Norwegian University of Life Sciences
Faculty of Environmental Sciences and Natural Resource Management

MINA fagrapport 108

Climate-Smart Forestry in Norway -

Balancing Mitigation, Adaptation, and Forest Ecosystem Services

2025
ISSN 2535-2806

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Baardsen, S., Eid, T. & Hoen, H.F. 2025. **Climate-Smart Forestry in Norway - Balancing Mitigation, Adaptation, and Forest Ecosystem Services** – MINA fagrapport 108. 144 pp.

Ås, November 2025

ISSN: 2535-2806

AVAILABILITY

Open

PUBLICATION TYPE

Digital document (pdf)

QUALITY CONTROLLED BY

The Research Committee (FU), MINA, NMBU

PRINCIPAL

Norwegian Research Council

COVER PICTURE

Different forest pictures. Photo: Sjur Baardsen and Tron Eid, NMBU.

NØKKELORD

Klimasmart skogbruk, klimaendringer, karbonopptak og karbonlagring, klimatilpasning i skogbruket, skogøkosystemtjenester, internasjonal skogpolitikk, skogskader

KEY WORDS

Climate-smart forestry, climate change, carbon sequestration and storage, climate adaptation in forestry, forest ecosystem services, international forest policy, forest disturbances

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Foreword

This report from the Climate-Smart Forestry Norway (CSFN; NFR project 302701) project has been prepared by a team working under its fifth and final Work Package. We have aimed to synthesise insights gained from the first four Work Packages and to present them in a broader context informed by prior research on Climate-Smart Forestry and related concepts.

We acknowledge the significant contributions of our colleagues and collaborators, which form much of the basis for this synthesis.

The challenges posed by climate change call for a holistic approach that simultaneously addresses carbon sequestration and storage, reduces greenhouse gas emissions, and prepares forests to withstand changing environmental conditions. By combining recent findings with established knowledge, this report presents an integrated perspective on how Norwegian forests can contribute to climate mitigation, enhance resilience, and support multiple other ecosystem services within the forest.

We hope the management options and recommendations provided here will deepen the understanding of climate-smart forestry in Norway, and stimulate dialogue and discussion among policymakers, forest managers, forest owners, and others involved and interested in forestry. We aim to help stakeholders align climate objectives with broader sustainability goals. Furthermore, we hope this synthesis will inspire further research and collaboration, unlocking the full potential of Climate-Smart Forestry.

The authors acknowledge the substantial contributions and support from Dr. Joyce Machado Nunes Romeiro to this report, and the excellent suggestions provided by Associate Professor Per Kristian Rørstad. Thanks also to Director Harald Aalde, Ministry of Agriculture and Food (LMD), as well as Head of Industrial Policy Yngve Holth, Glommen-Mjøsen Skog SA, and Chief Forester of Romedal Almenning and Stange Almenning, Gaute Nøkleholm, for their valuable contributions to the conference we organized on this topic in September 2025.

Finally, we gratefully acknowledge the funding provided by the Research Council of Norway, which made this work possible.

Parts of early drafts of this report were linguistically assisted using OpenAI's ChatGPT. The authors have reviewed and are solely responsible for the final content. Likewise, Figures 11, 12 and 13 are created using ChatGPT (DALL·E), OpenAI, and checked by the authors. The use is in line with NMBU's guidelines for use of AI.

We would like to point out that a Norwegian-language version of this report is also available.

Ås, November 2025

Sjur Baardsen, Tron Eid, Hans Fredrik Hoen

Terms and Abbreviations used and their Definitions

Term	Definition
Albedo	The proportion of incoming solar radiation reflected by a surface. In boreal forests, increased coniferous tree cover typically reduces albedo, potentially offsetting some climate benefits from carbon sequestration and storage.
BECCS (Bioenergy with Carbon Capture and Storage)	A technology that converts biomass into energy, capturing and permanently storing the resulting CO_2, typically underground, thus generating negative emissions.
BECCU (Bioenergy with Carbon Capture and Utilisation)	Similar to BECCS, but instead of permanent storage, the captured CO_2 is utilised in industrial processes or products.
Biodiversity	Biological diversity, landscape diversity, and geological diversity, which are not primarily the result of human influence.
CAPM (Capital Asset Pricing Model)	A theoretical model, first developed for financial (stock) markets, used to determine the relationship between expected investment returns and risk.
Carbon Credit	An (often) tradable credit representing one tonne of CO_2 removed from the atmosphere, used in carbon markets or voluntary offset schemes.
CC (Climate Change)	Long-term significant changes in global or regional climate patterns, primarily driven by greenhouse gas emissions resulting from human activities.
CCF (Continuous Cover Forestry)	A forest management that maintains a continuous forest cover by means of the selection system, group selection system or shelterwood system.
CO_2 (Carbon Dioxide)	The primary greenhouse gas released through fossil fuel combustion or biomass oxidation (burning or decomposition), significantly contributing to global warming.
CO_2e (Carbon Dioxide Equivalent)	A standard metric to express the global warming potential of various greenhouse gases based on their equivalence to carbon dioxide, normally over a period of 100 years.
CRCF (EU Carbon Removal Certification Framework)	Forthcoming EU regulation establishing a certification framework for permanent carbon removals, carbon farming and long-lived carbon storage in products (additional private market).
CSF (Climate-Smart Forestry)	Forestry practices are designed to simultaneously mitigate climate change, adapt forest ecosystems to climate impacts, and support a variety of forest ecosystem services.
DDR (Declining Discount Rate)	A discounting approach where the discount rate decreases over time, often used for evaluating long-term climate and forestry investments.
Ecosystem	An ecosystem is a functional unit of nature consisting of living organisms (the biotic community: plants, animals, microbes) interacting with each other and with their abiotic environment (climate, soil, water, nutrients, atmosphere) through flows of energy and cycling of matter. Ecosystems

	can vary greatly in scale, from a small pond or forest stand to the entire biosphere.
EEA (European Economic Area)	An agreement that integrates Norway, Iceland, and Liechtenstein into the European Union's single market, influencing forestry regulations and policies within these countries.
Ecosystem Services	See Forest ecosystem services.
EU BDS (EU Biodiversity Strategy)	Strategy aiming to protect and restore biodiversity, influencing forest management policies in member states and EEA countries.
EU DR (EU Deforestation Regulation)	Regulation aiming to reduce deforestation and forest degradation by banning imports linked to deforestation-intensive supply chains.
EU ESR (Effort Sharing Regulation)	Regulation that sets national greenhouse gas reduction targets for sectors not covered by the EU ETS (such as transport and agriculture). Through agreements with the EU, Norway follows a similar effort-sharing approach for its non-ETS emissions.
EU ETS (European Union Emissions Trading System)	The EU's cap-and-trade system for greenhouse gas emission allowances. Norway participates in the EU ETS through the EEA agreement, aligning its industrial emission reductions with EU targets.
EXW (Ex Works)	An Incoterm (International Commercial Terms) indicates that the seller makes goods available at their premises, with the buyer responsible for transport and associated risks from that point forward.
FAS (Free Alongside Ship)	An Incoterm in which the seller delivers goods alongside a vessel at a named port, after which the buyer assumes responsibility for loading, shipping, and associated risks.
Forest Ecosystem Services	Benefits derived from forests include *inter alia* timber production, carbon sequestration and storage, water regulation, biodiversity conservation, and recreational opportunities.
FRL (Forest Reference Level)	In the EU's LULUCF rules, the FRL is the accounting benchmark for managed forest land: an estimate (t CO_2e/yr) of the average annual net emissions or removals expected from a country's managed forests over 2021–2025, calculated under criteria set in the regulation, and based on the period 2000-2009. It is used to compare actual future outcomes and derive credits/debits in the LULUCF pillar. For the period 2026–2030 it will be called the NFRL, and the reference period will be 2016–2018. If Norway does not incorporate the update into the EEA regulatory framework, the country will continue to use 2000–2009 as the reference period for the 2026–2030 period.
FSC (Forest Stewardship Council)	An international certification organisation promoting responsible forest management through environmental, social, and economic standards.
GBF (Kunming-Montreal Global Biodiversity Framework)	The post-2020 global deal on nature was adopted by CBD COP 15 (2022). Sets 23 targets for 2030, including conserving 30% of land and sea areas, restoring 30% of degraded ecosystems, and ensuring that forestry, agriculture and other uses are sustainable, alongside four 2050 long-term goals.
GHG (Greenhouse Gases)	Gases in the atmosphere that absorb longwave radiation. The principal greenhouse gases are water vapour, carbon dioxide (CO_2), methane

	(CH_4), nitrous oxide (N_2O), and fluorinated gases such as CFCs. Increased concentrations of CO_2 and other greenhouse gases in the atmosphere enhance the greenhouse effect, thereby contributing to global climate change. Defined in Annex A of the Kyoto Protocol.
HWPs (Harvested Wood Products)	Products derived from harvested wood (such as lumber, furniture, and paper) that retain stored carbon and influence carbon accounting over their lifespan.
IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services)	A UN body assessing global biodiversity and ecosystem services, analogous to the IPCC's role in climate change assessments.
IPCC (Intergovernmental Panel on Climate Change)	A UN organisation providing scientific assessments on climate change, its impacts, and strategies for mitigation and adaptation.
LULUCF (Land Use, Land-Use Change, and Forestry)	A category used in national climate inventories covering greenhouse gas emissions and removals from activities related to forestry and land-use changes and EU regulations.
MEA (Millennium Ecosystem Assessment)	A comprehensive UN-supported assessment (2001–2005) that introduced and popularised the concept of ecosystem services and evaluated global ecosystem changes.
Nature	Nature generally refers to the physical world and its phenomena, independent of human activity. It encompasses the totality of the Earth's living organisms (plants, animals, microorganisms) as well as non-living components (land, water, atmosphere, minerals, climate). In scholarly use, nature is often contrasted with "culture" or "human-made environments," though humans and their actions are increasingly understood as embedded within and influencing nature.
NDC (Nationally Determined Contribution)	A nationally determined climate target under the Paris Agreement. Countries submit and update their NDCs at least every five years, with increasing ambition. Norway's 2030 target is to reduce emissions by at least 55% compared to 1990 levels. In June 2025, the Norwegian Parliament adopted a new, legally binding target of 70–75% emission reductions by 2035, which has been submitted to the UN as Norway's new NDC. The target is anchored in the EU climate framework, and the government aims to achieve it without using carbon credits outside Europe.
NFI (National Forest Inventory)	A systematic, large-scale survey assessing forest resources, health, and productivity over time.
NIBIO (Norwegian Institute of Bioeconomy Research)	A Norwegian research institute dedicated to the sustainable utilisation of land-based resources, including agriculture, forestry, and other bioeconomy sectors.
Paris Agreement	A legally binding international treaty on climate change adopted in 2015, aiming to limit global warming to well below 2 degrees Celsius above pre-industrial levels, while pursuing efforts to limit it to 1.5 degrees. Part of the United Nations Framework Convention on Climate Change (UNFCCC).

PEFC (Programme for the Endorsement of Forest Certification)	An international forest certification system, widely adopted in Norway, promoting sustainable forest management practices.
Payments for Ecosystem Services	Financial incentives provided to forest owners or managers in exchange for managing land to supply certain ecosystem services. In forestry, payments for ecosystem services schemes can reward practices that enhance carbon sequestration and storage, biodiversity conservation, water regulation, or other public environmental benefits.
RF (Rotation Forestry)	A forest management that involves periodic clear-cutting or seed-tree establishment and removal within a defined rotation (regeneration lag plus harvest age, typically 50–150 years under Norwegian conditions) followed by replanting or natural regeneration.
Rotstop®	A biological fungicide (*Phlebiopsis gigantea*) is applied to freshly cut conifer stumps to prevent root rot caused by the fungus *Heterobasidion*.
Strong vs. Weak Separability	Concepts describing whether multiple outputs or services are interdependent (weak separability) or independent (strong separability) within production or utility analyses, particularly important for aggregation across scales (e.g., stand, property, landscape, region).
VERRA (Verified Carbon Standard)	A voluntary, private-sector carbon-credit standard and registry managed by the non-profit organisation Verra. It develops and maintains methodologies and rules for quantifying, monitoring, reporting, and verifying greenhouse-gas emission reductions and removals. Projects certified under VERRA issue Verified Carbon Units (VCUs) that can be traded in voluntary carbon markets, subject to criteria for additionality, permanence, and third-party verification.

Reader's Guide

If you are new to Climate-Smart Forestry (CSF), start with **Chapter 1: Introduction and Background**. This section provides context on CSF, explaining its significance for both climate mitigation (especially carbon sequestration and storage) and adaptation (increasing resilience). It also clarifies the objectives of this report: to offer recommendations addressing carbon sequestration and storage, balance multiple Forest Ecosystem Services, and manage associated risks.

For a conceptual foundation, proceed to **Chapter 2: Conceptual Framework**. This section explains how climate changes, such as shifts in temperature and precipitation, impact forests. It further introduces key concepts: forest ecosystem services, risk and uncertainty, and discusses how these intersect with the dual objectives of mitigation and adaptation. If you seek a deeper understanding of risk, uncertainty, and trade-offs (for instance, between carbon sequestration and storage, and biodiversity) in forest management, Chapter 2 will be especially beneficial.

If you manage forests or provide advice on planning and operations, **Chapter 3: Climate Change – Mitigation and Adaptation Measures** will be especially relevant. This section details a range of management measures and options and discusses associated climate-change impacts. It is divided into three subsections:

Section 3.1: Stand-level Forest Management – Includes detailed information on rotation forestry and continuous cover forestry. It provides practical silvicultural guidance and recommendations to reduce risks (e.g., bark beetles, windthrow) while meeting carbon sequestration goals.

Section 3.2: Property level – Covers spatial and temporal harvest planning, strategies for responding to unexpected disturbances (such as storms or wildfires), and logistical coordination of operations. It highlights practices like salvage logging after disturbances, adaptive scheduling of thinning and harvest ages, and measures to protect water resources and biodiversity at the property scale.

Section 3.3: Landscape to National level – Addresses larger scale issues including zoning for different land uses, peatland (and the broad concept wetland in some cases) conservation or restoration, and multi-scale risk management. This subsection is essential for understanding how broader landscape planning and regional coordination can enhance resilience beyond individual properties.

For insights into the contribution of harvested wood products to climate mitigation, consult **Chapter 4: Harvested Wood Products (HWPs) and Their Role in Climate Mitigation**. This section explores how wood products store carbon over long periods, the substitution effects of using wood in place of more carbon-intensive materials, and avenues for possibly negative emission technologies such as bioenergy with carbon capture and storage/utilisation (BECCS/BECCU).

To gain an understanding of overarching policies and frameworks, refer to **Chapter 5: Policy and Institutional Framework**. It provides an overview of how CSF aligns with international and national policy efforts, including the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC), European Union initiatives, and Norwegian policies. This section outlines incentives and instruments (like subsidies, carbon-credit schemes, and certification programmes) that are available to forest owners and other stakeholders to support climate-smart practices.

Chapter 6: Policy Narratives presents seven stylised perspectives, each emphasising different goals - economic, environmental, social, or climate-oriented. By exploring these diverse management narratives, this section highlights where synergies and trade-offs may occur among competing objectives. Readers interested in how shifting emphasis (e.g. prioritising economic return vs. biodiversity conservation vs. climate mitigation) leads to different outcomes may find this section insightful.

For direct and practical recommendations aimed at the public sector and policymakers, and public institutions, turn to **Chapter 7: Recommendations for Climate-Smart Forestry from a Societal Perspective**. This section builds on the preceding analyses, with a public and societal interests' perspective (including the management of publicly owned forests). It discusses how governmental bodies, and public agencies can support and implement CSF to enhance resilience, conserve biodiversity, and ensure economic sustainability of the forest-based sector.

Closely related, Chapter 8**: Recommendations for Climate-Smart Forestry from a Forest Owner Perspective** mirrors the structure of Chapter 7 but is tailored to the operational decision-making of private forest owners and forest owner associations. While Sections 7 and 8 cover similar thematic areas and recommendations, Chapter 8 addresses the specific responsibilities, constraints, and opportunities faced by individual forest owners. Both sections are designed to stand alone as recommendations, drawing upon the analyses presented in earlier sections (which means there is some necessary repetition of key points). The recommendations have as a prerequisite that forest owners follow forest certification schemes.

Content

Summary

This report synthesises findings from the Climate-Smart Forestry Norway (CSFN) project, integrating them with recent research on forest and climate. Combining recent insights with proven principles, it presents a comprehensive approach addressing climate change mitigation (e.g., carbon sequestration and storage) and adaptation (e.g., enhancing resilience to disturbances) while taking multiple Forest Ecosystem Services into account.

Why Climate-Smart Forestry Matters
CSF arises from the urgent need to mitigate climate change while adapting forests to increasingly unpredictable conditions. Norway's boreal forests, facing longer growing seasons and more frequent extreme events (storms, droughts, insect outbreaks), may sustain robust carbon sequestration and storage in both biomass and harvested wood products while preserving biodiversity, recreation opportunities, water regulation and more. Achieving these multiple goals requires integrated approaches that balance ecological, economic, and social dimensions, recognising that climate change may undermine previously reliable forestry practices. Flexibility, long-term monitoring and planning thus become essential for forest owners and policymakers aiming to protect forest health, maintain steady revenues, and uphold vital ecosystem functions.

The Conceptual Framework
A key premise of the report is the need to balance mitigation and adaptation under the broader umbrella of forest ecosystem services. For example, maximising roundwood production could compromise habitat quality or scenic values, whereas adopting continuous cover forestry will reduce immediate timber yields but enhance long-term resilience. The extended timescales of boreal forestry, typically 50 to 150 years for a rotation (regeneration lag plus harvest age), amplify the planning challenge amid uncertain policy landscapes, market preferences, and climate scenarios. To address these complexities, the report advocates adaptive planning where day-to-day silvicultural decisions inform and adjust long-term strategies.

Management Measures at Multiple Scales is necessary

Stand-Level Approaches
Stand-level actions apply silvicultural principles to individual forest stands. Traditional rotation forestry involves distinct phases with regeneration, young growth tending, thinning, and final harvesting, while continuous cover forestry aims for a certain minimum forest cover maintained over time. Techniques like soil scarification, targeted treatment of stumps to prevent root rot, and choosing appropriate tree species distributions and densities can enhance stand stability and productivity. Similarly, careful planning of thinning and harvest age can impact both carbon sequestration and adaptation outcomes. There is no "one size fits all" recipe; a holistic approach to decision-making that balances different objectives is required.

Although individually small-scale, these stand-level measures can cumulatively yield considerable benefits when combined with active monitoring. If conditions deteriorate due to extreme weather or pest outbreaks, timely interventions can limit damage, thereby safeguarding carbon stocks, biodiversity values, and financial returns.

Property-Level Strategies
Most Norwegian forest properties contain multiple stands, making spatial and temporal coordination essential at the property level. Aligning harvest schedules across stands, avoiding large contiguous clear-cuts, and integrating features like riparian buffers or biodiversity corridors can reduce vulnerability to disturbances while preserving recreational and landscape value. Incorporating peatlands (and wetlands) into management plans provides additional risk mitigation by moderating flood risks, maintaining water quality, and protecting carbon-rich soils.

The forest management plan should be developed so that it to a larger extent can serve as a central tool when applying climate-smart forestry. Such a plan may provide an integrated overview of forest resources supporting the forest owner in assessing climate mitigation and adaptation measures such as tree species selection, harvesting strategies, and risk management.

Detailed property monitoring and the use of mapping tools may enhance management efficiency, enabling forest owners to align silvicultural interventions with market signals and ecological conditions. Such planning fosters stronger synergies among various forest ecosystem services. For example, a well-designed forest road network can simultaneously facilitate efficient timber extraction, support recreational access, and improve response times for wildfire control.

Landscape, Regional and National Coordination

Some challenges and disturbances transcend property boundaries, requiring cooperative responses at the landscape or regional level. Pest infestations, storm-felling events, and wildfires, may spread across multiple properties, necessitating shared monitoring efforts and coordinated action plans. National and international policies also shape management choices; regulations on biodiversity conservation, carbon accounting rules, and land-use plans can incentivise or constrain certain practices. This report calls for harmonised land-use frameworks that accommodate both commercial forestry and conservation needs, alongside robust early-warning systems to detect emerging threats. Coordinated cross-boundary planning, data sharing, and collective investments in research may enhance forest resilience and adaptive capacity at larger scales.

The Role of Harvested Wood Products

Harvested wood products (HWPs) extend the climate benefits of forests beyond the lifetime of the stand. Long-lived wood products, like structural timber in buildings or wood in insulation or in furniture, effectively store carbon in the built environment for decades. Substituting wood for more emission-intensive materials like steel or concrete reduces emissions, magnifying forestry's mitigation impact. Bioenergy with carbon capture and storage/utilisation (BECCS/BECCU) offers potential pathways for negative emissions when substitution is included, although technological, policy, and market uncertainties remain.

Realising the full climate mitigation potential of HWPs depends on factors such as strong demand for bio-based materials, transparent carbon accounting methods, and investment in wood processing and carbon capture technologies. Without supportive market and policy conditions, traditional roundwood production might remain the dominant objective, which could limit forestry's broader contribution to national climate targets.

Economic and Policy Considerations

Boreal forestry involves economic complexities due to its long-term horizons. Lengthy rotation periods complicate traditional cost–benefit analyses, especially under uncertainty about future climate impacts, timber markets, and policy changes. We argue that diversifying risk, for example by managing a mix of species and developing multiple revenue streams (timber, carbon credits, recreation), can improve outcomes for both forest owners and society. We also recommend declining discount rates in economic evaluations to avoid undervaluing long-term benefits like carbon sequestration and biodiversity conservation.

Public incentives and policies play a crucial role. Subsidies, carbon credit trading mechanisms, and international commitments like EU directives can accelerate the adoption of climate-smart practices. However, these instruments require careful design to remain effective as economic conditions change. If policy goals do not match everyday realities, they can undermine both the profitability of forestry operations and the health of forest ecosystems. In practice, forest owners may lack the resources or capacity to meet rigid rules. Therefore, policies should be adaptable and designed to fit what owners can realistically implement.

Narratives

Notably, the report includes multiple "policy narratives" or scenarios that illustrate how emphasising different goals (economic, environmental, social, or climate-focused) leads to varying trade-offs and synergies. This analysis underscores the importance of balanced, integrated strategies rather than one-dimensional approaches.

Practical Guidance and Implementation

We recommend that both authorities and forest owners integrate climate mitigation and adaptation measures into regular forest management, with a long-term perspective. In practice, the most important instrument is an updated and functional forest management plan. The forest management plan of today comprise few elements that are directly linked to climate change. We therefore recommend authorities to initiate a development of the forest management plan in a direction that to a larger extent enables it to work as an active decision-support tool under climate change. Such a plan should include considerations related to carbon sequestration and storage, identification of risk prone areas (e.g. areas with increased risk for wind, drought or insect damages), tree species selection and harvest planning adaptation. The plan may also integrate measures for biodiversity and hydrology and be linked to digital data bases for continuous updating. For the forest owner, such a plan will provide a detailed overview of the forest resources and enable the assessments of measures that strengthen carbon sequestration and storage and increase resilience to climate change. For the society, such forest management plans will constitute an important knowledge base to ensure that local measures support national climate and biodiversity targets.

From a societal perspective, we recommend that climate-smart forestry be anchored in clear frameworks and policy instruments. Authorities should strengthen compliance with existing legislation and certification requirements, particularly the regeneration obligation; continue to provide easy access to data on environmental values and forest conditions and further develop instruments that motivate forest owners to implement climate measures. We recommend that policies and planning place greater emphasis on climate adaptation, for example through requirements for species selection, improved monitoring of forest health, and increased coordinated action following damage from extreme weather. Coordination across property boundaries and governance levels is essential for addressing systemic risks such as bark beetle outbreaks and storm damage.

For practical implementation, forest owners should prioritise adequate regeneration, early tending of young stands, risk-conscious forest management programmes, and consideration for biodiversity. Available subsidies and advisory services can facilitate the adoption of climate measures. Cooperation with neighbouring properties, forest owner associations, and local authorities can contribute to more effective measures and improved preparedness.

Overall, practical climate-smart forestry is about linking long-term planning, continuous knowledge updates, and coordinated efforts between forest owners and authorities. A forest management plan that is actively used is the key tool for making this operational and ensuring that both the forest owner's and society's climate and biodiversity objectives are achieved.

1 Introduction - From Sustained Yield Forestry to Climate-Smart Forestry

Forestry concepts and management paradigms have evolved greatly since the 19th century, mirroring shifts in societal needs, scientific understanding, and environmental priorities.

Sustained-Yield (Enduring) Forestry – 19th Century Origins
The earliest modern paradigm was sustained-yield forestry, which emerged during the 18^{th}–19^{th} centuries in Europe as a response to deforestation and timber shortages (see e.g. Lowood (1990) and Frivold (2011)). Rooted in the concept of harvesting only as much timber as could be naturally regenerated, this approach sought to ensure a perpetual supply of wood. German foresters formalised this idea into what became known as *Nachhaltigkeit* ("sustained yield"), as famously articulated by von Carlowitz (1713). By the late 19th century, the sustained-yield doctrine had become the dominant framework in forestry, establishing a regulated, perpetual harvest system often achieved by converting diverse natural forests into even-aged stands.

Multiple-Use Forestry – Broadening Objectives in the Mid-20th Century
By the mid-20th century, there was a growing expectation that forests should provide more than timber alone. The multiple-use forestry paradigm emerged to balance a wider array of uses, including watershed protection, wildlife habitat, and recreation, alongside wood production. In the United States, the 1960 Multiple Use - Sustained Yield Act mandated that national forests should be managed for a "balanced combination" of outdoor recreation, rangeland, timber, watershed and wildlife purposes. This approach expanded forestry's scope by incorporating multiple renewable resources into management objectives. Multiple-use forestry thus maintained the principles of sustained yield for timber but extended the concept to accommodate broader societal needs.

Sustainable and Multifunctional Forestry – Late 20th Century Integration
The concept of sustainable forestry, or sustainable forest management (SFM), gained prominence in the late 20th century, influenced by the global environmental movement and the 1987 Brundtland Report's call for sustainable development (WCED 1987). SFM built upon sustained yield by aiming to preserve not only timber yields but also the other ecological, economic, and social functions of forests (MCPFE 1993; FAO 2005). In tandem, the notion of multifunctionality emerged, emphasising that forests inherently deliver a suite of services, from wood production and climate regulation to soil protection and cultural values. Multifunctional forestry (MF) underscores the need to manage these outputs concurrently rather than compartmentalising them. Together, sustainable and multifunctional forestry frameworks have guided policies and certification schemes worldwide, establishing criteria that ensure forests can remain productive, resilient, and beneficial on multiple levels.

Forest Ecosystem Services – From Concept to Practice
Advances in ecological science further suggested the Ecosystem Services (ES) framework, which categorises the benefits from SFM and MF into provisioning, regulating, cultural, and supporting services (MEA 2005; Costanza et al. 1997). We will specify the same concept as Forest Ecosystem Services. This perspective influenced policy and management practices, leading to the development of tools such as Payments for Ecosystem Services (PES), although such already existed for many forest activities.

Nature-Based (Close-to-Nature) Forestry – Working with Natural Processes
Nature-based forestry, which draws on the long tradition of close-to-nature silviculture in Europe, advocates managing forests in harmony with natural ecological processes (Schütz 1999; Brang 2001). This paradigm favours continuous cover forestry, natural regeneration, mixed-species stands, and selective harvesting. Nature-based forestry not only enhances long-term productivity and resilience but also supports biodiversity and other ecosystem functions by working with the forest's inherent regenerative processes rather than imposing artificial uniformity.

Climate-Smart Forestry – Integrating Climate Change Goals
Emerging in the 2010s as a direct response to the escalating climate crisis, CSF extends sustainable forest management by explicitly incorporating climate change mitigation and adaptation into its core objectives. Climate-Smart as a concept was introduced by Hansen et al. (2010) and articulated for forestry by Nabuurs et al. (2015) and further refined in subsequent research (FAO 2017; Kauppi et al. 2018; Yousefpour et al. 2018; Bowditch et al. 2020; Verkerk et al. 2020, 2022; Ekholm et al. 2023; and Shephard & Maggard 2023). CSF is structured around three pillars: reducing and removing greenhouse gas emissions, enhancing forest resilience to climate change, and sustaining or increasing forest productivity and associated socio-economic benefits. Rather than replacing established forestry paradigms, CSF reframes them through a climate lens, seeking win–win strategies that align climate objectives with ecological and social outcomes. For instance, climate-smart management may involve altering species composition to better cope with future climatic conditions, adjusting harvest ages to maximise carbon storage, or promoting wood use as a substitute for more carbon-intensive materials.

Overlaps and Distinctions
As with its conceptual predecessors, CSF overlaps strongly with earlier paradigms in its commitment to sustainable, multi-benefit management and often employs practices derived from green and nature-based forestry (e.g. enhancing natural regeneration to boost resilience). Its distinguishing feature is the prioritisation of climate change as a central driver, integrating both mitigation (through carbon sequestration and emissions reduction) and adaptation (by enhancing forest resilience) into forest management strategies. This integrated approach rebalances traditional objectives by placing new emphasis on managing forests as critical carbon sinks while ensuring their continued delivery of ecological, economic, and social benefits.

Climate-Smart Forestry Today – Boreal Context and Global Relevance
Climate-smart forestry has quickly moved from theory to practice in policy agendas worldwide. In Europe, it is promoted to meet carbon-neutral targets, and in North America, federal initiatives are increasingly incentivising climate-smart land management. Nowhere is its relevance more evident than in boreal forests, which comprise about 30% of the world's forest area and store a disproportionate share of global terrestrial carbon. As boreal regions experience warming at roughly twice the global rate, with attendant increases in wildfires, pest outbreaks, and permafrost thaw, climate-smart practices have become essential.

Typically, CSF addresses how forests and the forest-based sector need to adapt to likely changes in climate and environment while at the same time increasing productivity, contributing to sequestration and storage of CO_2 and providing benefits to owners and society of all kinds of forest ecosystem services. Our approach is in line with this. We propose recommendations to:

1) Mitigate climate change (i.e. reduce climate forcings by enhancing carbon sequestration and storage in living and dead forest biomass, in forest soil and in harvested wood products (HWPs)) and promote the use of HWPs when they replace alternatives (cf. Section 4.2) with a larger "CO_2-footprint", i.e. decarbonising the global economy (Verkerk et al. 2022) and adjust for consecutive changes in albedo if relevant.
2) Adapt forest management to a changing climate for improving forest resilience to natural disturbances such as bark beetle damages, root rot damages, windthrow, snow damages, drought damages, and wildfires at the stand, property and landscape level.

Recommendations should further (Nordic Council of Ministers 2017; Luyssaert et al. 2018; Hetemäki et al. 2024):

3) Take due consideration of other FES (cf. Section 2.4.1).
4) Incorporate (weigh) risks and uncertainties (cf. Section 2.4.2).
5) Finally, account for potential synergies and trade-offs among objectives (cf. Section 2.4.3).

It has earlier been argued that climate change adaptation and mitigation will impose a paradigm shift in theoretical and practical forestry (Schoene & Bernier 2012). Our approach is more modest and practically oriented and developed with forest stakeholders as a primary target audience. We have followed a kind of “bottom-up" approach, considering measures and actions at the stand-level (Section 3.1), property level (Section 3.2) and landscape, regional and national level (Section 3.3) and aimed for practical relevance and adaptability (Bull et al. 2018).

2 Conceptual Framework

2.1 Introduction

Our framework (Figure 1) starts with identifying likely changes in climate and the corresponding impacts on forests. We then follow two separate lines of analysis:

- **mitigation**, i.e. how changes and adjustments in forest management may improve the climate-forcing effects from forests and forest-based products, and
- **adaptation**, i.e. how management may be adapted to increase the forest resilience to natural disturbances in a changing climate.

We first analyse these two items in isolation. Then, we include a broader Forest Ecosystem Services perspective synthesising impacts along environmental, economic, and social dimensions, including considerations related to risk and uncertainty and synergies and trade-offs.

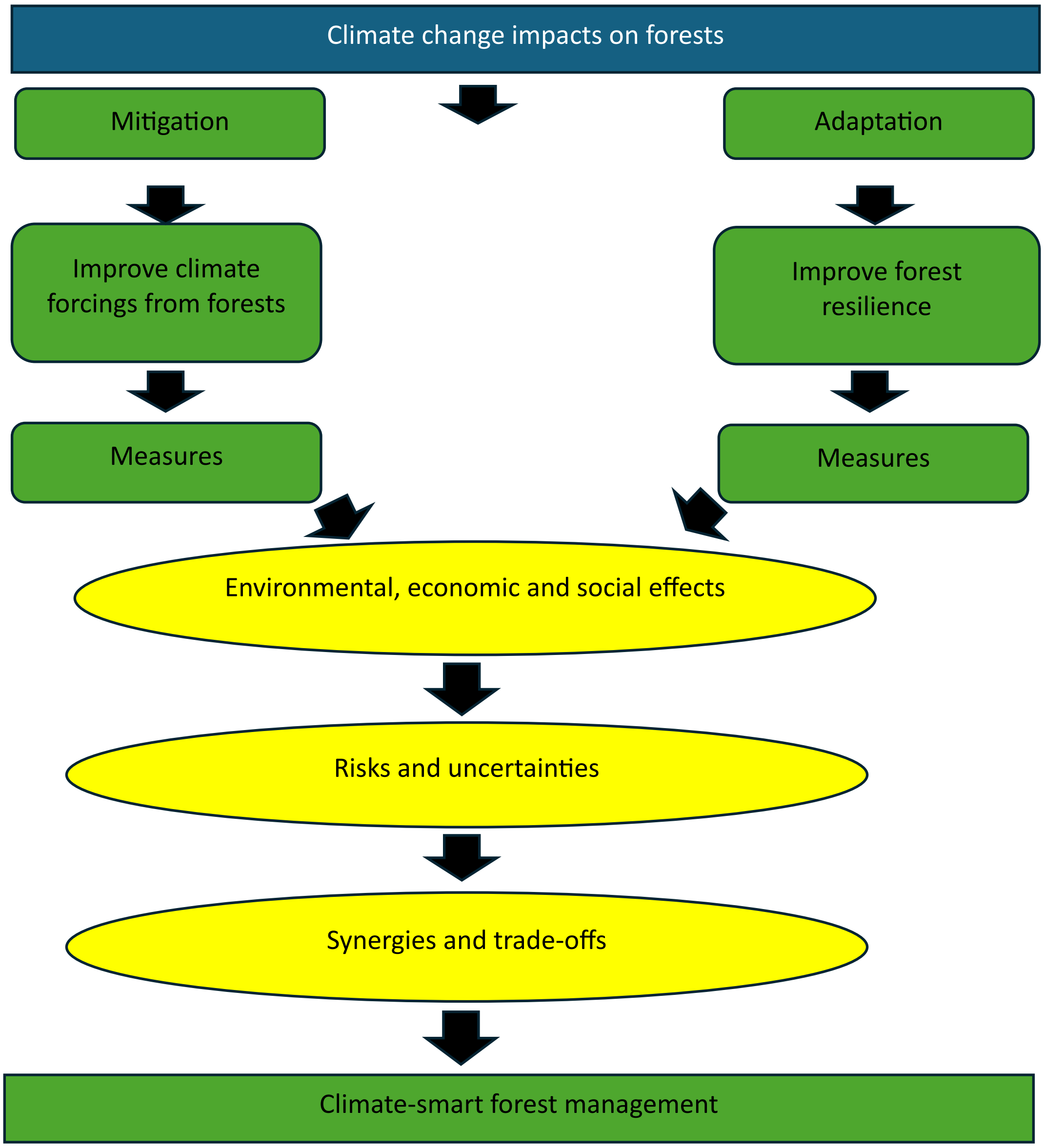

Figure 1. Conceptual Framework.

2.2 Climate Change and Impact on Forests

Increased temperatures and precipitation are generally expected in the northern regions of Europe, including Norway, due to climate change (IPCC 2019; 2022). In addition, more frequent extreme events such as storms, heavy rainfall and snowfall, floods, and drought periods are expected (Walsh et al. 2020; Seneviratne et al. 2023). These changes will likely have a significant impact on growth and production and on the frequency and severity of natural disturbances in Norwegian forests.

2.2.1 Forest Growth and Production

The extent and in what way climate change influences the long-term forest production (volume growth in a forest sector perspective) in Norway depends on many different factors. Climate change influences the actual growth of individual trees and the rates of natural mortality and regeneration. There may also be large regional differences regarding the impacts, where, for example, growth in northern and high-altitude forest areas is limited by temperature, while growth in southern forest areas is limited by precipitation. When considering long-term production, it is also difficult to disentangle the direct effects of climate change from management changes and other influencing factors such as nitrogen deposition and improved genetic plant material.

In general, it can be observed that the site index (dominant height growth) for stands established later generally tends to be higher than for stands established earlier, despite similar site conditions. However, based on Norwegian NFI sample plot data, Sharma et al. (2012) observed that this site index trend for spruce and pine has shifted to be faster over the last 60 years. This shift is likely caused by dynamic changes in growing conditions over time. They conclude that even though increased temperature and precipitation after 1990 seem to contribute, increased nitrogen availability and higher atmospheric CO_2 levels may also be important factors.

By using core samples from spruce and pine trees (tree ring data) and climate data from Norwegian NFI sample plots, Merlin et al. (2024) analysed the correlations between diameter growth and temperature and precipitation for the 1960–2020 period. Despite a warmer and wetter climate when comparing the 1960–1990 and 1990–2020 periods, they found that for both species the long-term diameter growth-climate relationship has remained relatively stable between the 1960-1990 and 1990-2020 periods.

These two examples illustrate that for individual tree growth, the climate change impacts might be positive, but they are, so far, generally small. The impacts of climate change on regeneration and mortality are uncertain, but most probably the mortality will increase due to more extreme weather conditions. . Lately, concerns have been raised because of a decrease in the standing volume for spruce observed in Norway since 2010 (Breidenbach et al. 2024). This decrease is partly attributed to reduced areas in the most productive development phases (development class III-IV) and a generally high harvest level over the past years, but also to increased natural mortality. When harvest level plus natural mortality is larger than growth, the standing volume will decrease. This has now been observed for spruce, especially in southeastern Norway, where intensive management has been applied. We do not know for certain if the increase in natural mortality is directly related to climate change. Similar recent trends are also observed in Finland and Sweden (Henttonen et al. 2024; Laudon et al. 2024). In the Swedish case they state that “climate-related drought is the most likely cause” and emphasise that research is urgently needed to avoid worsening the situation and delaying potential necessary adaptation in the management.

The recent development presented above reinforces with what has been the trend over a longer time period. The annual gross increment on the forest area in Norway has fluctuated around 24-26 million m^3 of stemwood (under bark) over the last 20 years (Statistics Norway, The National Forest Inventory, table 06289). This equals around 65% of reported national CO_2 emissions over the same period using a conversion coefficient of 1.375 t $CO_2 \cdot m^{-3}$ to convert one cubic meter of stemwood into sequestered carbon dioxide of whole-tree biomass (Kauppi et al. 2022). Higher conversion factors have been reported, i.e. 1.46 t $CO_2 \cdot m^{-3}$ (Rørstad 2022a) and 1.8 t $CO_2 \cdot m^{-3}$ (Løken et al. 2012), implying higher proportions for gross and net CO_2 uptake through forest growth compared to national emissions. The average net uptake (whole-tree biomass) in the forest area (gross growth minus natural mortality and harvest removals) fluctuated around 7-12 million m^3, corresponding to 18 - 31% of the emissions. For the period 2004-2023, Norway reported on average that the Land Use, Land-Use Change, and Forestry (LULUCF) sector contributed to sequestering 19.2 mill. ton CO_2e annually or around 36% of average national emissions from all other sectors (Miljødirektoratet 2023). However, the trend is a decline as the increase in growing stock started to level off, and the growth rate has fallen steadily from 3,54% in 2004 to 2,39% in 2023 (Statistics Norway, The National Forest Inventory, table 06289, see Figure 2). In absolute terms (percentage points), the decline in the growth rate is most pronounced for spruce, with a change from 4,24% in 2004 to 2,88% in 2023 (1,36%-points), for pine the growth rate fell from 2,58% in 2004 to 1,79% in 2023 (0,79%-points) while the growth rate for broadleaves fell from 3,56 in 2004 to 2,30 in 2023 (1,26%-points). For pine and broadleaves, the decline in growth rates started about a decade earlier than for spruce. For spruce, this development is likely connected to increases in both harvesting (overweight on productive sites) and natural mortality (Breidenbach et al. 2024), while for pine and broadleaves a result of reduced growth due to ageing.

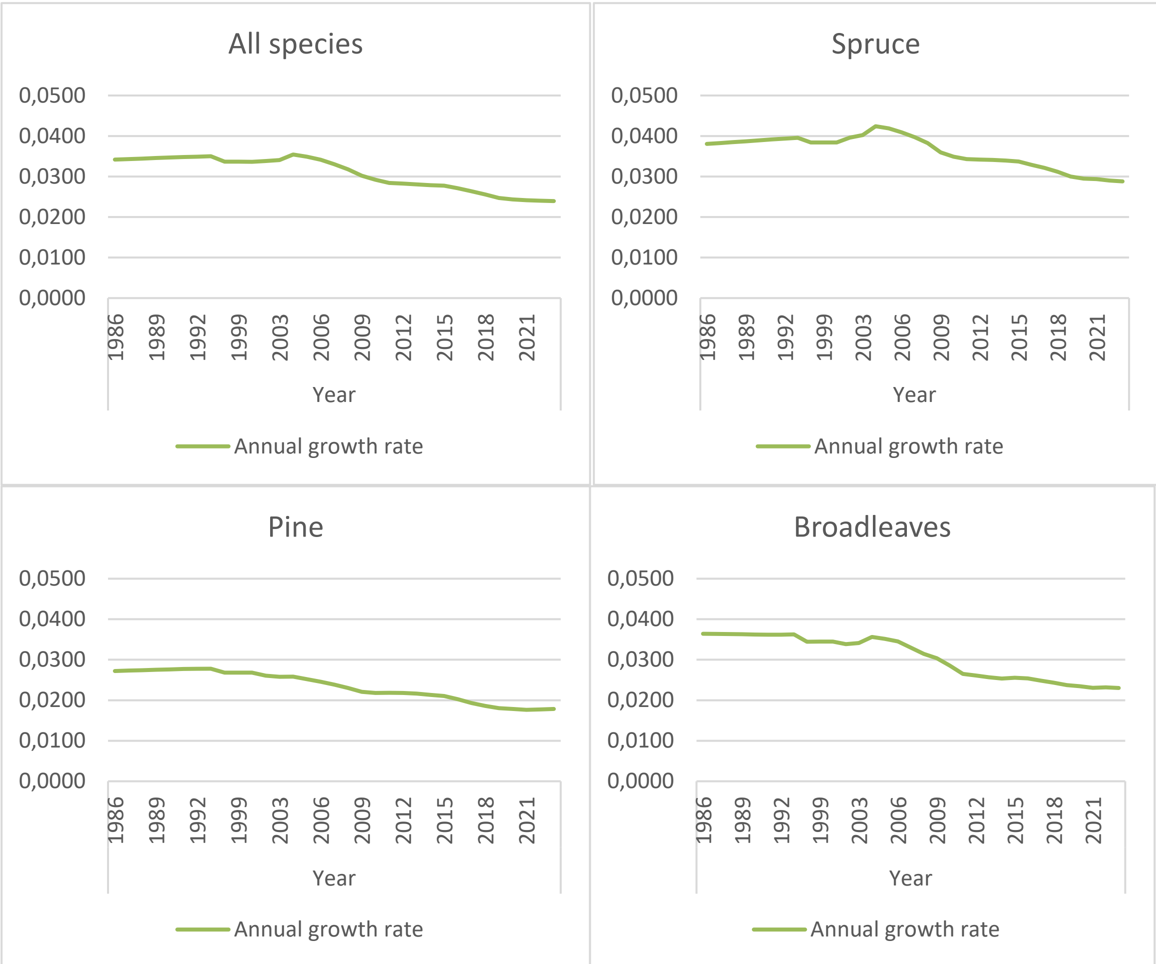

Figure 2. Gross growth rates in Norway (annual increment/growing stock for all areas) 1986 – 2023, based on SSB, the National Forest Inventory, table 06289.

