UK: Voluntary markets for peatland protection operate under the Peatland Code, with approximately 85% of costs funded through public finance and the remainder by private finance (IUCN, 2015).

Establishing a pan-European PES system (if this is something that one should strive for) would be even more complicated due to: (1) insufficient alignment between the demand for and supply of forest ES; (2) limited information on both sides of the market; (3) polarisation between economic interests and environmental concerns; (4) a widespread perception of regulatory frameworks as inhibiting rather than enabling; (5) the need to account for climate change adaptation; and (6) the diversity of forest contexts across Europe, which complicates the identification of common solutions (Winkel et al., 2022).

Biodiversity crediting is a market-based mechanism through which verifiable units of positive outcomes from habitat or biodiversity restoration, or from species protection are generated, certified, and sold to companies or developers to meet conservation goals or regulatory requirements (Forest Research, 2026). It is conceptually similar to voluntary carbon markets. However, to date, biodiversity crediting is less developed than carbon crediting and remains distinct from biodiversity offsetting, which aims to compensate for unavoidable biodiversity losses.

PES schemes in Europe range from voluntary markets to direct payments to shepherds for reducing forest fire risks through grazing (Varela et al., 2018), payments to forest owners for managing forests for water quality and quantity, or regulating access to non-wood forest products (NWFP), for example by issuing permits for picking wild mushrooms (Gatto et al., 2009; Valatin et al., 2017) (Box 6.2). Several programmes use mitigation banks, such as carbon stock banking, wetland mitigation, habitat or biodiversity banking, in which private landowners finance conservation or restoration activities by generating credits that can subsequently be sold (Primmer et al., 2019). These credits may be purchased by parties responsible for environmental impacts with the aim of achieving no net loss of biodiversity. Across Europe, biodiversity offsetting and emerging biodiversity crediting schemes are increasingly being explored as mechanisms to deliver biodiversity gains through conservation or restoration, although biodiversity offsetting remains more widespread.

In large-scale nature protection projects, particularly in contexts with unsupportive policy frameworks, private finance may entail high ecological and social risks. Blending private capital with public or philanthropic funding is therefore often the societally-preferred approach to financing such projects (Flammer et al., 2025). A lack of transparency and integrity may undermine outcomes when investors design practices that are misaligned with the needs and priorities of communities (Reed et al., 2025). Aligning the objectives of funders with local visions for forest use and stewardship is thus essential (Ermgassen and Löfqvist, 2024).

Other innovative tools of private investment in forestry are increasingly taking the form of impact bonds, which are issued to deliver environmental and social outcomes (Flammer et al., 2025). Issued by organisations, corporations



Diversifying forest structures and species can strengthen resilience to future disturbances
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or governments, these bonds channel capital from investors into revenue-generating projects, functioning similarly to loans, but traded on public markets, such as natural capital bonds or green sovereign bonds financing green recovery. Impact bonds are performance-based instruments in which repayment and returns depend on the verified achievement of agreed outcomes. Investors recover their capital, and potentially a return, only if outcomes are met, while lower-than-expected impacts result in reduced returns (Belt et al., 2017).

Through use of innovative tools, private investors seek financial returns on investments in natural capital, indirect financial return such as revenues from biodiversity and carbon credits, and non-financial returns (Heeb et al., 2023). In the forest sector, monetisation pathways include ecotourism activities such as accommodation and guiding, health and well-being services, outdoor recreation, bioprospecting for medicinal use, certification of wood and NWFP certification commanding higher premiums, hydropower schemes on pay-for-success models, and carbon and biodiversity credits.

Additionally, auctions can be used to support forest protection, biodiversity conservation and MFF. Two main auction types are commonly distinguished: reverse auctions and fundraising auctions. Reverse auctions function by landowners submitting progressively lower bids for contracts and act as incentive mechanisms through which government agencies or environmental organisations competitively purchase ES from private landowners. In reverse auctions, landowners submit bids specifying the compensation required, and buyers select bids that offer the greatest benefit at the lowest cost. Beyond trading credits, such auctions can also be used to raise capital for future ES delivery, for example to allow developers to secure upfront finance in exchange for future provision of credits at a discounted rate or with guaranteed minimum prices. Fundraising auctions, by contrast, take the form of charity events in which donations are allocated to the highest bidder.

The following points outline how incentives can effectively support MFF: i) they perform best when co-designed with forest owners, municipalities, civil society, and environmental organisations (Mann et al., 2022); ii) incentives must be tailored to local, natural conditions, ownership structures, and socio-economic settings; iii) blended finance, combining public and private investment, can help mobilise resources; iv) poorly designed or implemented incentives can undermine ecosystem integrity (Sotirov, 2025); and v) incentives are most effective when informed by ex-post measurable outputs that reflect societal expectations (Wunder et al., 2025).

Understanding and implementing the incentive mechanisms for MFF is not an easy task; education and knowledge sharing are required. Moreover, managing forests as complex SES and aiming at providing numerous and diverse

ES requires evidence, platforms for learning and dialogue, and the capacity to translate science-driven knowledge into action. What matters is the nature of that knowledge and how it is generated, shared, interpreted and integrated into MFF decision-making processes. Decision-support systems are commonly used as tools that assist decision-making by structuring information, linking data to models, and presenting outputs in a way that supports comparison of options under uncertainty. In forestry, such systems have been developed primarily to support planning at stand and forest levels, integrating growth models, spatial data, and optimisation routines to evaluate management alternatives (Nelson, 2003). More advanced applications extend this logic to multi-objective contexts, allowing users to explore trade-offs between wood production, biodiversity, and other ecosystem services within structured decision frameworks (Seely et al., 2004). Operational decision-support systems (DSS) in forestry typically combine biophysical modelling with decision rules and user interfaces that enable scenario analysis and evaluation of management strategies under different assumptions (Varma et al., 2000). Their core function is not to make decisions, but to make consequences visible, comparable, and transparent to decision-makers.