2.2.2 Natural Disturbances

Climate change imposes intensified and new risks to forests in Norway. This will likely, directly and indirectly, increase the occurrence and severity of natural disturbances such as bark beetle damage, root rot damage, windthrow, snow damage and wildfires. These events will affect boreal forests in general (Girona et al. 2023) as well as in the Nordic boreal regions (Venäläinen et al. 2020; Romeiro et al. 2022; Patacca et al. 2023; Romeiro et al. 2024). Although natural disturbances play important roles in nutrient cycling, in shaping structural heterogeneity of forests, and for biodiversity (Berglund & Kuuluvainen 2021), they also have negative impacts on the carbon storage and economic performance of commercial forestry activities (Knoke et al. 2021). As climate-driven disturbances intensify, active response measures become critical (see Section 3.2.2 for disturbance-management strategies such as salvage logging and wildfire control).

Díaz-Yáñez et al. (2016) showed that browsing damage occurred in 4% of the productive permanent plots from the Norwegian National Forest Inventory (NFI) between 1995 and 2014. This was the most frequent damaging agent before snow damages (3%), wind (2%), insects (1%) and fungi (1%). Information on monetary losses due to natural disturbances in the Nordic boreal forests is scarce, but as an example, Lehtonen et al. (2016) reported that over the past three decades, the annual insurance payouts in Finland due to snow damages averaged EUR 0.5 million, which constituted 7% of the total insurance compensation to forest owners. Payouts may, however, reach several million following severe snow damage events. Economic losses in Norway caused by snow damage were estimated to be EUR 3 million in southeastern Norway in the winter of 2020-2021 (Zubkov et al. 2024). Looking ahead, snow loads are generally expected to decrease in Norway, although projections show regional variations with an increase in the southeast (Solberg et al. 2018).

Across Europe, bark beetle damage has already reached unprecedented levels. In 2019, the Czech Republic reported 20.7 million m^3 of affected spruce (Fernandez-Carrillo et al. 2020), while Germany reported 43.3 million m3 damaged by insects, mainly the spruce bark beetle (Statistisches Bundesamt 2021). From 2018 to 2023, bark beetles killed an estimated 32 million m^3 of spruce in southern Sweden, with further increases expected in the coming years (Swedish Forest Agency cited by Kärvemo et al. (2023)). Although Norway has not experienced major bark beetle outbreaks since the 1970s, there is growing concern among researchers and forest managers about potential future outbreaks due to climate change. Specific figures on the volume of spruce trees affected by bark beetles in Norway are not readily available. Gohli et al. (2024) collected bark beetle trap data (1731 trap locations in different parts of Norway) over a period of 17 years without large outbreaks and used information from the surrounding landscapes on forest conditions and climate to identify factors influencing bark beetle population sizes. They found that the volume of mature spruce (m^3/ha), extent of newly exposed clear-cut edges, temperature and soil moisture were the most important factors. There are also concerns related to the bark beetle's ability to complete two generations within the same growing season, with a warmer climate. Previously, this was seldom observed, but in recent years completion of two generations has been frequently observed in south-eastern Norway (Krokene et al. 2025). This escalates the risk of new invasions and outbreaks. This combined pressure of warming conditions and expanding pathways intensifies threats not only from existing pests like bark beetles but also from historically minor or entirely new insect species that may establish in Norway's forests.

2.3 Forest Management for Mitigation and Adaptation

Rotation forestry in boreal forests, such as in Norway, has long production cycles (rotations) spanning from 50 to 150 years (or more), introducing substantial uncertainty and risk to the *ex-ante* assessment, ranking and sequences of individual treatments. This takes different forms depending on future scenarios on global emissions (greenhouse gas emission pathways) and consequential changes in climate, how this influences forest productivity, vulnerability and resilience at local (stand) and aggregated (landscape) scales, to how CC may influence policies and markets. Will market forces and policy changes be strong enough to let a "green shift" materialise and decarbonise global economies?

If so, how long will such a development take? Risks and uncertainties will be connected to developments, changes or shocks in physical environments (e.g. windstorms, heavy rain and snowfall, droughts, insects and wildfires) as well as in economies, commodity markets (prices of products, input factors, logistics) and policies. We try to consider uncertainties and risks in our analyses and considerations.

Treatments may also interact in time and space. In forestry, the timing and intensity of treatments in a schedule will influence the productivity and resilience at the local (stand) level through time (over the rotation). The location of treatments will influence the productivity and resilience in space or across the landscape. Clear-felling one stand may significantly alter susceptibility to storm or fire in neighbouring stands, as examples of the latter. In the synthesis and identification of recommendations, we thus try to incorporate possible synergies or trade-offs among options and treatment alternatives. An example of synergy may be changing the dominant species from spruce to pine on drought-exposed sites, making the stand more drought-resilient, less prone to storm-felling and less exposed to insect damage from bark beetles (*Ips typographus*), but at the same time perhaps more exposed to browsing damage.

Mitigation and adaptation measures imply considerable changes to the forest area and require a long period to be implemented over the whole forest area. Changes in tree species distributions, for example, can mainly only be done following a final harvest. Since 1950, we have annually regenerated about 1-2% of the forest area, which means that a period of 50 to 100 years is required to change the species distribution if we aim for this over the entire forest area. Similarly, converting forest areas with an even-aged structure, treated according to rotation forestry (RF) principles, into uneven-aged structures suitable for continuous cover forestry (CCF) can only be accomplished over many decades.

The uncertainty of the development in temperature, precipitation and extreme weather events under climate change is large, particularly over the very long production cycle needed for forest production. The stress factors influencing the forest are likely to increase over time and may even accelerate. An important basis for adaptation is therefore to preserve a flexibility facilitating the possibility of applying changes in treatments over time. It is, for example, much easier and faster to remove tree species than to add new species if conditions change. The mitigation and adaptation concepts are operationalised through concrete actions at multiple scales (see Sections 3.1–3.3 for detailed interventions at stand, property, and landscape levels).

2.4 Synthesising

This section discusses and gives examples of how forest management oriented to biomass or roundwood production may influence forest ecosystem services in a broader sense, discusses and considers risk and uncertainty when analysing and prioritising treatments and management options and to what extent synergies and trade-offs arise when two or more treatments or measures are implemented simultaneously. Hetemäki et al. (2024) provide a recent review of literature dealing with synergies and trade-offs in European forest bioeconomy research. They highlight that synergies and trade-offs in the European forest bioeconomy are frequently studied, yet often with varying definitions and scopes. A key finding from their review is that while trade-offs between wood production and biodiversity conservation are well established, other trade-offs, such as those between carbon sequestration, albedo effects, and water regulation, remain underexplored.

Studies highlight the importance of integrating climate change mitigation and adaptation strategies within forest management to address both economic and ecological sustainability challenges. Locatelli et al. (2015) categorise these interactions into three conceptualisations: joint outcomes, unintended side effects, and joint objectives, which reflect how adaptation and mitigation strategies can either complement or counteract each other. The trade-offs involved in these strategies, particularly in forest bioeconomy research, are crucial when assessing long-term policy effectiveness and resilience to climatic uncertainties.

2.4.1 Broad Forest Ecosystem Services Perspective

In the process of establishing the "millennium goals", the concept of ecosystem services (ES) evolved as a theory and framework for better explaining and understanding the interaction and relationship between nature, ecosystems, people and society (MEA 2005, cf. also Chapter 1). According to this framework, nature contributes to the welfare and benefit of humans through four main categories of services: i) basic life processes or supporting services, ii) regulating services, iii) provisioning services and iv) cultural services.

Basic life processes, also called ecosystem functions or supporting services, are needed for life on earth and all the other services - e.g. photosynthesis, primary production, nutrient cycling, soil and sediment formation. Regulating services are what nature contributes to providing a safe and sound environment - for example, climate regulation, (clean) water, disease regulation, biodiversity, pollination, and protection against floods. Provisioning (supply) services are the goods we get from nature - e.g. food, wood and fibre, fuel, genetic resources and biochemicals, while cultural services, also called experience and knowledge services, are what nature contribute in other ways giving us well-being - e.g. recreation and outdoor life, knowledge and learning, aesthetic and spiritual values. Whether biodiversity is an ecosystem service per se or should be regarded as an intrinsic property for the biosphere to exist is debatable. The establishment and naming of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) in 2012 was a signal that the global community put biodiversity on par with ES.

The two forest ecosystem services roundwood provisions and carbon sequestration and storage are of main interest in this report. However, forests and how the forest area is allocated influence forest ecosystem services in all four categories mentioned above. The most prominent and important additional forest ecosystem services in the context of this report are biodiversity, hydrological and water-balance concerns (regulating services), and recreation and tourism (cultural services). Concerning the UN's Sustainable Development Goals (SDGs), together, these forest ecosystem services represent both the environmental, economic and social sectors. For these reasons, we regard climate-smart forestry as sustainable forestry that also explicitly includes climate change.

2.4.1.1 Biodiversity

Biodiversity is multidimensional, as it refers to diversity within species, between species and between ecosystems. The IPBES's main report (IPBES 2019) highlights how human civilisation affects and reshapes nature through five direct drivers: changed use of areas on land and sea, direct exploitation (harvesting) of organisms, climate change, emissions and pollution, and the introduction of alien species into ecosystems.

Hunault-Fontbonne & Eyvindson (2023) propose a concise driver–response framework for forest biodiversity, distinguishing four driver categories: spatial connectivity, temporal continuity, stand structure, and abiotic environment, and three response categories: genetic diversity, species-level diversity, and functional diversity. Embedding this frame clarifies which mechanisms are already reflected in CSF indicators and which are currently overlooked, notably genetic variation and long-term habitat continuity. The concept is visualised in Figure 3.

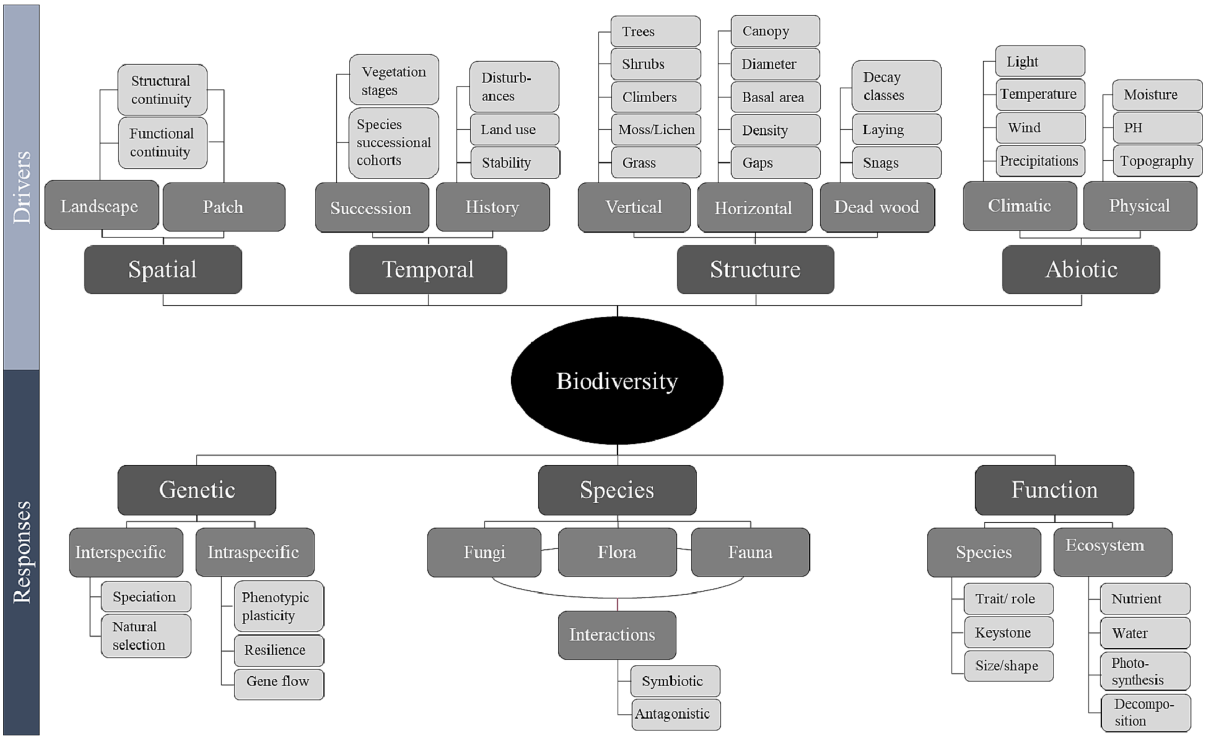

Figure 3. The main aspects of biodiversity based on a narrative review of biodiversity definition in ecology. The aspects are organised between drivers and responses (dark grey squares) with their relevant sub-components (in lighter shades of grey). Feedback loops and interactions between the aspects are not represented for simplification. Copied from: Hunault-Fontbonne & Eyvindson (2023).

In addition to established biodiversity-enhancing measures, literature suggests that integrated approaches can improve biodiversity outcomes without necessarily reducing roundwood yield. For example, landscape-level conservation planning can create synergies between roundwood production and biodiversity protection by optimising set-aside areas and buffer zones (Hetemäki et al. 2024). Furthermore, measures to increase forest resilience often overlap and act synergistically with measures to foster biodiversity, as biodiversity itself is a critical component of forest resilience (Lindner et al. 2020). Thus, incorporating species-specific habitat requirements into forest management can mitigate biodiversity losses while maintaining ecosystem service provision.

The Nordic Council of Ministers (2017) stresses that forest biodiversity strategies should be designed to integrate both mitigation and adaptation measures, ensuring that conservation areas not only serve as carbon sinks but also enhance ecosystem resilience. Furthermore, Locatelli et al. (2015) argue that trade-offs between roundwood production and biodiversity protection are often underestimated in climate policy discussions. Their findings suggest that adaptation-oriented biodiversity strategies, such as mixed-species afforestation and natural regeneration, can also contribute to long-term carbon sequestration and storage.

Typical measures to foster (safeguard/maintain and enhance) biodiversity in sustainable forest management are conservation and set-aside areas, corridors, dead wood, mixed-species forests, continuous cover forestry, and extended harvest age. Climate change directly influences biodiversity, and climate adaptation measures may influence biodiversity synergistically or as trade-offs. See, e.g. Krumm, Schuck & Rigling (2020) and Felton et al. (2024) for comprehensive treatments with a European perspective of balancing forestry and biodiversity conservation. See Sections 3.1.2 and 3.2.5 for detailed descriptions of biodiversity-oriented silvicultural and property-level measures.

At the stand-level, measures that may impact biodiversity are decisions on harvest age, leaving retention trees after final harvest, regeneration with mixed-species versus single-species stands, possible use of chemicals (herbicides and pesticides), managing with even-aged/rotation forestry vs multi-aged/continuous cover forestry and deadwood management.

Property, landscape-, and zoning-level measures enhance climate adaptation and mitigation by coordinating decisions across property boundaries and focusing on ecological connectivity. For example, set-aside areas and key-biotope protection reduce secondary pest outbreaks and safeguard vulnerable species. See Sections 3.3.1, 3,3,2 and 3.3.3 for Zoning, Cross-Boundary Cooperation, and Peatland Restoration, respectively. Well-planned forest roads (Section 3.2.4) support efficient salvage logging, wildfire response, and erosion control. Connectivity corridors (e.g., riparian buffers) help species migrate and maintain genetic exchange, boosting resilience to climate change.

In multiple-use areas, forest owners may opt for area-segregation (dedicated reserves) or area integration (joint production balancing roundwood and conservation). Triad or multi-zone strategies (Sections 3.2.3, 3.3.1) channel intensive production to high-yield sites, with buffers for biodiversity or recreation. Peatland restoration (Sections 3.2.6, 3.3.3) further improves water retention, mitigates emissions, and protects soil carbon stocks. Lastly, landscape protection preserves scenic and cultural values, often aligning with recreation, tourism, and possibly carbon credit opportunities (Section 5.3).

Indicator-based resilience assessments, as suggested by Lindner et al. (2020), are important for monitoring changes in forest vulnerability and resilience, enabling proactive and adaptive management decisions under climate uncertainty, and are central to adaptive management frameworks (see Section 7.7).

2.4.1.2 Recreation and Tourism

Forests have been used for recreational purposes for centuries. However, industrialisation, population growth, urbanisation, economic development and increased mobility are some key drivers that have opened up and influenced the recreational use of forests over the last century. In Norway, the Common Right of Access to Outdoor Areas is part of Norway's cultural heritage and was confirmed legally in the Outdoor Recreation Act of 1957. Thus, the public has a traditional and legal right to free movement, year-round, in forests and outdoor areas.

Forestry and forest management influence the landscape at various scales in space and time. Forest roads give access (walking, biking, skiing) to and open remote areas for recreational visits of different kinds (Gundersen & Vistad 2016). Nature-based tourism has evolved over the last 2-3 decades along with increased mobility and innovations in gear and equipment related to activities like ski touring, mountain biking or rafting. In a recent survey, 90% of Norwegians above 16 years used parks or nature for walking, and 75% went hiking in the mountains, forests or outdoors during the last 12 months (SSB 2024a). One out of three went skiing in the mountains, forests or outdoors, 25% went biking, while every second Norwegian picked mushrooms or berries. This document shows that a large fraction of Norwegians regularly visits nature and forests for recreational purposes.

Management and dynamics of forests and forest landscapes will influence the experiences and perceptions of recreational users. Recreational activity is highest in forests close to cities and densely populated (peri-urban) areas; thus, considerations for outdoor recreation should be given more weight in such areas compared to more rural and remote forests. The Recreational Opportunity Spectrum (ROS) has proven suitable as an approach to incorporate outdoor recreation priorities in land management and planning. This framework combines physical and social aspects into land management and seeks to classify areas into a spectrum concerning recreational opportunities, from city parks via production-oriented forests to wilderness (Gundersen et al. 2019).

Typical measures to foster (safeguard/maintain and enhance) recreational opportunities or attractiveness of forests:

- Forest roads create synergies (walking/trekking, biking, skiing)
- Landscape/scenic values create trade-offs with large-scale clear-cuts

- Mixed-species stands and CCF can be synergistic
- Extended harvest ages may be neutral or possibly synergistic with biodiversity maintenance

2.4.1.3 Hydrology and Water-balance

Forests constitute close to 40% or 12 mill. hectares of land area in Norway, with about 26% or 8.2 mill. hectares classified as productive forest land (SSB 2024b). Forests play a significant role in hydrology and water-circulation/-balance and may protect against flooding, landslides and avalanches. Thus, the forest and its management are of great importance to what extent the buildings and infrastructure below are exposed to such natural hazards.

In addition to regulating water flow, forests help mitigate flood risks and reduce soil erosion by stabilising hydrological cycles. Research shows that mixed-species forests and continuous cover forestry (CCF) improve water retention, especially in steep or high-precipitation regions (Laudon & Maher Hasselquist 2023). Expanding afforestation in headwater areas and protecting flood-prone zones can enhance these functions while supporting biodiversity.

In addition to flood protection, forests play an important role in regulating water quality and mitigating hydrological extremes. The effectiveness of these functions depends on forest composition, age structure, and soil management practices. Research suggests that mixed-species stands, and continuous cover forestry (CCF) can enhance water retention compared to monocultures. Similarly, according to Eyvindson et al. (2023), recent Finnish studies on drained peatlands indicate that water table management can significantly influence greenhouse gas emissions while preserving economic viability.

Restoring previously drained peatlands through rewetting and selective ditch-blocking (Section 3.3.3) may stabilise the water balance, reduce flood peaks, and enhance carbon storage. Such measures may also improve biodiversity in peatland habitats and help regulate water quality by limiting nutrient leaching. As climate patterns shift, integrating peatland restoration into forest planning may be important for hydrological stability.

The Norwegian Government (Meld. St. 27 (2023-2024)) recently pointed to a need for more knowledge about nature-based measures and solutions to reduce natural hazards, i.e. how forests limit the danger of flooding, avalanches and landslides (in the release area) and the consequences of such (in the run-off area). The latter particularly applies to avalanches, but also mass wasting and rockfalls. Forests are dynamic systems, and the forest's ability to mitigate floods or limit the danger and consequences of avalanches and landslides has only to a limited degree been investigated under Norwegian conditions (Nordrum et al. 2020). What is nature's capacity to hold water, and how is this affected by land use and changes in vegetation and forest condition? What is the water storage capacity of a bare surface, an even-aged single-species production forest in good growth or a mixed-species forest with trees of several ages at the same site? What is the effect of selective cutting or clear-cutting on stability vs landslides, avalanches or flooding? These are questions that have barely been investigated for Norwegian conditions. Related questions are linked to the effect of land use changes on the water storage capacity in development areas. What is the effect in a catchment area of large-scale cottage construction, at higher elevations and often on bogs? What is the effect of restoring previously ditched bogs on the water storage capacity of a catchment?

Typical measures to foster (safeguard/maintain and enhance) forests' ability to reduce natural hazards via sustainable forest management are conservation and set-aside areas, deliberate design of roads and road networks, careful planning of management in space and time and species selection. To limit negative hydrological impacts, modern forest road networks should incorporate climate-adaptive infrastructure. This includes strategic culvert placement to maintain natural water flows, erosion control structures, and adjustments of road gradients to prevent water concentration. Such measures can significantly reduce sedimentation in streams and maintain ecological balance in forested watersheds.

2.4.2 Risk and Uncertainty

With production cycles ranging between 50 – 150 years in rotation forestry, it is evident that many of the factors involved may take a different outcome than what was anticipated *ex-ante* in an analysis of management treatment options and their economic performance. The lack of certain knowledge may take different forms. It can be related to biological production and connected to abiotic or biotic production factors. Extreme events such as windstorms, precipitation (rain, heavy and wet snowfall), insect attacks or fire may occur with higher intensity and become more frequent with climate change. Gradual changes, e.g. connected to the fertiliser effect of increased CO_2-concentration in the air or extended growing seasons with higher mean temperature, may lead to a gradual, but uncertain, change in growth and productivity. Technologies for forest operations, as well as in forest industries, are likely to develop and change in unpredictable or unforeseen ways. Forest-based products and services will be prone to (out-)competition from alternatives with a different resource base or may be favoured by altered consumer preferences. Markets will thus develop and change, and may furthermore be influenced by policies and interventions, which also may change due to shifts in political priorities. It is an overwhelming task and probably not realistic or even beneficial to include and address all these in one complete analysis.

Individuals, businesses and societies will normally prefer to avoid or reduce risk for a given level of outcome, i.e. they are risk-averse. We take this as an assumption or prerequisite for this report.

Extreme events have the potential to cause devastating harm or major disturbance to a forest stand, group of stands or even a landscape. A simple way to illustrate this is by a cumulative exponential survival function, giving the cumulative probability of "survival" as a function of stand age, i.e. that an extreme event leading to collapse has not yet occurred.

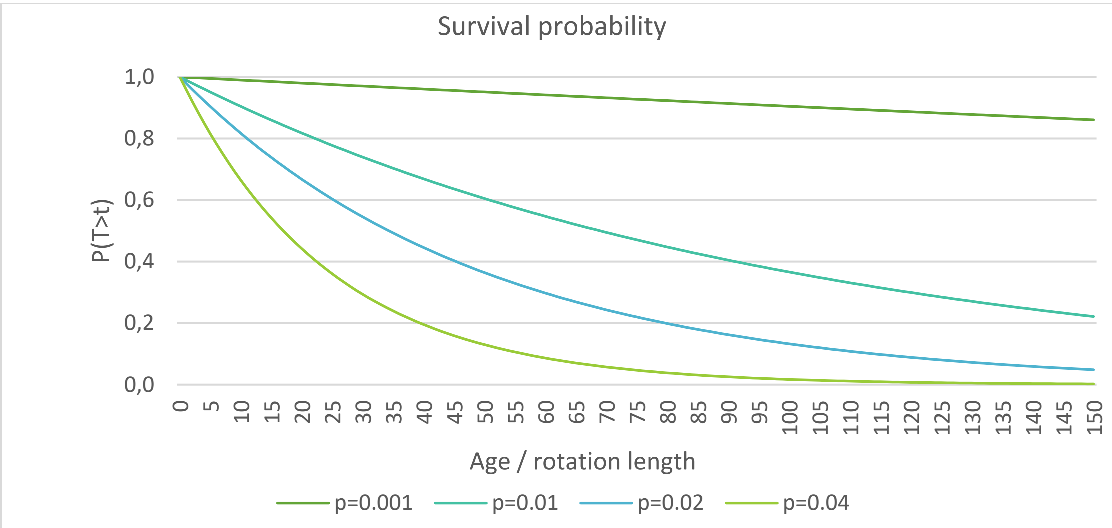

Figure 4. Probability of reaching harvest age without a stand-replacing disturbance (survival) as a function of stand age (t) up to harvest age for four (discrete) annual disturbance probabilities (p) assumed constant over the rotation. Adapted from Figure 1 in Schoene & Bernier (2012).

With an annual probability of p=0.001 (0.1%) for an extreme event causing a stand to collapse, about 90% of stands will reach (survive to) an age of 100 years. The survival probability drops to 37% if the annual probability of collapse is p=0.01 (1%), while only 13% of stands will survive to 100 years if p=0.02 is the annual probability of collapse. This is an overly rough and coarse approach; however, it illustrates somewhat the sensitivity to the risk involved with such long production cycles as in boreal forestry.

In a changing climate, risk and uncertainty in forest management must be considered in a broader context, including both short-term disturbances (e.g., storms, pests) and long-term shifts in productivity and ecosystem functions. Hetemäki et al. (2022) emphasise that the interaction of multiple stressors, such as drought, windthrow, and bark beetle outbreaks, requires adaptive strategies at both stand and landscape levels.

Basic and robust approaches to dealing with uncertainty and risk are expedient (Eyvindson & Kangas 2018). A useful and common distinction between risk and uncertainty is whether the probability distribution of possible outcomes is known or can be estimated (risk), or not (uncertainty).

2.4.2.1 Flexibility/Adaptive Management

Upholding flexibility and applying adaptive management is one such general and robust approach. In practical terms, this may mean establishing mixed-species stands, which, at a later development stage, when more precise knowledge about climate change, market developments, and future demand is available, can be upheld or directed in favour of one dominating species.

This is highlighted by the Nordic Council of Ministers (NCM 2017), who discuss how EU climate policy and carbon pricing mechanisms create additional risks for long-term forestry investments. It's underscored that economic viability is increasingly tied to how well forest management adapts to changing policy incentives and carbon market fluctuations. This calls for adaptive management frameworks that integrate both environmental, market and political risks.

Promoting resilience (robustness) is a connected approach. Regarding heavy wind/storm, this may be achieved by aiming at a spacing (density) that balances individual tree and stand or group stability. Bayesian or decision-tree analysis can be applied to investigate such and connected approaches (Aza et al. 2021; 2022). A third way may be to opt for variability across the property or in a landscape of several properties as a kind of insurance-oriented approach or hedging.

A basic measure of risk is variance, which simply describes the spread of possible outcomes around the mean or expectation value. Outcomes may be worse (unwanted) or better than the expectation value. The concept below-mean semi-variation considers only the unwanted or downside risk (Markowitz 1959). Based on this, the measures value at risk (VaR) and conditional value at risk (CVaR) emerged. A related concept, the certainty equivalent, understood as a return or outcome without risk which is regarded as equivalent to the expected return with risk, is also relevant. In short, approaches following this branch of research apply optimisation and mathematical programming techniques (e.g. integer or linear programming, max-min optimisation, stochastic programming) to typically investigate planning problems under risk with, e.g. even-flow constraints on roundwood harvests or maximising the minimum cash flow from roundwood harvesting together with biodiversity protection (Hartikainen et al. 2016). (Real) Option pricing approaches have been quite extensively applied to investigate rotation period problems/land value under risk, and robust optimisation techniques have found increasing application. Hildebrandt & Knoke (2011) recommend robust optimisation as a promising approach in dealing with decision problems with severe uncertainty as a consequence of very long production and investment horizons. Comprehensive reviews can be found in, e.g. Hildebrandt & Knoke (2011); Eyvindsson & Kangas (2018), and Knoke et al. (2025).

2.4.2.2 Diversification and Compensation for (Relevant) Risk

A related basic and robust advice from finance and investment (economic) theory and practice (capital markets) is that risk-averse investors will require compensation in terms of increased capital returns to accept (increased) risk. Building on Markowitz (1959), the Capital Asset Pricing Model (CAPM) was developed in the 1960s; see Perold (2004) for a review. The insight from CAPM may have a significant impact when analysing (risky) forestry investments. An increase in the required real rate of return will typically influence ex-ante investment analysis of silvicultural treatments in the direction of reduced investments in regeneration by planting, reduced young growth tending/thinning and shortened harvest ages. Facing increased risk, a risk-averse investor will thus reduce the capital accumulation in the forest. However, with efficient markets, investors will not get compensated for so-called diversifiable or unsystematic risk; they only get compensation for systematic, undiversifiable or relevant risk. In CAPM terminology, beta is a measure of systematic risk in a project and expresses the correlation between the project and the market portfolio. Investors should diversify and eliminate parts of the risk in the portfolio of investments (i.e. bring the beta down to the lowest possible value). By spreading investments on different projects or activities with outcomes (profits) which are not perfectly correlated, it is possible to reduce the overall exposure to risk (eliminating so-called unsystematic risk). In practical terms, diversification in forestry in a situation facing a changing climate might mean establishing stands with different species and different abilities to adapt to changes in temperature, precipitation and wind patterns.

2.4.2.3 Pure (Knightian) Uncertainty in the Long Run

Long production cycles are, per se, characterising boreal forestry due to relatively slow growth and development. The profitability of investments in silvicultural management is thus very sensitive to the required real rate of return (discount rate) on capital investment. Climate Change, due to anthropogenic emission of GHGs is similarly a process emerging and developing over long time. Projects or activities aimed at reducing emissions and consequently the concentration of GHG in the atmosphere typically imply significant investments or costs today, while the benefits will last for centuries. Whether such projects will pass the benefit-cost test will be very sensitive to the rate of discount.

Weitzman (2007; 2009a) discusses how pure (Knightian) uncertainty complicates the economic analysis of climate change. Unlike quantifiable risk, Knightian uncertainty reflects the fundamental inability to predict probability distributions for long-term climate and economic impacts. This has profound consequences for discounting and cost-benefit analyses. In particular, Weitzman argues that uncertainty over future economic growth rates, technological progress, and the severity of climate impacts means that traditional discounting approaches may systematically underestimate the value of precautionary climate policies.

Hanewinkel et al. (2013) highlight similar concerns in forestry, noting that economic projections over long periods face considerable uncertainty due to volatile timber prices, uncertain consumer demand, and changing climatic conditions. Their study finds that the choice of discount rate significantly affects the projected net present value (NPV) of European forests, with potential economic losses ranging between 14% and 50% by the year 2100, depending on climate and economic assumptions. These findings underscore how Knightian uncertainty amplifies financial risks in forestry and necessitates adaptive and flexible decision-making. They discuss major factors like time preference, the aversion to inter-generational inequality, the growth of consumption and the interest rate to discount future economic effects of climate change.

Weitzman (2007) highlights that the sectors of the economy most vulnerable to global warming are primarily "outdoor" activities, including agriculture, coastal recreation, and natural landscapes, which provide both economic value and other ecosystem services. These sectors are likely to experience profound climate-induced disruptions, such as rising sea levels and shifts in agricultural productivity, which are not strongly correlated with technological progress in other economic sectors. In contrast, "indoor" activities, which dominate modern economies, will be shaped largely by uncertain future advancements in labour-augmenting technology. This distinction suggests that the investment risks associated with climate change may be disproportionately concentrated in outdoor sectors, affecting economic analyses that rely on investment-beta calculations. Additionally, as per capita incomes rise over time, the high-income elasticity of environmental awareness may increase the perceived existence value of unaltered natural habitats, further reinforcing the long-term economic significance of preserving ecological integrity.

The economic implications of pure (Knightian) uncertainty, as discussed by Weitzman (2007) and Hanewinkel et al. (2013), thus reinforce the importance of precautionary approaches in CSF. Traditional cost-benefit models, which rely on fixed discount rates and quantifiable risks, may fail to capture the full economic consequences of low-probability, high-impact climate events. Weitzman (2007) specifically warns that standard economic models underestimate the potential for catastrophic climate outcomes, thereby justifying stronger climate mitigation efforts even when precise probabilities are unknown.

Similarly, Arrow et al. (2014) recommend applying declining discount rates (DDR) for analysing long-term public investments, ensuring that future benefits are not excessively undervalued. This aligns with arguments for adaptive forest management and resilience-building strategies that do not rely on precise future predictions but instead maintain flexibility to respond to unforeseen challenges. In the early 2000s, the UK (2003) and France (2005) introduced DDR in their policies for evaluating public projects (Arrow 2014). Norway followed this a decade later, and since 2014, the recommendation from the Ministry of Finance in Norway has been to use a DDR to evaluate public projects (Finansdepartementet 2021). The recommended risk-adjusted real rate of discount is 4.0 per cent for the first 40 years, 3.0 per cent for years 40–75, and 2.0 per cent thereafter.

Risk and uncertainty are central to forestry economics under climate change. While traditional risk management strategies, such as diversification and hedging, remain relevant, the presence of pure (Knightian) uncertainty necessitates adaptive decision-making and policy frameworks that account for irreducible unknowns. As Weitzman (2007) and Hanewinkel et al. (2013) highlight, long-term economic analyses of forestry and climate change must incorporate precautionary principles, recognising that the full impact of climate uncertainty cannot be reliably quantified and should likely be evaluated (discounted) with low and possibly declining real rates of return.

2.4.3 Synergies/trade-offs (Joint Production)

Synergies occur when the combined effects of two or more measures implemented together or jointly are greater than the sum of their effects when similar measures are implemented separately. A trade-off is typically referred to as a situation where the output (quantity or quality) of one commodity cannot be increased without at the same time compromising/reducing the output (quantity or quality) of one or more other commodities. In economics, this is illustrated by the concepts of production possibility frontier (PPF), indifference curves (IC) and utility possibility frontier or line (Hetemäki et al. 2022; Hetemäki et al. 2024). Both the PPF and IC illustrate trade-offs in production and consumption, respectively. With an efficient use of a given set of input factors, the PPF shows how much can be obtained of outputs when resources (input factors) are used efficiently. The shape of the PPF-curve (the angle of the tangent to the curve) shows how much a small increase in one output affects the other, either enhancing it (synergy part of the PPF) or reducing it (trade-off part of the PPF).

Recent research highlights that synergies and trade-offs in the forest bioeconomy are multidimensional and often involve complex interactions between different policy objectives, economic goals, and other forest ecosystem services (Hetemäki et al. 2024). The notion of synergies extends beyond simple complementarities, requiring careful integration of strategies to utilise positive outcomes or limit conflicts. While synergies often involve mutually reinforcing benefits, such as for example the simultaneous improvement of carbon storage and biodiversity conservation, trade-offs typically emerge when enhancing one ecosystem service leads to the degradation of another. For instance, afforestation projects intended for carbon sequestration can inadvertently affect local hydrology and increase competition for water resources (Locatelli et al. 2015).

The provision of most forest ecosystem services is the result of a so-called joint production process. In joint production, it is not possible to produce one product without simultaneously producing one or more other products. In commercial roundwood production, different assortments such as sawlogs, pulpwood and wood for energy can be seen as joint products. Another example can be the provision of roundwood and recreation from the same forest area. In the Nordic countries, we have the common right of access, giving the public free access to forest areas. Forest roads are frequently used also for recreational purposes, and thus, roundwood production benefits the recreational opportunities to a certain extent. Having some recreational users in the forest might benefit roundwood production e.g. if we assume that a few recreationists using the forest might increase the probability of identifying a possible forest fire at an early stage. On the other hand, many visitors might increase the risk of causing a fire, causing damage in newly regenerated stands or causing other harm to trees or stands. We may have a situation with joint production and a PPF that has a shape as shown in Figure 5 below. Along certain parts of the PPF, the production of the two outputs exhibits complementarity or synergy, whereas in other parts, trade-offs or competition dominate.

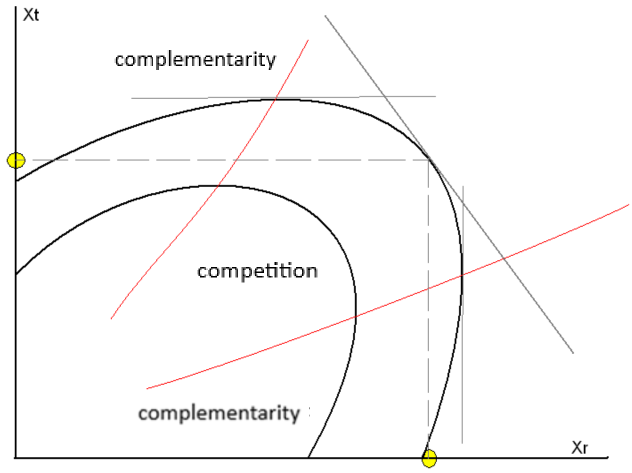

Figure 5. Joint production of recreation (x_t) and roundwood (x_r) from a forest area.

This illustrates that some bundles of forest ecosystem services might have production possibilities with clear synergies and a narrow part of the PPF with trade-offs, while for other bundles, trade-offs may be dominating along most of the PPF.

Synergies in forest management may also be classified into two broad categories: weak synergies, where benefits accrue independently but do not reinforce each other significantly, and strong synergies, where benefits mutually enhance each other (Nordic Council of Ministers 2017). A joint production of roundwood and recreation services can yield weak synergies when visitors contribute to monitoring forest conditions without significantly influencing roundwood yield. On the other hand, strong synergies arise when sustainable forest management practices not only improve biodiversity but also enhance carbon sequestration and storage, leading to a reinforced positive impact. For example, a weak synergy may occur when forest thinning operations improve recreational access but have minimal impact on overall biodiversity

Locatelli et al. (2015) and the Nordic Council of Ministers (2017) stress that mitigation and adaptation strategies should be assessed together to utilise synergies and avoid unintended trade-offs. For example, afforestation projects intended for carbon sequestration can reduce local water availability if not planned with hydrological concerns in mind. Additionally, Locatelli et al. (2015) identify cases where reforestation efforts have inadvertently increased wildfire risks due to species selection and forest structure changes. Another common trade-off in European forestry is between roundwood production and biodiversity conservation (Luyssaert et al. 2018). Intensively managed forests optimised for wood production may often lead to a loss of old-growth habitats and a reduction in species diversity, especially for species dependent on deadwood and complex forest structures.

The shape and dynamics of the PPF in forestry-based joint production systems are influenced by multiple biophysical and economic constraints, including land-use decisions, market drivers, and climate impacts (Luyssaert et al. 2018; Hetemäki et al. 2024). When considering roundwood production and carbon sequestration and storage, the PPF may shift outward as a result of technological innovations, such as precision forestry, improved silvicultural practices, or genetically improved tree species, providing enhanced resource efficiency. Conversely, climate-induced forest disturbances, including storms, droughts, and pest outbreaks, may cause the PPF to contract, sharpening trade-offs between competing objectives. Thus, forest management decisions should not only consider current production possibilities but also anticipate how changing environmental conditions may alter future trade-offs and synergies.

Future research should focus on quantifying the relative strength of synergies and trade-offs in different forest ecosystems, thereby informing policy decisions at both national and European levels.

Some forest ecosystem services are not provided through joint production. An example is the existence of pristine or primaeval forests, which in the pure sense cannot coexist with roundwood supply from the same area. This case may be termed as assorted production; see Figure 6.

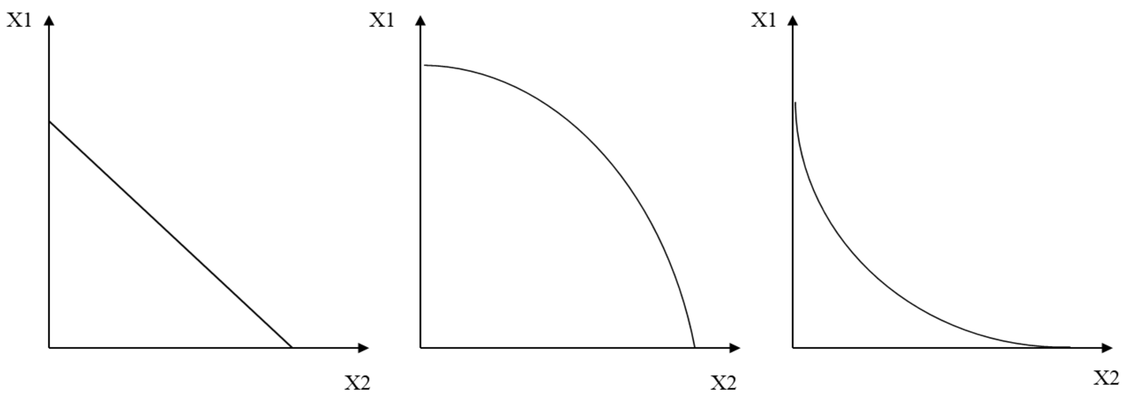

Figure 6. Assorted production process with pristine forest (X1) and roundwood supply (X2) from a forest area.

In the alternative to the left in Figure 6, the area is homogenous concerning roundwood provision, and there is no interaction between the part of the area allocated to roundwood provision and the (potential) area allocated to preservation as pristine forest. In the alternative in the middle, the area is non-homogeneous concerning productivity for roundwood provision while homogenous concerning the area of pristine forest. In the alternative to the right, there are interactions between the part of the area allocated to roundwood provision and the (potential) area allocated to preservation as pristine forest. In this case, only the innermost part of the preserved area will satisfy the criteria for a pristine forest, while an abandoned surrounding buffer zone will mitigate interactions between managed roundwood production and the undisturbed forest core.

Given the challenges of balancing synergies and trade-offs, policy frameworks must incorporate adaptive governance mechanisms that allow for dynamic adjustments based on emerging evidence (Hetemäki et al. 2024). This includes promoting cross-sectoral policy integration, ensuring that afforestation strategies align with biodiversity conservation goals, and fostering market incentives for forest ecosystem services beyond roundwood production. Moreover, financial mechanisms that support the valuation of non-market benefits, such as carbon credits for biodiversity-enhancing forestry practices, can further enable a holistic approach to forest management. A more detailed discussion of policy frameworks, regulatory instruments, financial incentives, and governance strategies for implementing CSF is provided in Chapter 5: Policy Implementation.

3 Climate Change – Mitigation and Adaptation Measures

This section describes forest management measures and options, and their impacts and potential under climate change, at the stand, property and higher levels (landscape, regional, national). The stand-level measures apply to silvicultural treatments where mainly the forest owner has the responsibility and authority to make decisions. The property-level decisions are also mostly shaped by the forest owner but depend in addition to some degree on local and regional authorities and include all biophysical characteristics of the whole land with roads, peatlands and rivers, etc. in addition to all forest stands. Finally, measures and decisions that extend the individual property into the landscape, regional, and national levels are needed because climate change presents challenges to the complete forest ecosystem and the entire community.

Throughout this report, we assume that all forestry is certified under at least one of Norway's two recognised sustainable forest management schemes (PEFC or FSC), and that all relevant stakeholders, including forest owners, forest owner associations, road engineers, and others, comply with these and other established regulations. Both certification schemes impose legally binding requirements for biodiversity conservation, cultural heritage protection, hydrology and soil safeguards, outdoor recreation values, Sami rights, worker safety, and other Forest Ecosystem Services. For simplicity, we refer only to the PEFC regulations for forest certification (not FSC) throughout this report, unless otherwise specifically stated (cf. PEFC 2022).

Parallel activity is emerging around private carbon-credit standards such as the Verified Carbon Standard (VERRA) and the forthcoming EU Carbon Removal Certification Framework (CRCF; see Section 5.3).

3.1 Stand-level Forest Management

This section gives an overview of stand level silvicultural treatments. When describing the treatments, we differentiate between the management principles "rotation forestry" (RF) and "continuous cover forestry" (CCF) (sections 3.1.1 and 3.1.2, respectively). We assume that rotation forestry includes "clear-cutting" and "seed tree harvest" while CCF includes the "selection system", "group selection system" and "shelterwood system". The split between seed tree harvest and the shelterwood system, and thus RF and CCF management, is defined by how many trees are left for regeneration purposes after the final harvest, amounting to a maximum of 150 trees/ha and a minimum 160 trees/ha, respectively. In addition, the gap size under all CCF systems should be less than 0.2 ha.