6.6 Science-driven knowledge sharing

In Europe, science-driven knowledge sharing operates across three main levels:

(1) Pan-European and international level (synthesis, foresight, and policy interface)

At this level, knowledge is synthesised into assessments and strategic frameworks that help to assess policy coherence, identify emerging implementation risks at a large scale, and provide options for integrating MFF into sustainability agendas. Such assessments may shape high-level policy alignment, ensuring that forest-related debates incorporate cutting-edge scientific evidence.

(2) National and regional level (advisory, monitoring, and implementation support)

National inventories, ES monitoring systems, and climate impact assessments provide an empirical foundation for adaptive management and restoration planning. Forest advisory services, either public, private, or mixed, translate scientific findings into practical guidance. New initiatives, such as forthcoming monitoring frameworks under Horizon Europe, aim to build the data pipelines needed to report on biodiversity and carbon indicators across countries. At this level, science-driven knowledge supports risk assessment, adaptive planning, training, the provision/acceptance of decision-support tools, technical guidelines, and more. This ensures that scientific insights become actionable knowledge embedded in day-to-day forest management.

(3) Local and landscape level (co-production, participation, and social learning)

Knowledge sharing is more concrete and participative. Forest owners and managers, municipalities, environmental NGOs, businesses, and community groups jointly produce knowledge through participatory planning, living labs, co-designed workshops, and landscape partnerships. This is essential because MFF reflects local ecological and cultural values, as well as social and economic trade-offs, which are often place-based, spatially explicit, and require negotiated decisions. Social learning can build trust and reduce potential conflicts. Long-term stewardship emerges from locally anchored responsibility and bottom-up decision-making, not from external directives. Effective knowledge sharing strengthens the social license to manage forests sustainably, enabling MFF practices to align with local expectations while contributing to meeting national and European goals. Knowledge exchange processes can be classified into: (1) one-way exchange, in which researchers generate outputs such as reports or academic papers and subsequently transmit them to intended users; (2) solicited exchange, when users formally request that researchers provide specific information; (3) network exchange, involving two or more actors who purposefully convene to share knowledge they have produced independently; and (4) participatory exchange, characterised by the active involvement of users in the co-production of knowledge (Westwood et al., 2021). Although linear knowledge "transfer" formats still dominate, science-driven knowledge sharing is increasingly framed not as one-way dissemination, but as a participatory process in which scientific, practical, and policy knowledge is co-produced and tested. Strengthening this exchange in MFF requires generally accepted definitions, improved metrics of potential impact, formal support for intermediary roles, meaningful involvement of relevant actors, and the practical application of interdisciplinarity and transdisciplinarity.

A number of advanced forest DSS have been specifically developed to support science-driven knowledge sharing in MFF by integrating ecological, economic and social objectives (ForestDSS, 2025a). They help to integrate multi-criteria analysis, scenario modelling, and ES and stakeholder-oriented planning to address the complex trade-offs inherent in MFF. Examples of such DSS include Heureka DSS (Sweden), which combines forest growth simulation, biodiversity, carbon, and recreation assessments (SLU, 2026); ForSys (COST Action FP0804), designed to help managers create spatial prioritization plans that meet predefined goals and targets while considering constraints to achieve them (FORSYS Consortium, 2026); FORMES – forest DSS (CTFC, Catalonia, Spain), used for long-term strategic planning to assess the impact of climate change, fires, and other factors on forest structure and composition (ForestDSS, 2025b); Monsu (Finland), a planning software for use in MFF to cover scheduling plans generation, numerical optimization, and results with graphical visualization (ForestDSS, 2026); and Spectrum (SLU, Sweden), designed to schedule management treatments (ForestDSS, 2012).

Forest development plans are enabling instruments for MFF when designed based on inclusive participation. They are regional-scale planning instruments that form the institutional backbone of MFF in many countries. Their primary purpose is to spatially identify and formally designate areas where specific forest functions (e.g., productive, protective) are of elevated public importance and to translate these designations into concrete MFF objectives and guidelines (Bončina et al., 2019). This makes them one of the few operational frameworks to systematically translate ES priorities into spatially explicit management at the landscape scale (Kindler, 2016). A central feature of these plans is its participatory character, typically based on consultation with forest owners, environmental agencies, non-governmental organizations, and the broader public, with the degree of mandatory participation varying by country. In Switzerland, for example, public participation is legally required, and maps frequently emerge from stakeholder dialogue processes that weigh policy and MFF priorities (Bernasconi and Gubsch, 2017).

In this context, several science-driven knowledge sharing approaches increasingly perform functions traditionally associated with DSS, even if they are not formally labelled as such. Marteloscopes, simulation games, participatory planning platforms, and digital knowledge infrastructures assemble information, make trade-offs visible, and facilitate discussion among actors with different objectives and value systems. Unlike conventional forestry DSS, which primarily focus on biophysical modelling and economic optimisation, these innovative approaches integrate educational and deliberative dimensions and move beyond optimisation-oriented tools towards interactive and participatory environments that foster social learning, reflection, and co-production of knowledge. This is particularly important for MFF, where decisions are not purely technical but negotiated, context-dependent, and inherently value laden.

Digital knowledge infrastructure bases can help promote science-driven knowledge sharing and address fragmentation and scalability issues. Existing platforms at European scale score highly on accessibility and interoperability. Yet, they often struggle with low practitioner engagement, limited multilingual reach, and insufficient linkage to advisory systems. Without facilitation and feedback loops, these platforms risk reproducing a “supply-driven” pattern in which project outputs are stored, but rarely inform concrete decisions (Westwood et al., 2021).

Advisory and policy networks can help. The Horizon Europe project Enhancing Forest Advisory (FORADVISE, 2026) aims to establish an European network of forest advisory organisations and to develop pathways towards the creation of a Forest Knowledge and Innovation System (FOKIS) to speed up knowledge flows and to strengthen advisor competences beyond timber-focused support. The project’s design mirrors lessons from broader science-policy interfaces that emphasise boundary roles and intermediary organisations.

Several recent knowledge sharing platforms and formats illustrate the shift towards innovative science-driven knowledge sharing in practice. Digital marteloscopes are training management tools that comprise a forest plot with a defined size (typically 1 ha) where every tree is mapped, and all their variables are recorded. Together with their associated digital platforms, these tools exemplify such experiential, science-based learning environments that enable joint reflection and decision-making. By confronting users with quantified outputs, such as timber, structure and habitat indices for tree-marking decisions, they make the trade-offs in MFF tangible and create a shared

reference for discussion among future forest professionals, foresters, representatives of NGOs and policymakers. The strengths of this format lie in the co-interpretation of data in situ and its ability to bridge experiential and scientific knowledge, promote a shared understanding of MFF, and produce data and visual-based evidence.

Marteloscopes are powerful tools, but they can only fully support the co-production of knowledge and mutual learning when used in formats that deliberately surface disagreement and uncertainty. Simulation games and board-game formats push this a step further by explicitly creating a platform for dialogues, negotiation, and value conflicts. Garcia et al. (2022) and Waeber et al. (2023) explain how MineSet, a strategy game for integrated MFF that couples forest management models with role-playing, allows players representing different interests to interact and jointly manage forests under disturbances and policy constraints. These tools are particularly effective at eliciting mental models, exposing trade-offs, and fostering dialogue across different actors to enhance knowledge sharing.

These examples show important policy and science-driven knowledge sharing initiatives and processes, as well as recent communication practices, which require: (i) further development/refinement of place-based, experiential tools (e.g., pilots, demonstration sites) that allow actors to jointly interrogate evidence (in living labs); (ii) participatory simulations, such as strategy and role-playing games, that make values and trade-offs explicit; (iii) digital infrastructures (digital learning platforms) that provide curated, interoperable access to knowledge; and (iv) institutionalised networks and political processes that secure intermediary roles, address inequality in knowledge systems, and connect learning to policy and organisational change. None of these formats alone can guarantee better decisions. The critical issue is whether these are designed and governed so that communication becomes a vehicle for participatory co-production of knowledge and mutual learning, rather than an increasingly sophisticated way of placing more information in front of already overburdened practitioners and policy makers.

6.7 Interlinkages of the enabling conditions

Forest governance literature emphasises that institutions, incentives, and knowledge sharing form an interdependent system shaping MFF. Outcomes depend not only on their choice, but on how they function as potential enablers embedded in broader institutional modes such as hierarchical regulation, scientific-technical steering, adaptive collaborative governance, and strategic behaviour (Primmer et al., 2015). Combinations of governance modes, rather than any single approach, tend to support multiple ES provision from forestry, with context-specific institutional arrangements shaping what is feasible and legitimate (Falk et al., 2018). For MFF, this implies that supportive institutions are less about a particular model but more about institutional fit, understood as coherent rules, organisational capacities, and coordination mechanisms that allow different objectives and instruments to be aligned. The literature on economic instruments provides a second strand, highlighting how incentives can both enable and constrain MFF. PES schemes can be powerful drivers of MFF when they are well targeted, transparently governed, and embedded in supportive institutional settings (Prokofieva, 2016). However, as highlighted in Section 6.5, their success is conditional and often challenging.

Experience has shown that economic instruments only deliver on biodiversity and multiple ES when they are coordinated with regulatory, informational, and voluntary measures (Barton et al., 2014). Empirical work in Norway (Helseth et al., 2024) and across European private forests (Bütler et al., 2021) reaches similar conclusions: subsidies and tax reliefs can rebalance production-versus-protection trade-offs, but they tend to favour commodities unless explicitly redesigned to promote biodiversity, climate mitigation, and other non-market benefits. The provision of forest ES in Europe is shaped by a dense multi-level governance system, including EU strategies, national laws, private property regimes, and soft-law processes, creating both opportunities and constraints for MFF (Winkel et al., 2022). FAO's forest-policy guidance similarly stresses that well-designed forest policies must combine clear legal mandates, participatory processes, and coherent instrument mixes, if they are to balance production, conservation, and social functions of forests.

Institutions and incentives are mutually constitutive: institutions set the rules for who can design and benefit from incentives, while incentives feed back into institutional legitimacy and capacity. Communication, knowledge

sharing and advise constitute a third enabling condition for MFF. These enablers rarely operate in isolation; their functionality and effectiveness depend on how they interact with each other within broader institutional settings and knowledge systems. Robust institutions provide frameworks within which incentives can function; effectual incentives shape behaviours that support institutional mandates; and science-driven knowledge sharing bridges these spheres, ensuring that decisions are evidence-based, legitimate, and adaptive.

Understanding these interlinkages is essential, as shortcomings in any one domain can undermine progress in others (Table 6.4).

Table 6.4 Interlinkages of institutional support, incentives, and knowledge sharing, produced by the authors

Enabling Condition	Supports…	Depends on…	Key interlinkages	Risks, if missing
Institutional support	Incentive design; knowledge legitimacy; implementation capacity	Knowledge systems for evidence; incentives for compliance and uptake	Creates legal mandates; allocates resources; ensures equity	Incentives become ineffective; knowledge unused; conflict increases
Incentives	Behavioural change; restoration uptake; innovation	Institutional clarity; robust monitoring; trust-building knowledge systems	Motivate multifunctionality; stimulate co-operation; require data systems	Perverse incentives; low uptake; misaligned management
Knowledge sharing	Policy coherence; adaptive management; monitoring	Institutional frameworks; incentive demand for metrics	Builds legitimacy; provides indicators; supports learning	Decisions lack evidence; poor monitoring; declining stakeholder trust

Conversely, when the three enabling conditions reinforce each other, they create a virtuous cycle that supports multifunctionality, resilience, and long-term stewardship of forest SES.

Institutions as the structural backbone for incentives and knowledge systems

Institutions provide the structural foundation for both incentives and knowledge sharing. Without clear tenure rights, coherent forest and land-use policies, and capable governance bodies, incentive schemes cannot be implemented fairly, nor can knowledge systems function effectively. Strong institutions guide the design of incentive mechanisms towards MFF outcomes by embedding ecological safeguards, enabling long-term commitments, and ensuring equitable access for diverse forest owners. Institutions also determine whether knowledge systems are trusted, whether monitoring data is standardised, and whether advisory services have the mandate and resources to support MFF practices. Institutions establish the rules of the game, shaping the legitimacy of incentives and the uptake of scientific knowledge.