When applying CCF systems, the stands usually develop into a forest structure that is more or less uneven-aged, as opposed to RF, where the forest structure is mainly even-aged. The shelterwood and group selection systems should only be considered as CCF management if the continuous minimum forest cover is an explicit objective and if it is actually maintained (Brunner et al. 2025; Cedergren et al. 2025). A fast and complete removal of shelterwood trees in a shelterwood system or large, many, or frequent gaps in a group selection system that do not aim for and maintain the forest cover is therefore outside the definition of CCF, and should thus defined as RF. In the following descriptions, however, we assume that the group selection system and shelterwood system are included as CCF management.

3.1.1 Rotation Forestry

For RF, we first describe the individual treatments without considering any temporal aspects. Subsequently, we include the temporal aspect where relevant treatments over a rotation are described. A sequence of treatments, from regeneration to final felling, is termed a "treatment schedule".

When applying RF, the stand is characterised as even-aged and may thus be divided into the following development phases: regeneration, young forest, production forest and mature forest. Relevant treatment options are specified according to these phases (Table 1). A treatment is defined as one single action that changes the conditions in the stand. A treatment may comprise several levels of choices that must be made. For example, if we choose "planting" as a regeneration method, we need to make several additional choices regarding tree species, plant material and, finally, tree density. The choice of not applying a certain treatment (e.g. thinning) is also considered a viable option. Generally, choices and decisions regarding all stand-level treatments rely upon the forest owner, provided that the Norwegian Forest Act (https://lovdata.no/dokument/NL/lov/2005-05-27-31) and the certification requirements. The actual implementation of the treatments in most cases relies on the forest owner's association and/or entrepreneurs.

In the following, we describe different aspects of the treatments shown in Table 1 and their potential mitigation and adaptation impacts related to climate change.

Table 1. Treatment options under rotation forestry according to different stand development phases.

Stand development phase	Treatment level 1	Treatment level 2	Treatment level 3
Regeneration	Root rot prevention	No root rot prevention	
		Choose method	Apply final harvest under winter conditions
			Apply Rotstop in final harvest under summer conditions
	Soil scarification	No soil scarification	
		Apply scarification	
	Planting	Choose tree species	Single-species spruce to pine
			Single-species spruce to mixed-species
		Choose provenance and genetic plant material	
		Choose tree density	Reduced compared to "recommended"
	Natural regeneration	Use spruce seed tree	Neighbouring stands
		Use pine seed trees	Seed tree establishment
Young forest	Young growth tending	No young growth tending	
		Choose tree species	Single-species spruce to mixed-species
		Choose tree density and intensity	Reduced compared to "recommended"
Production forest	Thinning	No thinning	
		Choose thinning method and intensity	Free thinning or thinning from above
	Fertilisation	No fertilisation	
		Fertilisation	
Mature forest	Final harvest	Choose regeneration method	Planting
			Natural regeneration
			Stem-only harvesting

		Choose harvest method	Stem- and residue-harvesting
		Choose harvest age	Optimal biological harvest age
			Optimal economic harvest age
			Reduced compared to optimal economic harvest age

3.1.1.1 Regeneration Phase

The regeneration phase is the starting point of a new rotation. Before actual regeneration, treatments such as root rot prevention and soil scarification may also be applied. Planting and natural regeneration are the two main regeneration options.

The Norwegian Forest Act states that the forest owner is responsible for regenerating all forest areas subjected to final harvests. Furthermore, the government can force forest owners to apply measures to secure this if the requirement is not met. Table 2 shows the minimum number of trees required to be established according to the regulations (https://lovdata.no/dokument/SF/forskrift/2006-06-07-593). The numbers apply to planting as well as natural regeneration.

Table 2. Minimum number of trees/ha over site index required to be regenerated according to the Norwegian Forest Act.

Spruce- and broadleaves dominated areas		Pine dominated areas	
Site index (H40, m)	Trees/ha	Site index (H40, m)	Trees/ha
G20-G26	1500	F17-F20	1500
G14-G17	1000	F11-F14	1000
G6-G11	500	F6-F8	500

Root Rot Prevention

Root rot is a disease caused by white-rot fungi *Heterobasidion* spp (see e.g. Solheim (2010), Dalen (2018), Aza et al. (2021; 2022)). In Norway, the fungi mainly affect Norway spruce and Scots pine. For spruce, the decay column can reach up to 10–12 m of the stem, while for pine, the decay is typically restricted to the root system. The infection happens when fresh wood (stumps and roots) is exposed to spores from the fungi and occurs when harvesting is done under summer conditions (unfrozen soil and temperatures above zero). The fungi may cause significant economic losses, particularly for spruce, because they destroy the most valuable part of the tree, which may be downgraded from saw log quality to pulpwood or energy wood.

Based on core-sampled spruce trees (18,141) from the Norwegian NFI, Hylen & Granhus (2018) found that about 10% of all trees were infested by root rot. A probability model for the occurrence of decay (rot) at breast height in spruce showed that the probability increased with increasing diameter, stand age, altitude and growing season temperature sum. They also found that spruce trees in mixed-species stands with pine as the dominant species had a significantly lower probability of rot than spruce trees in mixed-species stands dominated by spruce or birch.

The spread of root rot to the next generation of trees can generally be reduced if final harvests are applied under winter conditions on frozen soils and at temperatures below zero (Table 1). With climate change (increased temperatures) the extent of harvesting that can take place under winter conditions is likely to decrease, and a larger proportion must be harvested when the trees are prone to fungus attacks. Rotstop is a relatively new product that can be used to prevent the root rot from being transferred to the next rotation (Table 1). The substrate, which is an aqueous solution of spores from the fungus *Phlebiopsis gigantea,* is automatically sprayed onto the stumps by the harvester when the trees are cut to prevent the *Heterobasidion* spores from establishing on stumps and further spreading to living trees.

Prevention of root rot is important as an adaptation measure to increase forest resilience to damages and thus reduce monetary losses for the forest owner and avoid reduced supply of wood to the industry (e.g. Søgaard et al. (2017)). Optimal conditions for the growth of white-fungi species are temperatures around 22-24ºC (Hanssen et al. 2019). Increased temperature due to climate change is therefore likely to accelerate the spread and growth of the fungi. An increased growth of the fungi may consequently be larger than a potentially increased tree growth under climate change. Thus, root rot prevention is a measure that may increase carbon sequestration and storage and is, therefore, positive for climate change mitigation.

Soil Scarification

Soil scarification is a treatment applied to enhance conditions for new trees to establish after final harvesting, either they are planted, seeds are sown or regenerated naturally (Hanssen 2017a). Potential positive effects of soil scarification are decreased competition from other vegetation, more stable humidity in upper soil layers, increased soil temperature, which boosts root growth and faster decay of humus enhancing the nutrient supply. At the age of 10-15 years, trees may gain 10-25% increased mean height when soil scarification is applied (Sikström et al. 2020). Such a boost in height growth is, however, only temporary. There is also some evidence that soil scarification may reduce damage to seedlings from the pine weevil (*Hylobius abietis L.*) and in this way increase the number of surviving plants (see e.g. Hanssen (2017b) and Sikström et al. (2020)).

When applying soil scarification aiming for natural regeneration, or active sowing, the scarification should be relatively shallow and remove the humus layer only. Too deep a scarification may increase the probability of frost damages for the seedlings. Scarification is most effective if the humus layer is thick and solid, preventing the seedlings from reaching the mineral soil.

Soil scarification may be an important climate change mitigation measure to increase tree density and growth, and thus above-ground carbon sequestration and storage. Although the total amount of carbon in the forest ecosystem likely increases, there is still some uncertainty related to the impact of scarification on the amount of soil carbon (Søgaard et al. 2023). Another concern is related to erosion. Since we, due to climate change, can expect more frequent heavy rainfalls, it might be necessary to adapt the scarification methods to avoid soil erosion. This can be achieved by, for example, distributing the furrows in disc trenching along the elevation curve or applying more patch scarification to decrease the area of exposed soil.

Planting or Natural Regeneration

Planting and natural regeneration are the two main treatment options for establishing a new forest stand after the final harvest. The choice between the two options depends partly on the natural conditions at the site (tree species in previous rotation, productivity, vegetation, soil, etc.) and on the economic preferences of the decision-maker. If regeneration by planting is chosen, several additional active decisions regarding tree species, provenance and genetic plant material, and tree density must be made (Table 1).

In Norway, planting is the most common regeneration method used in spruce forests, while natural regeneration is the most common in pine forests. Natural regeneration of spruce mostly takes place on low-productivity sites, while planting of spruce is done on high-productivity sites. Natural regeneration of pine spans over a larger interval of site productivity, but for the most productive sites, planting of pine is also applied to some extent.

Natural regeneration requires seed trees of relevant species present in the stand or in neighbouring stands. Natural regeneration of pine is mainly facilitated by leaving seed trees (30-150 trees/ha) after final harvest. Sowing pine seeds, as an alternative or supplement to relying on seed trees only, might be an option if conditions for natural regeneration are poor. Generally, sowing has hardly been applied in Norway, but over the past few years, areas regenerated by combining sowing and soil scarification have increased (Skogkurs 2021). For spruce, the regeneration usually depends on seeds from spruce trees in neighbouring stands. Since spruce seeds are not spread over large distances, the maximum size of a stand to be sufficiently provided with seeds is limited to 0.5-1.0 ha.

Natural regeneration, as compared to planting, may have negative implications for climate change mitigation because the regeneration lag leads to longer rotations and therefore reduced volume and biomass production over time. The risk of failed regeneration and poor density under natural regeneration may have similar effects.

Given that planting is chosen as the regeneration method, there are several additional choices related to tree species, provenance and genetic plant material and tree density that must be taken (Table 1). The choices made at this stage are very important because of the long-term effects on the volume production. The choices are also important because they are partly conflicting regarding mitigation (carbon sequestration and storage) and adaptation (bark beetles, root rot, wind, snow and drought) effects.

Tree Species

When choosing tree species for planting, the objective of the decision-maker has, for decades, normally been to maximise volume production or income, and tree species selection has almost solely been based on information on tree species and site productivity of the previously harvested stand. However, because spruce generally is more prone to most natural disturbances than pine and increased concerns related to climate change, recent discussions regarding tree species selection have mainly been going along two main options; a shift from single-species spruce stands to single-species pine stands or a shift from single-species spruce stands to a mixture of different species (Table 1). Note that if the proportion of conifer volume (spruce and/or pine) in an existing stand prior to the harvest is larger than 50%, a shift of species to broadleaves can only be applied based on an approvement from the local municipality authorities (https://lovdata.no/forskrift/2006-06-07-593/§5).

The first option has been discussed because, typically over the past decades, large areas with pine and corresponding vegetation types (natural pine sites) have been replaced by spruce when planting to realise higher production and income. Under climate change, such areas will be particularly prone to drought incidents, especially in the lowlands of southeastern Norway, because spruce has relatively large foliage compared to a shallow root system (Hanssen et al. 2019). At the same time, it must be kept in mind that pine can be highly vulnerable to browsing damage, particularly in areas with high moose densities.

The second option, i.e. a shift from single-species spruce stands to a mixture of species (spruce, pine, birch or other broadleaves), has been considered as a general measure for risk reduction since spruce is the species most vulnerable to natural disturbances (Hanssen et al. 2019). For example, converting root rot-infested spruce stands to pine during the regeneration phase in areas normally more suitable for spruce may pay off economically in some cases (Aza et al. 2022). Similarly, when analysing the risk of bark beetle (*Ips typographus*) damages, Romeiro et al. (2025) found that the use of mixed-species stands (spruce and pine) yields economic advantages compared to single-species spruce stands. Furthermore, the risk of windthrow damages and damages from drought incidents may be reduced with mixed-species stands (spruce, pine, birch), because spruce has a shallow and relatively small root system (Hanssen et al. 2019).

Although shifts from single-species spruce stands to mixed-species stands or single-species pine stands generally may be efficient adaptation strategies under climate change to reduce natural disturbances, the effects on volume production, and thus carbon sequestration and storage, may be negative (Hanssen, n.d.a.). For medium site productivities, volume production over a rotation is likely about the same for mixtures of spruce and pine compared to monocultures of the same species. For higher site productivities, however, volume production will be lower for mixed-species stands. New analyses, based on experimental sample plots for mixed-species of spruce and birch established in the 1970s (Braathe 1988), show that volume production increases, the larger the spruce proportion is in the stand, mainly because growth is more durable for spruce than for birch late in the rotation (Søgaard et al. 2017). Therefore, if disregarding the likely positive effects related to reduced natural disturbances, shifts from monocultures spruce stands to mixed-species stands will in most cases negatively influence the mitigation potential through carbon sequestration and storage. A mixture of tree species, especially if the proportion of birch is large, may, however, have a positive mitigation effect related to albedo (Halim et al. 2019; Bright & Astrup 2019).

Provenance and Genetic Plant Material

In their report, Søgaard et al. (2023) highlight the critical role of provenance and genetic plant material in forest management, particularly in the context of climate change mitigation and adaptation. The selection of appropriate plant material directly affects forest production, resistance to environmental stressors, and the ability to sequester carbon. Note that strict regulations exist concerning the use of foreign tree species in Norwegian forestry (https://lovdata.no/dokument/SF/forskrift/2012-05-25-460?q=forskrift%20om%20utsettelse%20av%20utenlandske).

Forest owners have limited control over the development and availability of genetic plant material, as this is largely managed through breeding programmes and seed supply systems. However, they do have the responsibility to make informed choices about which plant material to use, based on the best available options. The primary goals of genetic improvement in forestry are to enhance tree growth rates and increase resistance to natural disturbances.

As climate change alters temperature and precipitation patterns, it is essential to select plant material that can utilise a longer growing season without becoming more vulnerable to damage. This means that genetic selection must strike a balance between optimising growth and ensuring that trees remain robust under shifting climatic conditions. Provenance selection plays an important role in this process, as trees from different geographic origins may exhibit varying degrees of adaptation to specific climatic conditions. By carefully choosing the most suitable provenances, forest owners can enhance forest resilience while maintaining productivity.

The use of genetically improved plant material is, therefore, not only an effective tool for increasing carbon sequestration and storage through enhanced growth (e.g. Sevillano et al. (2025) but also a key strategy for adapting forests to climate change. Ensuring that forests are planted with climate-resilient material helps maintain their long-term health and stability, securing their role as a carbon sink and as a provider of different ecosystem services in a changing world.

The conditions for heat-loving deciduous forests are expected to improve with climate change, and more active management of for example oak (*(Quercus robur L.) and (Q. petraea (Matt.) Liebl.))* has therefore received attention in recent years. Oak's potentially valuable wood, deep roots, drought tolerance and positive effect on biodiversity indicate that it can be an alternative tree species for climate adaptation in future forest management. A research project has therefore recently been established where, among other things, seeds from "plus trees" are collected and grown in nurseries, provenance experiments will be carried out and demonstration fields will be established, where oak is planted both as the main tree species and in mixtures with other tree species (Skogfrøverket 2024, NIBIO 2025).

The choice of tree species is also important in terms of biodiversity. Søgaard et al. (2023) write (our translation):

"In general, it can be concluded that increased species mixing, both within and between stand, as opposed to monocultures, is beneficial for biodiversity. In the boreal coniferous forest zone, species such as rowan (Sorbus aucuparia), aspen (Populus tremula), and goat willow (Salix caprea) - the so-

called ROS species - as well as alder (Alnus spp.), are particularly important for species diversity, both as living and dead trees. The planting of alien conifers, such as Douglas fir (Pseudotsuga menziesii), Sitka spruce (Picea sitchensis), or Lutz spruce (Picea × lutzii), is by definition negative, even if it locally increases the diversity of tree species. When it comes to the effect of tree species mixtures on the field-layer vegetation, the picture is more nuanced, and it is difficult to draw clear conclusions (Barbier et al. 2008). However, the choice of tree species after harvesting will result in differences in the availability of resources (e.g., light, water, and nutrients) to the ground layer, which in turn affects species diversity in the ground and field vegetation."

Tree Density

The choice of tree density when planting may have multiple impacts, both for mitigating climate change as well as for adapting to climate change. Tree density is also important for the volume production over a rotation and for the income of forest owners.

Table 3 shows the prevalent recommendations for plant density (number of trees/ha) according to site index and tree species (Skogkurs 2013a; Landbruksdirektoratet 2023). The numbers from Landbruksdirektoratet are presented as intervals, illustrating that the applied tree density may vary according to different objectives of the forestry activities. The recommended numbers from Skogkurs are more specific but well within the intervals as displayed by Landbruksdirektoratet. Similar numbers as those of Skogkurs are also recommended by several nurseries and county governors in Norway.

Table 3. Recommended number of planted trees/ha over site index for spruce and pine.

Site index (H40, m)	Spruce		Pine	
	Landbruksdirektoratet	Skogkurs*	Landbruksdirektoratet	Skogkurs*
23	1800-3000	2750	-	
20	1800-3000	2400	1900-3400	3100
17	1300-2300	2200	1900-3400	2600
14	1300-2300	1800	1200-2400	2150
11	600-1400	1400	1200-2400	1700
8	600-1400	900	800-1300	1200
6	600-1400	-	800-1300	-

* Numbers assume 10% of planted trees to die during the regeneration phase due to natural mortality

The impact on long term volume production and timber values of initial tree density when planting has been discussed for decades in Norway but relatively few scientific studies exist. Based on spacing experiments, however, Gizachew et al. (2012) indicate that the number of planted trees, within relatively wide intervals for a given site quality class, does not significantly impact the future standing volume, although they also emphasize that low densities (wide spacing) may to some extent reduce the volume production. However, in the following we use the recommended number of trees/ha from Skogkurs (Table 3) as a "benchmark" when discussing the treatment options related to the regeneration phase (Table 1).

There are, however, many reasons for forest owners to deviate from the recommended numbers. This could be based on "informed decisions" related to profitability, objectives related to biodiversity and recreational values, or "uninformed decisions" due to a lack of knowledge or commitment. In many cases, the actual observed densities (Landbruksdirektoratet 2024a) are lower than the recommended ones and even lower than the minimum numbers required according to the forestry law (see Table 2).

To support climate change mitigation, subsidies is provided to forest owners if they apply additional planting in already established regenerations to enhance carbon sequestration and storage. The funding aims to secure "optimal density" for volume production and thus contribute to increased carbon sequestration. An increase in tree density far beyond the numbers recommended by Skogkurs (Table 3) is neither a positive mitigation measure nor should it be included in the government funding scheme. If the initial tree density is below or near the minimum requirements according to the Forestry Act (table 2), this kind of funding will be positive for carbon sequestration and storage.

The choice of tree density may also be important for adaptation to several natural disturbances. Based on observed damages on permanent NFI plots during the period 2005-2015, Solberg et al. (2019) showed that an important factor leading to snow and wind damage is lack of individual tree stability. Reduced tree density compared to «recommended» density in the young forest phase has therefore been suggested as an adaptation measure to reduce wind and snow damages (Søgaard et al. 2017; Dalen 2021; Solberg et al. 2022; Skogbrand n.d.). The expectation is that decreasing density at early stages boosts diameter growth relative to height growth (increasing diameter-to-height ratio) and thus enhance individual tree stability and thereby reduce wind and snow damage (see also section 3.1.1.2).

A similar effect towards enhanced individual tree stability may also be achieved by applying low densities when planting. Scenario simulations comparing management with near-optimal densities and adapted management with reduced densities both in regeneration and young forest phases (Table 1), followed by one thinning and no thinning, respectively, showed that the resistance to snow load increased and that the probability of snow damages decreased (Strîmbu et al. 2025). Similar effects can also be expected for the combined effect of wind and snow damages (Díaz-Yáñez et al. 2019). As a mitigation measure, however, reduced density was less positive. The scenario results of Strîmbu et al. (2025) showed that the long-term volume production, to some extent, was reduced with lower density, and accordingly, also carbon sequestration and storage. The profitability of the forest owner, however, was not reduced, mainly because no thinning was applied.

Reduced density may reduce drought stress and damage, particularly for spruce stands (Hanssen et al. 2019; Søgaard et al. 2023). Drought stress may also facilitate bark beetle (*Ips typographus*) attacks. Although there are uncertainties and knowledge gaps related to such effects, reduced density as a potential adaptation measure to reduce drought and bark beetle damages should not be ruled out.

3.1.1.2 Young Forest Phase

The main objective of young growth tending is to secure growth conditions and quality for the future trees that are targeted to develop into the production and mature forest phases. Generally, the targeted trees should be those that will provide an income as high as possible for the forest owners based on tree species and size. Young growth tending should be applied before the targeted future trees are constrained in growth or damaged due to competing trees, normally at heights between 1 m and 4 m, depending on productivity and species mixture (e.g. Skogkurs 2017; Søgaard et al. 2017; Landbruksdirektoratet 2023; and Granhus, n.d.).

The tree species distribution and tree density commencing from the regeneration phase are important for how the young growth tending should be approached. In single-species stands, young growth tending is mainly about regulating density (spatially and trees/ha), while in mixed-species stands, the tending comprises species selection as well as density regulation. Note that trees often will establish naturally during the regeneration phase, even when planted, especially birch trees, but sometimes also spruce and pine. To avoid tending in the young growth phase may be an option, but only if the tree density is very low and/or if the tree species distribution commencing from the regeneration phase is suitable for the future incomes (i.e. a low proportion of broadleaves).

The choices made during young growth tending regarding tree species and tree density are important for climate change mitigation and adaptation effects. Traditionally, the objective has been to maximise future volume production and income when deciding on tree species and tree density. Because of the increased concerns about climate change, recent discussions have mainly been going along two main options: a shift from single-species spruce stands towards a mixture of different species and a shift from "«recommended»" density to a reduced density (Table 1).

Tree Species

A shift from single-species spruce stands towards a mixture of species (spruce, pine, and birch) during the young forest phase is considered a general adaptation measure to reduce risk because spruce is the tree species most vulnerable to natural disturbances such as root rot and bark beetle damages, and possibly also to windthrow and drought stress (cf. section 3.1.1.1). Furthermore, a mixture of tree species is generally positive for biodiversity, and it is also a requirement of the Norwegian forest certification regime that a certain share of broadleaves is facilitated during young growth tending.

The mitigation effect of a shift during the young forest phase from single-species planted spruce stands to mixed-species stands with a large proportion of naturally regenerated birch is usually negative because of reduced long-term volume production and thus carbon sequestration and storage. As a mitigation measure related to albedo, however, the effect might be positive, especially if the proportion of birch is large (Halim et al. 2019; Bright & Astrup 2019).

Tree Density

The main factors to consider when deciding on tree density after the young growth tending are the long-term volume and value production. Analyses show that if 1500-2500 trees/ha are left, the value production for the remaining part of the rotation will be at least 90% of the maximum production (Søgaard et al. 2017). Higher or lower densities than this will further reduce the production, particularly for lower densities. The general recommendation is, therefore, to leave 1500-2500 trees/ha to grow further into the production forest phase. Furthermore, even if no commercial thinnings are planned for later in the rotation, it is not recommended to leave less than 1500 trees/ha because of uncertainty and lack of knowledge related to the long-term production at such low densities (Søgaard et al. 2017). The scenario simulations by Strîmbu et al. (2025) showed that the standing volume at the property level at the end of the 100-year planning period, where the number of trees consistently was reduced to 1300 trees/ha during young growth tending to increase the resistance to snow damages, was about 8% lower than the corresponding standing volume of a management more similar to the above recommendations. The profitability of the forest owner, however, was not reduced for the alterative with reduced density, mainly because no thinning was applied. To reduce density compared to the "recommended" density (Table 1), is therefore a viable measure for adaptation to snow damages, and possibly also to wind damages, while the mitigation effect to some extent may be negative. For bark beetle damage, however, a reduced density may be negative as an adaptation measure (Romeiro et al. 2024; 2025).

3.1.1.3 Production Forest Phase

In the production forest phase of a rotation, there are basically two treatment options: commercial thinning and fertilisation. The main objective of both options is to increase the economic value of the stand at the final harvest. The purpose of thinning may, however, also be "non-commercial" to facilitate a transition to different continuous cover forestry (CCF) options (cf. section 3.1.2).

The main objective of thinning (commercial) is to increase the production and quality of the trees that are targeted to develop into the mature forest phase. Generally, the targeted trees should be those that are expected to provide the highest possible monetary value at the final harvest, based on tree species and size. The trees not targeted to develop further are removed during the thinning operations. Thinning is the first opportunity over the rotation to possibly gain income for the forest owner. The thinning is usually applied when the dominant height is larger than 12 m to achieve merchantable tree sizes and lower than 18 m to avoid instability (e.g. Skogkurs 2013b; Andreassen 2017; Søgaard et al. 2017; and Søgaard et al. 2023). The extent of commercial thinning in Norway differs largely over the forest area due to, for example, varying forest structure, productivity, terrain conditions, roundwood prices and traditions. In southeastern Norway, the share of volume thinned out of all harvested volume may peak to 15-20%, especially in areas dominated by pine, but normally, the share is lower. In other parts of the country, the volume share of commercial thinning is much lower (Søgaard et al. 2017).

Thinning or no Thinning

The choice of thinning (or no thinning) as a measure to increase income for forest owners depends on several factors. The prevalent recommendation is to prioritise thinning for areas where young growth tending has taken place earlier in the rotation. The trees in such stands are generally larger in diameter, and the individual tree stability is better. Furthermore, in previously tended stands, costly pre-clearance work before commercial thinning can be avoided, which means that the probability of a positive cash flow from the thinning increases. A positive cash flow from the thinning is also more likely if the terrain is smooth and the skidding distance is short. However, from an economic perspective, a positive cash flow from thinning does not imply that thinning per se should be implemented. It is the cash flow over the whole rotation (including the land value at the time of final harvest) that should be evaluated as the basis for prioritising silvicultural treatments.

Thinning Method

If an implementation of thinning is decided, the next step is to consider the thinning method, i.e. how many (trees/ha or basal area/ha) and which trees should be left for further production. The prevalent recommendation is to follow a strategy with “free thinning”, i.e. to remove trees around the trees targeted for further production (the most valuable trees), where a maximum of 35% of the basal area/ha is removed (Skogkurs 2013b). Such a strategy may be considered as a compromise between aiming for a high income at the final harvest without significantly reducing the future production and social stability of the stand. Another option is “thinning from above”, i.e. mostly large trees are removed, where the smaller trees are left for further growth. Such a strategy may secure a relatively high net income for the actual thinning operation but may also lead to smaller trees at final harvest and/or extended harvest ages.

The impacts of commercial thinning as a positive measure for climate change mitigation are questionable. A positive impact requires the total volume production over a rotation (and thus carbon sequestration and storage aboveground biomass) to increase. At best (potentially at high site productivities and/or with early thinning), the production may remain the same or even slightly increase, but in most cases, the production is reduced, thus also carbon sequestration and storage. It is worth mentioning, however, that reduced density due to thinning also leads to larger tree sizes, and accordingly increased sawlog proportions at the final harvest, which implies a higher potential for carbon storage in harvested wood products (HWPs, cf. chapter 4). A similar potentially positive implication of thinning is the possibility of harvesting trees for biofuel that otherwise would be lost in natural mortality.

The impacts of commercial thinning related to damages from natural disturbances are mainly negative. Root rot infection in spruce stands may be further triggered by thinning because fresh wood is exposed, not only to stumps from removed trees and roots, but also if the trees targeted for further growth are damaged during thinning operations. However, adaptations to this challenge can be implemented either by applying thinning during winter or using Rotstop when thinning takes place under summer conditions.

Lack of stability at the individual-tree and stand-levels is an important factor for snow and wind damage in Norway (Solberg et al. 2019). Such damages are therefore likely to increase due to thinning because the existing stand-level stability, where trees support and shelter each other, is weakened. This is especially the case when a large proportion of trees is removed through thinning at the late stages of the production phase. Generally, low densities established during regeneration and young growth phases will boost diameter growth relative to height growth (improving the diameter-to-height ratio) and thus enhance individual-tree stability. This may facilitate an adaptation strategy with no thinning to reduce wind and snow damages.

Bark beetle damage is an increasing concern under climate change. The influence of commercial thinning as an adaptation strategy is, however, uncertain. An Austrian model for the prediction of bark beetle damage probability and intensity was adapted to and simulated for Norwegian data and conditions (Romeiro et al. 2024; 2025). The results indicated that the potential economic losses, when not considering the risk of bark beetle damage, were larger in low-density stands compared to high-density stands. The reason indicated to explain this was that a low tree density increases sunlight level and temperature within the canopy and on bark, which in turn increases bark beetle susceptibility and numbers (Seidl et al. 2007). According to this, tree density should not be reduced through thinning. However, in the preparedness plan addressing bark beetle challenges in Norway, thinning is suggested as a measure to reduce bark beetle damage because this is expected to reduce competition between trees and thus increase robustness and vitality (Landbruksdirektoratet 2024b).

Thinning is also mentioned as a possible measure to reduce drought damage and thus tree mortality late in the rotation (Søgaard et al. 2017). The hypothesis is that in untinned stands, where the competition and stress are high, the natural mortality towards the end of the rotation will increase more compared to thinned stands, where weak trees are removed and the trees targeted for future growth experience less competition and stress.

Fertilisation

In forest areas where nitrogen (N) limits tree growth, N-fertilisation will boost the diameter growth of trees. The main objective of fertilisation is to increase growth and thus the economic value of the stand at the final harvest. Since the growth increase persists for only 8-10 years, fertilisation should be applied about 10 years before scheduled final felling. The usual recommendation is to apply 150 kg. N/ha, which is expected to give an increased annual stem-growth of 1,5 m^3/ha, or 15 m^3/ha over a period of 10 years (Hanssen, n.d.a.; Søgaard et al. 2023; Landbruksdirektoratet 2024a). The forest certification system sets certain requirements for fertilization to ensure that natural processes and long-term production conditions are maintained.

In addition to the positive impact on forest owner income, fertilisation is also a positive climate change mitigation measure since increased growth of biomass implies increased carbon sequestration and storage in the forest. Since fertilisation increases tree sizes and, accordingly, the sawlog proportions at final harvest, the potential for carbon storage in harvested wood products will also increase (HWPs, cf. chapter 4). Concerns related to the impact of fertilisation on soil carbon have been elaborated (Landbruksdirektoratet 2021), and the main conclusion was that the effect of fertilisation on soil carbon storage is generally positive. It is worth mentioning, however, that N-fertilisation also increases the N_2O emissions (Mäkipää et al. 2023), which is negative for climate change mitigation.

To support climate change mitigation, government funding (subsidies) (currently 50% of fertilisation costs) has been provided to forest owners since 2016. The funding aims to contribute to increased carbon sequestration and storage. Additional environmentally oriented requirements beyond the certification regime must be followed up on to get government funding (Landbruksdirektoratet 2023). In the 10 years from 2006 to 2015, the annual area of fertilisation in Norway varied from 450 ha to 1200 ha. Since government funding was implemented in 2016, the average annual area in the period 2016 to 2023 rose to nearly 5000 ha, with a peak in 2017 of 9000 ha (SSB 2025).

The effect of fertilisation as an adaptation measure to reduce natural disturbances seems rather insignificant, although reduced harvest ages, and thus lower probability of drought stress or bark beetle damage at late stages in the rotation, could be a consequence. However, there are some concerns and knowledge gaps related to the chemistry and defensive strategies of Norway spruce under climate change, indicating that fertilisation might leave the trees less robust and more prone to damages from forest herbivores and insects (Nybakken et al. 2018; Hanssen et al. 2020).

There are also some concerns and knowledge gaps related to the impact of fertilisation on forest biodiversity. The present practices and extent of fertilisation, however, are not considered to have significant negative effects at the landscape level. At the stand-level, fertilisation may, to some extent, change species composition and diversity, but with a moderate "once in the rotation application" of fertilisation, the changes are regarded as small and temporary (Landbruksdirektoratet 2021).

3.1.1.4 Mature Forest Phase

The final harvest is the main activity of the mature forest phase. The primary purpose of final felling is to harvest the outcome of forest production and provide the forest owner with profit. This profit represents the outcome in monetary terms of the biological growth in roundwood volume and quality over the rotation. In addition, regeneration for the next rotation must be secured when deciding on how and when to apply the final harvest. Planting and natural regeneration are the two main treatment options for establishing a new forest stand. If planting is chosen, decisions regarding tree species and tree density must be made, while natural regeneration requires that seed trees from relevant species are present in the stand or in neighbouring stands. Natural regeneration of pine is facilitated by leaving seed trees in the stand during final harvest operations. For spruce, natural regeneration depends on seeds from spruce trees in neighbouring stands. Furthermore, measures such as root rot prevention and soil scarification should be considered (cf. section 3.1.1.1 for details).

Requirements related to final harvests are given through certification standardsKlikk eller trykk her for å skrive inn tekst. and regulations (https://lovdata.no/dokument/SF/forskrift/2006-06-07-593). The aim of these requirements is, in addition to providing for satisfactory regeneration in the new stand, to secure the environmental values of the forest. Examples of requirements specified in the regulations and standards are to preserve key habitats, to remove forest residues from ditches, streams and trails, to restore damages due to machine operations and to leave retention trees (5 trees/ha).

The two main decisions regarding the final harvest, in addition to those facilitating regeneration and securing environmental values, are the choice of harvest method and the choice of harvest age.

Harvest Method

The total biomass of a tree includes approximately 25% in roots and stump, 50% in stem and 25% in branches and top (Løken et al. 2012). The branches and top part of the tree may potentially be chopped up and used for heating and biofuel purposes, replacing fossil energy. The final harvest may be implemented as stem-only harvesting or stem-residue harvesting (stump and root harvesting excluded). Stem-only harvesting is by far the method most applied in Norway, although the potential for using harvest residues (branches and tops) is large. If we assume that the annual harvest of stem volume in Norway is 13.0 mill. m^3, about 6.5 mill. m^3 are left as branches and tops. When harvesting branches and tops, usually about 30% if the biomass is still left in the forest (Alfredsen et al. 2018), indicating that about 4.6 mill. m^3 could potentially be used for heating and biofuel purposes. The extent of stem- and residue-harvesting is today almost absent while it was larger before a subsidise scheme was cancelled in 2014, e.g. amounting to 80,000 m^3 (chips) in 2013 (Alfredsen et al. 2018).

Stem- and residue-harvesting might be a better measure for mitigating climate change than stem-only harvesting (Miljødirektoratet 2015; Søgaard et al. 2020). When the biomass residues are removed from the forest through stem- and residue-harvesting and used for energy production, the carbon will be released into the atmosphere as soon as the biomass is burned. However, if energy production from biomass replaces production based on fossil fuels, the impact on climate change mitigation is positive. When harvest residues are left in the forest, the biomass will decay, and thus, most of the carbon is emitted to the atmosphere as CO_2 over a certain period. Some of the degraded biomass will also, over time, be stored in the forest soil as carbon. There are, however, knowledge gaps and uncertainty related to the timing of these processes, among others, because of local climatic variations and variations in tree species and tree dimensions.

Some concerns related to stem- and residue-harvests are also expressed regarding the reduction of nutrients in the soil. It seems, however, that up to about 70% of the biomass from branches and tops can be removed without impact on nutrient content and tree growth (Søgaard et al. 2020). Stem- and residue-harvesting may influence seedling growth negatively and increase pine weevil damages, especially close to residue piles. However, there are also indications of better growth for seedlings planted in the areas where residue piles have been placed and later removed (Hanssen et al. 2018).

Harvest age

The choice of harvest age (age of the stand when the final harvest is applied) is important for long-term volume production and for economic revenues to the forest owner. The optimal biological and economic harvest ages are determined by maximising the long-term volume production and the net present value (NPV), respectively. The maximum long-term volume production is achieved when harvesting at an age where the current annual increment (CAI) equals the mean annual increment (MAI). Economic optimum harvest age is achieved when harvesting at an age when the harvest generates the maximum NPV, i.e. for an existing stand, this is the net present value (NPV), for a given required rate of return, of the sum of the final harvest and the value of bare forest land.

Table 4 shows the optimal biological harvest age (years) for different tree species and site index classes. The numbers are calculated from a set of well-known growth models (Tveite & Braastad) based on long-term forest management trials maintained by the Norwegian Institute of Bioeconomy Research (NIBIO) (https://feltforsok.nibio.no/Kalkulator/BonKalk.cfm). A basic assumption for arriving at these numbers is to keep the density of the stand sufficiently high throughout the rotation (i.e. near the prevalent recommendations for density in regeneration, and after young growth tending and thinning, cf. sections 3.1.1.1 to 3.1.1.3). Note that new models have recently been developed based on updated data from the management trials (Allen et al. 2020; Kühne et al. 2022). These models predict higher volume production levels compared to the old models in un-thinned stands while the production is quite similar in thinned stands (Kühne et al. 2023). In addition, it seems that the optimal biological harvest ages are somewhat longer according to these models, particularly for the most productive sites (5-10 years).

Table 4. Optimal biological harvest age (years) according to tree species and site index class.

Site index (H40, m)	Spruce	Pine
23	84	82
20	90	90
17	98	99
14	108	110
11	122	127
8	141	154
6	163	182

Table 5 shows the optimal economic harvest age (years) according to different tree species, site index classes and required real rates of return (Hoen 2025). The numbers are based on simulations with Gaya 2.0 (Strîmbu et al. 2023).

Table 5. Optimal economic harvest age (years) according to site index class and required rate of return (Hoen 2025).

Site index (H40, m)	Spruce			Pine		
	Required real rate of return			Required real rate of return		
	2.0%	3.0%	4.0%	2.0%	3.0%	4.0%
23	65	55	50	60	50	50
20	70	60	55	65	60	55
17	80	70	65	75	65	60
14	90	80	70	85	70	65
11	105	90	85	95	85	75
8	135	120	105	115	100	90

The choice of harvest age is influenced by multiple factors such as forest owner income and profitability, mitigation of climate change, adaptations to climate change, biodiversity and harvested wood products (HWPs and mitigation, cf. chapter 4).

To maximise the climate change mitigation effect related to aboveground carbon sequestration and temporary storage, the optimal biological harvest ages (Table 4) should be applied since they provide maximum long-term volume and biomass production. Applying longer harvest ages than this will increase the short-term carbon storage in above-ground biomass, but the long-term carbon sequestration will decrease. Applying shorter harvest ages than the biologically optimal will decrease the long- and short-term carbon storage as well as sequestration.

The harvest age will also affect the soil carbon pool, but how much and in what way is still discussed (Dalsgaard et al. 2015; Mayer et al. 2020; Johannesson et al. 2025; Madsen et al. 2025). It is expected that soil carbon, amounting to 10-20% over about 20 years, is lost after the final harvest. Provided that the harvested area is regenerated, however, soil carbon is accumulated for the rest of the rotation. There is, however, uncertainty related to whether this accumulation is sufficient to completely restore the soil carbon over the entire rotation, among others, due to variation between different soil types. Based on field data from the Swedish Forest Soil Inventory, Ortiz et al. (2013) concluded that soil organic carbon (SOC) had a consistent increase (6.6 (±7) $TgCyr^{-1}$) in the period 1994 – 2000. Based on modelling (Yasso07) Norway has reported a slight and consistent increase in SOC to UNFCCC (Miljødirektoratet 2023). These results are, however, general and not directly linked to harvest age. In 2023 the Norwegian NFI started to collect soil samples connected to a sub-sample of the inventory plots. Data from this inventory may in future provide results where the development of soil carbon can be linked to harvest age.

The albedo effect of forests, particularly in snow-covered or high-latitude regions, can be conceptualised as a negative ecosystem service or climate disservice (cf. MEA 2005 for the term "climate disservice"), as forest cover reduces surface reflectivity and thus contributes to regional warming. To increase the climate change mitigation effect related to albedo, shorter harvest ages should be applied because this over time would increase the length of the period and the ability of the forest area to reflect sunlight to the atmosphere and thus mitigate the rise in temperature under climate change. Bright et al. (2024), however, found that only 4% of Norway's forested areas experienced albedo impacts substantial enough to offset the carbon sequestration effects. Similarly, (Rørstad 2022a) evaluated the economic and climatic implications of albedo in Norwegian forestry and concluded that CO_2 sequestration overwhelmingly surpassed the albedo effect. Therefore, in the context of changed harvest ages, the mitigation effects related to albedo are very limited.

To maximise the income and profitability of the forest owner, the optimal economic harvest ages (Table 5) should be applied since this provides the maximum NPV. In addition to the site index, these harvest ages depend on the required real rate of return. Generally, the optimal economic harvest ages, even with real rates of return in the lowest range (around 2%), are substantially shorter than the optimal biological harvest ages (Table 4), implying that carbon storage as well as sequestration are reduced. The lower harvest age limits imposed by the Norwegian certification regimeKlikk eller trykk her for å skrive inn tekst. are, however, far from being violated by the optimal economic harvest ages, even with an interest rate in the higher range (around 4%). Note that both optimal biological and economic harvest ages (Tables 4 and 5) assume "normal" natural mortality development over the rotation without severe impacts of natural disturbances.

Reductions of harvest ages below the economically optimal ones are generally recommended when considering damages related to most natural disturbances, particularly if emerging infestations of root rot and bark beetles, or initial wind throw, snow breakage and drought stress, are observed in a stand. Two simulation studies, where the risk of root rot and bark beetles was considered to some extent, support this, although the economic gains when reducing harvest ages were very small. Aza et al. (2021) found that harvest age changed in 14-23% of the simulated stands, depending on the rate of return and rot growth rate in the stem. The average reductions of harvest ages for the stands with changes were 1.3 years and 4.7 years, respectively, for rates of return of 2% and 3%. Similarly, Romeiro et al. (2025) found that under present climate conditions, the average reduction in harvest age of the simulated stands was around 2 years (rate of return 3%) for some regions in southeastern Norway, while they on average rose to around 5 years under climate change (RCP8.5). The variations between the simulated stands were large, and the results indicated that low-density stands with a high proportion of spruce situated in more productive sites yielded the largest reductions in harvest ages and economic gains when bark beetle risk was considered.

3.1.1.5 Treatment Schedules over a Rotation

In this section, the temporal aspects of the individually elaborated treatments (Table 1) are included in an exercise describing sequences of treatments involving a complete rotation. Such a sequence of treatments is termed "treatment schedule". This exercise aims to illustrate some of the stand-level complexities when considering the climate change mitigation and adaptation objectives associated with silvicultural treatments.

To simplify the exercise, we assumed that the schedules, in general, apply to spruce-dominated forest areas growing on medium to high productivity sites (H_{40}=11-26 m). The main reasons for this are that these spruce-dominated areas have the largest potential for climate change mitigation (highest growth), but at the same time, they are most prone to natural disturbances and, therefore, important for the adaptations to climate change. In addition, these areas are the most valuable in terms of NOK/ha. About 25% of the productive forest area in Norway, comprising about 40% of the standing volume, belongs to this category (https://landsskog.nibio.no/).

As bases for the exercise, we developed a set of treatment schedules that one-by-one focus on the different mitigation objectives (maximise carbon sequestration and storage, and albedo) and adaptation objectives (minimise bark beetle damages, root rot damages, wind damages, snow damages and drought damages). In addition, we developed one schedule minimising all natural disturbances jointly and one schedule maximising profitability (cf. Supplementary material, 10.1, for detailed descriptions of all schedules).

The treatment schedules are based on the individual silvicultural treatment options described in sections 3.1.1.1 to 3.1.1.4. Although the treatment schedules are derived from available documentation, uncertainty related to knowledge gaps, assumptions, and expert judgments are present. To simplify, we do not consider carbon sequestration and storage in soil and carbon storage in harvested wood products (HWPs) when developing the schedules.

The schedules are based on knowledge from years of theoretical and empirical research on forest growth and production, mostly in Norway. However, there are still uncertainties related to the actual numbers for density in regeneration and young forest phases (cf. Table 3 and Section 3.1.1.2) and to the numbers for harvest ages (cf. Tables 4 and 5, Section 3.1.1.4) because of the data and methods used to develop the growth and natural mortality models on which the numbers rely. We consider these uncertainties to be small. More serious uncertainties are connected to future climate changes in temperature and precipitation that are expected to change growth conditions and thus «recommended» densities and harvest ages, but how and to what extent is unknown.

When developing the schedules, we consider the forest owner's income to some extent. For example, we do not suggest a previous spruce stand at an appropriate site for spruce production to be regenerated with 100% pine or birch as an adaptation measure to avoid attacks from bark beetles. Instead, we assume a mixture of tree species, including spruce, to be planted to reduce the susceptibility to attacks. Similarly, to maximize maximise carbon sequestration and storage, strictly speaking, the stand should be left "untouched", but we assume that an active management take place. The schedules also, to some extent, depend on economic assumptions. The optimal economic harvest ages correspond to a required real rate of return of about 2.0% (cf. Table 5), and the net income (roundwood value minus harvesting costs) for clear-cutting is assumed to be around 400 NOK/m^3.