Incentives as catalysts for institutional and behavioural change

Policy instruments and incentives, including financial, regulatory, and social measures translate institutional goals into concrete behaviours. When well-designed, incentives signal societal priorities and make MFF viable while also stimulating governance innovation, for example by encouraging collaboration across administrative boundaries or motivating the adoption of monitoring systems required for results-based contracting. Incentives can also prompt institutional evolution: PES schemes often require new arrangements for contracting, verification, and dispute resolution; carbon certification frameworks depend on robust MRV systems and cross-sector coordination; and biodiversity payments may lead to the creation of new monitoring institutions or advisory networks. Conversely, when incentives are misaligned or under-resourced, they can create institutional strain by imposing obligations that forest administrations cannot enforce, or by generating expectations that existing governance structures cannot meet.

Knowledge sharing as the connective tissue across systems

Science-driven knowledge sharing ensures that institutions and incentives operate with consistency, transparency, and adaptive capacity. Knowledge systems translate ecological and socio-economic evidence into usable formats for policymakers, forest managers, and the public, and provide feedback loops needed to evaluate the effectiveness of incentive schemes and governance reforms.

6.8 Conclusions and recommendations

The MFF enabling conditions of supportive institutions, incentives, and knowledge sharing should act concurrently. Effective institutional frameworks can enhance MFF incentives. Institutional incentives can stimulate knowledge sharing and innovation. Knowledge sharing can strengthen forestry institutions and support the design of better incentive systems. The aim is to take advantage of opportunities, to steer them to be effective, and mitigate the risks of weak or absent enabling conditions, or their potentially unsustainable interlinkages. The enablers must be designed as an integrated system rather than a collection of separate tools. Bringing correctly together the right institutions, incentives, and knowledge sharing practices creates the conditions needed to maintain or improve the resilience and the multifunctionality of forest SES.

The advance of MFF requires:

- **Institutional coherence** between sectors and cross-sector coordination platforms to align pertinent policies and remove contradictions (e.g., between the promotion of urban forestry and residential development);
- **Secure and transparent tenure arrangements** (targeted support should be directed towards regions with highly fragmented ownership or limited administrative capacity);
- **Blended financial mechanisms of a results-based design** that reflect ecological and social goals;
- **Transparent monitoring systems** (with attention to digitalisation; remote sensing, open data platforms) co-produced with stakeholders;
- **Advisory services** that integrate ecological, economic, and social expertise; vi) participatory and transdisciplinary knowledge exchange and co-production (e.g., living labs, forest owner networks, participatory forest planning, public-private partnerships); vii) adaptive governance that incorporates mechanisms for iterative learning, scenario planning, and flexible policy adjustment;
- **Long-term strategies** that view forests as dynamic and evolving SES.

While selecting tools for enabling implementation of MFF, decision makers should strive: i) to minimize transaction costs; ii) adhere to principles of equity, equality, and integrity; iii) facilitate participation and build trust; iv) reward sellers of ES in a fair way; v) ensure long-term viability for achieving additionality and durability of the incentive schemes; vi) reflect values and respect aspirations of stakeholders, communities, and the public; and vii) ensure that investors have confidence that they are funding genuine positive changes.

Co-production and sharing of knowledge (theoretical, empirical, expert, traditional knowledge and local wisdom) are enablers of MFF. Science-driven knowledge sharing provides the conditions under which forest owners can navigate complex and uncertain management environments as well as the basis of coherent design and evidence-based strategies by policymakers. Evidence bases provide means of understanding and of making use of trade-offs and synergies. Innovations can emerge, develop, and spread through collective learning and actions taken, and conflicts can be mediated through shared understanding, building mutual trust and collaboration.

In the absence of strong knowledge systems, MFF risk being undermined by misinformation or asymmetric information, fragmented decision-making, improper institutional settings and governance structures, weak policy instruments, and low public trust. Conversely, when science-driven state-of-the-art knowledge is reinforced with other types of knowledge (e.g., of communities of interests, practices, and places), and when it is embedded within innovative and multilevel governance, participatory processes, and supportive advisory systems, MFF becomes a tangible and operational pathway towards more productive, biodiverse, resilient, and socially desirable forestry futures.

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Adaptive forest management helps forests remain resilient under increasing climatic uncertainty © Pamela Hallam (Unsplash)

Chapter 7

Synthesis and discussion

Lead Author: *Frank Krumm*

Contributing Authors: *Tommaso Chiti, Zuzana Dobšinská, Maria Nijnik, Nataša Lovric, Andreea Spinu*

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7.1 Introduction

European forests are increasingly expected to deliver wood and other ecosystem services, conserve biodiversity, and adapt to climate change simultaneously. Since strictly protected forests cover only a small proportion of Europe's forest area, biodiversity conservation must also be achieved within managed production forests. Experiences with such convoluted challenges do not really exist. Forests are long-lived and complex systems that develop over decades to centuries, progressing through many stages from seed germination to mature forest ecosystems. Their structure and functioning result from intricated interactions among biological, environmental, and historical factors, varying across regions and over time. While understanding these dynamics has always been challenging, changing environmental conditions are now altering forest dynamics, meaning that assumptions valid today may no longer hold in the future.

Climate change-driven heat and drought are rapidly altering European forests, exposing the instability of once-stable ecosystems while simultaneously increasing the importance of sustainably sourced wood as a carbon-storing, fossil-fuel and material substitute in a growing circular bioeconomy.

Increased trade and mobility as measures for urbanisation and globalisation facilitate the spread of invasive pests, pathogens, and plants that threaten native ecosystems. Meanwhile, growing populations and changing lifestyles are increasing recreational pressure on forests, enhancing their societal value while creating additional management challenges. These pressures occur against the backdrop of a global biodiversity crisis driven by habitat loss, deforestation, and intensive land-use practices.

Together, these interacting pressures demonstrate that future forest management cannot rely on single-objective approaches. Instead, forests must be managed in a way that addresses ecological integrity, economic viability, and societal demands simultaneously.

7.2 Towards integrated forest management

Much research has focused on understanding climate-change impacts, but an equally important challenge is adapting forest management to sustain ecosystem services and biodiversity. Forests provide far more than wood: they protect against natural hazards, regulate water, prevent erosion, support recreation, and provide habitat for countless species.

Management approaches vary. Some separate different objectives across the landscape, while others seek to deliver multiple benefits within the same forest stand. Integrated Forest Management (IFM) combines these perspectives by promoting biodiversity-friendly practices such as deadwood retention, natural regeneration, mixed-species stands, and the protection of key habitats while maintaining wood production and other ecosystem services.

In the European context, IFM builds on established European forestry approaches such as Continuous Cover Forestry, Close-to-Nature Forest Management, Retention Forestry, and TRIAD forestry. Its core principles include promoting natural regeneration and diverse tree species mixtures, retaining habitat trees and deadwood, enhancing structural heterogeneity, and coordinating management at the landscape level. Rather than prescribing a single management system, IFM encourages a diversity of silvicultural practices adapted to local, ecological, and socio-economic conditions.

A key feature of IFM is landscape-scale coordination. European forests are often fragmented and managed by multiple owners with different objectives, making biodiversity conservation dependent on cooperation beyond individual stands. IFM therefore promotes a landscape matrix that combines multifunctional production forests, strict reserves, habitat patches, and ecological corridors to maintain habitat diversity and connectivity. Diversifying management practices and forest structures across this matrix supports a broader range of species while also reducing risks associated with climate change and disturbances.

In this publication, **Chapter 2** "Integrative Forest Management for coexistence in Europe" describes how European forests face a critical paradox: they are expected to simultaneously mitigate climate change through carbon sequestration and the supply of renewable wood while halting the loss of biodiversity. With less than 5% of forests under strict protection, the vast majority of the landscape should be managed to support both production and ecological integrity. Forests are complex socio-ecological systems currently under pressure from urbanization, climate change, and high biomass demand. Traditional management paradigms



Management choices made today shape the resilience and productivity of future forests
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often force a choice between segregation and integration. Neither approach is sufficient in isolation; segregation often lacks the spatial capacity to meet conservation targets in densely populated regions, while pure integration can be difficult to implement across fragmented ownership.

IFM acts as an overarching strategy that integrates principles of resilience, biodiversity promotion, and production. Its effectiveness is based on a tiered landscape approach:

- **The Matrix:** A "non-hostile" environment where standard silviculture incorporates retention elements (habitat trees, deadwood, canopy gaps) to facilitate species dispersal.
- **Specialized Tiers:** The matrix is supplemented by strict reserves (for natural dynamics), old-growth relics ("stepping stones"), and habitat-specific patches (e.g., early-successional openings).
- **Silvicultural Diversity:** Instead of uniform management, IFM promotes a portfolio of regimes ranging from single-tree selection to irregular shelterwood systems. Research indicates that diversifying these regimes can increase multispecies-habitat availability by over 50% while reducing net present value (economic profit) by only 7-10%, which presents a cost-effective pathway for coexistence.

Resilience and the "coerced" vs. "ecological" dilemma

Climate change threatens the stability of existing forests. While management can enhance resilience, a distinction must be made:

- **Ecological Resilience:** Natural processes and biological diversity allow forests to absorb and recover from disturbances.
- **Coerced Resilience:** Human intervention (e.g., shorter rotations, sanitary felling) maintains predictable timber yields but often reduces biodiversity and limits the forest's long-term ability to endure unforeseen stressors.

IFM aims to favour ecological resilience by promoting site-adapted species, natural regeneration, and structural complexity, rather than relying solely on intensive human intervention. However, the balance between ecological processes and active management remains context-dependent. In some situations, targeted interventions may be required to support forest adaptation, particularly where climate change has altered species suitability or disturbance regimes.

7.3 Monitoring and adaptive management

Effective IFM is constrained by "lag effects", the delays between policy detection, decision-making, operational implementation, and ecological recovery. Current monitoring faces three primary hurdles:

1. **Indicator Reliance:** Systems rely heavily on structural proxies (canopy cover, stem density), which are easier to measure but often correlate poorly with actual species richness.

2. **Scale Mismatch:** Indicators often aggregate data, potentially concealing important local biodiversity declines or management failures.

3. **Methodological Fragmentation:** Differences in reporting across European nations hinder the ability to apply universal thresholds.

The authors advocate for scale-sensitive approaches that integrate stakeholder values through participatory processes rather than attempting to enforce absolute, universal metrics. By increasing the frequency of monitoring, foresters can shorten the decision-to-implementation lag, enabling more rapid responses to emerging pressures like pests or extreme climate events. Projections suggest that with proactive management, Europe has the biophysical capacity to maintain, or even increase, wood production while meeting ambitious conservation targets (e.g., 30% area set-aside), provided that forests are steered towards climate-resilient states. However, there is no "one-size-fits-all" solution. The future of European forestry relies on a landscape-level mosaic where management strategies are coordinated across fragmented ownership and contexts. Success will depend on the long-term commitment to integrating local knowledge with evidence-based indicators, ensuring that production forests transition from being mere wood sources to becoming functional, resilient elements of the continent's green infrastructure.

Chapter 3 "Defining and measuring forest biodiversity" states that forests serve as the foundation of Europe's environmental strategy, delivering critical ecosystem services, including carbon sequestration, climate resilience, and habitat provision, that are essential to the European Green Deal and the Biodiversity Strategy for 2030. Because most European forests are managed, modern policy emphasizes multifunctionality, aiming to balance economic production with the restoration and maintenance of ecological integrity. Biodiversity in forests is a multidimensional, hierarchical phenomenon defined by the interaction of three dimensions:

1. **Composition:** The identity of living components (genes, species, and ecosystems), encompassing genetic variation, species richness, and habitat types;

2. **Structure:** The physical organization and spatial arrangement of forest elements, such as vertical canopy layers, age distribution, deadwood, and landscape connectivity; and

3. **Function:** The ecological processes, such as nutrient cycling, regeneration, and trophic interactions, that drive system performance, stability, and resilience.