In the following, we describe in detail the individual silvicultural treatments over a rotation for three of the treatment schedules, i.e. maximising carbon sequestration and storage, minimising all natural disturbances jointly and maximising profitability. In addition, we describe their impacts (trade-offs and synergies) on objectives related to mitigation and adaptation and to the profitability of the forest owner. An overview is given in Table 6. Further descriptions are given below the table.

Table 6. Treatment schedules for maximising carbon sequestration and storage, minimising all natural disturbances jointly and maximising profitability. Each of the three treatment schedules (rows) is evaluated for its effect on different elements of mitigation, adaptation and profitability (columns).

Treatment schedule	Stand development phase	Treatment	Mitigation			Adaptation					Profit-ability
			Carbon seque.	Carbon storage	Albedo	Bark beetle damages	Root rot damages	Wind-throw	Snow damages	Drought damages	
Maximise carbon sequestration and storage	Regeneration	Plant single-species (S)	Green	Green	Red	Red	Red	Red	Yellow	Red	Green
		Recommended l density	Green	Green	Red	Green	Yellow	Red	Red	Red	Green
	Young forest	Keep recommended density	Green	Green	Red	Green	Yellow	Red	Red	Red	Green
	Production forest	No thinning	Green	Green	Red	Green	Green	Green	Green	Red	Red
		Fertilisation	Green	Green	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Green
	Mature forest	Clear-cutting at optimal biological harvest age	Green	Green	Red	Red	Red	Red	Red	Red	Red
Minimise all natural disturbances jointly	Regeneration	Plant mixed-species (S, P, B)	Red	Red	Green	Green	Green	Green	Yellow	Green	Red
		Apply low density	Red	Red	Green	Red	Yellow	Green	Green	Green	Red
	Young forest	Keep low density	Red	Red	Green	Red	Yellow	Green	Green	Green	Red
	Production forest	No thinning	Green	Green	Red	Green	Green	Green	Green	Yellow	Red
		No fertilisation	Red	Red	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Red
	Mature forest	Clear-cutting before optimal economic harvest age	Red	Red	Green	Green	Green	Green	Green	Green	Yellow
Maximise profitability	Regeneration	Plant single-species (S)	Green	Green	Red	Red	Red	Red	Yellow	Red	Green
		Recommended density	Green	Green	Red	Green	Yellow	Red	Red	Yellow	Green
	Young forest	Keep recommended density	Green	Green	Red	Green	Yellow	Red	Red	Yellow	Green
	Production forest	Thinning	Red	Red	Green	Red	Red	Red	Red	Green	Green
		Fertilisation	Green	Green	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Green
	Mature forest	Clear-cutting at optimal economic harvest age	Red	Red	Red	Red	Red	Red	Red	Red	Green

Green: synergy, Red: trade-off, Yellow: neutral

The general lesson learned from the exercise (Table 6) is, not surprisingly, that there is no "one size fits all" type of answer to how to mitigate and adapt to climate change and at the same time take care of the forest owner's cash flow and profitability. If a strategy maximising carbon sequestration and storage is implemented, the impacts on mitigating climate change by means of albedo are negative, the impacts on adaptation to natural disturbances are mainly negative, and the impacts on profitability are partly negative and partly positive. With a strategy minimising all natural disturbances jointly, the impacts on mitigating climate change through carbon sequestration and storage are negative; they are mainly positive for the mitigation impacts related to albedo, while the impacts on profitability are negative. Finally, with a strategy maximising profitability, the impacts of mitigating climate change through carbon sequestration and storage, as well as albedo, are partly positive and partly negative, while the impacts on adaptation to natural disturbances are mainly negative. Below, a detailed description of the three treatment schedules is given.

Maximise Carbon Sequestration and Storage
Regeneration phase: plant spruce with «recommended» density according to volume production. Young growth phase: keep «recommended» density according to volume production. Production forest phase: no thinning but apply fertilisation. Mature forest phase: clear-cut at optimal biological harvest age.

Comments on the schedule:
This schedule assumes that spruce is planted with a density according to the recommended numbers of trees/ha from Skogkurs (cf. section 3.1.1.1, Table 3) and that the prevalent density recommendation of 1500-2500 trees/ha (cf. section 3.1.1.2) is followed throughout the young forest phase. In the production forest phase, we avoid thinning because this reduces stand-level volume production, but we apply fertilisation (10 years before final harvest) because this increases the stand-level volume production (cf. section 3.1.1.3). The final harvests (clear-cutting) are assumed to be applied at harvest ages where the CAI equals the MAI (cf. section 3.1.1.4, Table 4).

Impacts on mitigation and adaptation objectives (cf. Table 6):

- For mitigating climate change by means of albedo, all individual treatments applied in the schedule maximising carbon sequestration and storage, except fertilisation, are negative.
- For adaptation to bark beetle damages, planting single-species spruce stands and applying harvest ages as long as those maximising volume production are negative while keeping an «recommended» density throughout regeneration- and young production forest phases probably is positive (Romeiro et al. 2024; 2025), although some uncertainty exists related the effect of thinning (cf. section 3.1.1.3).
- For adaptation to root rot damages, planting single-species spruce stands and applying harvest ages as long as those maximising volume production are negative, while avoiding thinning is positive because rot infestation may be reduced. Keeping an «recommended» density and applying fertilisation are probably neutral in the context of root rot damage.
- For adaptation to wind throw and snow damages, the effects are generally the same for all treatments except for the species distribution when planting. For wind throw, planting single-species spruce is negative because of the shallow root system for spruce, while we for snow damages have no empirical evidence of spruce being more prone to damages than pine. Generally, for adapting to wind throw and snow damage, we should apply low density when planting and keep it low in the young growth phase to increase individual tree stability and avoid thinning to preserve stand-level stability at later stages (Solberg et al. 2019; Strîmbu et al. 2025). To apply harvest ages as long as those maximising volume production, very likely leads to more wind throw and snow damages.
- For adaptation to drought damages, all individual treatments applied in the schedule maximising carbon sequestration and storage, except fertilisation, are likely negative.

Minimise All Disturbances Jointly

Regeneration phase: plant mixed-species (spruce, pine, birch) with a lower density than «recommended» according to volume production. Young growth phase: keep a lower density than «recommended» according to maximum volume. Production forest phase: no thinning or fertilisation. Mature forest phase: clear-cut before economic harvest age.

Comments on the schedule:

No schedule exists that can fulfil all requirements for adaptation to all the individual natural disturbances jointly because the different treatments are partly conflicting. The schedule is, therefore, a compromise where some treatments are applied at the expense of perfect adaptation to individual natural disturbances. The chosen treatment schedule assumes that mixed-species stands of spruce, pine and birch are planted with a lower density than the recommended numbers of trees/ha from Skogkurs (cf. section 3.1.1.1, Table 3), at the expense of adapting to bark beetle damages. In the young forest phase, we assume to keep a lower density than the prevalent density recommendation of 1500-2500 trees/ha (cf. section 3.1.1.2), also at the expense of adapting to bark beetle damages. In the production forest phase, we avoid thinning and fertilisation. The final harvest (clear-cutting) is assumed to take place at lower harvest ages as compared to when NPV is maximised (cf. section 3.1.1.4, Table 5). It should be noted that in this treatment schedule, where we seek to minimise all natural disturbances jointly, we should also consider applying Rotstop and/or harvest during winter to reduce root rot, applying soil scarification and choosing relevant plant material to reduce pine weevil damages.

Impacts on mitigation and adaptation objectives (cf. Table 6):

- For mitigating climate change through carbon sequestration and storage, all individual treatments applied in the schedule during regeneration (plant mixed-species with low density) and young forest (keep low density) phases are negative. In the production forest phase, no thinning is positive, while no fertilisation is negative. The final harvest at lower harvest ages as compared to when NPV is maximised is negative for carbon sequestration and storage.
- For mitigating climate change through albedo, most treatments in the schedule are positive, except to avoid thinning because maintaining a high density in the production forest phase may slightly reduce the ability of the forest to reflect sunlight to the atmosphere.
- For adaptation to natural disturbances, most treatments applied in the schedule are, of course, positive, while a few are considered neutral. The only exception is for adaptations to bark beetles, where a low density in regeneration and young forest phases is most likely negative.

Maximise Profitability

Regeneration phase: plant spruce with «recommended» density according to volume production. Young forest phase: keep «recommended» density according to volume production. Production forest phase: Apply thinning and fertilisation. Mature forest phase: clear-cut at optimal economic harvest age.

Comments on the schedule:

The basic assumption of this treatment schedule is that no natural disturbances occur during the rotation. The schedule further assumes that NPV is maximised according to a real rate of return of around 2.0%. To achieve this, we assume that spruce is planted with a density according to the recommended numbers of trees/ha from Skogkurs (cf. Section 3.1.1.1, Table 3) and follow the prevalent density recommendation of 1500-2500 trees/ha (cf. Section 3.1.1.2) throughout the young forest phase. Since young growth tending takes place earlier in the rotation, it is assumed that pre-clearance work before thinning operations is avoided and that costs, therefore, to some extent, is reduced during thinning operations. We also assume that thinning, to some extent, enhances timber quality and size and thus timber value at the time of final harvests compared to if no thinning is applied. Similarly, due to thinning, we assume somewhat larger tree sizes and thus lower harvesting costs at the time of final harvest. Furthermore, we assume smooth terrain conditions and relatively short transport distances. It is important to note that "the margins" for the profitability of thinnings generally are small, thus, most of the assumptions described above must be fulfilled for thinning to be profitable. Fertilisation is applied (10 years before final harvest) because this is expected to increase volume production and thus profitability (cf. section 3.1.1.3). The final harvest (clear-cutting) is assumed to take place at harvest ages where NPV is maximised (cf. section 3.1.1.4, Table 5).

Impacts on mitigation and adaptation objectives (cf. Table 6):

- For mitigating climate change by through carbon sequestration and storage, all individual treatments applied in the schedule during regeneration (i.e. plant spruce with «recommended» density) and young forest (i.e. keep «recommended» density) phases are positive. The same applies to fertilisation. Thinning and final harvest at optimal economic harvest age, however, are negative for carbon sequestration and storage.
- For mitigating climate change through albedo, most individual treatments in the schedule (i.e. plant spruce with «recommended» density, keep «recommended» density in the young forest phase and clear-cut at optimal economic harvest age) have negative impacts, while thinning may have a small positive impact.
- For adaptation to bark beetle damages and root rot, planting of spruce and thinning are negative. There are also small negative effects of final harvest at an optimal economic harvest age because harvest ages should be even lower when adapting to reduce bark beetle and root rot damages. Keeping an «recommended» density according to maximum volume production throughout regeneration and young production forest phases is positive for adapting to bark beetle damages while it is probably neutral when considering root rot damages.
- For adaptation to wind throw and snow damages, most treatments applied in the schedule are negative. For wind throw, planting spruce is negative because of the shallow root system for spruce, while for snow damages no empirical evidence exists for spruce being more prone to damage than pine. To apply «recommended» density when planting, maintain «recommended» density in the young forest phase and apply thinning in the production forest phase are all negative treatments for wind throw and snow damages. To apply optimal economic harvest ages are considered negative because harvest ages should be even lower for adaptations to reduce wind throw and snow damages
- For adaptation to drought damages, planting single-species spruce stands is negative because spruce is prone to drought stress. To apply optimal economic harvest ages is also considered negative because harvest ages should be even lower. Thinning is considered positive because this may enhance tree vigour at the late stages of the rotation.

3.1.2 Continuous Cover Forestry

Over the past few years, significant attention related to continuous cover forestry (CCF) has been observed in Norway, partly because of recently revised certification standards (PEFC 2022), increased attention to biodiversity issues and as a potential measure for climate change adaptation. Many public and private forest owners also show an increasing interest in applying CCF. Presently, however, rotation forestry (RF) is by far the most common. The share of productive forest areas managed according to CCF principles was in 2017 estimated to be 6.8%, while the corresponding harvested volume share was 3.6% (Stokland et al. 2020). This means that most forest owners and managers neither have in-depth knowledge nor experience related to CCF. The same also partly applies to the research community. A recent book, however, authored by a large number of researchers from the Nordic countries, has reviewed and elaborated on multiple aspects of CCF (Rautio et al. 2025). The book presents the state of the art, but also, in general, concludes that extensive research is needed because of existing knowledge gaps and uncertainties related to CCF in the countries.

The general definition of CCF in Norway is that 160 trees/ha or more are left for regeneration purposes after harvest or that the harvest gaps are smaller than 0.2 ha (Brunner et al. 2023; Granhus et al. 2024). The most important CCF options are termed the **Selection system**, **Group selection system** and

Shelterwood system. These systems not only include the actual harvest operations but may also comprise a sequence of different measures related to regeneration, young growth tending and different harvesting schemes. When applying these systems, the stands usually develop into forest structures that are more or less uneven-aged, as opposed to RF, where the forest structure is mainly even-aged. The shelterwood and group selection systems should only be considered as CCF management if the continuous minimum forest cover is an explicit objective and if it is actually maintained (Brunner et al. 2025; Cedergren et al. 2025). A fast and complete removal of shelterwood trees in a shelterwood system or large, many, or frequent gaps in a group selection system that do not aim for and maintain the forest cover is therefore outside the definition of CCF.

The so-called "mountain forest harvest" is a method that, to some extent, has been applied at high altitudes in Norway for many years. Often, a combination of group selection harvest and selection harvest is applied depending on local conditions on the site (Granhus et al. 2024). Due to harsh climatic conditions for natural regeneration, this method applies longer intervals between harvests and larger removals than are usually practised in CCF. This means that the required continuous minimum forest cover over time, as described above, is hardly accomplished with this method.

Given the long history of applying extensive RF in Norway and the presently low activity related to CCF, Conversion to CCF is a possible option. Such conversions involve risks of natural disturbances, for example, due to wind and snow, with corresponding negative effects on volume production and carbon storage. Still, however, this is expected to be an important activity for the coming decades, which needs attention and where different options exist (Granhus et al. 2024; Brunner et al. 2025).

Before initiating the application of CCF, it is necessary to evaluate whether the stands actually are suitable for CCF. Based on NFI sample plots from development class IV (production forest) and V (mature forest), and some biological (e.g. tree species, tree stability, tree size variation, vegetation type) and operational (terrain) criteria, Granhus et al. (2024) estimated that about 38% of the productive forest area for these development classes in Norway is suitable for at least one of the CCF systems described. This is a very rough estimate with very few criteria, which, among others, does not include economic aspects or risk preferences among individual forest owners. According to Brunner et al. (2025), the criteria to be used for assessing suitability should vary between each specific CFF system. Although no complete list has been developed for any of the systems so far, they mention the importance of site-adapted species mixture, the speed of the regeneration, crown length, root rot and browsing susceptibility as criteria that must be assessed.

The choice of suitable areas for applying CCF is very important for the outcome of long-term volume production, the income of the forest owner and for impacts related to climate change mitigation and adaptation. There are ongoing research projects at NMBU related to these challenges, both concerning rough suitability assessments using remote sensing methods and developing procedures for assessments in the field with a detailed criteria list that also includes management goals and risk considerations of individual forest owners. Given the lack of experience and in-depth knowledge among forest owners, managers and researchers concerning CCF in Norway, this work is very important.

In the following, we first describe the CCF systems, including conversion to CFF, mainly based on Brunner et al. (2025). Next, we discuss potential mitigation effects of CCF for carbon sequestration and storage and adaptation to natural disturbances, and finally, some impacts of CFF related to economic performance and biodiversity.

3.1.2.1. Descriptions of continuous cover forestry systems

Selection System

The selection system is based on the harvest of individual trees and the continuous maintenance of a multi-layered stand structure. Because the selection system requires a continuously high stand density, it is best suited for shade-tolerant species such as spruce in Norway. However, some experience and a few trials with pine exist. To secure continuous ingrowth for less shade-tolerant species, such as pine, stand density must be reduced, something that may limit volume production. Alternatively, supplementary planting of pine could be an option.

The multi-layered structure in stands managed by the selection system is characterised by a decreasing number of trees with increasing diameter (inverse J-shaped) distribution. It is important to note, however, that these stands also may be structured horizontally, with small openings and dense groups (see example for a spruce stand in Figure 7). To maintain the multi-layered stand structure over time, a stand density that guarantees high production and sufficient ingrowth must be preserved. The harvest intervals and removals must be adapted to this. Individual tree selection is most often guided by principles of target diameter harvest (remove all trees when they reach a certain diameter) but may also include elements of “normal” thinning.

The selection system is an intensive management system and should not be understood as copying natural disturbance dynamics. Since mostly the largest trees are removed, large living and dead trees will not automatically be present in stands managed according to this system. Therefore, large retention trees from various species should be left in the forest, also for this system.

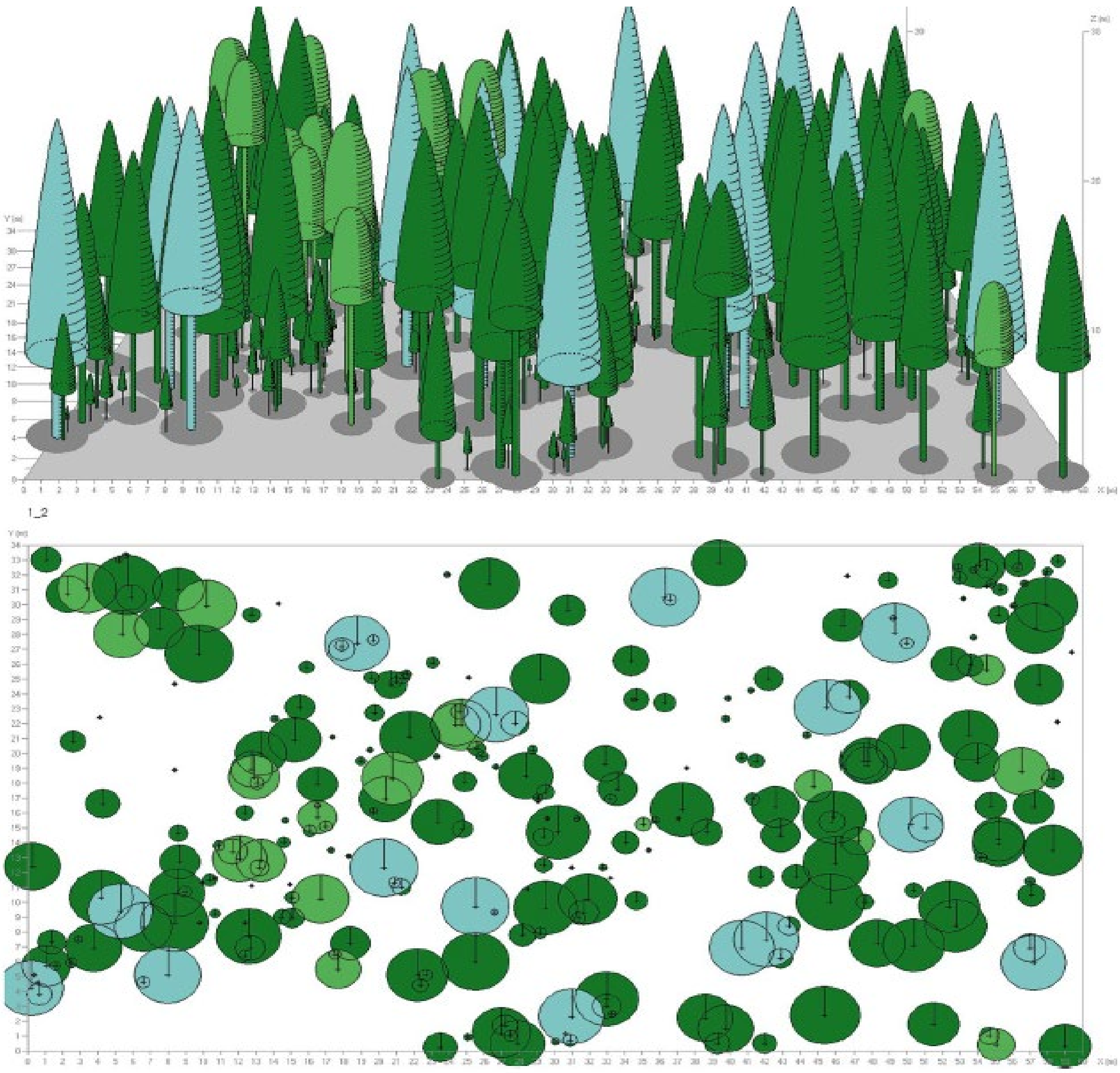

Figure 7. Stand structure and harvest instructions for a sample plot dominated by spruce in Norway managed with the selection system. Dark green = spruce, light green = birch, light blue = spruce trees to be removed in the next selection harvest. The planned harvest will remove about 100 m^3/ha of a standing volume of 255 m^3/ha (adapted from Brunner et al. 2025).

Group Selection System

In the group selection system, established stands are opened (harvested) by creating gaps. The gap size, number, location and chronological gap sequence may vary a lot. After initiating the regeneration process with gaps, the remaining parts of the stand may be harvested at once or remain for a period. The gap size and sequence must be adapted to the level of shade tolerance of the species aimed for in the next generation. Gap extension is a common prescription of the group selection system (see, for example for a spruce stand in Figure 8). There are, however, very few examples of the practical application of the group selection system in the Nordic countries.

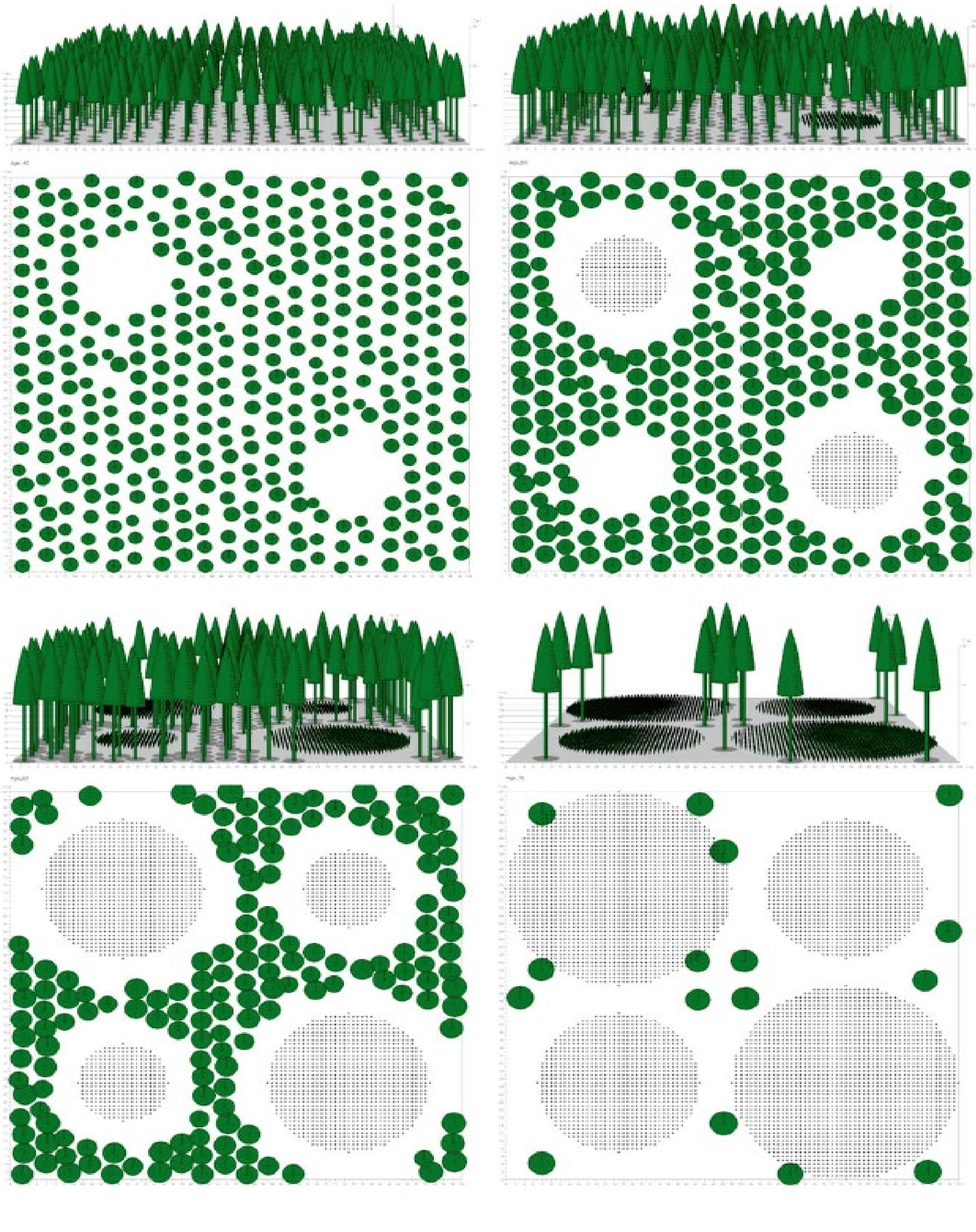

Figure 8. Time series of the regeneration phase in a group selection system for spruce. The first two groups (gaps) with a diameter of 20 m are opened at the age of 40 years when the dominant height is 20 m (upper left). The two gaps are extended to a diameter of 35 m at an age of 50 years at the same time as two new gaps are opened (upper right). All gaps are extended at the age of 60 years (lower left). The remaining trees are harvested at the age of 70 years when they have a height of about 30 m and a diameter at breast height of 40 cm (lower right). At this stage, the regeneration has a minimum height of about 0.5 m, while the height of the regeneration established from the first opened gaps is about 2 m in height. The large trees not harvested at this stage illustrate that retention trees should also be left under this system (adapted from Brunner et al. 2025).

Shelterwood System

The shelterwood system has, to some extent, been practised in Norway over the past decades, both in spruce and pine forests, but for small areas. The system should be applied in stands that previously have been thinned and, therefore, comprise individual trees with long crowns and high individual-tree stability. The first preparatory harvest initiates the regeneration phase and is followed by a series of harvests that maintain a shelter over several decades. Over time, this is supposed to provide regeneration with a relatively high density distributed homogeneously over the area. The last shelter trees should not be removed before the entire area is regenerated and covered by small trees with a minimum height of at least 50 cm (see example for a spruce stand in Figure 9). This example of the shelterwood system creates a stand for the next generation with an age variation of up to 30 years, which usually develops into a relatively homogeneous structure despite the large age range. Wind damages to the shelter trees are common during the regeneration phase, but this varies largely according to stand location and structure and local climatic conditions like wind exposition.

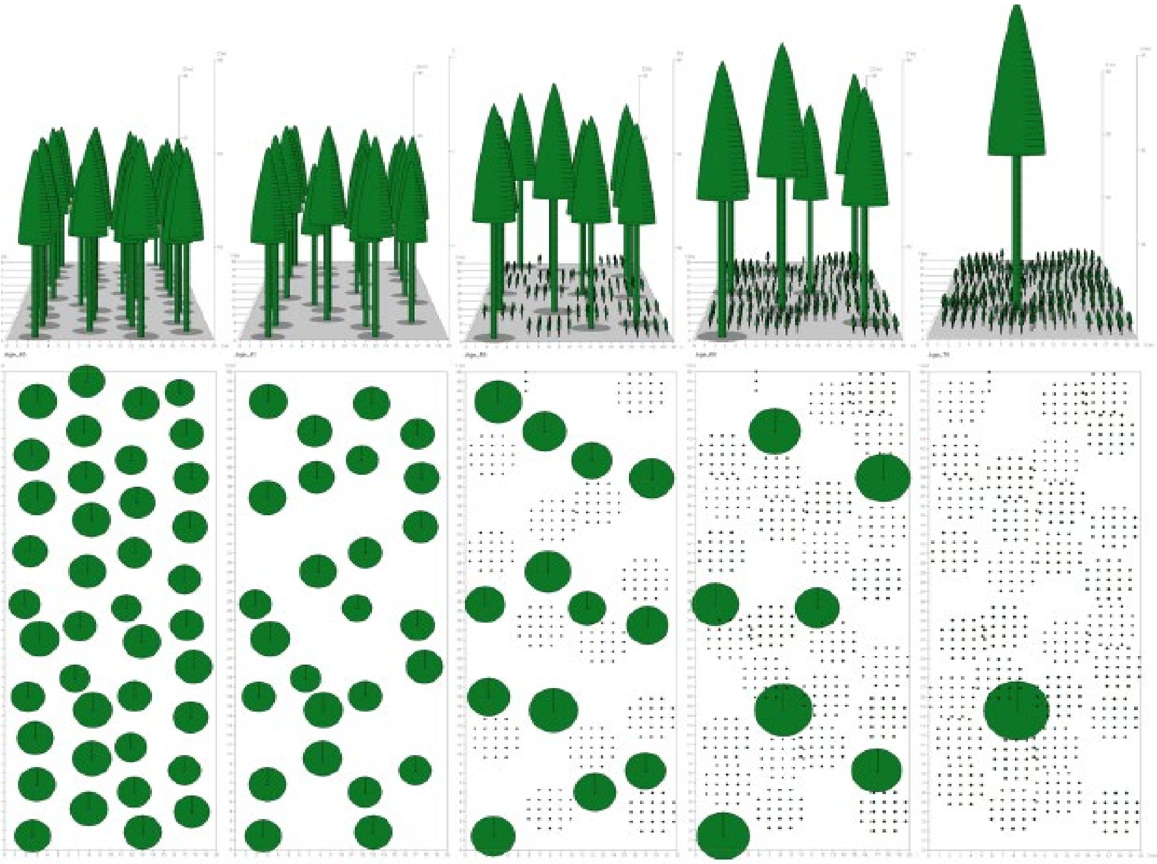

Figure 9. Time series of the regeneration phase in a shelterwood system for spruce. The starting point is a stand that has previously been thinned (far left). The first preparatory harvest is applied at the age of 40 years, when the dominant height is about 20 m, to enhance individual tree stability (left). Two different shelterwood harvests at the ages of 50 and 60 years reduce the basal area to about 12 m^2/ha and initiate the regeneration (middle and right). The shelterwood trees are removed at the age of 70 years (far right). At this stage, the shelterwood trees have a height of about 30 m and a diameter at breast height of 40 cm, while the regeneration established after the first shelterwood harvest has reached a height of about 2 m (adapted from Brunner et al. 2025).

Conversion to CCF

The complexity and methods for conversion to CCF vary according to the CCF system aimed for. Conversion to the Shelterwood system or the Group selection system is relatively simple, while conversion to the Selection system requires a distinct change in practices (Granhus et al. 2024; Brunner et al. 2025).

Conversion to the Shelterwood system or the Group selection system does not require a multi-layered structure to start with. However, trees with high individual stability are important to avoid wind damage at later stages. The stand must, therefore, be sufficiently thinned in early development phases. No further conversion is necessary before applying these systems, as the regeneration is assumed to be initiated using the different harvest methods applied during the regeneration phase in the systems (Figures 8 and 9).

Conversion to the Selection system implies a distinct change in silvicultural practices where areas with an even-aged structure over time are changed into uneven-aged structures suitable for the application of the system. This can only be accomplished over many decades, involving good conditions for natural regeneration processes and requiring sufficient trees with high individual tree stability, able to develop and survive over a long period. This task is generally difficult in Norway because the forest management practices in most cases have created stand structures that are even-aged and single-species, often dense and not thinned. Accordingly, many of the oldest stands have a very low individual-tree stability and therefore no other option than clear-cutting exists. In younger stands, however, a lower risk of wind damage may make it possible to create openings and initiate regeneration that, over time, develops into multi-layered stand structures.

The practical experience with conversion to the selection system in Norway is very limited. Two approaches that to some extents, have been tested in Nordic boreal forests are "variable-density thinning" and "target diameter harvest" (Granhus et al. 2024; Brunner et al. 2025). In variable-density thinning, the aim is to develop a horizontal structural variation by dividing the stand into sectors where the thinning intensity among the sectors varies from creating open gaps (harvest all trees), via thinning with different intensities and to leaving them untouched (harvest no trees). The treatments should be initiated in relatively young stands, preferably before the height of the trees is 15 m. Recently, a practical but scientific experiment for this conversion approach, with a design adapted to harvester-based operations in Norway, was established (Brunner 2024). So far, the experiment has confirmed the practicality of the harvest operations with this approach, but empirical results related to the development over time are still pending. In target diameter harvest, individual trees are removed (harvested) as soon as they reach a certain size in diameter, regardless of the general maturity at stand-level maturity. This method has not been tested in Norway, but some experience exists in Sweden and Central Europe.

3.1.2.2 Impacts of Continuous Cover Forestry Systems

Given the minor practical experiences and lack of empirical scientific data for the application of CCF in Norway, knowledge gaps and many uncertainties also exist regarding the impacts. The following summary considers the potential impacts of CCF as mitigation and adaptation measures under climate change but also reflects on the effects on the forest owner's income and on biodiversity. The summary is mainly based on comparisons between CCF and RF. It is important to note that the choice of suitable areas for the implementation of CCF is important for the impacts. If this fails, the potential benefits related to CCF will be reduced and perhaps even negative.

Carbon Sequestration and Storage, and Mitigation

The effects of CCF on mitigating climate change by increasing carbon sequestration and storage are complex and uncertain. There are few empirical studies on carbon dynamics when applying CCF, and if empirical data exists, comparisons with RF are complicated due to for example varying types (trees, litter, dead wood and soil) of examined carbon stocks, inappropriate growth data and models, inadequate descriptions of productivity, and differences in local climatic conditions and in studied time horizons. Literature reviews indicate that no clear conclusions can be drawn from such comparisons at the present stage (Felton et al. 2024; Bianchi et al. 2025; Högbom et al. 2025). A similar conclusion can be drawn based on a recent Norwegian study of 12 pairs of near-natural and previously clear-cut stands where the results indicated limited or minor differences in the current soil carbon balance (Madsen et al. 2025).

Based on Norwegian NFI sample plots, a simulation study by Granhus et al. (2024) compared carbon storage for a "business as usual scenario" (BAU, almost entirely RF) with different CCF scenarios. For all scenarios, the total annual harvests were assumed to increase gradually from the present level of 12.5 mill. m^3 to 16.7 mill m^3 at the end of the simulation period (2100). For the BAU scenario, 1.5% of the annual harvest was assumed to be harvested according to the selection system, 2% to the shelterwood system and the remaining (96.5%) according to RF principles (clear-cutting and seed tree harvesting) while the most intensive CCF scenario assumed the respective proportions to be 3%, 22% and 75%. The results of the simulations showed that the most intensive CCF scenario provided total carbon sequestration (in living aboveground biomass, litter, dead wood and soil) over the 80-year period that was 31.8 Mt higher than in the BAU scenario. This means that the annually added sequestration due to a shift from RF towards more CCF was 0.4 Mt CO_2. This corresponds to only 0.8% of the annual anthropogenic emissions from Land Use, Land-Use Change, and Forestry (LULUCF) in 2021 in Norway (Miljødirektoratet 2023).

Increasing the application of CCF in Norway to the extent assumed by Granhus et al. (2024), and at the same time maintain an annual harvest at the same level as that of the RF, will be practically challenging because many of the even-aged forest areas in Norway must be converted to forest structures facilitating the different CCF systems, which will take several decades. Furthermore, studies of conversion to CCF systems often show a lower volume growth during the conversion period (Brunner et al. 2025). The exact reductions in growth are uncertain because the growth models applied in the studies are usually not properly designed for conversion, but a certain reduction is very likely because of the reduced tree density that must exist during the conversion period.

A general limitation of CCF systems is that they rely on natural regeneration, which means that genetically improved or provenance-selected plant material cannot normally be used. Unlike RF, which allows for planting with breeding material selected for increased growth and resilience to natural disturbances, the CCF approach restricts such interventions. This may reduce potential gains in growth or stress tolerance to disturbances as compared to RF.

Therefore, in a short-term perspective (conversion period to CCF), a radical shift from RF to CCF in Norway will not be an efficient mitigation strategy related to carbon sequestration and storage. Such a conclusion, however, does not necessarily apply to a long-term perspective. The uncertainty related to the carbon balance is still large, and more empirical data by means of long-term monitoring of the biomass dynamics above- and belowground are required.

Natural Disturbances and Adaptation

The effects of CCF as an adaptation measure under climate change to increase forest resilience are also complex and mixed. In general, the risks of damages differ between CCF and RF, but there is not much research comparing them. In their review, however, Hantula et al. (2025) conclude that damages from wind, snow, bark beetles and pine weevils (*Hylobius abietis)* are likely to be less severe in CCF than in RF, although conversion from RF to CCF may, over a certain period expose stands to more wind damages. On the other hand, the review also concludes that root rot constitutes a larger risk under CCF than RF, regardless of whether the selection-, group selection- or shelterwood system is applied. Furthermore, they emphasise that a stand already affected by root rot should not be converted to CCF under any circumstances.

As already observed in Central Europe, a significant increase in forest damages and stress due to climate change is expected also in Norway. More research is therefore needed to further develop existing monitoring programmes and to explain causal connections between management and disturbances (Granhus et al. 2024). Most importantly, we need more insight on how CCF may influence individual- and stand-level tree stability, and thus the resistance to wind and snow damages, but also on interaction effects between drought stress, bark beetle attacks and root rot infections.

One argument for increased use of CCF has been to increase the variation in forest structures, locally at the stand-level (tree species, tree size) and over the landscape as a mosaic of different CCF and RF systems, as a general adaptation strategy for risk spread under climate change (cf. e.g. Felton et al. (2024); Hantula et al. (2025)). This is a viable strategy also in Norway, and although we lack concrete research on this issue, we should already now, to some extent, start implementing CCF to gain more experience and empirical evidence. It is important to derive more knowledge, particularly given the present large areas of even-aged spruce stands in Norway, on how forest landscapes consisting of a mosaic of different forest management practices and their stages may work as a risk adaptation measure to reduce natural disturbances.

Economic Impacts

The factors influencing income and profitability in CCF will vary considerably between the different CCF systems. Also, the uncertainty and knowledge gaps related to the economic performance of CFF are large, especially for the group selection system and for conversion to CFF. However, long-term volume production, roundwood quality and values, and harvesting costs are considered the three most important aspects when comparing CCF and RF (Granhus et al. 2024; Ahtikoski et al. 2025).

Based on literature from the Nordic countries, including Norway, Granhus et al. (2024) summarised the present knowledge regarding volume production for the different CCF systems. For shelterwood harvest, they indicate a 10-20% reduction in long-term volume production as compared to RF. The main reasons mentioned for the lower production are prolonged harvest ages to facilitate regeneration and lower growth for the regenerated trees in the period when they compete with the shelterwood trees. To some extent, the reduced production may be compensated for because the remaining trees from the shelterwood harvest often receive increased diameter growth in the period before they are finally harvested. Wind damages, however, that are frequently observed among the remaining trees in the shelterwood system, are a major challenge for the long-term volume production, and accordingly also for the economic performance, of this system. For the group selection system, no empirical studies exist regarding volume production. However, an edge effect reducing the growth of regenerated trees is mentioned as a challenge. Generally, we can also expect a reduced long-term volume production compared to RF when applying this system.

For the selection system, the reduction in the long-term volume production compared to RF may be smaller than for the two other systems. This requires, however, that a near-optimum density is maintained over time by applying the selection harvests in an appropriate way regarding intensity and frequency. Bianchi et al. (2025), in their review, conclude that although the trend leans toward a higher volume production in the RF system, there is empirical evidence showing that the production in the selection system might be close to that of the RF system. This requires, however, that a near-optimum density is maintained over time, applying relatively frequent but moderate harvests of the largest trees.

In addition to volume production, roundwood quality and value, as well as harvesting costs, are important for the economic performance of CCF. Regarding roundwood quality, the review by Granhus et al. (2024) indicates that wood properties related to density, strength and branches might be better with CCF compared to RF. In addition to the wood properties, the roundwood value is also affected by the size (diameter) of the logs, where large diameters, in general, yield higher roundwood values. CCF systems, particularly in the selection system where removals primarily are directed towards the largest trees, may therefore arrive at higher roundwood values than the RF systems. Recent changes in the

Norwegian price system for roundwood sales, however, have reduced the effect of higher roundwood value for larger diameters; thus, the positive effect of tree size on the roundwood value in the CCF systems is also reduced.

The costs per m^3 for logging operations are generally expected to be quite similar for CCF compared to RF. The time consumption per tree for the logging operations in CCF systems will be larger than for RF systems, partly because the distance between the removed trees is larger and partly because the harvest machine operator must try to avoid damage to the remaining trees. This effect on the time consumption, however, may be compensated because the size of the removed trees generally is larger for the CCF systems (Granhus et al. 2024), thus, the total harvesting costs per m^3 compared to RF will be quite similar for logging. For transport operations, however, the cost per m^3 will be somewhat higher in CCF since the time consumption increases because the removal per area unit is lower and because the machine operator must try to avoid damage when loading. An additional element that should be considered when comparing CCF and RF is the fixed cost per m^3 for the operations when moving equipment from one harvesting site to the next. No time studies have been done in Norway to assess these costs when applying CCF. To keep the fixed costs at the same level as in RF, however, the lower removal per unit area must be compensated by a larger area per harvest operation.

In conclusion, when comparing the CCF and RF systems, the cash flow per m^3 for the forest owner is probably not significantly different between the systems and thus not decisive for differences in profitability (NPV). The actual long-term volume production levels of the two systems are much more important. When Ahtikoski et al. (2025) reviewed the financial performances of CCF and RF based on simulation studies, mainly from Finland and mainly for the selection system, they concluded that the estimates of the long-term volume production have the most pronounced impact on the results regarding profitability in comparisons between CCF and RF. In this context, they also emphasise the importance of developing reliable growth, natural mortality and ingrowth models to describe the CCF systems since such models hardly exist in the Nordic countries. In addition, they conclude that the simulation studies show that the profitability of CCF heavily depends on the initial state of a stand, i.e. the more the initial forest structure of a stand resembles the target structure of the CCF system, the more profitable it is to shift from RF to CCF. Such a conclusion is also confirmed in a Norwegian simulation study of the selection system for a set of spruce stands with different tree diameter distributions (Gobakken et al. 2008). The selection system yielded the largest NPV for the stands with a clear inverse J-shaped diameter distribution, while for the more uniform and normal diameter distributions, RF was the most profitable.

Biodiversity

The main scientific knowledge gaps regarding CCF and its impacts on biodiversity are primarily related to the long-term effects (60-100 years), while the short-term effects (10-15 years), to some extent, have been studied (Felton et al. 2024; Granhus et al. 2024; Koivula et al. 2025). In their review, however, Koivula et al. (2025) conclude, when they compare with RF, that CCF is likely to benefit species that suffer when the tree cover is removed, such as bilberry and its associated species (food for herbivores, birds), and species requiring spatial continuity in host trees or canopy cover (lichens which support a diverse and abundant invertebrate fauna, which is also an important food source for birds). Furthermore, they conclude that CCF promotes more abundant and diverse mycorrhizal communities compared to RF systems, which is important because mycorrhizal fungi comprise a large proportion of biodiversity in boreal forests.

The review of Koivula et al. (2025) also points out some differences between the different CCF systems regarding effects on biodiversity. The selection system is likely to preserve the majority of species present in old mature forests, but the most sensitive species may still decline or even disappear. The group selection system may affect the forest-interior species (specialised species relying on stable, undisturbed conditions) relatively little. These species' abundances when implementing this system may, however, be reduced with increasing gap sizes. The shelterwood system may be quite similar to the selection system regarding different species responses, but over time, the forest tends to develop into a more even-aged and sparse overstorey structure, which does not provide the biodiversity benefits of CCF. It is also important to note that large living and dead trees will not automatically be present in stands managed according to the different CCF systems. Therefore, large retention trees from various tree species should be left to secure species that mostly require large living and dead trees for their survival, as required by law.

In addition to a larger area to maintain a certain harvest level, a shift from the RF to the CCF system requires more frequent harvest operations and more strip and forest roads. This may increase ground damages and thus imply potential negative effects on biodiversity. On the other hand, it may also enhance the potential for recreational use of the forest by the public (Felton et al. 2024; Granhus et al. 2024). Studies show that the forest structure resulting from CCF systems may enhance the aesthetic value of the forest because the public prefers such landscapes due to their variably sized trees and lack of clear-cutting.