This integrative "biodiversity triangle" acknowledges that forests are not static; they are shaped by long-term successional dynamics, natural disturbances, and historical human management.

7.3.1 Monitoring frameworks and indicators

Robust monitoring is the empirical backbone for policy evaluation and adaptive management. Current frameworks operate across three primary levels:

1. Pan-European: The FOREST EUROPE process uses six criteria, with Criterion 4 specifically targeting biodiversity. It relies on National Forest Inventories (NFIs) to track indicators such as tree species diversity, deadwood, and protected forest status.

2. EU Policy: The EU Biodiversity Strategy for 2030 and the New EU Forest Strategy mandate strict protection for primary/old-growth forests and promote "Closer-to-Nature" forestry. These strategies push for indicators beyond simple species counts to include forest health, resilience, and structural complexity.

3. Nature Restoration Regulation (NRR): This legally binding framework formalises monitoring for forest ecosystems, requiring countries to report on key metrics, including standing and lying deadwood, forest connectivity, carbon stocks, and the common forest bird index, to demonstrate progress in restoration.

Effective monitoring requires a "complementary system" approach, as no single data source is sufficient. NFIs serve as the long-term, harmonized backbone but often lack detail on fine-scale biodiversity (e.g., rare functional traits). Remote sensing tools are essential for large-

scale, structural, and connectivity monitoring, utilising Copernicus and LiDAR data to fill spatial gaps. Specialized networks provide critical data on specific taxa (birds, fungi, lichens) and functional processes. Citizen science and/or administrative data supplement formal monitoring by expanding spatial coverage and providing management context.

Key challenges include the discrepancy between long-term ecological response times and short policy-reporting cycles, persistent data gaps for soil organisms and genetic diversity, and the difficulty of scaling local measurements to regional policy needs.

7.3.2 Strategic outlook: integration and communication

The future of forest biodiversity monitoring lies in moving beyond simple species counting toward integrated indicator portfolios that capture structural and functional change. To bridge the gap between scientific complexity and policy utility, monitoring must be **operational** while leveraging standardised data from NFIs and Earth observation.

Communication-oriented indicators such as deadwood and bird indices can help build stakeholder trust and make the value of active, biodiversity-oriented management more visible. Monitoring systems must also remain **adaptive** while supporting decisions that mitigate trade-offs between wood production, climate mitigation, and conservation.

In conclusion, forest biodiversity monitoring is no longer just a conservation exercise; it is an essential component of sustainable finance, climate adaptation, and the bioeconomy. Successful implementation requires harmonising monitoring systems across borders and ensuring that biodiversity indicators directly inform active, evidence-based forest management.

7.4 The policy arena

In **Chapter 4** "Maximising forest carbon storage", the authors show that forests are Europe's primary carbon reservoir, playing a critical role in reaching 2050 climate neutrality by sequestering CO_2 and providing renewable resources. To harness this potential, the European Union is implementing a comprehensive framework anchored by the Carbon Removals and Carbon Farming (CRCF) Regulation. This framework establishes harmonized Monitoring, Reporting, and Verification (MRV) protocols to ensure that carbon removal activities based on human interactions are quantifiable, additional, permanent, and sustainable. Effective climate mitigation requires forest management tailored to specific climatic zones, balancing carbon storage with biodiversity, soil health, and resilience. It is therefore essential to distinguish between:

- **Boreal zones:** Focus on minimising disturbances through continuous cover forestry and retention forestry to maintain stable carbon stocks and protect soil organic carbon.
- **Temperate zones:** Strategies emphasise continuous carbon stocks, species diversification (mixed stands) to enhance climate resilience, and soil protection measures against heavy machinery compaction.
- **Mediterranean zones:** Priorities centre on fire-smart management, fuel-reduction thinning, and converting abandoned coppice forests to high forests to mitigate risks from drought and catastrophic wildfires.
- **General practices:** Afforestation on non-agricultural land, extension of rotation periods to increase biomass, and strategic shortening of rotations to facilitate the transfer of carbon into harvested wood products remain key tools, provided they are managed to avoid carbon leakage.

Integrating forest management with the broader bioeconomy is essential for a circular climate strategy. The cascading use principle is central to this transition. Wood products act as a critical carbon sink while substituting fossil-intensive building materials avoids "carbon lock-in".

For forest carbon to mobilise private finance effectively, crediting systems must overcome historical integrity gaps. Credible market participation requires a risk-priced issuance that moves away from flat-rate deductions towards adaptive approaches, and that accounts for additionality, temporality, leakage, and reversal risk (e.g., fires or pests). Additionally, utilising group certification, aggregation programmes and remote sensing would help reducing barriers by making high-integrity standards accessible to small forest owners.

The successful contribution of the forestry sector to Europe's climate goals depends on a shift from simply maximising carbon volume to ensuring high-quality, verifiable mitigation. This requires a synergistic approach that aligns forest-based carbon farming with biodiversity strategies, supports a circular bioeconomy through cascading wood use, and employs rigorous, transparent MRV systems. By addressing these complexities, Europe can transform its forests into a stable, reliable pillar of its long-term climate neutrality strategy.

7.5 Pathways for alignment

Chapter 5 "Aligning forest management with climate resilience and socioeconomic goals" examines how European forests can simultaneously deliver economic value, biodiversity conservation, and climate resilience within an increasingly complex policy environment shaped by EU strategies. It argues that achieving these multiple objectives requires an integrated forest management approach built on three interconnected pathways: forest certification, value-added wood products, and coherent governance frameworks.

First, forest certification systems, particularly the Forest Stewardship Council (FSC), are presented as key market-based tools for promoting sustainable forest management. Evidence suggests that certification can contribute positively to biodiversity conservation, for example through habitat protection, retention of deadwood, and safeguarding high conservation value areas. However, results remain context-dependent and mixed, with about half of the studies reporting positive effects, while others show neutral or variable outcomes. Certification is therefore best understood as a complementary governance instrument rather than a standalone solution, constrained by its voluntary nature and its coexistence with practices such as clear-cutting in some regions.

Second, the chapter highlights the role of value-added wood products, especially mass timber, as a strategy to align economic incentives with climate and ecological goals. Mass timber can significantly reduce the carbon footprint of the construction sector by substituting emissions-intensive materials such as steel and concrete while also storing carbon. At the same time, it can generate new revenue streams that support sustainable forest management and rural development. However, increasing demand for wood raises concerns about overharvesting, biodiversity loss, and ecosystem degradation, making it essential to implement strong safeguards and balanced, context-specific management practices.

Third, the chapter emphasizes the importance of governance, policy instruments, and stakeholder engagement in shaping forest outcomes. Forest policy in Europe is highly fragmented across sectors and scales, often leading to inconsistencies between climate, biodiversity, and economic objectives. Effective governance requires policy coherence, multi-level coordination, and active stakeholder participation, including forest owners, industry, policymakers, and civil society. Instruments such as payments for ecosystem services, biodiversity strategies, and collaborative research initiatives play a crucial role in aligning incentives and supporting multifunctional forestry.

Across these three pathways, the chapter stresses that trade-offs are unavoidable, particularly between timber production and biodiversity conservation. Therefore, the goal is not optimisation of a single objective, but the integration of multiple functions through adaptive, evidence-based, and locally tailored approaches. Biodiversity is framed not only as an ecological goal, but also as a foundation for forest resilience, supporting ecosystem stability, carbon sequestration, and long-term productivity.

The chapter further highlights the need to better align climate adaptation and mitigation strategies, which are often treated separately in policy and practice. Integrated models such as climate-smart forestry offer promising frameworks but require careful implementation to avoid unintended consequences. Bridging the gap between science and practice, strengthening monitoring systems, and fostering knowledge co-production are identified as critical steps for improving decision-making.

In conclusion, the chapter argues that successful forest management in Europe depends on systemic integration across markets, policies, and knowledge systems. Certification provides standards, value-added products create economic incentives, and governance frameworks enable coordination and scaling. To move forward, policymakers and practitioners must prioritise robust quality criteria, equitable and well-designed market incentives, inclusive stakeholder engagement, and stronger policy coherence. Only through such a holistic approach can European forests remain both productive and biodiverse in the face of climate change and growing societal demands.



Balancing ecological, economic, and societal goals is central to sustainable forest management
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7.6 Multifunctional forestry

The text of **Chapter 6** "Enabling multifunctional forestry" analyses how multifunctional forestry (MFF) in Europe can be effectively supported through three interdependent enabling conditions: institutional frameworks, incentives, and science-driven knowledge sharing. Together, these elements form a systemic foundation for transitioning forestry from a primarily production-oriented model towards one that simultaneously delivers ecological, economic, and social benefits.

MFF reflects a shift in both societal demand for forest ecosystem services (ES) and the management approaches needed to meet these expectations sustainably. While traditional forestry emphasised wood production, contemporary approaches seek to balance biodiversity conservation, climate regulation, recreation, and other services. However, no single management model can optimise all ecosystem services simultaneously, and trade-offs, particularly between production intensity and biodiversity, are inevitable. This makes context-specific, adaptive, and participatory approaches essential.

Institutional support provides the structural backbone for MFF. It encompasses governance systems, policies, tenure arrangements, and coordination mechanisms across sectors and scales. Effective institutions ensure clarity of roles, long-term commitment, and legitimacy in decision-making. In Europe, a dense policy landscape, including strategies on biodiversity, climate, and forest management, creates both opportunities and tensions, particularly between conservation goals and production demands. Increasingly, governance is evolving towards polycentric and participatory models, incorporating state, market, and community actors. Strong institutions also depend on capacities such as monitoring systems, advisory services, and stakeholder engagement, as well as intangible factors such as trust and social learning.

Incentives translate institutional goals into concrete actions by forest owners and managers. These include financial tools (e.g., subsidies, carbon markets, payments for ecosystem services) and non-financial mechanisms (e.g., tenure security, recognition). There is a notable shift from traditional regulatory approaches towards market-based and results-oriented instruments, including blended finance and biodiversity or carbon credits. Payment for ecosystem services schemes are particularly prominent but remain challenging due to high transaction costs, governance complexity, and concerns over equity and commodification. Effective incentives must be carefully designed, context-specific, and aligned with broader policy mixes; otherwise, they risk reinforcing production biases or creating unintended environmental and social outcomes.

Science-driven knowledge sharing acts as the connective tissue linking institutions and incentives. It ensures that decisions are evidence-based, transparent, and adaptive. Knowledge processes operate across multiple levels, from international assessments to local co-production, and are increasingly moving from one-way information transfer towards participatory and transdisciplinary approaches. Tools such as advisory networks, digital platforms, living labs, and simulation games help stakeholders understand trade-offs, co-create solutions, and build shared understanding. However, challenges remain in ensuring accessibility, engagement, and integration of knowledge into practice. A key insight is that these three enabling conditions are deeply interdependent. Institutions shape the design and legitimacy of incentives and knowledge systems; incentives drive behavioural and institutional change; and knowledge sharing supports learning, evaluation, and adaptation. When aligned, they create a virtuous cycle that enhances forest resilience, multifunctionality, and long-term stewardship. Conversely, weaknesses in any one component can undermine the entire system.

The chapter concludes by stating that successful implementation of MFF requires an integrated, systems-based approach. This includes coherent cross-sector policies, secure tenure, well-designed and equitable incentives, robust monitoring systems, and participatory knowledge co-production. Ultimately, multifunctional forestry depends not only on technical solutions but also on governance innovation, stakeholder collaboration, and the ability to navigate complexity and uncertainty in forest socio-ecological systems.

7.7 Conclusion

Growing demands for forest ecosystem services, combined with biodiversity loss under climatic changes, require new approaches to forest management, but also to administration and planning management. Traditional models that prioritise single objectives are increasingly inadequate. Wood products are increasingly demanded and are also considered to have a high potential for climate change mitigation.

The authors of this assessment advocate for the integrative forest management approach, an option that offers a promising pathway by combining production, conservation, and protection objectives across multiple spatial and temporal scales. By promoting diversity, resilience, and adaptive management, this approach can help forests continue to provide essential ecosystem services while conserving biodiversity (Kraus and Krumm, 2013; Krumm et al., 2020).