3.2 Property-level Forest Management

Here in section 3.2, we extend the focus from individual stands (Section 3.1) to the broader scope of an entire forest property, encompassing multiple stands, roads, watercourses, and other site features. At this level, managers determine harvest timing and location, coordinate operations efficiently, and handle unplanned disturbances (e.g., storms or pests) in ways that meet financial, ecological, and regulatory goals. Table 7 summarises these measures, illustrating their contributions to climate change mitigation, risk adaptation, and other forest ecosystem services while also noting possible synergies or conflicts.

Property-level approaches integrate economic viability, biodiversity goals, and climate objectives by tailoring interventions to local conditions and forest owner aims. Although less extensive than regional or national frameworks, this scale still covers more varied environmental elements than a single forest stand, such as wetlands including peatland, roads, and diverse stand structures.

This section highlights how decisions at the property scale advance CSF by raising carbon sequestration, bolstering biomass and thus carbon storage, and strengthening resilience against climate-driven stressors. Key activities, biomass removal, spatial and temporal harvest planning, water management, and biodiversity conservation affect both productivity and stability. Informed choices may enhance roundwood revenues, ensure sustainable regeneration, and support other forest ecosystem services while mitigating risks like wildfires, pests, and soil degradation.

Although the focus here is on practical methods, property-level initiatives operate within the context of national regulations, certification requirements, EU directives, and market forces (detailed in Chapter 5). Forest owner characteristics and cooperative management also shape effective forest stewardship, and these factors appear throughout the discussion. The broader landscape perspective is addressed more extensively in Section 3.3.

Recent studies by Patacca et al. (2022) show that natural disturbances in European forests have increased sharply since 1950, mainly due to climate change. This highlights the need to adjust biomass removal strategies to account for changing disturbance patterns, especially in areas more exposed to storms, drought, and pests.

In addition to traditional silvicultural practices, these kinds of emerging challenges necessitate adaptive strategies at the property level. For example, as elaborated in Section 3.1, the increasing threat of bark beetle outbreaks, exacerbated by climate change, highlights the importance of integrating risk-based forest management models into decision-making processes (see e.g. Romeiro et al. 2025). Similarly, the role of Harvested Wood Products (HWPs) in carbon storage and substitution underscores the multifaceted contributions of forestry to climate change mitigation (Kallio et al. 2023). Recent studies underline the potential of adaptive management frameworks, such as the Triad approach and Functional Complex Networks, in enhancing forest resilience to climate-induced disturbances. These strategies promote structural and species diversity at the stand, property and landscape levels, thereby mitigating the risks posed by extreme weather events and biotic stressors (Triviño et al. 2023).

Forest management practices not only affect ecological outcomes but may also have measurable economic implications for surrounding properties. Kim & Johnson (2002) found that proximity to forests positively influence neighbouring property values, whereas visibility of clear-cut areas reduces property prices.

Furthermore, monitoring of multifunctionality in property-level forestry may be enhanced through the application of indicators like those identified in the ongoing MoniFun project (Muñoz et al. 2024). These indicators will address key forest ecosystem services like biodiversity, carbon dynamics, and economic functions, supporting data-driven decision-making aligned with relevant EU policy mandates and sustainable forest management goals.

Forest owners' decisions regarding harvesting, regeneration, and investments are influenced by structural conditions, economic motives and preferences in general, knowledge, planning, and ownership characteristics. Property rights and predictability in the regulatory framework affect the willingness to make long-term investments in measures that promote climate adaptation, carbon storage, and biodiversity considerations. Key aspects are summarized below.

Property size and fragmentation: Forest owners with larger holdings have a higher probability of harvesting (Bolkesjø & Baardsen 2002; Beach et al. 2005; Størdal et al. 2008; Bashir et al. 2020), whereas harvesting intensity per unit area may be higher on smaller, often more productive properties (Bashir et al. 2020). Fragmentation and small, scattered parcels increase operational and transaction costs, resulting in lower activity levels (Beach et al. 2005; Størdal et al. 2008).

Economic objectives, prices, and the role of forest income: Forest owners who emphasise financial goals and economic security show a clearly higher propensity to harvest and deliver more timber per hectare than others (Bashir et al. 2020). When forest income is marginal relative to other income sources, the likelihood increases that non-market objectives (recreation, environmental values) will dominate and that harvesting will be postponed (Beach et al. 2005; Petucco et al. 2015).

Knowledge, competence, and planning: Familiarity with policy instruments and forest operations increases activity. In Norway, knowledge about the skogfond (forest fund) represents the single largest positive factor affecting the probability of harvesting. Frequent forest visits have a similar effect (Bashir et al. 2020). Forest management plans are consistently associated with more active forest management (Størdal et al. 2008; Bashir et al. 2020).

Ownership type, demographics, and residence/distance: Younger and resident forest owners are generally more active; greater distance between owner and property reduces the willingness to harvest (Bashir et al. 2020).

Table 7. Forest property level management needs and measures for mitigation and adaptation in CSF.

Need	Measure	Intention	Mitigation/ Adaptation	Decision maker
Biomass Removal after Unplanned Disturbances	Salvage Logging	Recover roundwood quickly post-disturbance to limit economic losses and reduce pest spread.	Adaptation	Forest owner
	Sanitary Logging	Remove infested or high-risk trees to prevent further disturbance propagation and safeguard remaining stand health.	Adaptation	Forest owner, may involve community or county authorities;
	Forest Fire Management	Reduce wildfire risk by applying, e.g. thinning and firebreaks and enhancing post-fire recovery through soil protection and retention of burnt patches for regeneration.	Adaptation	Forest owner, may involve community or county authorities;
Planning and Management in Space and Time	Spatial Harvest Planning	Arrange harvest layouts to reduce exposure to natural disturbances and to protect key ecological areas.	Adaptation	Forest owner
	Adaptive Rotation Scheduling	Adjust rotation periods in response to market conditions and climate risks.	Mitigation and adaptation	Forest owner (guided by market signals and policy incentives)
	Long-Term Monitoring & Compliance	Continuously track forest conditions and performance to enable adaptive management and ensure adherence to sustainability and regulatory standards.	Mitigation and adaptation	Forest owner
	Afforestation	Increase income and carbon sequestration and storage and diversify land use by establishing new forests while limiting ecological trade-offs.	Mitigation and adaptation	Forest owner; Possibly supported by incentives
Forest Operations and Logistics	Harvesting	Optimise the use of harvesting systems and timing (season) to reduce soil erosion, lower operational costs, and enhance natural regeneration while achieving efficient regeneration.	Mitigation and adaptation	Forest owner, with technical and operational support

	Road Network Establishment	Build or upgrade forest roads to reduce harvesting costs, improve year-round access, and enable climate-adaptive operations.	Mitigation and adaptation	Forest owner, and government regulations/incentives
	Road Network Maintenance	Maintain road infrastructure to ensure reliable access and minimise environmental impacts (e.g. soil erosion, water quality degradation) during roundwood extraction and transport.	Adaptation	Forest owner
	Transport Logistics	Optimise roundwood transport through route planning, real-time tracking, and multi-modal options to reduce transport costs and carbon emissions.	Mitigation and adaptation	Forest owner/Logistics provider
Conserving Biodiversity	Adaptive Management	Enhance ecosystem resilience and species diversity through adaptive silvicultural practices.	Adaptation	Forest owner (with guidance/ incentives from the certification government)
Hydrology Management	Peatland Rewetting	Raise the water table in drained peatlands to restore carbon storage, stabilise hydrology, and support overall ecosystem function under changing climatic conditions.	Mitigation and adaptation	Forest owner; government; The Norwegian Water Resources and Energy Directorate (NVE); The Norwegian Public Roads Administration (SVV)

3.2.1 Forest management planning

Stakeholders and roles in forest management planning

The scheme for forest management planning with environmental registrations and the preparation of forest management plans in Norway is important for obtaining information about the forest for both the public sector and the individual forest owner. The lifespan of a forest management plan varies, but in most cases, new plans for an area are prepared every ten to fifteen years. The Ministry of Agriculture and Food and the Norwegian Directorate of Agriculture have the overall responsibility for the planning, while the most important stakeholders in the process of implementing a project (often for one municipality or several municipalities) are the relevant county governor, relevant municipalities and a project group including representatives of forest owners (Landbruksdirektoratet 2025). The actual forest inventory work and preparation of the forest management plan itself is done by the producer (usually the planning department of a forest owner association) after a selection process with a requirement specifications/offers.

The government provides funding to the individual forest owners prepare a forest management plan (including both forest data and environmental information). The Regulations relating to government funding for forestry planning with environmental registrations therefore impose certain requirements for both the methodology used in the forest inventory work and for the content of the forest management plan (https://lovdata.no/dokument/SF/forskrift/2004-02-04-449). In most cases, to obtain the necessary basic data for the wood resources, remote sensing with airborne laser scanning and systematic sampling (measurements in the field) are carried out based on a pre-division of the forest property into stands from aerial photographs. The environmental registrations are done according to current MiS instructions where criteria for the design of areas with habitats are specified. The registration methodology rely on research that shows relationships between species and habitats for species, and since 2017, the Nature in Norway's (NiN) type and description system has been used for this mapping (https://artsdatabanken.no/naturtyper/natur-i-norge/kartlegging-etter-nin).

Requirements for forest management plans today

A standard forest management plan must comprise a map of the forest property, including a division into stands and infrastructure in the form of roads, paths, boundaries and terrain. All information that has been registered or calculated must be located and linked to a stand. For each stand, the following information must be available: area, development class, site quality, volume by tree species, age, volume growth and environmental values related to biodiversity, landscape, outdoor recreation and cultural monuments. In addition, the forest management plan must include the following information for the property: total area divided by soil type, productive forest area divided by site quality and development class, volume distributed by tree species, site quality and development class, and volume growth and production capacity.

In addition to the mandatory parts of the forest management plan, the forest owners can choose to include more information and functionality to it to adapt to their own needs and competences. This entails additional costs depending on which products/functionalities chosen. Examples of such products are proposals for silvicultural measures in stands (automated or based on additional field inspections, often in the form of "must", "should" or "can"), and proposals for annual average harvest quantities at property level for the next 10-year period based on forecasts. The forest owner can also choose to receive the forest management plan on a digital platform. On this platform, it is also possible to update age, development class, volume growth/standing volume and the implemented measures. Updating can be done by the forest owner personally or it can be outsourced to the producer of the forest management plan.

Use of data from forest management plans
The stand level data that emerges from the forest management plan are of course a key basis for decisions related to silvicultural treatment that forest owners must make at stand level (section 3.1) and property level (section 3.2). In addition, the County Governor, the municipality, NIBIO, the Norwegian Directorate of Agriculture and the Land Consolidation Courts have been ensured access to property and map data from the management plan and from environmental data as a basis for management and decisions at the landscape, regional and national level (see section 3.3). This is data with information that is important in connection with various measures in forestry (certification, laws, regulations, etc.). The data are also used for the design of statistics, research and follow-up related to different policy instruments. The forest owner association also have access to the data if the forest owner actively gives permission when ordering a forest management plan (Landbruksdirektoratet 2025). The forest and environmental data are collected in central databases managed by NIBIO, see e.g. in Kilden - Skogportalen (https://kilden.nibio.no/?topic=skogportal&zoom=0.1&x=284337.75&y=-7219344&bgLayer=graatone)where detailed forest and environmental data are presented as map figures.

Forest plan with proposals for climate management included
Ideally, the forest owner should have an up-to-date forest management plan with proposals related climate smart forest management that extends many decades into the future. A standard forest management plan as it stands today does not, strictly speaking, include any element that directly point to climate smart forest management. The plan in general only comprises a description of the current state of age, volume and tree species distribution in stands, while all proposals for silvicultural measures have a traditional focus related to volume production and income. Although the current forest management plan of course may be used indirectly as a basis for decisions in the direction of climate smart forestry, there are presently few concrete proposals for forest management that point in the direction of climate change mitigation and adaptation measures.

Some examples of elements that could be included in the forest management plans are:

- To illustrate synergies and trade-offs between different objectives (cf. Figure 6): a general description of treatment schedules in stands over a rotation, where the main priority is, for example, climate mitigation (increasing carbon sequestration and storage), climate adaptation (reducing natural disturbances) and profitability.
- Long-term scenarios (forecasts) at the property level with, for example, the main priority on climate mitigation (increasing carbon sequestration and storage), climate adaptation (reducing natural disturbances) or profitability (cf. Romeiro et al. (2025), Strîmbu et al. (2023), (2025)).
- A quantification of carbon sequestration and storage levels for the stands and the forest property based on the current state (derived from volume growth and standing volume for stands and property existing in the current forest management plan).
- Soil moisture maps to identify potential drought damage to forests or operational challenges related to harvesting (already available with some producers of forest management plans).
- Maps for forest road analyses (already available with some producers of forest management plans).
- Thematic maps for potential areas (stands) where forest damage is likely (vulnerability maps for wind, snow, bark beetle or rot damage).
- Thematic map for potential areas (stands) where tree species change is relevant.

Some of these proposals can be implemented relatively easily, while others require more research and development of functionality/software. There will also be questions about whether such elements of climate management in the forest management plan should be "mandatory" (in line with environmental registrations) or "voluntary" (the forest owner bears the cost). All this indicates that an implementation of a "forest management plan with climate management" requires a process in which the ministry and directorate take the lead and involve the planning departments of the forest owner association, forest owners and researchers.

3.2.2 Biomass Removal after Unplanned Disturbances

3.2.2.1 Salvage and Sanitary Logging

Natural disturbances, including storms, insect outbreaks, drought-driven tree mortality, and wildfires, present significant environmental challenges for property-level management. While these events can reduce short-term roundwood yields, they also influence long-term forest resilience and carbon storage. For this reason, biomass removal after a disturbance should be strategically planned to safeguard ecological recovery while maintaining economic viability. Such targeted salvage operations, carried out in line with the certification criteria, help prevent secondary damage (e.g. bark beetle infestations), minimise habitat loss, and protect soil integrity, thereby reducing risks associated with future disturbances.

The necessity and extent of biomass removal depend on several factors, including the type and severity of the disturbance, the potential for further damage, and the prevailing site conditions. Windthrows, for instance, often create ideal breeding grounds for bark beetles, leading to secondary infestations if left unmanaged. Studies have shown that rapid removal of windthrown or weakened trees can help mitigate subsequent outbreaks, particularly in Norway spruce stands, which are susceptible to bark beetle attacks (Hanssen et al. 2019).

The increasing threat of bark beetle outbreaks, exacerbated by climate change, highlights the importance of integrating risk-based forest management models into decision-making processes (Romeiro et al. 2025). Climate projections suggest that regions such as Vestfold, historically prone to bark beetle outbreaks, will experience amplified risks due to increased temperatures and drought stress. Adaptive management practices, including the use of mixed-species forests and lower harvest ages, are important in mitigating these threats, cf. Section 3.1.

Snow damage represents a significant abiotic disturbance, particularly in Nordic boreal forests. Adaptive forest management may enhance resistance to such damage, as demonstrated in southeastern Norway, where controlling stand density during regeneration and young growth phases increases snow load resistance and decreases yearly damage probability (Strîmbu et al. 2025). Furthermore, advanced technologies like UAV-based aerial imagery and airborne LiDAR have proven effective in detecting and mapping snow disturbances at the tree level (Puliti & Astrup 2022; Räty et al. 2024). These tools support targeted forest management by improving the efficiency of disturbance detection, which may enhance post-disturbance decision-making.

The efficacy of salvage logging in mitigating subsequent disturbances is, however, subject to debate. Leverkus et al. (2021) reviewed that while this kind of logging can reduce fuel loads and mitigate some disturbance risks, it may also increase small ground fuels, exacerbate microclimatic stress, and inadvertently heighten susceptibility to additional disturbances. They advocate for a decision-making framework that balances economic recovery with ecological resilience, suggesting partial retention of deadwood to support biodiversity and ecosystem stability.

Also, the carbon dynamics of biomass removal following disturbances remain a subject of debate. While salvage logging can, in some cases, prevent further carbon losses by reducing the risk of secondary disturbances (such as pest outbreaks or additional windthrow in weakened stands), it also reduces carbon stored in deadwood and soil detrital pools.

One should also take into account the needs of many forest-dependent species, including fungi, invertebrates, and cavity-nesting birds, that rely on deadwood for habitat.

Studies have shown that moderate retention of standing dead trees and coarse woody debris can significantly enhance biodiversity while still allowing for productive forest management (Lindenmayer and Noss 2006). This is particularly relevant in boreal and temperate forests, where decomposing logs serve as reservoirs of moisture and nutrients, enhancing forest regeneration.

Collaboration among neighbouring forest owners may enhance the efficiency and ecological effectiveness of biomass removal. Cf. Section 3.3 for these kinds of landscape effects. Further, incorporating traditional and local ecological knowledge into biomass removal strategies may enhance biodiversity outcomes. Crowley et al. (2019) highlight how these knowledge systems contribute to more ecologically sensitive forest management, ensuring the retention of important habitats and other forest ecosystem services during post-disturbance interventions.

The timing of salvage operations is also important and regulated by the certification schemes. Extraction during dry periods and frost minimises soil compaction and rut formation, whereas operations conducted under high moisture conditions may severely damage soil structure, reducing long-term site productivity (Han et al. 2006). Additionally, retaining a portion of the biomass, such as logs and branches strategically placed across the site, may help stabilise the microenvironment, reduce erosion, and support biodiversity conservation.

3.2.2.2 Forest Fire Management

Forest fires are emerging as a critical environmental concern in boreal and temperate zones, where climate change is intensifying drought cycles and increasing fire-prone conditions. Though historically less common in Nordic regions, the combination of rising temperatures, altered forest structures, and extended dry periods underscores the need for integrated fire risk management. We can reduce fire risk by reducing excess fuel, such as dry brush and dead trees, planting a diverse mix of tree species, and creating well-placed firebreaks. And, after a fire, by leaving some burned wood behind provides essential habitat and helps the ecosystem regenerate.

The increasing threat of wildfires in northern forests is largely driven by climate-induced changes in temperature and precipitation patterns. Warmer conditions extend the fire season, while prolonged dry spells and rising atmospheric moisture deficits increase fuel flammability. Alongside climatic drivers, human activities such as roundwood harvesting, road construction, and increased recreational use of forests contribute to ignition risks, further underscoring the need for comprehensive fire management strategies.

After a forest fire has been extinguished, restoration is essential to re-establish ecosystem functions and prevent degradation. Burned areas are particularly vulnerable to erosion and hydrological instability and should be stabilized quickly. Fast-growing ground cover and erosion control measures, such as wood chip mulch, can reduce runoff and preserve soil moisture. However, the following certification requirements must be observed: “In the case of forest fires in older forest stands where more than 0,5 hectares are burnt 0,5 hectares of the most biologically valuable areas with fire-affected forest per property shall be set aside as untouched for 10 years. In the case of forest fires in older forests on areas less than 0,5 hectares, the entire area shall be set aside as untouched for 10 years” (PEFC 2022).

Salvage logging is frequently used to recover economic value and prepare sites for replanting; however, removing too much biomass can cause long-term site degradation. Ibáñez et al. (2022) found that high burn severity inhibits seedling regeneration by reducing organic material and soil biota. Conversely, low burn severity fosters soil microorganisms that support conifer species like Scots pine and Norway spruce, enhancing natural regeneration. These findings suggest that post-fire management strategies should retain some burnt biomass to promote soil microbial recovery and healthy forest regeneration (cf. section 3.2.2.1).

Restoring forest cover after a fire in Norway may rely on natural regeneration, especially by birch, pine, and spruce. Where production goals require it, replanting with suitable species may be carried out, but is less common than in more fire-prone regions. Promoting mixed species stands can increase resilience against future disturbances, including fire. Post-fire monitoring of regeneration, soil conditions, and ecosystem development provides valuable knowledge for improving forest management strategies in a changing climate.

3.2.3 Planning and Management in Space and Time

Property-level spatial and temporal planning is critical to sustainably managing forest resources while simultaneously addressing economic, environmental, and climate goals. By good planning of harvest layouts, road placement, and thinning schedules, managers ensure that forest owner objectives, such as maintaining habitat continuity or maximising carbon storage, are effectively integrated with long-term ecological stability. The thoughtful scheduling of silvicultural activities also helps reduce disturbance risks (e.g. windthrow or pest outbreaks) and promotes healthy regeneration across diverse site conditions.

To achieve these goals, property-level management must integrate spatial planning principles that regulate where and how, e.g. harvesting occurs, alongside temporal planning strategies that determine when interventions are most efficient. Meilby et al. (2001) underscore the importance of incorporating risk considerations into management models, which can significantly affect roundwood yield and carbon storage. By integrating such risk factors, management plans become more robust and adaptive to both ecological and economic uncertainties. See Section 2.4.2 for a broader analysis of risk considerations.

Further, by leveraging advanced decision-support systems, digital forestry tools, and adaptive management frameworks, forest owners may optimise land use while ensuring long-term productivity.

Suvanto et al. (2025) show that while the condition of a stand, its species composition, age structure, and basal area play a central role in determining when and how intensely it is harvested, regional practices add an extra layer of variability. Their analysis of European forest inventory data reveals that harvest schedules differ considerably across regions. For example, eastern Central European forests often experience more frequent but lower-intensity harvests, whereas northern regions tend to follow a regime with infrequent yet high-intensity cuts. These regional differences arise from factors such as national policies, economic incentives, cultural preferences, and even regulatory frameworks that guide forest management practices.

Thus, beyond technological tools, understanding the socio-economic context of forest owners is important for effective planning. Joshi (2007) highlights how Nonindustrial Private Forest (NIPF) forest owners' characteristics, such as age, education, and income, significantly influence their forest management decisions. Furthermore, Crowley et al. (2019) and Grøndahl (2025) emphasise the role of forest owner engagement and advice sources in shaping forest management outcomes. Forest owners who seek professional guidance and participate in community-based initiatives are more likely to adopt sustainable practices, suggesting that fostering knowledge-sharing networks may improve overall management effectiveness. This is very relevant to the Norwegian case since most Norwegian forest owners are members of a forest owner association.

3.2.3.1 Spatial Harvest Planning

The spatial arrangement of harvesting units within a forest property plays an important role in mitigating climate risks and optimising resource efficiency. Poorly planned interventions can increase susceptibility to windthrow, pest infestations, fire risks, and hydrological disruptions. In contrast, thoughtful spatial planning enhances ecosystem stability and facilitates more effective forest regeneration. Several key strategies may support this objective.

Forest disturbances are strongly influenced by overall stand structure and management practices (Seidl et al. 2007). Reducing forest vulnerability to cascading disturbances requires careful consideration of stand dynamics, particularly in regions prone to disturbance events. Strategies that maintain structural diversity and enhance forest resilience at the property level may help balance roundwood production with long-term ecosystem stability.

Advances in Geographical Information Systems (GIS)-based spatial modelling and decision support have transformed forest management by enabling more precise planning and adaptive strategies. Geospatial technologies may integrate terrain data, soil stability assessments, and biodiversity considerations into the design of harvest units, ensuring interventions are environmentally sound. Furthermore, tools such as remote sensing and Light Detection and Ranging (LiDAR) scanning may allow forest managers to adjust harvest plans dynamically based on close to real-time monitoring of tree growth, soil moisture levels, and disturbance trends (Baskent et al. 2024). Spatial zoning is also a valuable tool, helping prioritise risk-prone areas for adaptive management. This helps in ensuring that vulnerabilities are addressed proactively before escalating into larger crises.

Advancements in simulation models, such as GAYA 2.0, have provided robust tools to optimise planning. Developed specifically for Norwegian forestry, this tool integrates detailed carbon flux modelling with economic evaluations, allowing for effectiveness. Sub-models predicting bark beetle and snow load damages have also been integrated in GAYA 2.0, facilitating risk analyses and scenarios related to natural disturbances (Romeiro et al. 2025, Strîmbu et al. 2025).

Incorporating risk and uncertainty into property-level harvest planning is very valuable to address the risks associated with natural disturbances. Recent studies have shown that relying solely on deterministic models may underestimate the variability of wind and snow damage, leading to suboptimal management prescriptions. For instance, Eyvindson et al. (2024) found that inaccurate assumptions about wind intensity and frequency can substantially alter optimal harvest schedules by affecting harvest ages and thinning regimes, which in turn influence the even flow of timber income. Similarly, research by Eyvindson et al. (2023) and Hunault-Fontbonne & Eyvindson (2023) highlights the benefits of using stochastic programming approaches to integrate disturbance risk into forest planning. Such methods allow for the analysis of, e.g. a wide range of wind disturbance scenarios, enabling forest managers to develop adaptive strategies that balance economic objectives with enhanced resilience. Incorporating these probabilistic risk assessments at the property level can, therefore, lead to more robust and flexible management plans, ultimately reducing risk in timber production and improving ecosystem outcomes.

In addition to harvest layout and modelling, fire-resilient landscape design is expected to become increasingly important in the face of climate change. One strategy involves increasing the proportion of broadleaf species in conifer-dominated areas, which reduces overall flammability and limits fire spread risks. Maintaining natural firebreaks and low-fuel zones through selective thinning or mixed-species plantings may further enhance long-term fire resilience.

3.2.3.2 Adaptive Temporal Scheduling

Temporal planning governs the timing of harvests, thinning cycles, and silvicultural interventions, in order to ensure that roundwood production aligns with both market dynamics and ecological sustainability. By adapting operations to climate variability and economic conditions, property owners may maximise yields while maintaining forest health. Several approaches can guide effective temporal planning.

One consideration may be the balance between even-flow and market-oriented harvesting strategies. Even-flow harvesting ensures stable yields (in m^3) over time, providing more continuous income streams and steady regeneration cycles. This approach prioritises predictability. In contrast, market-driven harvesting leverages fluctuations in roundwood prices, allowing forest owners to capitalise on favourable economic conditions (responding to market signals).

Another important aspect of temporal planning is the management of harvest ages (cf. section 3.1.1.4). Harvest ages should preferably be adjusted based on species composition, site productivity, roundwood prices, carbon sequestration and storage, and exposure to climate-related risks. For instance, in areas prone to storm damage or pest outbreaks, shorter rotations and proactive thinning may reduce vulnerability while maintaining productivity.

3.2.3.3 Long-term Monitoring and Regulatory Compliance.

Effective property-level CSF management necessitates continuous monitoring to track changes in forest dynamics, assess carbon storage efficiency, and ensure compliance with national and EU sustainability frameworks

Periodic assessments of carbon sequestration trends enable forest managers to adjust harvest intensity and harvest ages to better align with their objectives. This will, however, typically require some economic incentives. Rørstad (2022a) underlines that when both roundwood and carbon sequestration have a monetary value; their relative pricing determines the optimal forest management strategy. If the value of carbon sequestration exceeds the roundwood value per cubic meter, it becomes economically favourable to allow increased standing volume. This analysis indicates that under current carbon pricing trajectories, reduced harvest levels would be more beneficial from a net present value perspective.

One may also integrate biodiversity indicators in property-level monitoring programmes. These indicators help track species diversity, habitat quality, and ecosystem health, ensuring that ecological targets are met alongside production goals.

In addition to environmental monitoring, alignment with national forestry standards is important for effective management. Data from the Norwegian National Forest Inventory (NFI) offers important insights into forest related parameters. This information supports evidence-based decision-making, allowing forest managers to tailor interventions to specific site conditions and broader environmental trends.

Finstad (2025) examined how municipalities gain access to information about planned logging activities and to what extent current notification routines provide genuine administrative oversight. The study shows that many municipalities lack systematic information about when and where logging will take place, which weakens their ability to follow up on environmental requirements and coordinate land-use interests. The findings also indicate that current digital notification systems and the legal reporting requirements in the Forestry Act do not always ensure sufficient information flow between forest owners, forestry authorities, and municipal land-use management. A more integrated and digitally coordinated notification system could support climate adaptation, resource planning, and the monitoring of ecosystem services across property boundaries.

Spatial and temporal forest planning should account for albedo-related effects as changes in forest cover alter surface reflectivity. Ramtvedt et al. (2024) demonstrate that boreal forest albedo is particularly sensitive to tree height, canopy cover, and species composition. However, Bright et al. (2024) find that only about 4% of Norway's forests currently experience negative albedo impacts sufficient to offset carbon sequestration and storage benefits, a figure expected to drop below 1% in future scenarios. In support, Rørstad (2022a) shows that the cooling contribution from albedo changes at harvest represents merely 1.3% of national greenhouse gas emissions, while the carbon stored in standing forests is over 40 times greater. Consequently, given the modest albedo variations across Norwegian forests, their impact on optimal forest management decisions remains limited.

Incorporating cutting-edge technologies into spatial and temporal planning is also important. Wang et al. (2025) advocate for the use of smart sensing technologies and AI-driven modelling to enhance the precision of forest management decisions. These tools support dynamic scenario analysis, allowing forest owners to anticipate climate impacts and adjust their management strategies proactively, thereby strengthening forest resilience and optimising carbon sequestration.

Financial incentives may play an important role in influencing long-term forest management decisions at the property level. For instance, CO_2 credits funded through private buyers or carbon taxes may encourage the establishment and maintenance of protected areas, aligning economic interests with environmental goals (Nabuurs et al. 2017). Currently, few initiatives in Norway aim to finance such credits in the open market. Cf. Chapter 5 for a description of policy instruments.

3.2.3.4 Afforestation Initiatives and Their Impacts

Afforestation initiatives might be both climate mitigation and mitigation. By establishing trees in open, virgin or naturally regenerating areas, these efforts may convert underutilised or poorly naturally regenerated lands into productive forest stands, thereby enhancing ecological functioning. Søgaard et al. (2019) show that planting Norway spruce on overgrown pasturelands or land never been forested can substantially increase carbon stocks in both live biomass and soils. This process bolsters the forest's carbon sequestration capacity but may also reduce biodiversity. The potential area for afforestation in Norway is estimated at approximately 9.6 million decares, corresponding to about 12% of the country's current productive forest area. This represents a comparable untapped opportunity for carbon sequestration and storage, even before accounting for HWP substitution effects (cf. Section 4.2). However, it should be noted that the certification schemes are quite restrictive when it comes to afforestation, particularly regarding the choice of tree species.

The benefits of afforestation go beyond carbon accumulation. Creating denser and more structured forest stands may foster favourable microclimatic conditions and enhance habitat connectivity, essential factors for diverse biological communities. Incorporating afforestation measures into property-level management plans is therefore important for building a more resilient forest landscape. Such planning addresses long-term ecological challenges by accounting for both current and future environmental pressures.

As part of CSF strategies, afforestation initiatives provide practical means to reinforce forest health and ecological integrity while also advancing broader goals such as carbon sequestration and storage, and biodiversity conservation. Beyond these environmental gains, afforestation may bring economic advantages, as well as collaborative opportunities for local communities and forest owners.

However, annual deforestation due to constructions, roads etc. (0.05% of the forest area, about 58 km²) eliminates an estimated 0.55 million tonnes of carbon (about 2 million tonnes CO_2) in standing stocks. This one-off loss is roughly 4% of Norway's total greenhouse-gas emissions in a typical year and about 11% of the net carbon the remaining forest removes from the atmosphere each year. It is important to be aware that under the EU/EEA LULUCF rules (cf. Section 5.3), a hectare converted out of forest counts as a debit for 20 years; every additional hectare therefore locks Norway into a long-lasting obligation to find compensating removals elsewhere.

Most forest losses stem from infrastructure development, including new buildings, roads, and high-voltage lines. Importantly, while deforestation is an issue, a critical limitation in Norway's current forest management is the insufficient rate of active reforestation; only about 78% of the areas are satisfactorily regenerated after felling (Landbruksdirektoratet 2024a). As Sevillano et al. (2025) emphasise, intensifying management practices, such as increasing active reforestation, planting density, use of genetically improved material, fertilisation, and pre-commercial thinning, have the physical potential to substantially boost carbon uptake and storage over the long term. Addressing the reforestation shortfall is therefore important to unlocking the full climate mitigation potential of Norway's forests.

3.2.4 Forest Operations and Logistics

Effective coordination of forest operations and logistics is essential for ensuring that management measures achieve both economic efficiency and climate resilience. This section integrates some of the important aspects outlined in Table 7 by addressing harvesting, road network establishment and maintenance, and transport logistics. Decisions in these areas are interdependent; for example, the choice of harvesting method influences the condition of the forest floor, the performance of access roads, and ultimately, the efficiency of roundwood transport.

Harvesting

Optimised harvesting is central to achieving effective roundwood removal while protecting environmental values and ensuring robust regeneration in line with the certification scheme. Strategies include both the selection of appropriate methods and the timing of operations. The main approaches encompass:

- Selection, group-selection or shelterwood systems under CCF: Gradual removal of trees (individuals, small groups, or an overstorey shelter; see Section 3.1.2) is carried out to foster natural regeneration and preserve structural diversity while a continuous canopy is maintained. Because these CCF systems involve shorter cutting cycles than rotation forestry, machinery must enter the stand repeatedly over time, which raises the risk of rutting, soil compaction and ground disturbance on wet or otherwise sensitive soils. Therefore, operational plans must be in line with certification requirements; confine traffic to pre-planned extraction trails; and deploy low-ground-pressure or winch-/cable-assisted equipment where appropriate.
- Clear-cutting with variable retention: Harvesting most trees while leaving behind key retention areas that preserve habitat structure and sustain ecosystem functions (cf. Section 3.1.1 about Rotation Forestry).
- Seasonal harvesting adaptations: Scheduling operations in difficult areas during favourable conditions, such as winter logging on frozen soils, to minimise soil compaction and reduce the risk of fungal infections. Williamson & Neilsen (2000) found that soil moisture significantly influences compaction susceptibility, with wet soils being more prone to displacement and structural damage.

Road Network Establishment

A well-planned forest road network is critical for providing access to roundwood stands while ensuring low ecological impacts. Establishment measures include:

- Planning in line with the certification scheme.
- Strategic route selection: Using terrain and hydrological data to choose road alignments that avoid sensitive ecological zones and keep disruption of soil and water systems low. This planning also considers future needs for salvage logging or emergency access.
- Infrastructure design: Features such as culverts and drainage systems are incorporated during road construction to mitigate erosion and manage runoff effectively.

Road Network Maintenance

Once established, maintaining a high-quality road network is important to sustain its functionality and protect the adjacent forest areas. Key maintenance practices include:

- Regular grading: Keeping the road surface even to reduce the risk of rutting and excessive soil compaction.
- Effective drainage management: Upkeep drainage structures such as water bars and culverts to control runoff and prevent soil erosion.
- Seasonal adjustments: Implementing temporary closures or load restrictions during wet conditions to limit wear and environmental degradation.

Regular maintenance extends the road network's lifespan, supports efficient roundwood extraction, and helps reduce negative environmental impacts, such as sedimentation in nearby waterways.

Transport Logistics
Efficient transport logistics ensure that harvested roundwood reaches processing facilities or markets in a cost-effective and environmentally responsible manner. Key components include:

- Optimised haul routes: Utilising decision-support tools and real-time tracking systems to design efficient extraction routes from the forest to landing sites, thereby reducing forwarding distances and lowering fuel consumption. Research by Flisberg et al. (2021) indicates that optimal landing site selection and route planning can significantly reduce operational costs and environmental impacts.
- Multi-modal integration: Combining truck transport with alternative modes (e.g., rail or barge) when feasible to further reduce fuel use and greenhouse gas emissions.
- Coordinated scheduling: Organising roundwood removals to minimise downtime and ensure that transport resources are used effectively.
- In Norway, roundwood is sold at the roadside (Incoterms: EXW/FAS), and buyers or cooperatives handle transport logistics. Key considerations include optimised routes, real-time fleet tracking, and multi-modal solutions (such as rail or barge) to reduce costs and carbon emissions.

3.2.5 Conserving Biodiversity Through Adaptive Management

Adaptive forest management at the property level must take biodiversity into account for both ecological resilience and long-term profitability. Preserving species diversity and habitat structure provides not only ecological benefits but also practical advantages, such as improved natural regeneration and reduced vulnerability to pests and extreme weather.

A varied species composition is an important risk-reducing measure. When one species is affected by damage, mixed stands provide a buffer. They tolerate disturbances better than monocultures and can retain greater volume and value after, for example, bark beetle outbreaks (Romeiro et al. 2025). Mixing, for instance, pine and spruce can reduce economic losses during beetle infestations while still producing timber with market value. The measure also has a stabilizing effect in the event of sudden price drops. Certification requires forest owners to consider such solutions.

Selective cutting can reduce the risk of stand collapse in a changing climate. Even modest investments in diversity and adaptive capacity can yield returns through more stable timber production, increased carbon storage, and income from ecosystem services or certification premiums.

Overall, measures such as species diversity, buffer zones, and retention of old-growth elements function as effective risk-reducing strategies. They may contribute to stable cash flow and increased long-term returns. Forest owners who implement such solutions in an adaptive manner may strengthen both ecological sustainability and their capacity to cope with climate change, regulations, price fluctuations, and productivity requirements.

3.2.6 Hydrology Management

Historically, extensive artificial drainage networks were introduced in Nordic forests to boost tree growth and improve soil aeration. In Sweden alone, over one million kilometres of ditches were dug to increase roundwood production (Laudon et al., 2022; Laudon & Maher Hasselquist, 2023), with similar programmes implemented in Finland and Norway. These ditches removed water and enhanced soil conditions, significantly raising increment throughout much of the 20th century.

However, drainage of peat soils for forestry and agriculture significantly alters greenhouse gas (GHG) dynamics. Maljanen et al. (2010) highlight that those drained peatlands, especially those converted for forestry, may act as net sources of CO_2 and N_2O due to enhanced aerobic decomposition processes, even decades after the cessation of active land use. Additionally, ditches themselves contribute notably to GHG emissions, an often-overlooked factor in drainage impact assessments.

Today, shifting precipitation patterns, rising temperatures, and increasing evaporation are altering hydrological conditions. In some areas, rainfall has intensified during parts of the season but become scarcer in other periods, possibly leading to acute drought stress. This disrupts tree growth and heightens vulnerability to pests and pathogens (Laudon et al. 2024). Drainage systems that once benefited forests may now reduce soil water-holding capacity, forcing trees to close their stomata in blades and needles more frequently. The resulting drop in photosynthesis may cause long-term declines in tree health and increment.

Furthermore, subsidence resulting from peat decomposition due to drainage disturbs hydrological stability, leading to both flooding risks and reduced water retention during droughts (Kløve et al. 2017). This process, coupled with increased nutrient leaching and potential metal mobilisation, threatens both forest ecosystems and downstream aquatic environments. Therefore, the Forest Act , with its sustainable forestry regulations, makes water protection a legal duty for all forestry operations: harvests must maintain vegetated buffer strips along watercourses, avoid pollution, and prohibit harmful new drainage. PEFC permits ditch cleaning under certain conditions.

Laudon et al. (2022) and Laudon & Maher Hasselquist (2023) advocate balancing increment goals with soil moisture retention, e.g. using selective ditch maintenance and peatland restoration to reduce both flooding and drought risks. Kløve et al. (2017) further suggest that rewetting drained peatlands, where feasible, may mitigate GHG emissions and restore hydrological balance. However, they caution that successful rewetting depends on local hydrological conditions, as long-term drainage may irreversibly alter peat properties, complicating restoration efforts.

Furthermore, soil-based greenhouse gas dynamics may require greater attention in climate-smart forest strategies. While most climate mitigation measures focus on carbon sequestration and storage in biomass and harvested wood products, soil emissions of CO_2, CH_4, and particularly N_2O can significantly offset these gains. For example, nitrogen fertilisation, although beneficial for growth and soil C storage, also increases N_2O emissions, which have a 100-year global warming potential nearly 300 times that of CO_2 (Mäkipää et al. 2023). These emissions are particularly high in nutrient-rich soils and peatlands.

Remote sensing, GIS-based hydrological modelling, and automated soil moisture sensors may provide real-time data for proactive water management. Internet-of-Things (IoT)-based systems, as proposed by Wang et al. (2025), may further improve monitoring of soil moisture, groundwater levels, and precipitation, enabling timely, adaptive responses to a changing climate.

3.3 Landscape, Regional, and National Level Forest Management

3.3.1 Fragmented Ownership, Zoning, and Adaptive Measures

With more than 125,000 forest properties in Norway, most under private ownership, forest management is highly fragmented at the landscape scale. Although certification requires the preparation of landscape plans for the largest properties, most holdings are too small to contribute significantly on their own to the coherent management of larger landscape elements. To address diverse environmental and economic needs across so many parcels, a Triad zoning approach has gained attention. Under this framework, intensive production areas, multi-use zones, and conservation reserves are designated to enhance multifunctionality. By grouping land according to its primary function, managers may protect critical habitats in reserves, maintain moderate-use zones for recreation and biodiversity, and concentrate high-yield production where appropriate.

The fragmentation of forest ownership in Norway makes coordination between public and private actors particularly challenging. Finstad (2025) points out that the lack of logging notifications to municipalities often results in land-use planning and environmental considerations being handled reactively rather than proactively. This reinforces the difficulty of achieving landscape-based planning and coordinated climate adaptation. For climate-smart management, there is therefore a need for mechanisms that link logging notifications and municipal planning more closely, so that local ecological and hydrological considerations can be addressed in advance of interventions.

Although the basic idea is old, recent advancements in forest management propose the Triad landscape functional zoning approach as a possible strategic framework to enhance multifunctionality in boreal forests. This approach allocates landscapes into zones prioritising intensive production, extensive multi-use, and conservation reserves. Blattert et al. (2023) found that applying this zoning in Finnish boreal forests led to a reduction in the net present value from 0% with no multifunctionality to 39% at maximum multifunctionality, the latter represented by 20% intensive production, 50% extensive production and 30% allocated to forest reserves.

Furthermore, recent research highlights the necessity of integrating adaptive management strategies into landscape-level planning to mitigate the increasing risks of climate-induced disturbances. Romeiro et al. (2025) stress that regions with historical bark beetle outbreaks may achieve substantial economic gains by adopting early harvesting strategies and incorporating mixed-species forests to boost resilience against pest infestations and other natural disturbances. These proactive measures not only enhance forest health but also contribute to long-term climate mitigation goals.

3.3.2 Fostering Cross-Boundary Cooperation

Property-level forest management is inherently interlinked with neighbouring land use practices, making cross-boundary cooperation vital for sustainability and efficiency. Forest management in the Nordic countries increasingly requires coordinated actions across property boundaries to address climate-induced challenges such as pest outbreaks, wildfire risks, water management, and biodiversity conservation. As climate change intensifies these threats, coordinated action grows increasingly important to maintain productivity and resilience against forest damages.

Approximately 80% of Norwegian forest properties account for just 20% of the productive forest area, highlighting a significant disparity in land distribution. Moreover, properties smaller than 20 hectares, which constitute around 50% of all forest holdings, are hardly a relevant entity for addressing many forest ecosystem services. Spatial considerations or connectivity related to habitat corridors, scenic beauty, recreational attractiveness, or preservation of rare entities call for management approaches that transcend individual property boundaries. Thus, management decisions ideally should be coordinated in space and time across properties constituting the landscape or otherwise relevant areas. Such coordination or cooperation at the landscape level might offer economies of scale and efficiency gains (Hoen et al. 2006; Martins et al. 2021; Londo & Grebner 2004). Still, it will also require that an operational cooperative setup or organisation can be established at a cost lower than the efficiency gains. It is also worth mentioning that the uncoordinated management of individual properties safeguards variation in management practices among properties. This variation might act as a kind of insurance at an aggregate (landscape) level and be beneficial in terms of biological resilience and for the provision of several forest ecosystem services. In Norway, these economies of scale may be obtained by planning and coordination made by forest owner associations, who are often executors of logging in neighbouring forest properties. This can, for example, build on the old tradition of hunting cooperatives ("jaktvald").

Coordinated Risk Management

Many forest hazards traverse property lines, making isolated management efforts insufficient. Pests such as bark beetles, fungi, and other pathogens spread rapidly across adjacent stands, rendering piece by piece responses ineffective. Joint monitoring networks and synchronised pest control strategies can significantly reduce the severity of infestations.

Wildfire prevention measures also benefit greatly from coordinated efforts. Strategically placed firebreaks shared early-detection systems, and joint fuel reduction initiatives are more effective when implemented across property boundaries. Furthermore, shared investments in emergency access roads and fire suppression infrastructure bolster regional response capabilities while reducing overall costs.

Beyond biotic threats, forest owners face increasing risks from climate-related disturbances such as windthrow, drought-induced tree mortality, snow and ice damage, wildfires and flooding damage. Adaptive management approaches, including stochastic programming and scenario-based planning (Eyvindson et al. 2024), help anticipate the frequency and intensity of such disturbances. When implemented collaboratively, these strategies enhance landscape-level resilience, enabling resource allocation to be both proactive and responsive to emerging threats. This integrated approach ensures that natural disturbance risks are mitigated more effectively than would be possible through isolated property-level actions.

Effective cross-boundary cooperation relies on accurate, standardised data. Variations in pest monitoring protocols or inconsistent fire-risk assessments can introduce both random and systematic errors, undermining management decisions. Scenario analysis, fuzzy logic models, and probabilistic forecasting may help to handle these uncertainties by considering a range of potential outcomes. Establishing shared data platforms and standardised monitoring protocols improves reliability, ensuring that collective actions are grounded in robust, comparable information.

While strengthening monitoring and coordination systems is essential, it is important to mention that Norway already has a well-established foundation of forestry monitoring, planning, and cross-boundary collaboration. The National Forest Inventory (Landsskogtakseringen), managed by NIBIO, provides systematic, nationally representative data on forest volume, species composition, regeneration, carbon stocks, and forest health, serving as the basis for both national greenhouse gas accounting and long-term forest management. This should be complemented by targeted damage monitoring programmes for root rot, drought, snow damage, and insect outbreaks, supported by national bark beetle trapping networks that feed into risk models and early-warning systems.

Digital platforms such as NIBIO's Kilden, with the Forest Portal as a thematic module, compile and visualise forest resource data together with available environmental registrations (e.g., MiS), key habitats and protected areas. This provides a comprehensive knowledge base that supports planning and documentation for forest owners, industry stakeholders and public authorities. Collaboration across properties and administrative levels is facilitated by forest owner associations, which coordinate harvesting, logistics, environmental considerations, and climate adaptation measures. This may also be extended to climate adaptation measures. Besides, numerous national and regional R&D initiatives have supported joint learning and methodology development.

However, despite these well-developed structures, large-scale, landscape-level coordination, particularly for wildfire prevention and pest control, remains mostly voluntary and project-based. Bark beetle monitoring and warning services (e.g., Skogskader.no, NIBIO alerts) illustrate a successful national-level coordination, yet response measures to handle bark beetles are largely implemented by individual landowners. Similarly, wildfire prevention efforts benefit from local initiatives and insurance-sector support (e.g., Skogbrand), but systematic cross-boundary risk management is still rare. Strengthening institutional frameworks, incentives, and financing mechanisms to scale up existing collaborations and embed them more deeply in climate change mitigation and adaptation strategies offers a pragmatic pathway forward, avoiding the inefficiencies of building entirely new systems from scratch.

Integrated Water Management Across Boundaries

Water systems, including streams, groundwater, and drainage networks, naturally transcend property lines. Drainage on one parcel may lead to water shortages, flooding, or erosion on adjacent lands. Joint efforts and coordination to maintain peatlands, riparian buffers, and retention ponds stabilise hydrological flows, protect soil integrity, and support aquatic biodiversity. In regions prone to extreme weather, cooperative flood and drought management, encompassing controlled drainage systems and vegetative buffers, proves significantly more effective than isolated interventions.

Economic Synergies Through Shared Infrastructure and Market Access

Collaboration among forest owners may also yield substantial economic advantages. Membership in forest cooperatives allows Norwegian forest owners to pool roundwood outputs, negotiate more favourable contracts, and reduce operational costs through economies of scale. Group certification under sustainability schemes becomes more accessible when administrative responsibilities and fees are shared. Moreover, joint investments in infrastructure, such as road networks, biomass processing facilities, and storage depots, minimise redundant costs, enhance year-round accessibility, and strengthen regional economies.

Enhancing Biodiversity Through Landscape-Level Conservation

Biodiversity conservation may benefit markedly from coordinated landscape-level strategies. Wildlife depends on continuous habitats, making cross-boundary conservation efforts important, cf jaktvald above. By aligning protected set-asides, riparian buffers, and retention patches across properties, forest owners may maintain and expand ecological corridors. Strategically distributed mixed-species forests support biodiversity while creating more resilient ecosystems. Additionally, managing invasive species and exotic pests is far more effective when approached at the landscape scale rather than through isolated property-level interventions (Hunault-Fontbonne & Eyvindson 2023).

3.3.3 Coordinated restoration of wetlands

Hydrological measures in forestry do not only operate at the property level but have cumulative effects throughout entire catchments. When many small interventions, such as buffer zones, ditching, peatland restoration, or prevention of ruts, are added together, they affect water balance, erosion, and flood dynamics on a larger scale than what matters on the individual property.

At the landscape level, several considerations therefore become particularly important:

- Coordination between properties. Individual measures can be useful, but their effect is amplified when forest owners coordinate their efforts. Cooperation may involve anything from wetland restoration to the establishment of continuous buffer zones along waterways.
- Flood and surface water management. The hydrological functions of forests extend beyond property boundaries. Large clearcuts or drained areas can increase runoff and amplify downstream flood peaks, whereas the preservation of moist areas (peatland) can mitigate them.

- Water resources and societal interests. In many regions, forests are part of catchments that supply towns and settlements with drinking water. Forestry measures can thus have direct consequences for water quality and treatment. Hydrological management at the landscape level should therefore be linked to spatial planning and the safeguarding of long-term water supply.

Taken together, this means that hydrological management at the landscape level is not merely about the sum of individual measures but about building integrated strategies in which forestry is seen in connection with water resources, biodiversity, and societal safety.

3.3.4 Regional-Level Coordination and Collaborative Infrastructure

Regional forest management may integrate broader policy frameworks and economic strategies to address climate change mitigation and adaptation. Verkerk et al. (2022) argue that regional coordination may amplify the effectiveness of CSF by harmonising practices across different administrative areas and forest types.

- Regional Policy Integration: Harmonising forest management policies across regions ensures consistency in climate adaptation strategies and carbon accounting methods. Regional authorities can facilitate the sharing of best practices and technical expertise.
- Market Access and Economic Incentives: Regional cooperatives enhance market access for small forest owners, allowing them to benefit from economies of scale.
- Infrastructure and Technology Sharing: Investing in shared infrastructure, such as biomass processing facilities and advanced monitoring technologies (e.g. GIS and remote sensing), can improve the efficiency and effectiveness of regional forest management.

Elaborating on the Functional Complex Network approach may enhance forest resilience. This method emphasises functional and structural diversity at both the stand and landscape levels, improving adaptability to climate change and extreme events.

To effectively implement CSF at the landscape scale, robust decision support systems are required (Hunault-Fontbonne & Eyvindson 2023). Combining forest ecosystem modelling with multi-objective optimisation allows managers to balance competing policy demands while adapting to regional forest dynamics. Tools such as those already used in Norway (e.g. GAYA 2.0), may simulate different management strategies for local forest and climate conditions. By integrating this tool with spatial indicators, forest managers can evaluate trade-offs and synergies, optimising carbon sequestration, storage and biodiversity conservation outcomes across large, forested landscapes.

3.3.5 Aggregation Challenges: Moving from Stand to National Scales

Regional variations in site growth conditions, terrain and climate may influence strategies for biodiversity conservation and carbon sequestration. Thus, policy measures tailored to regional differences may optimise the ecological and economic outcomes of forest management. Recent simulation-based assessments show that biodiversity and carbon policies exhibit distinct effects across productivity gradients, necessitating adaptive strategies at different spatial scales (López et al. 2024). Ensuring that local measures aggregate to meet national targets is crucial (see Section 5.2 for Norway's commitments under the Paris Agreement that frame these mitigation objectives).

As CSF strategies are implemented across various spatial scales, from individual stands to national markets and policy frameworks, the issue of aggregation becomes increasingly complex. Aggregation involves combining data, management practices, and ecological and economic outcomes from smaller units (e.g. stands or properties) to larger scales (e.g. landscapes, regions, and nations). This process introduces several challenges that may affect the accuracy of predictions, the effectiveness of management strategies, and the coherence of policy frameworks.

A central concept in this challenge is separability, which for example may concern how, e.g. independent stand-level outcomes contribute to broader-scale performance. When outcomes are strongly separable, interdependencies between stands are minimal, and the aggregate result on property/-landscape/national levels can be obtained by simply summing the performance of individual stands. In contrast, if only weak separability holds, significant interaction, such as overlapping pest dynamics, hydrological connectivity, or wildlife movement, introduces synergies or trade-offs that complicate straightforward aggregation.

In practical terms, even if a management practice appears optimal for a single stand, its effects might amplify or diminish when scaled up. For instance, a uniform approach to maximising carbon sequestration and storage in individual stands might inadvertently increase regional vulnerability to pests or disrupt connectivity crucial for biodiversity. Therefore, effective national-scale planning must employ integrated analytical models that capture these interdependencies, ensuring that local decisions collectively advance long-term sustainability and resilience across the landscape.

4 Harvested Wood Products and Their Role in Climate Mitigation

Harvested Wood Products (HWPs) contribute to climate change mitigation through carbon storage and substitution effects. In storing carbon, wood-based goods may retain the carbon absorbed by trees well beyond the harvest date, delaying its return to the atmosphere. In substituting for more emission-intensive materials or fuels, HWPs can indirectly reduce the overall greenhouse gas footprint of a given economic activity. The magnitude and longevity of these benefits depend on a range of factors, including product lifespans, alternative materials substituted, technological innovations, end-of-life handling, and overarching policy frameworks. This section explores how HWPs can help mitigate climate change, examining their storage capacity, substitution potential, possible pathways for negative emissions, and the challenges and uncertainties inherent in aligning HWP development with national and international climate goals.

4.1 Extending HWP Lifespans to Increase Carbon Storage

A well-known way HWPs mitigate climate change is by functioning as a carbon reservoir for varying lengths of time. Construction roundwood and engineered wood products typically have service lives of several decades, while short-lived items like paper and packaging materials release carbon more swiftly (Sathre & O'Connor 2010; Leskinen et al. 2018). A portion of the carbon in harvested logs is lost early on in processing, in the form of bark and residues used for process energy or discarded. Consequently, the fraction of carbon that remains in a final product depends on both industrial practices and the manufactured product type (Myllyviita et al. 2021).

When the stock of HWPs accumulates faster than it decays or is discarded, it serves as a carbon sink. In national greenhouse gas inventories, the HWP carbon pool is often reported separately (IPCC 2019; Norwegian Environment Agency 2021), using standard assumptions of product lifetimes and half-life parameters to track how quickly each product category releases carbon back into the atmosphere. While short-lived products like paper and paperboard quickly saturate their carbon pool, shifting the use of pulpwood and sawmill residues to produce more durable goods, like wooden panels or bio-based insulation, may help maintain or even increase net storage over time. Sawnwood has, by default longer lifetime than the other product categories. However, since nearly all harvested sawlogs in Norway are already used for sawnwood production, a crucial consideration is how pulpwood and sawmill residues are utilised. Kallio et al. (2023) estimated that in 2020, around 40% of the carbon from industrial roundwood harvested in Norway was retained, at least temporarily, in HWPs other than energy biomass, while 25% was exported. Approximately one-third of the carbon is converted to CO_2 during industrial processing, primarily because it is utilised as energy.

A key challenge in maintaining HWPs as a carbon sink is that, since all products have limited lifetimes, the HWP sink can only persist over the long term if HWP production, and consequently, harvest levels, increase. This may happen if a greater share of pulpwood is redirected toward higher-value, longer-lived products, such as engineered panels or insulation materials, in future production structures (Kallio et al. 2025). However, raising harvest levels to boost the HWP sink inevitably reduces the forest carbon sink, and there are ecological and policy limits to how much harvest can be expanded. Therefore, extending product lifetimes through improved product design and circular-economy measures (e.g., reuse, remanufacturing, and recycling) remains an effective strategy to enhance the HWP sink without compromising in-forest carbon stocks.

4.2 Substitution Effects of Biomass Supply

Besides their ability to store carbon, HWPs often confer substitution benefits by displacing fossil-intensive materials or fuels. This impact is typically more important than that of carbon storage. In material substitution, wood used in structural applications can replace steel and concrete, which generally have higher life-cycle emissions (Sathre & O'Connor 2010). Similarly, wood-fibre packaging can substitute for plastics or metals, while emerging wood-based textile fibres may take market share from far more emission-intensive man-made materials like polyester (Kallio et al. 2023).

Wood biomass may be used to generate heat, electricity and the production of transportation fuels, offsetting the use of coal, natural gas, and oil. The climate benefit of bioenergy depends on feedstock origin, regeneration rates, and the overall system boundary. Burning stemwood that could be used for products other than energy must be compensated by new growth over time. Furthermore, that would compete with the material uses of wood. Also, relatively fast-decaying branches and tops could be removed from the forest and used for energy. Then, some concerns of site fertility and soil carbon dynamics should be accounted for (Suter et al. 2017; Röder & Thornley 2018), e.g. by letting the needles drop before the roundwood is transported out of the forest.

Not all HWPs provide substitution benefits. The data presented in Kallio et al. (2023) identifies construction materials, bio-based insulation, and wood-based textile fibres as examples of products with relatively high displacement factors. For biofuels and many paper grades, substitution benefits are more than offset by the loss in forest carbon sinks due to harvesting biomass for these products. While the supply of forest-based products is influenced by market demand, the climate policy measures should prioritise HWPs with verifiable life-cycle benefits and, at least, avoid creating demand for products which are harmful from the climate point of view. Transportation fuels produced from wood is a good example of the latter. Kallio et al. (2025) show that reallocating biomass from pulp and paper production to bioethanol would provide only a marginal – but still positive - climate benefit. Moreover, due to the high demand for wood biomass in their production process, subsidising their production might crowd out other products with better greenhouse gas footprints.

The strong policy support for low-carbon construction could boost the role of wood in mitigating climate change. Yet, over the longer term, the effectiveness of substitution will also hinge on how successfully other industries decarbonise. If steel, cement, and plastics production drastically reduce their greenhouse gas footprint, the comparative advantage of wood-based materials may shrink (Leskinen et al. 2018).

In their study of the substitution factors for different bioenergy levels toward a fully decarbonised energy system, Jåstad & Bolkesjø (2023) found that forest biomass may continue to play a pivotal role in decarbonising energy production, at least in the short to medium term. If the use of forest biomass is restricted, the system must compensate with other energy sources, including wind power, solar PV, and power-to-heat, possibly incurring higher overall land use and, in certain scenarios, increased reliance on fossil fuels. Such shifts could prolong or elevate carbon emissions.

4.3 Negative-Emission Avenues: Bioenergy with Carbon Capture

Bioenergy with carbon capture and storage (BECCS) or utilisation (BECCU) represents a pathway to deliver negative emissions, assuming that harvested biomass is regrown, and that captured carbon is stored or used in a manner preventing its rapid release (IPCC 2019). In principle, if wood-based biomass is combusted for energy and the resulting CO_2 is captured and stored geologically, the net effect may reduce atmospheric CO_2, provided that replanting or natural regeneration offsets the extracted biomass.

However, scaling BECCS poses multiple challenges. High costs, limited CO_2 transport and storage infrastructure, and uncertainties around feedstock sourcing all complicate the widespread deployment of this technology. Consequently, any push to incorporate BECCS into forest-based climate strategies must consider the opportunity costs of using wood for direct combustion rather than durable goods.

Modelling by Hu et al. (2023) shows that large-scale BECCS deployment in the Nordic region is technically feasible but will require EU ETS integration, stronger international sustainability standards, and careful biomass allocation to avoid carbon leakage and sectoral trade-offs.

A closely related approach to bioenergy with carbon capture is the production of biochar through pyrolysis of logging residues and other forest biomass. Biochar can contribute to increased carbon storage in soils and reduced greenhouse gas emissions, but its effect depends on the availability of biomass and the long-term sustainability of its use. Hagenbo et al. (2022) show that biochar produced from Norwegian forest residues under boreal conditions could remove approximately 0.4–0.8 Tg CO_2-equivalents per year, corresponding to 0.8–1.5% of Norway's annual emissions. At the same time, soil carbon stocks in forests decrease when residual biomass is removed, and nutrient losses (especially nitrogen) may limit growth and carbon uptake in the long term. The authors therefore conclude that biochar could play a moderate but not decisive role in Norwegian climate policy, and that the measure requires careful evaluation of resource availability, nutrient losses, and economic feasibility before any large-scale implementation.

4.4 Strengthening Competitiveness in a Circular Bioeconomy

A circular bioeconomy emphasises optimising resource utilisation, extending product lifespans (cascading use, and shifting away from fossil-based inputs. Despite these prospects, significant uncertainties remain. One involves market dynamics, as demand for climate-smart wood products depends on price, performance, and consumer preferences. Another lies in technological evolution: if alternatives such as green steel or low-carbon cement emerge swiftly, wood's relative advantage may narrow. Investment risk in mills or refineries designed to produce advanced biomaterials is also high, as these facilities typically require large upfront capital expenditures and long payback periods (Suter et al. 2017). Policy instability, whether in carbon pricing, subsidies, or trade regulations, may further discourage long-term commitments to wood-based innovation. Continuing research and development, coupled with stable policy signals, may help reduce these uncertainties and encourage private-sector engagement. Collaborations between forest owners, processing industries, and academic institutions may foster breakthroughs in product design, cascade utilisation, and integrated energy and materials production.

4.5 Aligning HWPs With National and International Climate Policy

National reporting under the Land Use, Land-Use Change, and Forestry (LULUCF) framework typically includes HWPs alongside in-forest carbon stocks. Yet accounting approaches differ in how they treat exported vs. domestically used wood, and it can be difficult to capture the full climate benefits or potential leakage associated with global trade (cf. section 5.3 for leakage). Norway, for example, applies a production-based approach in which only HWPs derived from domestically processed roundwood are credited to national inventories (Norwegian Environment Agency, 2021). This method may not fully reflect the actual climate impacts of Norwegian-harvested logs processed abroad.

4.6 Carbon Farming and Policy Integration for HWPs

Mandatory LULUCF accounting sets the baseline, but carbon-farming programmes – existing voluntary schemes or contracts to be certified under the upcoming EU Carbon Removal Certification Framework (CRCF; see Section 5.3) create parallel, market-based rewards for any additional carbon retained in forests, soils, or long-lived wood products. Scaling up the climate role of HWPs, therefore, hinges on a policy environment that actively promotes such incentives (see Section 5.4 for Norway's current instruments).

Carbon farming links a financial or regulatory benefit to actions that boost carbon storage in living biomass. Extending these schemes to HWPs can motivate forest owners, mills, and downstream industries to favour long-lived uses and adopt climate-smart end-of-life strategies for wood (Leskinen et al. 2018).

Credit designs that pay more for durability, e.g. assigning higher carbon credits to products with longer half-lives, may channel more roundwood into construction timber or furniture instead of short-lived packaging. Their success, however, rests on rigorous monitoring-reporting-verification (MRV) and robust leakage safeguards that stop intensive management from simply shifting elsewhere.

In practice, carbon-farming incentives work best as part of a wider policy mix: binding CSF standards, targeted subsidies for innovative wood-product development, and extension services all reinforce the role of HWPs in economy-wide decarbonisation.

5 Policy and Institutional Framework

Climate-Smart Forestry (CSF) builds directly on the long-standing economic imperative that forest owners face: to secure timber revenues and rural livelihoods through sound forest management and market-oriented decision-making. The climate and biodiversity dimensions described below do not replace those economic drivers but layer additional objectives on top of them. In other words, when we talk about new policy frameworks, incentives or trade-offs, we assume as our starting point that forest owners continue to emphasise economic performance. CSF simply asks: how can those same forests deliver timber value while simultaneously sequestering carbon, enhancing resilience, and safeguarding biodiversity at low costs? This is not to say that forest owners focus only on market-based economic performance, as most owners typically also have a set of other priorities in their forest management (conservation, hunting, recreation, biodiversity, etc.). Nevertheless, pure climate mitigation activities may be regarded more as a societal than a private challenge and may thus require specific economic incentives. Adaptation activities, on the other hand, may be perceived more as a private character, but the concept is still new to most forest owners.

CSF operates within a multi-layered policy environment. This is explained in the following Sections 5.1-5.6. An effective framework must coherently align international commitments, European regulations, and national policies while also addressing long-term risks and on-the-ground constraints. This section details the policy context, from global agreements through domestic laws, regulations and institutions, and highlights how recent developments, including new climate and biodiversity plans, shape the path forward. It also notes areas of stakeholder consensus and debate, underscoring the importance of balancing climate and biodiversity goals in Norway's forest sector.

5.1 Overarching Framework and Coherence

CSF policies must create a coherent regulatory and economic environment that simultaneously supports multiple objectives. This includes:

Mitigation and Adaptation: Policies should integrate traditional forestry regulations (e.g. the Forest Act), certification standards, and international commitments, ensuring consistency with broader climate and environmental goals while also incorporating non-regulated forest ecosystem services. In practice, this means aligning climate-mitigation efforts (like carbon sequestration) with adaptation measures (enhancing forest resilience) and biodiversity protection. The emerging integration of climate and nature strategies amplifies this need for coherence.

Synergies and Trade-offs: As discussed in Section 2.4.3, forest management decisions can yield synergies (e.g. increased carbon uptake alongside habitat improvements) but also involve trade-offs (e.g. intensive biomass harvesting may reduce biodiversity). Policy coherence requires actively managing these interdependencies. Cross-boundary collaboration – among private owners, municipalities, and state agencies – is important so that actions at the stand-level do not conflict with landscape-level conservation needs. For instance, expanding timber harvest for climate-friendly products should be coordinated with habitat conservation to avoid undermining biodiversity.

Integration Across Scales: The policy framework should operate from the local stand-level up to national and international levels. Forest management decisions at the stand and property levels (species selection, thinning regimes, harvest age, road construction, etc.) may, in some cases, need supportive incentives and guidelines that scale up to regional coordination. Avoiding fragmented efforts may be key; for example, a municipality's land-use plan should complement national climate commitments. As detailed in Section 3, multi-scale management may ensure that a forest owner's actions (like choosing climate-resilient species) contribute to larger goals (such as biodiversity networks). Therefore, CSF policy instruments should be designed accordingly.

5.2 Norway's Commitments – the Paris Agreement and Global Goals

At the global level, the Paris Agreement (2015) under the UNFCCC defines the core objectives for climate action. Norway, as a Party, has pledged ambitious emissions reductions through its Nationally Determined Contribution (NDC). The current NDC is to cut greenhouse gas emissions by at least 55% by 2030 relative to 1990, roughly limiting 2030 emissions to 23.1 million tonnes CO_2-e. Importantly, Norway aims to fulfil this commitment in tandem with the EU, leveraging international mechanisms under Article 6 of Paris (cooperative approaches and credit transfers) and close policy integration with EU climate schemes. The Paris framework also sets a longer-term goal for all parties: Norway's Climate Change Act defines the country's aspiration to become a close to zero-emission society by 2050, in line with global net-zero aims.

In addition to its domestic mitigation efforts, Norway is committed to international biodiversity goals under the Kunming–Montreal Global Biodiversity Framework (GBF). Meld. St. 35 (2023–2024), introduced to Stortinget in November 2024 and adopted in January 2025, translates all 23 GBF targets into Norwegian policy. It sets a national goal to protect at least 30 % of terrestrial areas by 2030 (GBF Target 3), to restore 30 % of degraded ecosystems on land, in fresh-water, along the coast and at sea by 2030 (GBF Target 2), and to ensure the sustainable management of working landscapes such as forests (GBF Target 10). Key instruments include a "menu of measures" for sustainable forest management, the development of a national natural-accounting system, and strengthened due diligence requirements for industries that impact biodiversity. In this way, Meld. St. 35 (2023-2024) provides a policy framework for nature restoration and protection analogous to how the Paris Agreement guides climate action.

Norway is now adding a time dimension to its climate commitments beyond 2030. In June 2025, the Norwegian parliament agreed on the climate action plan (Meld. St. 25 (2024–2025)), outlining the climate strategy toward 2035. This implies that a new 2035 emission target of a 70–75% reduction from 1990 levels will be anchored in law. The intention is to update Norway's internationally pledged target in 2025 as required by the Paris Agreement's cycle. The Government clarifies that the 2035 target will apply to the entire economy, including land use and forestry. Additional carbon sequestration from forests may, therefore, contribute to meeting the target. It is worth noting that the White Paper signals the following regarding long-term objectives (translated from Norwegian):

"Experience from many years of climate policy shows that climate targets with a ten- to fifteen-year time horizon have not provided sufficient incentives for climate measures in the forestry sector. This is because it takes a long time before such measures result in the desired climate effects. Consequently, the work has not been able to make significant contributions to the achievement of short-term climate targets. To support such a long-term perspective, the government will work to establish a long-term climate target for managed forests. The target must be set based on what can be considered a realistic level of CO_2 uptake and carbon storage. Such a long-term climate target for forests must also be viewed in connection with, and not undermine, the achievement of objectives for ecological condition in forests. Measures and instruments aimed at fulfilling a climate target for forests must furthermore take into account other societal goals and consider how future climate change may affect CO_2 uptake and carbon storage in forests. In the long term, forest measures may increase forest uptake to an extent that can make a substantial contribution to future climate targets and to the Paris Agreement's balance objective in the second half of this century."

By "long term," a time frame of 25–75 years is thus implicitly meant. This should be understood as an acknowledgment that forests must be managed from a longer-term perspective (cf. Article 2 of the Climate Convention and Article 4.1 of the Paris Agreement) than that of the more short-term objectives of the Paris Agreement.

Norway's dual commitments to the Paris climate goals and the GBF biodiversity goals underscore the need for integrated strategies. On one hand, increasing forest carbon sequestration is part of the climate solution; on the other, expanding conservation is central to the biodiversity solution. The challenge and opportunity for Norway is to implement policies that satisfy both: enhancing the forest carbon sink (as a contribution to climate mitigation) while simultaneously halting nature loss. These global commitments set the stage for the European and national measures described below.

5.3 European Climate Regulations under the EEA

Although Norway is not an EU member, it is closely aligned with EU climate policy through the EEA Agreement and specific bilateral accords. Norway has opted to fulfil its 2030 climate targets in concert with the EU, effectively embedding itself within the EU's climate policy architecture for 2021–2030. This architecture has three main pillars: the EU Emissions Trading System (ETS) from 2005, the Effort Sharing Regulation (ESR) with roots from ESD 2009, and the Land Use, Land-Use Change and Forestry (LULUCF) Regulation from 2018. Norway participates in all, as follows:

EU ETS (Emissions Trading System)
Norway is a full participant in the EU ETS, the cap-and-trade system covering large stationary emitters (power, industry, aviation, etc.). An EU-wide cap on emissions (shrinking annually) dictates the total allowances which companies trade as needed. By joining, Norway accepts the same cap constraints for its covered sectors as EU countries, meaning emissions from Norwegian oil & gas, manufacturing, aviation, etc., are regulated by the ETS market. The EU has recently tightened the ETS to achieve a 62% reduction in ETS emissions by 2030 (vs 2005), driving up ETS allowance (quota) price. A higher allowance price benefits CSF indirectly: it increases the competitiveness of wood-based bioenergy and biomaterials as substitutes for fossil-intensive products. In the long run, a robust carbon market could even spur negative emissions technologies (e.g. bioenergy with carbon capture and storage) in which Norwegian forestry might play a role. Thus, a strengthening ETS pushes the economy toward low-carbon solutions, potentially expanding markets for sustainable timber and biomass.

The EU is establishing a separate ETS II for buildings and road transport (starting 2027/28), which Norway is expected to join via the EEA. While compliance obligations will fall on fuel suppliers rather than end-users, ETS II will further raise the cost of fossil fuels and strengthen incentives for renewable energy, electrification, and sustainable biomass in heating and transport areas where Norwegian forestry and bioenergy could become increasingly relevant.

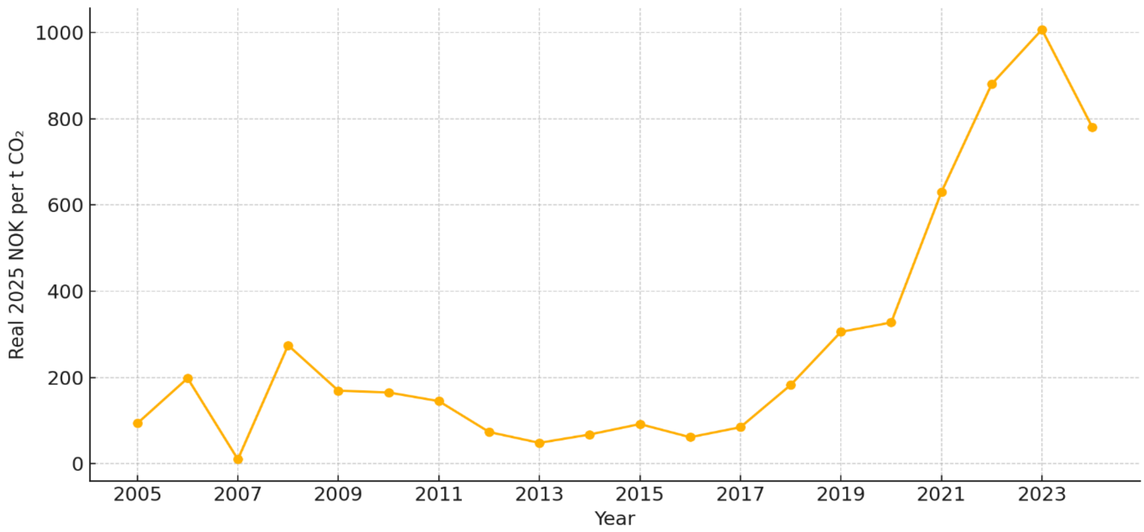

Figure 10. Indicative development of the EU ETS Allowance (quota) price (EUA). Measured in 2025-NOK. Note that the figure is based on a compilation of data from different sources (EEA, EC, ICAP): *https://www.eea.europa.eu/publications/trends-and-projections-2012; https://commission.europa.eu/publications/report-functioning-european-carbon-market-2022_en https://data.europa.eu/doi/10.2834/63208; https://data.europa.eu/doi/10.2834/157367; https://icapcarbonaction.com/en/ets-price-explorer/****).***

EU ESR (Effort Sharing Regulation)

The EU ESR sets binding national targets for sectors outside the ETS (transport, buildings, waste, agriculture, small industry). Under the Norway-EU climate cooperation, Norway has a reduction target for these non-ETS sectors analogous to those of high-GDP EU states. While the exact percentage is negotiated, it is likely in the range of a 45-50%+ cut by 2030 for Norway, compared to 2005. Meeting the ESR target domestically will require policies like increased vehicle electrification (especially for trucks), heating efficiency, and farming emissions cuts. This may have indirect effects on forestry. For example, electrifying transport and industry increases demand for clean electricity, potentially boosting wood-based biofuel demand (cf. Section 4.2 for the questionable effect of biofuels); agricultural emission cuts might encourage tree planting on marginal farmland as a sink enhancement. The ESR also permits limited flexibility: if Norway overachieves in the LULUCF sector (sequesters more CO_2 than expected), it may offset some shortfalls in ESR sectors- but not the other way around. Norway has negotiated the opportunity to use surpluses in the land-use sector in this way, up to 1.5 million tonnes of CO_2 equivalents (equivalent to about 3% of Norway's total emissions, thereby directly linking forest carbon sequestration and storage to the climate targets for transport, construction, and agriculture.

EU LULUCF (Land Use, Land Use Change and Forestry)

The EU LULUCF regulation (EU 2018) governs how carbon emissions and removals from forests and land are accounted for and incentivised. Norway's forests are a significant carbon sink, and in 2019, Norway voluntarily aligned with EU LULUCF rules for 2021–2025, committing to the EU's "no-debit" rule. This means Norway pledged that net emissions from land use and forestry will not increase (i.e. the forest and land sector should be net zero or better). To implement this, Norway submitted a National Forestry Accounting Plan with a Forest Reference Level (FRL) as a baseline for its managed forest CO_2 removals. If Norway's actual net sink falls short of the FRL baseline, the shortfall counts as an emission that must be compensated, effectively capping how much the sink can diminish. In the first compliance period (2021–2025), there is concern that Norway's FRL was set ambitiously (based on a period of unusually high uptake: 2000-2009), so current management may not meet it. Indeed, projections suggest Norway will face an accounting deficit in the LULUCF sector, which would require purchasing LULUCF credits from other countries or making additional corrections to avoid breaching the no-debit rule. Possible positive contributions may be used to compensate for deficits in ESR, but only up to 0.8 MT CO_2e per year.

Looking ahead, the EU updated its LULUCF Regulation in 2023 (EU 2023) to set a more ambitious collective EU target: a net removal of 310 million tonnes CO_2e from LULUCF by 2030. This entails significantly higher sink contributions from each member state. FRLs will no longer be used. Norway, while not automatically bound by this new EU Regulation (LULUCF is outside the EEA core acquis), is considering whether to opt into also the second period (2026–2030) under these revised terms. The updated framework would likely assign Norway a tougher commitment for its forest sector by 2030. If Norway does not join, the regulations for 2021–2025 will still apply for 2026–2030. Critics note that the short 2030 horizon is challenging for forestry – measures taken now (planting, changed silviculture) may only yield incremental gains by 2030, given biological growth lags. In the near term, the simplest way to increase net CO_2e removals is to reduce emissions from land-use changes (e.g. limit deforestation) or temporarily harvest less so that carbon stocks build up. Such actions, however, may conflict with forest owners' income goals and industry interests by reducing the timber available as inputs. This illustrates a core tension: to meet strict climate targets, policymakers might favour maximising the carbon sink (through conservation, longer rotations, or delaying harvests), which may constrain wood supply and economic returns in the short and medium run.

European policy thus places a dual expectation on Norwegian forestry: contribute to climate mitigation by maintaining or enhancing the sink, and support broader decarbonisation through biomass supply, all within a tightening regulatory envelope. Norway's alignment with EU climate policy assures a high level of ambition and access to flexibility mechanisms, but it also means Norwegian forestry is subject to increasingly stringent carbon accounting rules. Notably, the government's new 2035 proposal reiterates that Norway intends to remain in step with EU climate cooperation beyond 2030, including whatever successor to the LULUCF regime emerges. In sum, Europe's regulations both constrain and incentivise Norway's forest sector: they discourage activities that weaken the sink, while rewarding innovation in sustainable biomass and carbon farming. The balance struck at the European level will influence Norway's domestic policy choices for forests significantly.

Kallio & Solberg (2018) show that 60–100% of any Norwegian harvest restriction might be offset by extra cutting abroad. This is called leakage, see e.g. Päivinen et al. (2022); Kallio & Rannestad (2025, manuscript). Further, Päivinen et al. (2022) show that many EU Member States are already harvesting above the FRLs fixed by the LULUCF Regulation, so few are expected to generate surplus carbon removal units for trade. Korosuo et al. (2023) likewise project that only a handful of countries will meet their 2021–2025 FRL, implying that the credit pool available to Norway could be very small. Further, Garvik & Kallio (2025, manuscript) find that the forthcoming, stricter EU LULUCF targets and the EU Biodiversity Strategy for 2030 (EU BDS) would displace an even larger share of harvesting outside Europe unless global safeguards are introduced. Recent modelling by Hu et al. (2024) confirms that harvest leakage rates for Norway range between 61% and 76%, with over half of the compensating harvest occurring outside the Nordic region. This study also traces detailed trade flows, showing that domestic harvest constraints in any Nordic country trigger substantial adjustments in neighbouring countries and globally, reinforcing the need for internationally coordinated safeguards. Together, these studies highlight that Norway's strategies for climate and biodiversity must be developed with a global market perspective; otherwise, domestic gains risk being offset, or even reversed, by higher emissions and ecological pressure abroad. The latter would imply an expensive solution to Norway (and Europe), and with a very marginal, possibly negative, climate effect, as we may end up importing the roundwood from outside Europe.

The current LULUCF regulation in the EU/EEA (EU 2018) applies the so-called production-based approach for harvested wood products. All carbon removed through harvest is immediately recorded by the country where the harvest takes place, and the subsequent emissions from product decomposition are reported over time by that same country, regardless of whether the wood is exported and used elsewhere.

This methodological choice is well justified by considerations of data availability, control, and verifiability. However, it introduces two structural imbalances:

- Asymmetric burden-sharing: Exporting countries must report future emissions even when the wood is used in climate-friendly, long-lived products abroad, while importing countries receive no corresponding credit for the actual carbon storage.
- Weak demand-side incentives: Countries that import timber and wood products for long-term use see no positive effect in their national greenhouse gas inventories, thereby reducing the incentive to replace more carbon-intensive materials such as steel and concrete in the construction sector.

With current technologies for value chain traceability, including origin labelling, customs codes, electronic certification systems, and digital building logbooks, it is, in principle, fully feasible to track carbon throughout the entire lifecycle from harvest to end use. Thus, the methodological framework is not outdated, but inadequate for capturing the climate-policy realities of an increasingly globalised bioeconomy.

(CRCF) (EU Carbon Removal Certification Framework)

Regulation (EU) 2024/3012 established a Union certification framework for permanent carbon removals, carbon farming and long-lived carbon storage in products and entered into force on 26 December 2024. The CRCF is voluntary, but it sets Union-wide quality criteria for quantification, additionality, long-term storage and sustainability, and requires third-party verification plus registration in an EU-wide registry. The Commission will now translate the framework into practice: delegated acts laying down activity-specific methodologies are scheduled for 2025, with implementing acts on verification and the interim registry to follow. According to the Commission's roadmap and market trackers, the first EU-certified removal units (credits) are expected to be issued in 2026, and by July 2026, the Commission will report on possible links to compliance markets. The CRCF framework emphasises the importance of integrating EU QU.A.L.ITY criteria (Quantification, Additionality, Long-term Storage, and Sustainability) into any forest-based carbon farming system. As underlined by Chiti et al. (2024), without clear standards for permanence and leakage avoidance, carbon credits risk lacking environmental integrity.

For Norway, the CRCF is likely to be incorporated into the EEA Agreement. The Norwegian government has already opened an EEA memorandum on the regulation and is assessing how and when to transpose it. Once incorporated, Norwegian farmers, forest owners and industrial actors will be able to certify projects under CRCF recognised schemes and market "EU Carbon Removal Units" alongside EU operators. The Ministry of Climate and Environment notes that CRCF credits could become an important revenue stream in the voluntary market and potentially, after 2026, in compliance settings, provided Norwegian methodologies and measurement, reporting and verification systems align with the forthcoming EU rules. Although CRCF and LULUCF address many of the same land-based activities, they serve different purposes and are not formally integrated. The LULUCF Regulation governs national-level emissions and removals reporting for compliance purposes, while CRCF provides voluntary certification of individual projects based on strict quality criteria. For Norway, this means that removals certified under CRCF, for example through carbon farming, cannot be counted toward LULUCF targets unless future EU rules explicitly allow it. Still, the two frameworks are complementary: certified CRCF projects must use robust monitoring and verification systems, which could also support national reporting if kept clearly separate. See also Section 5.4 for private initiatives on buying and selling carbon credits.

RED II (and III) (Revised Renewable Energy Directive)
RD II is expected to be incorporated into the EEA by the end of 2025, and might thus also have some effects for Norway's forests: by tightening sustainability criteria for forest biomass used for bioenergy and raising the share of renewables in heating and electricity, it is likely to increase demand for wood-based fuel while simultaneously imposing somewhat stricter requirements on harvest practices, sourcing transparency, and carbon accounting under LULUCF. Information about Norway implementing RED III is still limited.

EU DR (EU Deforestation Regulation)
The EU Deforestation Regulation (EUDR), although primarily directed at imports into the EU, will be incorporated into the EEA Agreement, as was the case with the earlier EU Timber Regulation. For the Norwegian forest sector this means that compliance obligations will extend beyond existing certification schemes, requiring the systematic provision of geolocation data at polygon level for all harvesting sites destined for the EU market. Even though Norway is expected to be classified as a low-risk country, with little or no actual deforestation pressure, the Regulation nevertheless demands full traceability and due diligence reporting for each consignment. This will impose additional administrative and financial burdens, particularly on smaller forest owners and enterprises that may lack the digital infrastructure to deliver the required documentation. Larger operators, already integrated into PEFC or FSC systems, are better positioned but will still need to upgrade their procedures to ensure alignment with the Regulation's strict geospatial and reporting requirements. The Norwegian authorities will in turn need to establish a competent enforcement body once the Regulation is formally incorporated into EEA law, a process that is currently under consideration but not yet completed. While these changes may initially increase transaction costs, they also present an opportunity: by demonstrating robust compliance in a jurisdiction already characterised by sustainable management and high certification levels, Norwegian timber and wood products may consolidate a competitive advantage on the EU market. The European Commission has proposed to postpone the implementation for small enterprises by another year, i.e. until December 2026, while larger companies may use the first half of 2026 to calibrate the systems needed.

5.4 National Climate Policy and Private Initiatives

Norway's domestic climate policy framework is anchored by the Climate Change Act. This Act codifies the key targets, currently the 2030 target of at least 55% emission reduction and the 2050 vision of a low-emission society and establishes legal accountability for achieving them. Under the Act, the government must update interim targets at least every five years in line with the Paris Agreement cycles and regularly report progress. Accordingly, in 2025, the Act will be amended to include the new 2035 target (70–75% cut), following the Parliament's approval of Meld. St. 25 (2024-2025). By enshrining these goals in law, Norway ensures continuity of climate policy across governments and provides predictability for all sectors, including forestry.

The Climate Change Act also specifies that targets can be met via a mix of domestic action and international cooperation. In practice, this means Norway leverages EU trading mechanisms and credits but must still implement a suite of domestic measures to drive emissions cuts and carbon removals. A variety of policy instruments directly or indirectly influence the forest sector in this national context:

Forestry Legislation and Sustainable Management
The Forest Act requires sustainable forest management and includes a set of regulations and incentives. For example, after final felling, forest owners are obliged to regenerate the forest (normally within three years) to ensure continuous carbon sequestration and resource renewal. This legal mandate prevents overexploitation and helps maintain the carbon sink over time. In addition, forestry in Norway is, as mentioned several times in this report, governed by certification schemes, which impose further sustainability criteria. These include setting aside a portion of productive forest for

nature considerations (e.g. retention of biodiversity-rich habitat patches) – effectively a minimum conservation standard on private land. Through such regulations, Norway aims to secure both climate and environmental integrity in managed forests.

Protected Areas for Biodiversity

The government has committed to increasing the share of forest area under formal protection. Presently, about 5% of Norway's productive forest land is protected (mostly as nature reserves). Plans are in place to roughly double this to 10% in the coming years, a target initially adopted by Parliament in 2016 and reaffirmed as part of the 2022 GBF commitments. This expansion will most likely occur via the voluntary forest protection programme; wherein private owners offer areas for conservation in exchange for compensation. While raising the protected percentage to 10% (or more in the future) will restrict the area available for timber production, it is viewed as essential for halting biodiversity loss in forest ecosystems and contributing to the overall 30% land protection goal. Policymakers see this as a long-term investment: conserving old-growth and ecologically important forests preserves carbon stocks and resilience, and supports species that are part of healthy, climate-adapted forest systems. Notably, the nature action plan (Meld. St. 35 (2023-2024)) emphasises that enhanced protection, along with other effective area-based conservation measures, is needed to representatively conserve Norway's forest types and species. Thus, climate and nature policy are being pursued hand-in-hand – increased forest conservation is justified not only for biodiversity but also for strengthening natural carbon storage capacities.

Forestry Specific Economic Incentives

Norway employs various financial instruments to encourage climate-smart forestry. One long-standing tool is the Skogfond (Forest Trust Fund) scheme, under the Forest Act. In this programme, a portion of a forest owner's timber sale value (the forest owner decides between 4% and 40%) must be set aside in a fund that can only be used for approved forestry investments (replanting, tending, forest roads, and other activities related to climate-smart forestry), with 85% of contributions being tax-deductible. This mechanism, in effect, subsidises reinvestment in the forest and helps fund activities that enhance growth and carbon uptake (such as site preparation, planting improved seedlings, or thinning operations). In addition to Skogfond, the government provides grants for specific climate-related forestry measures – for example, subsidies for afforestation of abandoned land, restoration of drained peatlands to peatland (to curb CO_2 and N_2O emissions), and pilots for intensified regeneration and forest fertilisation to boost growth. These incentives are designed to increase the carbon sink while also supporting rural incomes.

Moreover, there are already private companies buying and selling carbon credits for extra carbon storage, in line with the EU's CRCF initiative mentioned in Section 5.3 above. Although not yet part of a well-developed and regulated carbon market, such efforts are stimulated by the expected rising social cost of carbon. Both the EU ETS carbon (quota) price (see Fig. 10) and the Norwegian carbon tax are expected to double between 2025 and 2030, from NOK 770 today to about 1500, and from NOK 1400 to about 2400 per t CO2, respectively (Sources: Prop. 1 LS (2024-25); BloombergNEF (2024); Morgan Stanley Research (2024); Reuters (2024)). This implies that the societal value of carbon sequestration in forests is already high and increasing at a fast rate.