However, successful implementation depends on several factors, including supportive governance frameworks, cooperation among stakeholders, and locally adapted management practices. Through the combination of theoretical insights and practical examples, integrative forest management aims to guide the development of resilient forest landscapes capable of meeting both present and future societal needs. This means that the approach must be interpretated in a broader sense. It is not only about the integration of measures that directly improve habitat availability and quality. It is also about the socioecological systems that support the management. One crucial precondition is the mutual understanding of stakeholders on their expectations and preferences. All relevant players shall be integrated in discussions and decision making for forest management issues.

Based on all the above, the following are some key principles for integrating biodiversity into forest management:

Structural complexity and habitat heterogeneity

Maintaining structural diversity is one of the most effective strategies for conserving biodiversity in managed forests. Features such as large old trees, deadwood, understory vegetation, and canopy gaps provide essential habitats for many species (Lindenmayer and Franklin, 2002).

Retention forestry, a management practice in which structural elements are preserved during harvesting, has shown to significantly improve biodiversity outcomes as compared to conventional clear-cutting (Gustafsson et al., 2012). However, the level of applied retention certainly makes a difference.

Landscape-level planning

Biodiversity conservation must be addressed across spatial scales. Protected areas play a crucial role at the regional level, while habitat corridors and buffer zones enhance connectivity within managed landscapes (Fischer et al., 2006). A landscape approach ensures that biodiversity is not confined to isolated reserves but is integrated throughout production forests.

Reduced management intensity

Lower-intensity forest management generally benefits biodiversity. Practices such as longer rotation periods, selective logging, and reduced chemical use help maintain ecological integrity (Paillet et al., 2010). Combining reduced management intensity with designated conservation areas significantly improves biodiversity outcomes without fully compromising economic returns.

Promotion of native and mixed species

Using native species and promoting mixed-species stands are essential approaches for supporting biodiversity. Mixed forests provide a greater variety of ecological niches and are more resilient to disturbances (Jactel et al., 2017).

In the context of climate change, species diversity enhances adaptive capacity and reduces the risk of large-scale forest dieback. For the promotion and provisioning of certain ecosystem services also non-native species may be considered, especially for biomass production, since native species may not be reliable enough to ensure a stable supply in certain regions.

Conservation of disturbance regimes

Natural disturbances such as fire, windthrow, and insect outbreaks play a key role in shaping forest ecosystems. Emulating these disturbances through management can help maintain biodiversity and ecosystem processes (Kuuluvainen and Gauthier, 2018). However, such approaches must be carefully balanced with economic and safety considerations.

Adaptive and multifunctional forest management

Modern forest management increasingly adopts a multifunctional perspective, aiming to deliver multiple ecosystem services simultaneously. These include, among others, wood production, biodiversity conservation, carbon storage, and protection against natural hazards. Diversified management strategies combining different silvicultural systems across landscapes can enhance both biodiversity and ecosystem service provision (Messier et al., 2015).

Adaptive management is essential in the face of climate change and ecological uncertainty, as it remains unclear how particular tree species can cope with warmer climate (Gessler et al., 2026). Continuous monitoring and flexible decision-making allow forest managers to respond to changing conditions and improve long-term outcomes (Seidl et al., 2017).

Policy and economic instruments

The integration of biodiversity into forest management depends heavily on supportive policy frameworks and economic incentives. Certification schemes such as FSC and PEFC promote sustainable practices, while payments for ecosystem services can encourage conservation efforts (Bennett et al., 2015). Innovative economic instruments, including conservation auctions and carbon credits, can help balance economic and ecological objectives.

To conclude, having **productive and biodiverse forests is achievable in Europe**, but it is clear that integrating forest management and biodiversity conservation is a complex goal. While trade-offs are inevitable, they can be minimised through evidence-based, adaptive, and multifunctional management approaches. Key strategies include maintaining structural complexity, promoting species diversity, reducing management intensity, and implementing landscape-scale planning. By aligning forest management with ecological principles, it is possible to sustain both biodiversity and the ecosystem services upon which human societies depend.

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Long-lived wood products contribute to climate mitigation through carbon storage and material substitution © Brice Cooper (Unsplash)

Appendix: List of authors

Tommaso Chiti
Tuscia University
Italy

Zuzana Dobšinská
Technical University in Zvolen
Slovakia

Frank Krumm
Swiss Federal Research Institute (WSL)
Switzerland

Nataša Lovric
University of Eastern Finland
Finland

Maria Nijnik
The James Hutton Institute
United Kingdom

Andreea Spinu
University of Freiburg
Germany

List of Contributing Authors
Jürgen Bauhus
University of Freiburg
Germany

Denis Dobrynin
UEF Connect
Finland

Adam Felton
Swedish University of Agricultural Sciences (SLU)
Sweden

Oliver Frings
AgroParisTech
France

Lenka Haluskova
Technical University in Zvolen
Slovakia

Silvina Manrique
University of Alcalá
Spain

Simone Martino
The James Hutton Institute
United Kingdom

Mariana Melnykovych
Bern University of Applied Sciences
Switzerland

David Miller
The James Hutton Institute
United Kingdom

Stefanie Linser
BOKU University
Austria

Sandra Lupinen
University of Eastern Finland
Finland

Yoan Paillet
French National Institute for Agricultural Research (INRAE)
France

Petra Palátová
Czech University of Life Sciences Prague (CZU)
Czech Republic

Chad C. Papa
Michigan State University
United States

Ana Rey
National Museum of Natural Sciences (MNCN), National Spanish Research Council (CSIC)
Spain

Christian Rosset
Bern University of Applied Sciences
Switzerland

Patrick O. Waeber
Independent researcher
Switzerland

Livia Zapponi
Institute of BioEconomy (IBE)
Italy

Miguel Zavala
University of Alcalá
Spain

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IUFRO Headquarters
Marxergasse 2
1030 Vienna, Austria
Tel + 43 (0)1 877 01 51-0
Fax +43 (0)1 877 01 51-50
Email office@iufro.org
www.iufro.org