This development is expected to continue post-2030, as underlined by Rørstad (2022b). The government's real CO_2-price path, rising 8% per year over 2030-2040, 4% in 2040-2060, and 3% in 2060-2090, implies that the present social value of carbon capture and storage already exceeds timber stumpage values, tilting the welfare optimum toward longer rotations.

Advisory and Extension Services

Finally, Norway invests in knowledge dissemination and capacity-building for climate-smart forestry. Research, education, and advisory services help translate policy goals into practice on the ground. For example, the Norwegian Institute of Bioeconomy (NIBIO) and the Forestry Extension Institute

(Skogkurs) develop guidelines on climate-adaptive silviculture, such as which tree provenances to plant under future climate scenarios or how to manage forests to reduce pest risks under warming conditions. Digital tools (like the Forestry Climate Calculator – offline autumn 2025) are offered to forest owners to estimate the carbon impacts of different management choices. By improving awareness and technical competence, these services ensure that forest owners are equipped to respond to evolving policies and can implement measures, ranging from nature-friendly logging techniques to carbon-oriented forest planning, that collectively advance Norway's climate and biodiversity objectives.

All these domestic measures form a policy mix that seeks to align forestry with climate-smart goals. They illustrate the approach of combining regulatory requirements, economic incentives, and knowledge support to encourage desired practices. On one hand, there are clear restrictions, e.g. limits on harvesting in protected or sensitive areas, obligations to regenerate, and pressure to reduce forestry's carbon footprint. On the other hand, there are opportunities and supports, funding for forest improvements, potential revenue from carbon credits, and a favourable market outlook for wood products in a carbon-constrained future.

For forest owners and industry, this means adapting management strategies to meet new expectations. Some may extend harvest ages or set aside more areas for conservation, while others might intensify management on suitable lands (using improved planting stock or fertilisation) to compensate for areas taken out of production. The interplay of policies requires navigating trade-offs: international agreements might imply actions that reduces the national carbon sink, while economic incentives encourage innovations that increase sequestration, storage substitution.

Main Interest Groups and their Opinions

Broadly, there is agreement in Norway's forest sector that sustainable forest management is important for both climate mitigation and ecological health. Virtually all stakeholders agree that forests can deliver climate benefits (through carbon storage and renewable materials) and that these benefits must be achieved in tandem with revenues and biodiversity conservation. However, differences in emphasis do exist. Forest sector organisations (such as NORSKOG, Norwegian Forest Owners' Federation, and Norwegian Timber Industry Association) tend to emphasise active management and the utilisation of forests for climate solutions. They highlight that increasing forest growth and timber use can contribute significantly to emissions cuts – for example, via wood products that store carbon and substitute for steel or concrete, or bioenergy that replaces fossil fuels. They typically also support incentives for increased long-term forest growth, and thus carbon sequestration and storage, e.g. in line with the additional 6.5 - 8 million tons CO_2 referred to in Meld. St. 13 (2020-2021). They also stress the importance of keeping conservation efforts voluntary and collaborative. For instance, industry and forest owners argue that expanding forest protections should proceed through the voluntary scheme with adequate compensation, rather than strict new compulsory regulations. Proposals for very strong protection (such as banning all old-growth logging) have met resistance because they would undermine trust and ongoing voluntary conservation efforts. In their view, Norwegian forestry is already on a path of continuous improvement in sustainability, and they caution that overly stringent constraints could reduce timber supply and hinder the sector's climate contributions.

On the other hand, environmental organisations (e.g. WWF Norway, SABIMA, Biofokus or Norwegian Society for the Conservation of Nature) emphasise the need for stronger conservation and ecological safeguards. Several of these groups adopt the Storaunet & Rolstad (2020) definition of natural forest, classifying any woodland uncut since around 1940 as "natural forest" or "old-growth forest", and argue that such forests harbour disproportionately high levels of biodiversity (including many red-listed species), store significant amounts of carbon both above and below ground, and serve as critical reference ecosystems for guiding sustainable forest management and restoration efforts. They point out that despite progress, only about 5 % of Norway's forests are strictly protected, and many old-growth forests remain unprotected. These groups advocate accelerating toward the 10 % forest protection target, and beyond, to ensure Norway meets its international biodiversity commitments (note that the forestry organisations and forest owner groups agree on 10% as long as it is voluntary and economically compensated).

They call for "real" protection – meaning not just quantity (area percentages) but also quality and representativeness of conserved forests. For example, the Norwegian Society for the Conservation of Nature argues that Norway should not count on paper protections or remote areas alone to fulfil the 30% goal; instead, more lowland and productive forests with high ecological value must be set aside to halt species loss. Environmental NGOs also urge changes in forestry practices across the landscape: better regulation of logging methods, retention of deadwood and older stands, and a precautionary approach to new interventions. They support the idea of a separate, additional climate goal for natural carbon storage (as WWF has proposed) so that increasing the land carbon sink is pursued forcefully in addition to cutting fossil emissions, not as a substitute. On this point, conservationists and forest owners find common ground; both agree that forest removals (carbon sequestration and storage) should complement, not replace, emissions cuts. But where environmental groups differ is in their willingness to accept short-term harvest reductions for long-term climate and biodiversity gains; they contend that meeting climate goals should not come at the cost of continued nature degradation, thus favouring measures like stricter harvest limits in old forests and stronger enforcement of environmental considerations during logging.

There is broad agreement on the overarching vision of "sustainable, CSF" that delivers multiple benefits. The debates centre on how best to balance the goals of carbon sequestration, timber production, and biodiversity conservation – essentially, on the optimal mix of utilisation and preservation. The ongoing policy development (with the 2035 Climate Plan still under parliamentary review and the Nature Action Plan entering implementation) provides an arena for these stakeholders to influence the details. Policymakers are attempting to steer a middle course: for example, by coupling any increase in forest conservation with support for the forest industry's transition to higher value-added wood products, or by ensuring that climate-related forest measures (like planting and fertilisation) are done in an ecologically considerate way. The end goal is a set of policies that most stakeholders can endorse, where Norway's forests are managed such that they remain a robust carbon sink, a source of renewable materials, and a reservoir of biodiversity over the long term. Achieving this balance through an inclusive policy framework is fundamental to the CSF approach outlined in this report.

Closing Remarks on CSF Policy

When designing climate policy for the forest sector, it is crucial to keep three ledgers in view at once:

1. The land ledger (forest carbon sequestration and storage);
2. The product ledger (harvested wood products tracked with default half-lives of 35 years for sawnwood, 25 years for panels and 2 years for paper);
3. The substitution ledger (the emissions avoided when wood replaces concrete, steel, plastics, fossil fuels or other products with a higher greenhouse gas footprint).

Only the first two appear explicitly in national and international GHG inventories (incl. LULUCF); substitution must be captured through life cycle carbon rules, product standards or carbon removal certificates such as the upcoming EU Carbon Removal Certification Framework (CRCF). A meta-analysis (Sathre & O'Connor, 2010) indicates an average of 3.9 t CO_2 saved per tonne of dry wood through material substitution, with substantial variation depending on product type and reference material. Thus, in order to store carbon for a longer time, policy should steer more pulpwood and residues into engineered timber, insulation, wood-based textile fibres and other durable goods, following a cascading hierarchy in which combustion is a last resort. Bio-energy, whether through direct combustion of wood or production of biofuels, can contribute to decarbonisation when it replaces high-carbon fossil fuels and is sourced sustainably (with no net loss of forest carbon or biodiversity).

5.5 Risk, Uncertainty, Multi-Scale Coordination, and Permanence of Incentives

Long-term investments in forestry are inherently subject to risk and uncertainty (Section 2.4.2), from climatic shifts and natural disturbances to market price volatility and policy changes. Effective CSF policies, therefore, need to be both robust (providing stability and confidence) and flexible (able to adapt to unforeseen changes). Several considerations are important:

Risk and Uncertainty Management

As described in Section 2.4.2, forestry decisions often face Knightian uncertainty (unknown probabilities or even unknown outcomes) and require dealing with future conditions that are difficult to predict. Trees planted today will grow over decades, during which climate and economic conditions may change significantly. This calls for adaptive management in policy design. One approach is to implement flexible, long-term financial instruments that account for uncertainty in discount rates and allow adjustments as new information arises. For example, the state could offer insurance or guarantee schemes for carbon storage: if a storm or pest outbreak reverses sequestration gains, policies might share that risk by not penalising the owner (or by providing recovery funds). Likewise, revolving funds or bonds for carbon farming could be structured with adjustable terms if expected carbon prices or growth rates shift. The key is that stability and adaptability are balanced. Forest owners need confidence that if they invest in climate-smart practices (like longer rotations or novel silviculture), supportive policies and incentives will endure; yet policies must also be able to evolve in response to new science or outcomes. An example is the use of sunset clauses or periodic reviews for subsidy programmes – this ensures that incentives remain aligned with current conditions and do not become counterproductive under altered circumstances. In sum, managing risk in CSF means providing tools to reduce downside uncertainty (e.g. insurance against fire or pest loss, as explored in Section 2.4.2) and maintaining the ability to revise strategies as climate and markets develop.

Stable yet Flexible Incentives

Building on the above, incentives must be credible over the long term but avoid creating complacency. If a subsidy or carbon payment is expected to last indefinitely, some owners might delay action, preferring to wait and see or to time their activities for maximum benefit. For instance, if there is an open-ended subsidy for harvesting in difficult terrain, owners might postpone harvests in hopes of higher subsidies later (or simply because there is no urgency). On the other hand, if incentives are too short-lived or uncertain, owners may not invest at all, fearing the rug could be pulled out from under a long-term project. Policymakers may mitigate these issues by clearly communicating the duration and trajectory of incentives. One strategy is to use declining incentives: for example, a payment for carbon sequestration that gradually reduces over 20 years may motivate early action (to capture the higher initial payments) while still providing some long-term support. Another strategy is to have "last-chance" deadlines: when an expiration date is announced for a subsidy, there is often a flurry of uptake before the deadline. This may be harnessed to accelerate the implementation of practices that otherwise move slowly. Ultimately, ensuring credibility (that promised incentives will be honoured and not suddenly withdrawn) is as important as the monetary value of the incentive. Forestry requires long planning horizons; therefore, maintaining broad political support for core CSF programmes (so that they survive election cycles) and embedding them in legal frameworks (so that beneficiaries trust their longevity) are measures to reduce perceived policy risk.

Multi-Scale Coordination

Risk management in forestry requires action at multiple governance levels. No single forest owner can fully address systemic risks such as climate change or landscape-level disturbances on their own. Therefore, policy frameworks must enable, and in some cases require, coordination across spatial and administrative scales, including stand, landscape, regional, and national levels. To achieve this, policies should facilitate cooperation among both private and public forest owners and forest owner associations. For instance, regional forest plans may be used to coordinate fuel-reduction thinnings across multiple properties, thereby reducing wildfire risk more effectively than isolated efforts. Similarly, basin-level planning can time harvests and restoration activities to avoid cumulative impacts on water flow and quality.

In Norway, municipalities and counties have important responsibilities for spatial planning, and these local governance levels may serve as key arenas for integrating forest-related climate risk into broader land-use strategies. Aligning local forestry operations with national climate adaptation goals requires that planning instruments explicitly account for landscape-scale risks and synergies.

A CSF approach supports the use of collaborative models such as landscape partnerships or cluster-based initiatives (as discussed in Section 3), where groups of forest owners work together toward shared climate objectives. These efforts should be supported by public programmes that provide technical guidance and financial incentives for collective action. In this way, policy not only recognises the limitations of individual actors but also creates the institutional conditions necessary for effective, coordinated responses to systemic forest risks.

5.6 Institutional Framework and Regulatory Constraints on Practical Forestry

While policy instruments aim to encourage CSF, practical operations in Norway are also governed by a complex institutional framework of laws and regulations. These set important constraints on how, when, and where forestry can occur, often to safeguard environmental and social values. Below is an overview of key public authorities and legal frameworks shaping Norwegian forestry, along with their implications for day-to-day management:

Norwegian Agriculture Agency
Legal basis: Forest Act. Role: National oversight and coordination of forest policy enforcement. Practical constraints: This agency issues detailed regulations and guidelines under the Forest Act. For example, it enforces reforestation obligations: after a clear-cut, an owner must regenerate the forest (normally within three years) or face orders and penalties. As previously mentioned, the follow-up in this area should be strengthened. It also sets technical norms (e.g. acceptable harvesting methods, road construction standards) and ensures consistency across municipalities. If a forest owner were to harvest unsustainably (such as repeated over-cutting without regeneration), the agency can intervene to halt operations. In essence, the Agriculture Agency provides the top-down authority to uphold sustainable forest management practices, which in turn supports the long-term carbon sink.

Municipal Forestry Authorities
Legal basis: Forest Act. Role: Local (municipal) implementation of forestry law. Practical constraints: The municipalities have (alone or in cooperation with other municipalities) a forestry authority that monitors logging activities on the ground. Municipal authorities inspect sites post-harvest to verify successful regeneration; if an owner fails to take action to establish a new stand, the municipality can issue a formal order or even carry out replanting at the owner's expense. They approve forest road construction, assessing factors like erosion risk or impacts on sensitive habitats. Through these powers, local authorities ensure that forestry conforms to legal standards and local land-use considerations. From a forest owner's perspective, this means additional steps and occasional restrictions – a necessary process to balance private forestry uses with public environmental interests.

Norwegian Environment Agency
Legal basis: Nature Diversity Act and associated regulations. Role: National authority for biodiversity and environmental protection. Practical constraints: This agency (often via the County Governor's environmental department) can impose restrictions on forestry to protect wildlife, habitats, and ecosystems. For example, if a planned logging area includes a known nesting site of an endangered bird or a registered key biotope (regulated through certification), forestry can be seasonally restricted or entirely prohibited there. The Nature Diversity Act's precautionary principle means that if there is

uncertainty about potential serious damage to biodiversity, the burden of proof falls on the forest operation to show it will not cause harm. Certain habitat types (like peatland, old-growth patches, or ravines) may be designated as requiring special care, effectively forbidding clear-cutting or road building in those areas. Moreover, any activity that could significantly alter an ecosystem may trigger an environmental review. In practice, this framework ensures that Norway's push for increased timber or carbon uptake does not override critical nature considerations. It does, however, add complexity to forest management. Detailed environmental assessments are sometimes needed, and parts of a property might be off-limits to harvest to preserve ecological values. Under the new nature action plan, we may expect even stronger implementation of these measures, such as more systematic surveying of biodiversity before logging and expanded mapping of key habitats that must be left intact.

An ongoing consultation by the Norwegian Environment Agency proposes new Planning and Building Act rules that would restrict/forbid development on peatlands; if adopted, this could affect permanent forest roads, landings, and other forestry infrastructure.

Directorate for Cultural Heritage
Legal basis: Cultural Heritage Act. Role: Protection of archaeological and historical sites. Practical constraints: Forests in Norway often hide cultural heritage (stone age sites, old Sami settlements, charcoal kilns, etc.). The law strictly forbids damaging protected monuments, and this applies to forestry operations. If an owner plans a logging road or a clear-cut, they must ensure no known cultural sites are affected – typically this is checked via databases before approval. Even unknown sites that are discovered during forestry work trigger an immediate stop in operations until authorities evaluate the find. Infractions may lead to substantial fines. This means forest owners have to incorporate heritage considerations into planning, sometimes altering road routes or harvest boundaries to avoid interfering with historical sites. Although such constraints don't directly relate to climate, they are part of the holistic management environment and reflect society's expectation that forestry respects not just nature but also cultural legacy.

Norwegian Mapping Authority
Legal basis: Cadastre Act. Role: Maintaining property boundaries and land-use records. Practical constraints: Clear property boundaries are crucial for managing and monitoring forest use. The Mapping Authority delivers information so that forest operations occur within one's land and do not encroach on others' property or protected public land. While this is generally not a contentious issue, in some forest areas, unclear boundaries may lead to disputes or inadvertent logging across lines. There are requirements to have boundaries marked and, in some cases, surveyed before large-scale operations. Additionally, any land-use change (e.g., converting forest to another use) must be properly registered. This primarily administrative framework supports the enforcement of all other regulations by clarifying where they apply.

County Governor
Legal basis: Various (Forest Act, Nature Diversity Act, Planning and Building Act). Role: Regional authority that often serves as an intermediary between national policies and local implementation. Practical constraints: The County Governor's office often reviews large or controversial forestry cases (like disputes over environmental protection versus timber rights) and can uphold or override municipal decisions. They ensure that national policy goals (climate targets, biodiversity commitments) are being considered at the local level. They may also coordinate inter-municipal forest initiatives and handle appeals. For a forest owner, the County Governor is typically the appellate body if one disagrees with a municipal restriction. The presence of this institutional layer means that important decisions – e.g., designation of a new protected area on private forest – involve a thorough process and adherence to national guidelines.

PEFC Norway (Programme for the Endorsement of Forest Certification)
Legal basis: Voluntary certification scheme but widely adopted (almost all forest owners). Main role: Defines standards for sustainable forest management in certified forests. Practical constraints:

- Imposes stricter environmental rules than the Forest Act alone, such as:
  - Minimum set-aside areas (5%) for conservation and biodiversity.
  - Limits on clear-cut size, often lower than legal maximums.
  - Buffer zones along water bodies and cultural monuments.
  - Detailed operational guidelines for soil protection, rutting, and road construction.
- Prohibits certain chemicals and practices (e.g., no GMO trees, restrictions on pesticide use).
- Requires documentation and audits: forest owners must keep records of planning, harvests, and environmental measures.
- Group certification system: Most forest owners are certified through forest owner associations and must comply to stay in the group.

While certification is technically voluntary, it is functionally mandatory for forest owners who wish to:

- Sell timber to the main Norwegian processors and exporters.
- Participate in certified timber markets.
- Retain membership in forest owner cooperatives.

FSC Norway (Forest Stewardship Council)
Legal basis: Voluntary global certification scheme, implemented in Norway via the Norwegian FSC National Forest Stewardship Standard. Main role: Specifies ten global Principles and 56 Criteria for responsible forest management, with a strong emphasis on environmental integrity, Indigenous and community rights, and full chain-of-custody transparency. Practical constraints:

- Mandatory identification and protection of High Conservation Value Forests (HCVF) and prohibition of natural-forest conversion.
- Requirement for Free, Prior and Informed Consent (FPIC) of Indigenous Peoples and robust stakeholder-consultation processes.
- Detailed chain-of-custody documentation from stump to final product, including third-party audits.
- Strict social criteria covering labour rights, health & safety, and community relations.
- Continuous-improvement mechanism: non-conformities trigger corrective-action plans and follow-up audits.
- Available to individual and group certificates (including SLIMF for small/low-intensity owners).
- Use of FSC labels ("FSC 100%," "FSC Mix," "FSC Recycled") for premium market access and zero-deforestation commitments.

As with PEFC, FSC certification requires forest owners to document planning, harvests, and environmental/social measures, and to undergo periodic surveillance and recertification audits. While PEFC underpins the vast majority of Norwegian certification, FSC offers a complementary pathway with stronger conservation and social-safeguard criteria, favoured in many export and niche markets. For this report, we assume that either certification provides a solid sustainability baseline on which to build the additional Climate-Smart Forestry measures.

As such, PEFC and FSC shape day-to-day forest operations and chain of custody as much as, or more than, public regulation in many areas.

6 Policy Narratives

In this section, we introduce seven stylised policy narratives. Each narrative intentionally emphasises one policy goal (or a closely related set of goals). Although none of them is likely to dominate future forest policy on its own, examining them side by side helps to reveal the multiple synergies and trade-offs inherent in CSF. In that sense, each narrative serves as a lens through which we can evaluate how different measures, described at the stand, property, and larger spatial scales (Sections 3.1–3.3), may advance or hinder specific objectives. None of the narratives is "better" in an absolute sense; each aligns with different stakeholder priorities, risk attitudes, policy instruments, and market conditions.

An overview of the narratives is given in Table 8. It sets out with the three common dimensions of sustainability (Economic, Environmental and Social) and then follow Sustainable Forest Ecosystem Services Management (a merger of Sustainable Forest Management and Forest Ecosystem Services), Climate Mitigation, Climate Adaptation, and, finally, Decarbonising the Economy (Circular Bioeconomy). All these are of relevance to the CSF concept.

Table 8. Stylised Policy Narratives.

Narrative	Priority	Synergies	Trade-Offs
Economic Management	Optimise harvest ages, species, and harvest timing for profit (NPV)	Can provide some carbon substitution if market incentives align	Often, low harvest ages & intensive methods reduce in-forest carbon storage and biodiversity values
Environmental Management	Conserve and enhance ecological integrity and biodiversity while maintaining ecosystem processes	Promotes natural resilience and improves in-forest carbon storage through ecosystem restoration and conservation measures	Reduces NPV, requiring trade-offs between conservation, roundwood production and CO_2-sequestration
Social Management	Prioritise community well-being, equitable access to forest benefits, and the preservation of cultural values	Enhances stakeholder engagement and builds social sustainability through community-led forest initiatives	A strong focus on social outcomes will typically conflict with profit (NPV) but may also create income in certain cases
Sustainable Forest Ecosystem Services Management	Balance economic, environmental, and social objectives for the long-term health of forests	Integrates multiple objectives to build robust and resilient forest systems with improved multifunctionality	Balancing diverse goals may mean compromising on NPV or carbon storage in the short run
Maximising Climate Mitigation	Enhance forest carbon sequestration and storage through management practices that extend harvest ages, promote high-yielding (biomass) species, and improve HWP use	Maximised carbon sequestration and storage can strengthen market-based climate incentives and contribute significantly to national mitigation targets	Overly aggressive strategies may reduce stand diversity and ecological resilience, potentially increasing vulnerability to pests and disturbances and decreasing NPV. Harvest ages that maximise

			biological production reduce NPV
Maximising Climate Adaptation	Build adaptive capacity by selecting resilient species, diversifying age classes, and incorporating adaptive silvicultural practices to cope with long-term climatic shifts	Enhanced adaptation measures can improve overall forest stability and maintain forest ecosystem services under changing conditions	Adaptation strategies may lead to lower maximum biomass accumulation and require higher management complexity and thus costs, in total also reducing NPV
Decarbonising the Economy (Circular Bioeconomy)	Substitute fossil-based materials with long-lived wood products	Aligned with industrial demand, long-lived HWPs extend carbon storage	Overharvesting can deplete the forest carbon sink, and may conflict with biodiversity if not carefully managed

6.1 Economic Management

Core Objective: Maximise financial returns from forestry (NPV) by aligning management practices with market conditions, operational costs, and risk considerations. This economically driven perspective builds upon intensive silvicultural practices (see Section 3.1 for stand-level management aimed at maximising NPV).

Figure 11. Illustration of a stylised policy narrative for Economic Management.

Principal Approach:

- **Optimise Species and Site Use:** Favour high-yield, high-value species matched to site conditions (e.g. planting spruce on fertile sites, pine on drier or poorer soils) to capitalise on growth potential and market demand.
- **Harvest age for Profit:** Choose harvest ages that maximize net present value (NPV), which means harvesting at the economically optimal rotation age, shorter than the biological maximum age for mean annual biomass increment (section 3.1.1.4).
  Profit-Driven Thinning: Carry out thinning only if it is economically profitable (section 3.1.1.3). In some cases, thinning can improve the overall profitability of a stand by utilizing the value of small-diameter timber and by enhancing the growth and quality of the remaining trees, thereby increasing the total economic return of the stand.
  Rapid Salvage Logging: In the event of disturbances (windthrow, pest outbreaks), act quickly with salvage or sanitary logging (Section 3.2.2) to recover merchantable roundwood and prevent further losses (e.g. removing beetle-infested wood before the infestation spreads).
- **Risk Management Strategies:** Incorporate risk and uncertainty into planning (Section 2.4.2). On high-risk sites, adjust species mix or shorten harvest ages to avoid major loss; alternatively, use insurance or cooperative agreements to spread risk across multiple owners or a wider area. This ensures that profit maximisation does not come at the expense of unacceptable individual risk exposure.

Synergies:

- **Risk-Responsive Resilience:** An economically driven regime may still enhance resilience if the risk is factored in. For example, owners focused on maximising NPV will lower harvest ages or diversify species in areas prone to storm or pest damage (Sections 3.1.1.5, 3.3.2). Diversifying species will improve disturbance resilience while preserving NPV.
- **Bioeconomy Alignment:** Strong financial performance in forestry supports the broader bioeconomy. Profitable operations ensure a steady supply of roundwood to industries, feeding high-value wood product markets (Chapter 4). For instance, quality sawlogs may go into construction, which not only yields good prices for owners but also provides long-term storage of carbon in buildings. Thus, economic optimisation may align with climate mitigation if policy incentives (like carbon credits for long-lived wood products) are in place.

Trade-Offs:

- **Carbon Stocks:** Harvesting at the point of maximum economic return often means cutting trees younger and more often than the carbon-maximising strategy. This reduces the average carbon stock in forests compared to higher harvest ages (cf. section 3.1.1.4; Tables 4–5 for yield vs. carbon trade-offs). In pursuing profit, some potential carbon sequestration is forfeited.
- **Biodiversity and Structure:** Intensive management for profit may simplify forest structure. Monocultures or even-aged stands of the most profitable species (often spruce) may crowd out broadleaf trees and reduce deadwood, lowering habitat diversity. Certain wildlife and understorey plant species dependent on mixed or old-growth conditions may decline (cf. Section 3.2.5 for biodiversity-friendly practices that might need to be forgone). This narrative challenges the certification rules.
- **Policy Constraints:** National climate commitments (e.g. Norway's LULUCF obligations; Chapter 5) might restrict unfettered profit-driven harvesting. If many owners lower harvest ages simultaneously, and thus intensify harvests, the aggregate drop-in carbon sink could conflict with policy targets. This may force regulations or require economic instruments (carbon taxes, subsidies, cf. Section 5.3) to balance private profit goals with public climate objectives.

6.2 Ecology and Biodiversity

Core Objective: Conserve and enhance the forest's ecological integrity and biodiversity while maintaining essential ecosystem processes and functions over the long term. Its emphasis on ecological outcomes aligns with adaptive management for biodiversity (see Section 3.2.5 for measures that prioritise habitat conservation within forest management).

Figure 12. Illustration of a stylised policy narrative for Ecology and Biodiversity.

Principal Approach:

- Expand protected areas and set aside high-ecological-value forests (e.g. old-growth stands, key habitats) through landscape zoning (Section 3.3.1) to preserve biodiversity hotspots and allow natural processes to unfold with minimal interference.
- Extend longer rotations in areas under RF (Section 3.1.1.4), promote natural regeneration and mixed-species stands (including more broadleaves) to mimic natural forest structure and dynamics.
- Enhance habitat quality via active restoration: retain deadwood and veteran trees, re-wet drained peatlands, and protect riparian buffers to support species diversity, nutrient cycling, and water regulation (Sections 3.2.5–3.2.6).
- Limit intensive interventions that disrupt ecosystem processes, for example, avoid clear-cutting large areas, reduce soil compaction by harvesting in winter or on stable soils, and no use of chemical inputs, ensuring that necessary management (thinning, final harvest) is done in an ecologically sensitive manner.

Synergies:

- **Resilient Ecosystems:** Biodiversity-focused management builds natural resilience. Diverse, structurally complex forests might be better able to withstand pests, diseases, and extreme weather, thereby securing forest ecosystem services under climate change (paralleling the stability benefits noted in Section 3.1.1.5). In the long run, these intact forests continue to provide clean water, soil protection, and other services even as conditions change.
- **Carbon Co-Benefits:** Conservation and ecosystem restoration measures (such as encouraging old-growth characteristics and soil carbon retention) tend to increase in-forest carbon stocks in biomass and soils. This contributes to climate mitigation goals; the forest maintains a larger carbon pool, even though carbon is not the primary objective. Intact forests can sequester carbon over very long timeframes, complementing dedicated climate strategies.
- **Public and Policy Support:** Strong environmental stewardship aligns with international biodiversity targets and national conservation policies. It also enjoys broad public support, which may translate into funding or incentive programmes (Section 5.4), for instance, payments for forest ecosystem services or conservation grants that reward forest owners for protecting biodiversity.

Trade-Offs:

- **Reduced Roundwood Yield:** Prioritising ecological values typically means lower harvest levels. Extensive set-asides and low-intensity management result in reduced roundwood output and revenue. Forest owners will face lower NPV, and wood-based industries could see reduced raw material supply from these forests.
- **Opportunity Cost:** Emphasising conservation over production often requires financial trade-offs. Forest owners might need compensation or policy incentives (Section 5.4) to make up for lost income when shifting to less intensive practices. Without such support, there is tension between conservation goals and the economics of traditional forestry.
- **Limited Substitution Benefits:** By harvesting infrequently and conservatively, these narrative sacrifices contribution to HWP substitution effects. Roundwood volumes may be too low to replace fossil-intensive materials on a large scale, meaning society leans more on in-forest carbon storage than on wood use for climate mitigation. In essence, the climate benefit is high on the land (carbon retained in the ecosystem) but lower in terms of wood outputs for the bioeconomy.

6.3 Social Management

Core Objective: Prioritise community well-being in forest management, ensuring local stakeholders have equitable access to forest resources and benefits and that cultural values and traditions linked to forests are preserved. This social-oriented approach underlines the importance of cultural services (see Section 2.4.1.2 for background on recreation and tourism as key forest ecosystem services in Norway's forests).

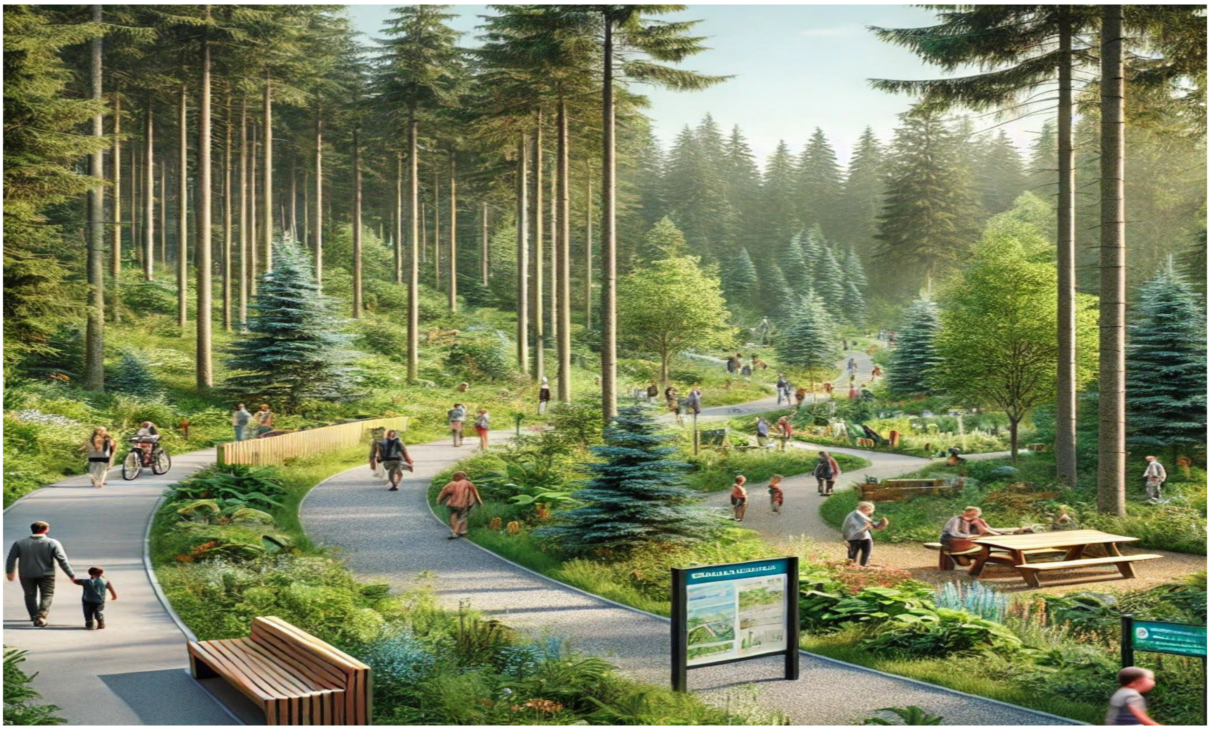

Figure 13. Illustration of a stylised policy narrative for Social Management.

Principal Approach:

- **Participatory Governance:** Involve local communities and stakeholders in decision-making and planning. For example, strengthen collaboration with such stakeholders in the forest management planning process and within forest owner associations, so that operational plans (harvest timing, buffer zones, trail planning) reflect local knowledge and priorities.
- **Equitable Benefit Sharing:** Design management regimes that distribute benefits fairly. This could include community forestry initiatives where local people, for example, can collect firewood. The Norwegian tradition of common access rights (Outdoor Recreation Act) or using hunting permits is a practical way to share benefits.
- **Preservation of Cultural Values:** Identify and protect sites of cultural, historical, or spiritual significance in the forest. Management plans should accommodate traditional land uses and safeguard landscape features that have cultural importance. Silvicultural operations are adjusted or restricted in these areas to maintain aesthetic and heritage values.
- **Multi-use and Education:** Promote forest uses that benefit the community at large, such as recreation, education, and tourism. Developing and maintaining hiking trails, gathering areas, and educational signage can make forests more accessible and valuable to the public.

Synergies:

- **Empowered Communities:** When local stakeholders are genuinely engaged and see tangible benefits, they are more likely to support sustainable forestry practices. Community-led initiatives, for example, a village managing a woodlot or a local volunteer group monitoring biodiversity, foster stewardship and social cohesion. This social capital may improve compliance with regulations and facilitate the implementation of practices that also benefit the environment (e.g. community agreement to set aside a riparian buffer for water quality).

- **Social Resilience:** A forest managed for community needs helps sustain rural livelihoods (through jobs, forest products, or tourism income) and preserves cultural traditions tied to the land. This builds social resilience: the community is economically and culturally invested in keeping the forest healthy for future generations. In turn, a socially resilient community is more likely to mobilise in support of forest conservation or restoration after disturbances.
- **Broad Support for Forestry:** Emphasising well-being and equity may increase public support for forestry initiatives. Policies or projects framed around local benefits, and cultural values tend to encounter less opposition. This synergy means other objectives (like restoration or climate measures) might be implemented more smoothly when wrapped in a social co-benefit context. Stakeholders see forests as delivering more than just roundwood or carbon, but as a community asset.
- Public health and recreation: Especially urban and peri-urban forests provide accessible green spaces that support physical and mental well-being. Increased tree cover in cities is associated with lower stress levels, reduced air pollution, and enhanced opportunities for exercise and social interaction.

Trade-Offs:

- **Lower Economic Efficiency:** Management for primarily social outcomes may conflict with profit maximisation. For instance, reserving areas for community recreation or traditional uses might reduce the land available for roundwood production. Likewise, employing more labour-intensive, small-scale harvesting to create local jobs is less economically efficient than mechanised, large-scale operations. In the short run, this dampens roundwood revenues and NPV for the owner. Forest owners may expect subsidies or public funding to cover the costs of community facilities or to compensate for income forgone by favouring social uses.
- **Management Complexity:** Balancing many social expectations (cultural preservation, and recreation) alongside ecological and economic goals makes planning and decision-making more complex. Reaching consensus among diverse stakeholders can be time-consuming, and conflicts may arise if, say, recreational users push for no harvesting while forest owners need income from roundwood. This necessitates strong facilitation and sometimes compromises on timing or methods of operations, potentially increasing administrative overhead.
- **Uncertain Carbon/Production Outcomes:** A social-first approach does not automatically optimise for carbon or roundwood. In some cases, it may indirectly aid in-forest carbon storage (if, say, less area is harvested to preserve scenery), but in others, it might limit climate mitigation efforts (for example, if preferences for certain traditional practices prevent the planting of higher biomass species). Similarly, roundwood production might take a back-seat. There is a risk that, without careful integration, other objectives (economic or climate) might underperform, meaning additional policy measures would be needed to meet overall targets for wood supply or carbon sequestration.

6.4 Sustainable Forest Ecosystem Services Management

Core Objective: Achieve a balanced integration of economic, environmental, and social objectives in forest management, ensuring the long-term health, productivity, and diversity of the forest. This scenario reflects an integrative management philosophy (see Section 2.4.3, which examines how to balance climate mitigation, adaptation, and other ecosystem services in unison).

Principal Approach:

- **Integrated Planning:** Develop management plans that give due weight to roundwood production, biodiversity conservation, and social values (like recreation). This often involves spatially and temporally explicit planning, for example, using a Triad approach (Section 3.3.1) where some areas are managed intensively for wood, some set aside for protection, and others managed in a mixed-use, moderate way. By planning at the landscape scale, synergies (such as using less productive areas for habitat and productive sites for roundwood) may be captured efficiently.
- **Best Practice Silviculture:** Apply a mix of silvicultural techniques aligned with sustainability criteria. For instance, productive sites use rotation forestry with environmental safeguards (e.g. retention of buffer strips, selective thinning to maintain structure), while sensitive sites employ close-to-nature forestry. Ensuring soil health, water quality, and regeneration success after harvest is key. Measures like e.g. controlled traffic to reduce soil compaction and protecting peatland (Section 3.2.6) are routinely included alongside roundwood-oriented practices.
- **Adaptive Management & Monitoring:** Because sustainable forest management and its closely related concept, forest ecosystem services, require balancing multiple values, continuous learning and adjustment are essential. Managers implement monitoring indicators for economic performance, biodiversity status, and ecosystem service provision (the MoniFun multifunctionality indicators in Section 3.2 may offer one such framework). Regular monitoring of carbon stocks, species composition, and possible revenue streams allows practices to be tweaked, for example, if revenues are declining, exploring new income streams like carbon credits (Section 5.6).
- **Diversified Revenues:** Encourage a variety of forest-derived incomes. In practice, this means supporting not just roundwood sales but also non-roundwood products (e.g. hunting leases), recreation or tourism (trail permits, guided tours), and payments for ecosystem services (carbon credits, and possibly emerging biodiversity credits). A diversified portfolio may make it economically feasible for the forest owner to sustain conservation and social efforts because they are compensated by other income, embodying a triple-bottom-line approach.

Synergies:

- **Robust & Resilient Systems:** Balancing ecological, economic, and social factors inherently promotes resilience. A forest managed for diversity (in uses and species) is less vulnerable to any single perturbation, e.g. a market downturn in roundwood may be cushioned by recreation income, or a pest outbreak in one species might have less impact if the forest is not a monoculture. This multi-faceted resilience means the forest may continue delivering benefits under a wider range of future conditions (market or climate).
- **Multifunctionality:** Sustainable management results in forests that provide multiple services simultaneously, often with mutual reinforcement. For instance, maintaining watershed quality (an environmental goal) also benefits local communities (clean water, less flooding) and may enhance the brand value of roundwood from that area (marketed as sustainably harvested). By integrating objectives, practices like selective harvest or extended harvest ages serve both production and conservation aims, increasing overall system efficiency (Section 2.4.3 discusses such joint production synergies).

- **Stakeholder Alignment:** A sustainable forest ecosystem services approach is more likely to gain broad support and meet regulatory standards. It aligns with the certification schemes and policy commitments, which may open access to premium markets and funding. Demonstrating a balance of interests, it also reduces conflict; industries may get a steady but moderated supply of wood, conservationists see biodiversity considerations met, and communities have their values respected. This alignment may make policy implementation (such as LULUCF measures or rural development programmes) more effective since they can build on a foundation of balanced management.

Trade-Offs:

- **No Maxima, -No "Jack of All Trades":** In pursuing all objectives, no single goal is maximised. Roundwood yields will not reach the theoretical maximum of an all-out economic strategy, and biodiversity will not be as high as in a strict preservation scenario. Carbon sequestration and storage, similarly, might be intermediate. This is an inherent compromise: each sector gives up a bit of potential benefit to achieve a broader overall outcome. Stakeholders focused on one outcome might view this as a shortfall (e.g., the roundwood industry noting lost volume or ecologists noting fewer pristine areas).
- **Complex Planning & Costs:** Balancing diverse goals requires more sophisticated management and potentially higher costs. Managers must conduct multi-criteria analysis, engage in stakeholder consultations, and perhaps invest in certification and monitoring. This complexity may increase administrative overhead and demand higher expertise. At small properties it may find it difficult to implement sustainable forest ecosystem services ideals on their own because of the required know-how and resources, potentially necessitating government support, cooperative management models, or advisory services.
- **Tension and Negotiation:** Even with a balanced approach, trade-offs will periodically surface sharply, for example, whether to log a valuable stand now for economic return or leave it longer for carbon sequestration/storage and habitat. Such decisions may lead to stakeholder tension. Continuous negotiation is needed, and there is a risk that without a long-term commitment, economic pressures or policy shifts could tilt the balance away from sustainability. In essence, sustainable forest ecosystem services is an ongoing process rather than a fixed endpoint, and it demands enduring commitment, which may waver if short-term needs start to dominate.

6.5 Maximising Climate Mitigation

Core Objective: Enhance and harness the forest's capacity to mitigate climate change by maximising carbon sequestration and storage in living biomass and soils, carbon storage in HWPs, and increased substitution. Prioritising carbon sequestration often entails silvicultural adjustments (for example, extended harvest ages – see Section 3.1.1.4 for how harvest age affects carbon storage in forests).

Principal Approach:

- **Extended Harvest ages:** Allow trees to grow longer and larger than conventional economic rotations (Section 3.1.1.4). By postponing the final harvest, stands accumulate greater biomass and thus store more carbon on site. Older, high-volume stands act as substantial carbon sinks.
- **High-Biomass Species:** Select species or provenances with fast growth and high tree density that are well-suited to the site (Section 3.1.1.1). On highly productive sites, this often means favouring Norway spruce. Ensure high initial planting densities and vigorous regeneration to capture site potential and consider silvicultural enhancements like genetic improvement or fertilisation (where environmentally acceptable) to boost growth rates. The goal is to maximise net primary production in the forest.
- **Silviculture for Volume:** Manage stands to optimise carbon accumulation. Thinnings, if used, must be light and only done when they increase overall volume growth or prevent natural

losses (Section 3.1.1.3). Otherwise, a "no-thinning" regime might be employed to keep maximum carbon standing until the final harvest. Protect forests from setbacks: implement pest monitoring and preventive measures (stump treatment for root rot, bark beetle surveillance) and carry out prompt salvage logging after disturbances (Section 3.2.2) to avoid decay emissions and recover carbon into products.

- **Harvest for Carbon Storage:** Shift the harvesting focus toward producing long-lived wood products. This means preferentially harvesting for sawlogs and veneer (larger diameter, high-quality wood) rather than pulp or energy wood. It may involve adjusting harvest techniques (e.g., cutting trees at ages or sizes optimal for construction roundwood). Coordination with industry (Chapter 4) may be key: ensure that when wood is harvested, it enters supply chains (like construction and furniture) that lock away carbon for decades. Encourage cascading use so that even residues end up in products or (possibly emerging) bioenergy with carbon capture and storage (BECCS), thereby minimising waste.
- **Afforestation and Reforestation:** Where feasible, expand forest area to increase the overall carbon sink. Establish new forests on former marginal lands, using species mixes that have high carbon sequestration potential. While this extends beyond stand management, it is a crucial part of a maximal mitigation strategy (tying in with land-use policy, cf. Chapter 5). Similarly, avoid deforestation or conversion of forest land, as maintaining continuous forest cover preserves the accumulated carbon stock.

Synergies:

- **Climate Policy Incentives:** A carbon-maximising strategy aligns strongly with climate policies. Forest owners implementing this narrative may benefit from carbon pricing mechanisms or subsidy schemes rewarding greenhouse gas removals (Section 5.4). Carbon credits may provide an additional revenue stream if the extra sequestration beyond business-as-usual (additionality) is recognised. At the national level, this approach may contribute significantly to meeting LULUCF targets and Paris Agreement commitments.
- **Bioeconomy Linkages:** By emphasising long-lived wood products, this narrative supports the broader bioeconomy and circular economy goals. High-volume growth coupled with targeted harvesting for durable goods means more renewable materials to replace steel, concrete, or plastics. It ensures that increased forest growth translates to climate mitigation beyond the forest boundaries (through substitution). In essence, forests managed for maximum mitigation become a backbone for climate-smart industries (construction roundwood, engineered wood), merging ecological carbon storage with economic value.
- **Long-Term Productivity:** Maintaining healthy, vigorous forests for carbon often coincides with practices that keep the land productive in the long run (good silviculture tends to preserve site quality). Soil conservation measures taken to protect carbon (like minimal soil disturbance and maintaining cover) also preserve site fertility and water, which can sustain roundwood yields for future rotations. Thus, although roundwood harvest is de-emphasised in the short run, the capacity of the land to produce biomass is maintained or improved, securing mitigation potential for future cycles as well.

Trade-Offs:

- **Biodiversity Constraints:** Managing forests as high-density, high-biomass carbon sinks may conflict with biodiversity objectives. Monocultures of fast-growing species or very dense equally-aged stands with little light reaching the understory provide less heterogeneous habitats. Species that require open conditions, deadwood, or diverse structures may decline. Additionally, ecological resilience might drop, and a forest optimised for carbon (often even-aged and uniform) may be more vulnerable to pests or windthrow (Section 3.1.1.5), which ironically could jeopardise the carbon stocks if a disturbance hits. This necessitates careful risk management (e.g., maybe a slight mix of species or strategic thinning) even in a carbon-centric regime.

- **Economic Risks and Delayed Returns:** Pushing harvest ages longer means deferring income. Forest owners carry the risk of a potential disturbance destroying accumulated wood value.
- **Site and Operational Limitations:** Not every site can be a productive carbon warehouse; harsh climates, poor soils, or steep terrain might not support much extra growth, even if harvest ages are extended. Furthermore, some intensive practices (like fertilisation or introducing exotic high-growth species) might raise environmental concerns beyond carbon (nutrient runoff, invasive risk) and face regulatory or public pushback. There is also a limit to how much carbon can be stored in a given area before growth tapers; after that point, delaying harvest yields diminishing returns in sequestration but increases risk. This narrative must carefully evaluate where the marginal carbon gains are truly worth it, and it may be complemented by adaptation measures to protect the accrued carbon, illustrating the tension between pure mitigation focus and the need to temper it for stability. Besides, more frequent operations when CCF is applied may negatively affect soil integrity and some ground-dwelling species. Forest road development should thus be planned to balance access and ecological preservation.

6.6 Maximising Climate Adaptation

Core Objective: Proactively adjust and equip forest ecosystems to withstand and thrive under future climate conditions, minimising the risks and adverse impacts from long-term climate change on forest health, productivity, and services. This resilience-focused strategy embodies adaptive management principles (see Section 2.4.2.1 for a discussion of flexibility and adaptive management in the face of climate uncertainty).

Principal Approach:

- **Climate-Smart Species Selection:** During regeneration and planting, favour tree species and provenances that are expected to perform well under projected future climates (Section 3.1.1.1). This includes introducing or favouring more drought-tolerant, heat-tolerant, or pest-resistant species/varieties. In Norway, for instance, this might mean blending in more pine or hardwoods on sites likely to get drier.
- **Diversify Stand Structures and Ages:** Increase both species diversity and age-class diversity as a hedge against uncertainty (Sections 3.1.1.1, 3.1.2). Instead of large, uniform stands, create irregular, mixed-species stands. Techniques include planting or encouraging the natural regeneration of a mix of conifers and broadleaves, maintaining some veteran trees during harvests, and using group selection or shelterwood cuts rather than clear-cuts. A diversity of age classes across the landscape ensures that not all stands are equally vulnerable to a given stress; younger cohorts might survive a pest that targets mature trees or vice versa.
- **Reduce Stand Density and Fuel Loads:** Especially in regions projected to face more drought, carefully manage stand density so that remaining trees have more water and nutrient resources in lean years. This might involve more frequent but lighter thinnings to keep competition in check (Section 3.1.1.3). In areas at risk of wildfire, reduce fuel loads by removing excess slash, conducting controlled burns, or favouring less flammable species. These practices improve individual tree vigour and lower the risk of catastrophic loss, enhancing overall adaptation.
- **Reinforce Ecosystem Protective Functions:** Take measures that bolster the forest's natural defences against climate stressors. For example, maintain and restore peatland and riparian zones to secure water availability during droughts and moderate microclimates (Section 3.2.6). Use genetic diversity in regeneration (mixing seed sources or planting stock) to increase the likelihood of some trees thriving under novel conditions. Ensure soil conservation (minimal erosion, rich organic matter) so the foundation for tree growth remains strong even as weather patterns shift. In pest-prone areas, diversify species and implement preventative silviculture

(like sanitation, thinning of diseased trees) to prevent climate-weakened stands from succumbing to infestations (Section 3.2.2).

- **Adaptive Planning & Monitoring:** Integrate climate model projections into forest planning (Section 3.3.2). Establish long-term monitoring plots to track growth, health, and regeneration under changing conditions. Adaptation is an ongoing process: as new information arises (e.g., a novel pest is established or a series of drought years hits), management guidelines are revised. This might include revisiting harvest ages, adjusting harvest schedules (perhaps harvesting earlier if mortality risk is rising), or updating planting schemes in a continuous feedback loop aimed at keeping the forest one step ahead of climate impacts.

Synergies:

- **Long-Term Forest Stability:** An adaptation-maximised forest is less likely to experience devastating die-off or loss. By reducing the risk of future damage (storms, pests, drought-induced decline), this narrative helps ensure continuous carbon sequestration and a steady flow of roundwood and other services over time. While it may sacrifice some growth in the short term (by not pushing sites to their monoculture maximum), over decades, it may yield greater cumulative production than a non-adapted forest that might suffer a severe disturbance event. In this way, strong adaptation measures may indirectly support mitigation and economic goals through risk avoidance.
- **Ecosystem Service Protection:** Many measures taken for adaptation (increasing tree diversity, protecting water bodies, maintaining cover) inherently support other forest ecosystem services. For example, a diverse, well-structured forest is also good for biodiversity (providing varied habitats) and for recreation (visually appealing, less often ravaged by pests or fire). Thus, this narrative aligns well with broader ecosystem service goals; it maintains recreation opportunities and aesthetic values (people are less likely to encounter large, clear-felled areas), and it safeguards water regulation by preventing large-scale disturbance that could disrupt hydrology. In essence, it future-proofs the provision of multiple benefits.
- **Cost Savings & Resilience:** Although adaptation measures can be costly upfront, they may save significant resources in the long run by avoiding disaster costs. A forest engineered for resilience might avoid the significant salvage and replanting costs that follow a bark beetle outbreak or windthrow disaster. Furthermore, stable forests mean communities and industries that depend on them (for tourism, wood, hunting, etc.) face less interruption, contributing to social and economic resilience in the region under climate change. This narrative often pairs well with insurance schemes or government programmes that recognise the value of proactive risk reduction.

Trade-Offs:

- **Lower Maximum Yield:** For instance, mixed-species stands will grow more slowly than a single fast-growing species chosen purely for volume. Also, maintaining lower densities or lower harvest ages in high-risk zones directly reduces the roundwood that could have grown if one gambled on no disturbances. Over a given rotation, the total biomass harvested may be less than in a non-adaptive “optimistic” scenario. This trade-off is essentially trading some volume potential for security.
- **Opportunity Costs for Carbon:** Some adaptation strategies, like thinning to reduce risk or harvesting a stand early before it “over-matures” into vulnerability, may decrease short-term carbon storage on the landscape relative to a no-action or mitigation-focused approach. While the intention is to prevent catastrophic carbon losses later, there is a near-term carbon cost to, say, keeping stands more open or not pushing harvest ages to the biological maximum. This could make it challenging to simultaneously meet aggressive carbon removal targets in the short run, policy frameworks might need to accommodate the fact that a slightly lower carbon sink now ensures a more sustainable sink in the future (a timing issue that carbon accounting must consider).

- **Increased Management Input:** A highly adaptive approach demands more frequent interventions, careful planning, and sometimes novel practices, which may increase management complexity and cost. Regular thinnings, diverse species procurement and planting, continuous monitoring, and the flexibility to change plans are management-intensive. Owners may face higher silvicultural expenses (for planting mixed stands, tending them, pest control, etc.) and will need greater knowledge or extension support. Without coordination or incentives (for example, cost-share programmes to implement adaptation measures), some owners could be hesitant to incur these additional costs purely for long-term benefits that are hard to quantify at present. The payback for adaptation investments is real but mostly realised in avoided future losses, which can be a difficult sell in the absence of clear policy or market signals.

6.7 Decarbonising the Economy (Circular Bioeconomy)

Core Objective: Maximise the forest sector's contribution to an economy-wide transition away from fossil fuels and materials by providing renewable, wood-based alternatives. This narrative prioritises producing high-value and long-lived wood products (and sustainable bioenergy) to support a circular, low-carbon economy. Achieving economy-wide decarbonisation hinges on efficient wood utilisation (see Section 4.2 for an examination of how wood products substitute for more carbon-intensive materials).

Principal Approach:

- **Boost Wood-based Product Supply Chains:** Invest in and strengthen domestic processing industries to make sure more of each harvested tree goes into long-lived, carbon-storing products. For example, expand capacities for engineered wood (beams, CLT panels for construction), wood-fibre insulation, bioplastics, and other innovative biomaterials. A reliable flow of quality roundwood from forests to mills is maintained so that wood can replace steel, concrete, plastics, and other products wherever feasible.
- **Promote Cascading Use of Biomass:** Encourage a utilisation hierarchy where wood is first used in the highest market value, longest-lasting applications, and then recycled or down-cycled before finally being used for energy. Such cascading use extends the carbon storage time in products and maximises the displacement of fossil-intensive materials (Chapter 4). For instance, a log might be sawn into building roundwood; later, off-cuts or end-of-life wood could become particleboard or pulp; only at the final stage is it burned for energy (ideally with carbon capture).
- **Integrate with Carbon Capture Technologies:** Provide incentives for synergy between forestry and (possibly) emerging carbon capture and storage/utilisation. This could involve dedicating a portion of forest output to bioenergy with carbon capture and storage (BECCS) facilities. Forest residues or energy plantations feed BECCS plants that generate heat or fuels while capturing CO_2. In practice, this links sustainable forest management with negative-emission technologies, ensuring that even when wood is used as an energy source, its emissions do not enter the atmosphere.
- **Collaborative Harvest Management:** To supply a growing bioeconomy without degrading the forest base, coordination among owners may be helpful. Management plans might maintain "correct" harvest ages, long enough to build volume and quality, but not so long as to secure industrial supply needs. Silvicultural techniques (like targeted thinning and pruning) should focus on producing high-quality sawlogs for long-lived products while still leaving enough residual biomass and deadwood to keep forests healthy and carbon-rich.

Synergies:

- **Climate Change Mitigation:** Using more wood in place of fossil-heavy materials and fuels has a dual benefit. First, harvested wood products (HWPs) store carbon externally, e.g. in buildings or furniture for decades, which is accounted for in carbon inventories (Section 4.1). Second, every ton of wood-based product that replaces cement, steel, or coal avoids the large emissions that would have been caused. This narrative thus links forest management with broader decarbonisation: Forests provide the raw material for emission reductions in other sectors, amplifying the climate impact beyond the forest boundaries.

- **Economic and Rural Development:** A circular bioeconomic approach may stimulate innovation, jobs, and income in rural and industrial sectors. By diversifying products (from lumber and paper to textiles, plastics alternatives, and energy), the forestry sector becomes more resilient to market swings. New value chains (like bio-chemicals, textiles, insulation or wood-based construction technology) create employment and encourage skills development in forestry communities. This synergy means climate-positive actions in the forest sector also support livelihoods and regional development goals, garnering broader political support for forest-based climate strategies.

Trade-Offs:

- **Intensive Management and Costs:** Producing a high volume of premium, long-lived wood products may demand more intensive forest management than conventional roundwood production. Practices such as high-density planting, frequent thinning and pruning, and extended harvest ages to grow large-diameter logs may raise management costs and complexity. These practices might not always align with profit maximisation (NPV), especially if policy incentives for low-carbon products (e.g. subsidies for construction roundwood or carbon payments for stored carbon in HWPs) are insufficient. Managers must balance the push for quality and volume with the risks (e.g. a high stand ages in the forest is exposed to more storm risk) and ensure the strategy remains economically viable.
- **Biodiversity Pressure:** An aggressive focus on roundwood and biomass output for the industry could lead to more homogenous forests (fewer species, less old-growth, increased share of even-aged stands) if not checked. Habitat features that don't directly contribute to production, like standing dead trees, mature forests, or certain keystone species, might be undervalued. Without deliberate safeguards (such as reserving conservation areas or integrating biodiversity-friendly practices per Section 3.2.5), the pursuit of a wood-based economy could conflict with biodiversity objectives. Ensuring that some areas or structural elements are left for nature is necessary to prevent long-term ecological degradation.
- **Sustainable Yield Limits:** A thriving bioeconomy increases demand for wood, which may tempt overharvesting. If forests are cut faster than they regrow (exceeding sustained yield), the forest carbon sink may weaken. This undermines the climate benefits CSF seeks to achieve. Strong governance and certification (Section 5.2 touches on regulating harvest levels) are needed to avoid jeopardising climate targets and to make sure "decarbonising the economy" with forests remains truly sustainable in the long run.

7 Advice and Recommendations from a Societal Perspective

From a societal perspective, climate-smart forestry is about managing the nation's forests in a way that contributes to achieving climate targets while also safeguarding other forest ecosystem services. The parliament (as the legislative authority) and public authorities (ministries, directorates, county governors, and municipalities as the executive authority) represent society and establish the framework for forest management. This framework must be designed so that it balances climate mitigation and adaptation, economic value creation, and biodiversity. The recommendations below are presented from such a societal perspective. They emphasise long-term thinking, climate mitigation, climate adaptation, and incentives for forest owners. Predictable framework conditions and respect for property rights are essential to motivate long-term investments in climate measures and climate adaptation.

A broad set of guidelines and policy instruments (legal, economic, and informational) already exists for regulating sustainable forestry. In addition, there are some instruments specifically targeting climate-smart forestry (such as fertilisation and denser planting). The following discussion should be read with this in mind, as the format does not allow for detailed treatment of each individual instrument.

7.1 Policy and International Frameworks

Recommendations for climate-smart forestry must be adapted to both national conditions and international obligations. Norway is committed under the UN Framework Convention on Climate Change (UNFCCC) and the Paris Agreement to report and reduce greenhouse gas emissions in all sectors, including land use, land-use change, and forestry (the LULUCF sector: Land Use, Land-Use Change and Forestry). Guidelines for climate-smart forestry must therefore be aligned with both these overarching international commitments and national targets. Norway's participation in the EU's LULUCF regulation means that changes in forest carbon stocks are included in the national climate accounting. The system is intended to stimulate increased carbon uptake and reduced emissions from land-use change, but the framework may also produce unintended consequences for a country like Norway, where forests have contributed substantial net carbon uptake over the past decades.

The LULUCF regulation measures changes in carbon uptake relative to a fixed reference level (FRL/NFRL) over a short reporting period. This means that even high net CO_2 uptake may appear as a "deficit" if uptake falls below the reference level. As a result, Norway may need to purchase credits even though the country's forests, in absolute terms, sequester far more carbon than those of most European countries. For climate-smart forestry, this creates unclear incentives: measures that increase long-term carbon uptake but fall outside the reporting window have limited effect on this climate account. The core problem is that the regulation is short-term in its temporal scope, whereas forestry operates with time horizons of 50–150 years. Many climate measures, such as species changes or improved regeneration, yield their greatest effects far beyond the LULUCF period. When such measures are not rewarded within the system's timeframe, the motivation to prioritise them is weakened.

Another issue is the risk of carbon leakage. If, for example, national restrictions on harvesting reduce the supply of timber in Norway, production and associated emissions may shift to other countries with weaker environmental standards. The global net effect may then be negative, even if national climate accounts show improvement.

To ensure that climate-smart forestry functions as intended, we therefore recommend the following:

- Emphasise measures with documented long-term climate benefits, even if they fall outside short-term reporting periods.
- Promote data-driven and transparent calculation methods so that carbon uptake and storage are measured more accurately and over longer time spans.

- Contribute to policy development that minimises carbon leakage by combining climate considerations with continued sustainable timber production.
- Ensure that national strategies for forestry and climate do not become limited to reporting obligations alone but support active and integrated management that strengthens carbon storage, substitution, value creation, and biodiversity.

7.2 Strengthened Compliance with Legal and Certification Requirements

A fundamental measure is to ensure better compliance with the requirements already established in legislation and through the forest sector's certification schemes. The Forestry Act includes, among other things, requirements for sustainable management and mandatory regeneration after harvesting, and certification standards (PEFC Norwegian Forest Standard or FSC) require the safeguarding of biodiversity through a wide range of specified measures.

It is a well-known fact that violations of the Forestry Act's regeneration requirements are quite wide-spread (see, for example, the report "Kartlegging av foryngelse og miljøhensyn ved hogst og skogkulturtiltak" published by Landbruksdirektoratet in 2024), and that such violations often have no practical consequences, resulting in reduced carbon uptake and storage. Authorities should therefore establish a more effective monitoring and enforcement system. This may include increased resources for forest inspection and municipal forest administration, enabling more harvested sites to be monitored. During inspections, it should be ensured that each harvested area meets minimum regeneration requirements within the deadline, and that environmental considerations such as buffer zones, retention trees, and key habitats are upheld.

Another concrete policy instrument that may be considered is a notification requirement for harvesting in selected cases. Currently, forest owners can in many cases begin harvesting without notifying the municipality, which limits the possibility for pre-harvest control. Authorities may consider introducing a limited notification requirement, for example in areas with vulnerable nature or where repeated legal violations have been documented. Such a notification system would enable the authorities to assess planned harvesting in advance and ensure that regeneration and environmental considerations are planned before operations are carried out. For a notification requirement to have the desired effect, it must be combined with clear guidelines for case processing and sufficient resources for municipalities.

7.3 Balancing Climate, Market-Oriented Value Creation, and Biodiversity

Climate-smart forestry requires that three main considerations are balanced: climate, market-oriented value creation, and biodiversity. A holistic approach is essential.

The climate dimension means that forests must be managed in ways that maximise their contribution to climate mitigation. This is achieved through carbon uptake during growth, carbon storage in the ecosystem, and by providing wood products that can substitute fossil-based materials. We recommend highlighting measures that increase carbon uptake, storage, and substitution, strengthen forest resilience against climate-related damage, and simultaneously safeguard other considerations to an adequate degree.

Economic considerations imply that forestry should be profitable for forest owners and contribute to employment and value creation in society. We recommend supporting an active forestry sector that supplies raw materials for industry and energy while fulfilling climate and environmental requirements. This requires clear priorities with room for flexibility: forest owners must be able to supply timber to industrial markets and manage forests for income, but within frameworks that ensure sustainability.

Biodiversity constitutes the third pillar. Rich biological diversity in forests is a value in itself and ensures the resilience of ecosystems. However, some climate mitigation and adaptation measures, as well as intensive forestry, may conflict with species diversity and ecological balance.

7.4 Climate Adaptation in More Detail

We recommend placing strong emphasis on climate adaptation that increases forest resilience to the impacts of climate change. Climate adaptation is also a societal responsibility and benefit, as resilient forests protect both environmental values and societal interests (such as protection against landslides and flooding, recreation, and timber production).

Some key strategies for climate adaptation in forestry that should be emphasised include:

- **Robust species and provenance selection:** During regeneration, emphasis must be placed on using tree species and planting material suited to the site and capable of thriving under future climate conditions. Guidance should be provided on which species are climate-adapted for different regions, based on research and climate projections.
- **Silviculture for stability:** Silvicultural measures that reduce vulnerability to windthrow, snow breakage, drought stress, and pests are recommended. Authorities may develop specific recommendations for stand density and silvicultural regimes that balance production and stability under various climate scenarios.
- **Monitoring and early warning:** As part of climate adaptation, systems should be established for improved monitoring of forest health, for example insect outbreaks, diseases, and drought damage, enabling rapid intervention. Authorities can also facilitate access for forest owners to updated information (for example via digital tools) on risks related to pests or extreme weather damage, as well as advice on what to do when such events occur. Guidelines should describe the division of responsibilities and emergency measures for such incidents.
- **Adaptation of infrastructure:** We recommend establishing guidance on how forest roads, operational systems, and logistics should be planned in a changing climate. Increased precipitation and more frequent heavy rainfall require roads and ditches to be dimensioned to handle greater water volumes and avoid erosion.
- **Afforestation:** This can provide increased carbon uptake and storage in the long term, particularly on suitable areas that were previously productive forest or that do not have high nature values. At the same time, afforestation on certain open areas, cultural landscapes, or peatlands can lead to significant biodiversity loss and reduced public acceptance. We therefore recommend that afforestation be supported where the climate effect is clearly positive, environmental conflicts are low, and the measure is part of long-term regional land-use plans. Guidelines for land-use prioritization and ecological assessment should be strengthened.
- **Forest land conversion (deforestation due to development):** This represents a permanent loss of carbon stocks, reduced future carbon uptake, and weakened ecosystem services. We recommend reducing the net conversion of forest land, particularly productive forest of high site quality, and ensuring that consequences for carbon, biodiversity, and hydrology are systematically assessed in land-use planning. Alternatives to forest conversion should be prioritized, including densification and the use of already converted areas.

7.5 Motivation and Policy Instruments for Forest Owners

For climate-smart guidelines, advice, and policy instruments to have real impact, forest owners must be motivated to follow them. They should therefore be designed and implemented with consideration for what drives forest owners to act. For example, the balance between “carrot and stick” in the choice of instruments should be assessed. Clear minimum requirements with a real risk of sanctions in cases of legal violations appear necessary.

Forest owners should take into account the current and expected impacts of climate change in their own management in order to safeguard their forests and the income derived from them. Climate adaptation to avoid forest damage is therefore largely a matter for the owners themselves. At the same time, society may wish to promote certain climate mitigation measures to increase carbon uptake and storage, measures that may, in isolation, reduce the profitability of individual forest owners. In such cases, and from a societal perspective, forest owners should be compensated for altered management practices, for example through subsidy schemes or tax instruments such as the Forest Trust Fund (skogfond).

Information and knowledge constitute another key factor. Many forest owners will make wise and sustainable choices if they understand the effects of different measures and see their benefits. Present forest management planning builds on an established system in which state and municipal actors, forest owner organisations, and professional inventory teams collaborate. Remote sensing, field inventories, and environmental mapping according to current standards ensure high data quality. Plans are usually updated every 10 to 15 years and can be expanded with functions for decision support, projections, and assessment of management options related to climate change.

We recommend the forest management plan to be used as the central tool for integrating climate-smart forestry into practical management at the property level. An updated plan provides a comprehensive and detailed overview of forest resources, including species composition, age, volume, site productivity, environmental values, and relevant restrictions. This offers a solid knowledge base for decisions in which climate, economic, and biodiversity considerations must be weighed against one another.

It is recommended that the authorities initiate a process to develop the forest management plan into an even more active decision-support tool in climate-related work. Such a plan should enable assessments of carbon sequestration and storage, identification of stands at risk (for example areas with increased susceptibility to windthrow, drought, or pests), planning of species selection, and adaptation of harvesting strategies. It should also integrate measures for biodiversity and hydrology and be linked to digital databases for continuous updates.

It is also important that guidelines and policy instruments are perceived as practical and easy to implement. If new requirements or routines are introduced (for example notification requirements or increased documentation demands), authorities should ensure that these are made as simple as possible for forest owners.

7.6 Summary List

Climate Mitigation

- Prioritise enforcement of existing regulations, strengthen inspections and reactions in cases where legal and certification requirements apply but are insufficiently followed in practice.
- Consider establishing a simple, risk-based pre-harvest notification system for major harvests in vulnerable areas to ensure that climate and environmental considerations are assessed before operations begin.
- Increase the use of the Forest Trust Fund and subsidies for measures with documented CO_2 benefits, such as regeneration, tending of young stands, and targeted fertilisation on suitable sites.
- Ensure access to data through national, open, and operational maps showing environmental values, harvesting activity, and regeneration status, enabling compliance and learning.

Climate Adaptation

- Integrate climate adaptation as an explicit requirement in plans and policy instruments (without duplicating certification requirements) and request documented measures that increase forest resilience.
- Establish a national early warning system for forest health risks, such as insects, diseases, drought stress, and fire danger, preferably linked to operational advice and emergency resources.
- Strengthen subsidy and compensation schemes for rapid recovery after damage (sanitary felling, planting, supplementary planting), so that carbon uptake and value creation can restart quickly.
- Adapt infrastructure requirements (roads, operating seasons, machinery use) to wetter winters and more extreme rainfall, in order to reduce damage and costs.
- Consider supporting measures across property boundaries (landscape level) to avoid landscape-scale vulnerability related to stand size, wind, snow, pests, and similar risk factors.

8 Advice and Recommendations from a Forest Owner Perspective

This chapter presents advice and recommendations for climate-smart forestry directed toward private forest owners and forest owner associations. The aim is to enable forest owners to integrate climate mitigation and climate adaptation into forest management while safeguarding economic returns and biodiversity. Particular emphasis is placed on the long-term perspective. Forest management today must plan for a changing climate and a changing society, with a long-time horizon. The recommenddations assume that forest owners comply with current laws and forest certification standards, which already provide the framework for sustainable forestry. Many of the proposals, perhaps most of them, therefore, reflect existing requirements. We emphasise the importance of improved practical follow-up in areas where such requirements are often neglected. In this way, forest owners can demonstrate responsibility and avoid the need for stricter regulations from the authorities.

8.1 Long-Term and Climate-Adaptive Planning

An updated forest management plan is potentially the most effective tool available to forest owners for integrating climate-smart forestry in practice. The forest management plan provides a systematic and spatially explicit overview of the forest resources on the property, including information on tree species, age, volume, site productivity, harvesting classes, and environmental values. This gives the forest owner a basis for assessing measures that safeguard climate, economics, and biodiversity. Forest management planning in Norway is based on an established governance system, in which state and municipal authorities, forest owner organisations, and professional inventory companies collaborate on data collection and plan production. Plans are normally prepared every 10 to 15 years, and public subsidies help make this economically feasible for individual owners.

The present forest management plan comprise few elements directly linked to climate change. A more climate change-oriented forest management plan may therefore provide a better foundation for climate adaptation and risk management by identifying stands that are particularly vulnerable to windthrow, snow breakage, drought, or pests, and make it possible to plan measures such as species mixtures, adjusted harvesting ages, choice of harvesting methods, and prioritisation of robust regeneration strategies. For forest owners and forest owner associations seeking targeted climate actions, such a plan provides a structure for identifying which measures will have the greatest effect.

The forest management plan may also function as a shared management tool for forest owner cooperatives. When several properties have plans based on the same methodology and datasets, it becomes easier to coordinate operations, plan road projects, manage disturbances, and ensure that environmental registrations are followed up in accordance with certification requirements. We therefore recommend that forest owners and forest owner cooperatives use the forest management plan actively as the basis for climate-adapted and sustainable management. An updated and well-utilised forest management plan will strengthen both forest growth and resilience while documenting responsible management to authorities, markets, and certification systems.

Generally, when considering forest management, prioritise long-term thinking, resilience, and risk management. Identify which stands are most exposed to the effects of climate change, such as shallow soils with wind-exposed forest, monocultures that may be heavily affected by insects and other pests, or areas with high fire risk. Develop strategies for these areas: this may involve spreading risk by varying species and age classes (avoiding a situation in which all forest reaches harvesting age simultaneously), or, in some stands, aiming for low regeneration density and avoiding heavy thinning late in the rotation, in order to reduce the risk of windthrow and snow breakage. Forest owners should also have preparedness plans for natural disturbances: how should a sudden bark beetle outbreak be handled, or the consequences of an extreme weather event? A good plan includes procedures for rapid clean-up and regeneration after damage so that values are not lost and damage is not exacerbated, for example by windthrown timber becoming breeding material for harmful insects.

8.2 Climate Mitigation: Increased Carbon Storage and Renewable Products

A core aim of climate-smart forestry is to increase the forest's uptake and storage of carbon. Forest owners should therefore aim to keep forests productive through continuous regeneration and good silviculture. The regeneration obligation requires satisfactory regeneration to be established no later than three years after final harvesting (preferably immediately). Unfortunately, many do not comply with this, which undermines both the forest's long-term productivity and its carbon uptake and storage. Forest owners must ensure planting or natural regeneration quickly after harvest and follow up with supplementary planting if needed. Use high-quality seed or planting material adapted to local conditions and consider expected climate changes when selecting species or provenance.

Increase growth through sustainable silvicultural measures. Forests that grow well take up more CO_2. Measures to increase productivity may therefore be relevant. In some cases, forest fertilisation may be a climate measure. Subsidy schemes exist for limited fertilisation on suitable sites where this provides increased net CO_2 uptake. Such measures must be implemented responsibly, avoiding over-fertilisation or use near watercourses, to prevent nutrient runoff. Certification standards also require that fertilisation be carried out in an environmentally sound manner.

Prioritise the production of durable and substituting wood products. From a climate perspective, it is desirable that as much harvested timber as possible is used for long-lived wood products such as construction timber, furniture, or other materials that substitute steel, concrete, or plastics. These products store carbon for long periods and replace more emission-intensive materials. Forest owners can contribute by producing high-quality timber, for example by letting the best stands grow somewhat longer (where the risk of damage allows), and by thinning where appropriate in ways that improve timber quality at final harvest. The result is a larger share of high-value sawlogs with a long lifespan. Less valuable assortments (pulpwood, energy wood) will always emerge as by-products; these also serve a climate function by being used for bio-based products or bioenergy. Forest owners should also pay attention to new opportunities: markets may emerge for biomass for negative emissions technologies, for example bioenergy with carbon capture and storage. If so, market conditions may shift in ways that influence the relative prices of various assortments, possibly including high-quality timber.

It is also important that some carbon remains on the harvested site in the form of dead wood and roots that decompose slowly. Leaving logging residues on site (in reasonable quantities) contributes to carbon storage in the soil and provides important habitat for insects and fungi, in line with certification requirements. At the same time, balance is essential: excessive amounts of slash can hinder regeneration and increase fire risk.

8.3 Climate Adaptation: Increased Resilience and Reduced Risk

Diversify the forest to spread risk. Climate adaptation is about making forests more resilient to extreme weather events, such as drought, wind, heavy rainfall, and wet snow that can cause forest damage, as well as changes in precipitation patterns and temperature. A key strategy is diversification. Avoid having only one tree species or even-aged monocultures over large areas. Mixed stands, for example pine and spruce together, or a proportion of broadleaved trees in coniferous stands, can make forests less vulnerable to species-specific damage such as insect attacks and disease. When clear-felling spruce stands on typical pine sites, it should be carefully assessed (spruce trees vulnerability to bark beetles and drought versus pine trees vulnerability to browsing) whether the area ought to be regenerated with pine. Different tree species and genetic variation increase the likelihood that part of the forest will tolerate new climate-related stressors. Also consider age distribution: a property where all stands are of similar age entails increased climate risk. For example, a storm may have especially severe impacts when many stands are old at the same time.

Adapt harvesting methods and silviculture to terrain and climate. In vulnerable areas, forest owners may consider alternative harvesting methods instead of clear-cutting. Close-to-nature methods such as selective cutting, group selection, or shelterwood systems leave more standing trees as windbreaks and seed trees, which may be advantageous in wind-exposed areas or where soils are prone to erosion. In steep terrain or near watercourses, more careful harvesting can reduce the risk of landslides and runoff, while allowing for easier regeneration. In cooler upland areas, closed harvesting systems may also protect young trees by moderating the microclimate. At the same time, the potentially positive effects of such methods must be weighed against lower harvest levels and reduced short-term production compared to clear-cutting.

Strengthen forest health through silvicultural routines. Good and frequent silviculture contributes to more resilient forests. For example, pre-commercial thinning in dense young stands helps strengthen stem development; trees that grow with appropriate spacing develop stronger root and stem structures and are better able to withstand wind and snow. During thinning, diseased or damaged trees can be removed, increasing resistance to pests. Consider the use of Rotstop (biological stump treatment against Heterobasidion root rot) during harvesting in vulnerable areas. This can prevent future rot and help maintain carbon storage capacity in standing forest. Promote species mixtures where possible through tending and thinning, for example by retaining some broadleaved trees in spruce stands. This provides both biodiversity benefits and climate adaptation advantages, as many broadleaved species are more resistant to storms.

Plan for rapid recovery after disturbances. Despite preventive measures, damage will occur from time to time. Effective routines for forest recovery are therefore essential. If storms cause windthrow or pests overwhelm a stand, the forest owner must quickly consider sanitary felling to salvage value and prevent further damage. Regeneration should follow without delay. Use the opportunity to establish a more climate-resilient forest if the previous stand proved vulnerable. For example, after large-scale windthrow in spruce, planting a mixture of spruce and pine may be appropriate. Make use of Forest Trust Fund (skogfond) resources and apply for subsidies where available, as some regions offer financial support for replanting after natural disturbances.

8.4 Balancing Climate Considerations, Economics, and Biodiversity

For forest owners, it is important to find a balance in which climate considerations and economic operations go hand in hand while safeguarding biodiversity. At the same time, rich biodiversity supports the long-term health and resilience of forests. The key is to integrate biodiversity considerations in ways that strengthen climate objectives and economic outcomes. Some recommendations:

Young growth tending. Provide necessary tending (density regulation/species selection) at early stages. This increases growth and carbon uptake. Young growth tending is a cost-effective climate measure. It also improves root development and stability, making forests more robust against wind, snow, drought, and pests.

Adapt species and regeneration. Choose one or several species and regeneration methods based on site conditions, climate, and expected markets. Matching species to site productivity ensures high growth, carbon uptake, and carbon storage.

Active silviculture and choice of harvesting time. Follow up stands throughout the rotation. Thin when needed to promote stable, vigorous trees. This can improve total long-term volume and value. Avoid stands that become too dense, increasing risks of insect outbreaks and storm damage, and avoid premature final felling which results in low volumes and reduced carbon uptake and storage. Plan harvests when trees have reached good dimensions and value, but before growth declines too much or the risk of damage becomes too high. Very low harvest ages and very intensive management may reduce carbon stocks unnecessarily and weaken biodiversity, whereas harvesting too late may increase the risk of rot and windthrow.

Prevention and management of forest damage. Climate change increases the risk of forest damage from wind, insects, and disease. Include risk assessments in management planning. In vulnerable areas, it may be appropriate to spread risk by diversifying species or reducing stand density. Monitor forests regularly and act quickly when damage occurs. For example, windthrow and bark beetle–infested stands should be salvaged as soon as possible. Rapid sanitary felling after storms or pest attacks preserves value and prevents further spread of damage. It also prevents carbon from being released as damaged timber decays. Ensure quick regeneration (natural or planting) after clearing damaged forest so that carbon uptake and timber production resume.

Use economic instruments. Make use of available support schemes and financial mechanisms that allow climate measures to be implemented without unnecessary loss of profitability. Public subsidies can cover part of the costs of, for example, denser planting, improved planting material, or soil preparation. Use Forest Trust Fund resources wherever applicable so investments in climate-friendly measures (young stand tending, supplementary planting, and similar) benefit from tax advantages. Investing today in climate adaptation and increased growth will pay off over time through higher quality and volume, while reducing future costs associated with forest damage. Cf. section 8.5 for the use of economic instruments.

Targeted land use and conservation. Plan land use on the property so that both production and biodiversity are considered. Identify areas with high nature value or low productivity (for example key habitats, steep slopes, wetlands) and leave these untouched or manage them carefully. Such small protected or conservation-oriented areas generally make up a minor share of the property and do not significantly reduce total harvestable volume. In return, important species and ecosystems are maintained, and these areas function as long-term carbon stores. On the remaining areas, more intensive and efficient management can be practised. Certification already requires consideration of key habitats and the retention of veteran trees; by fully implementing these requirements, forest owners safeguard biodiversity at minimal cost while old and dead trees contribute to carbon storage.

Varied forest structure and species mixtures. Strive for variation in the forest to improve resilience and increase biodiversity. Mixed stands with several species and age classes can reduce the risk of forest damage and provide habitat for a broader range of species. For example, including broadleaved trees in coniferous stands can limit the spread of certain harmful insects and offer alternative revenue sources (energy wood, specialty wood) without reducing production of spruce or pine. A varied forest is often better able to tolerate climate change and continue delivering timber and carbon storage under stress that homogeneous stands may not withstand. Where conditions permit, continuous cover forestry methods may also be used to maintain continuous forest cover.

Low-impact operations. Choose harvesting and management systems that minimise unnecessary damage to soil and water resources. Avoid rutting, erosion, and runoff by placing extraction trails where the ground is most stable and avoiding operations under very wet conditions. Careful terrain transport and good road planning not only protect the environment but also ensure that soils remain productive for future forest growth. This is essential for continuous carbon uptake and storage and for long-term economic performance. In general, low-impact forest operations build goodwill and improve the forest owner’s reputation.

8.5 Economic Instruments and Support Schemes for Climate-Smart Forestry

Use Forest Trust Fund resources and subsidies actively to finance climate measures. The Forest Trust Fund scheme is a unique opportunity for forest owners to allocate funds from timber sales tax-free (85 percent of the deposited amount) for reinvestment in the forest. By setting aside part of the timber revenue in a Forest Trust Fund account, capital is built up for future silvicultural, environmental, and climate-related measures. Costs for supplementary planting, soil scarification, young growth tending, maintenance of forest roads, and many other activities can be fully or partially covered through the

Forest Trust Fund with tax benefits. Other climate adaptation measures can also be financed through the scheme if they form part of silviculture.

Apply for public subsidies. Authorities offer several subsidy schemes to support sustainable and climate-smart forestry. These include, for example, subsidies for denser planting as a climate measure, where financial support is provided per hectare for planting slightly more densely on suitable sites to increase CO_2 uptake. Another example is subsidies for forest fertilisation aimed at climate benefits. There are also schemes for environmental measures and for forest management planning with environmental registration (where the state covers part of the cost of preparing or updating a forest management plan). Stay informed via the Norwegian Agriculture Agency or the County Governor in your region about active schemes and apply in due time.

Forest owners can today receive payment for storing carbon beyond the ordinary level in the voluntary carbon-credit market. Such schemes open up new opportunities but may also involve risks. You are encouraged to seek independent advice, for example from the forest owners' association, before entering into agreements on carbon compensation or similar arrangements.

Most active forest owners in Norway are today part of a certification scheme (PEFC or FSC through their forest owner cooperative or individual certification). Follow up the requirements actively, not only "on paper". Certification covers everything from planning, biodiversity, and cultural heritage to competence requirements for those carrying out work in the forest.

8.6 Competence, Cooperation, and Practical Responsibility

Stay updated on research and practical knowledge. Climate-smart forestry is interdisciplinary and dynamic and forest owners will benefit from continuously seeking new knowledge. Participate in courses (for example through Skogkurs or local forest owner associations), read professional journals, and follow advice from the Norwegian Agriculture Agency and others. New or increased occurrences of diseases or pests, such as bark beetles, or new technologies, such as drones for forest monitoring, may emerge. A forest owner who is willing to learn will be better positioned to adapt.

Cooperate with other forest owners and landscape actors. Climate challenges do not stop at property boundaries. Collaboration between neighbouring properties can often increase the effectiveness of measures and the efficiency of operations. A concrete example is coordinated harvesting planning: by communicating with neighbouring forest owners or through the cooperative, harvesting can be planned over a larger area to avoid, for example, large continuous clear-cut areas. Coordination can also apply to biodiversity considerations, such as wildlife corridors that cross property boundaries, where sequential harvesting and regeneration help ensure continuous cover in all parts of the corridor. In the face of insect outbreaks, cooperation is essential: harmful insects do not respect property boundaries, so control efforts should be coordinated across larger areas. Organise through forest owner associations or neighbours to share information quickly and implement joint measures when needed. Collaboration may also benefit from economies of scale in forest operations.

Communicate and be transparent about major harvests and measures. A common source of conflict between forest owners and society is a lack of information. Although there is usually no mandatory notification before harvesting (except in protection forests or where local regulations apply), it is still good practice to give notice before major interventions. Consider informing the municipality and any affected neighbours before planning a large clear-cut, especially in areas with high public use or vulnerable nature.

Strengthen documentation and self-monitoring. The Norwegian model for forestry is based on the principle of freedom with responsibility rather than detailed regulation by authorities. For this model to be sustainable, forest owners must fulfil this responsibility in practice. This means that as a forest owner, you should document that you comply with statutory requirements and certification obligations.

8.7 Summary List

Climate Mitigation

- Ensure rapid and adequate regeneration after harvesting (planting or natural regeneration, with supplementary planting if needed) and use the Forest Trust Fund actively to finance it.
- Choose planting material and tree species with an eye to future climate conditions; prioritise good planting density on suitable sites and active young stand tending for high growth and CO_2 uptake.
- Manage for quality: thin and tend stands to increase the proportion of sawlogs and deliver long-lived products that store carbon and substitute more emission-intensive materials.
- Leave some dead wood and veteran trees (this is already required in certification, but sometimes weakly implemented in practice).
- Monitor support schemes that can reduce the cost of climate-related investments.

Climate Adaptation

- Diversify risk: mix tree species where possible, avoid spruce on pine sites, ensure a good distribution of age classes across the property, and avoid large, even-aged monocultures that are vulnerable to wind and bark beetles.
- Adapt harvesting methods to site conditions and risk: consider continuous cover forestry methods where appropriate and use rotation forestry methods on the most suitable sites.
- Thin at the right time to strengthen stem and root stability, remove weak or diseased trees.
- Prepare for disturbances: in case of storm, fire, or insect attack, act quickly (sanitary felling, clean-up) and re-establish forest immediately using a more robust species mixture.
- Adapt operations to milder winters: avoid soil damage by operating on bearing surfaces or using lighter machinery where necessary.
- Cooperate with neighbours and cooperatives on roads, logistics, and joint pest control measures.
- Practise transparency in larger harvesting operations: voluntary advance notification to the municipality or neighbours can reveal local concerns before operations begin and thus avoid conflicts.
- Conduct self-monitoring and documentation: use checklists before, during, and after harvesting (regeneration, buffer zones, key habitats) to demonstrate that “freedom with responsibility” works in practice.

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10. Supplementary material

10.1. Treatment schedules

The treatment schedules apply to spruce-dominated forest areas growing on medium to high productivity sites (H_{40} = 11-26 m) and is a supplement and a specification for the analyses done in section 3.1.1.5.

Maximise carbon sequestration and storage
Regeneration phase: plant spruce with «recommended» density according to volume production. Young growth phase: keep «recommended» density according to volume production.
Production forest phase: no thinning but apply fertilisation.
Mature forest phase: clear-cut at optimal biological harvest age.

Maximise albedo
Regeneration phase: plant birch with a lower density than «recommended» according to maximum volume production.
Young growth phase: keep low density.
Production forest phase: apply thinning but no fertilisation.
Mature forest phase: clear-cut before economic harvest age.

Minimise bark beetle damages
Regeneration phase: plant mixed-species (spruce and pine) with an «recommended» density according to maximum volume production.
Young growth phase: keep «recommended» density according to maximum volume production. Production forest phase: do not apply thinning or fertilisation.
Mature forest phase: clear-cut before economic harvest age.

Minimise root rot damages
Regeneration phase: plant mixed-species (spruce and pine) with an «recommended» density according to maximum volume production.
Young forest phase: keep «recommended» density according to maximum volume production. Production forest phase: do not apply thinning or fertilisation.
Mature forest phase: clear-cut at before economic harvest age.

Minimise wind damages
Regeneration phase: plant mixed-species (spruce, pine) with a lower density than «recommended» according to maximum volume production.
Young growth phase: keep a lower density than «recommended» according to maximum volume. Production forest phase: do not apply thinning or fertilisation.
Mature forest phase: clear-cut at economic harvest age.

Minimise snow damages
Regeneration phase: plant single-species (spruce) with a lower density than «recommended» according to maximum volume production.
Young growth phase: keep a lower density than «recommended» according to maximum volume. Production forest phase: do not apply thinning or fertilisation.
Mature forest phase: clear-cut at economic harvest age.

Minimise drought damages
Regeneration phase: plant mixed-species (spruce, pine, birch) with «recommended» density according to volume production.
Young growth phase: keep «recommended» density according to maximum volume.
Production forest phase: apply thinning (to reduce competition) but no fertilisation.
Mature forest phase: clear-cut before economic harvest age.

Minimise all disturbances jointly
Regeneration phase: plant mixed-species (spruce, pine, birch) with a lower density than «recommended» according to volume production.
Young growth phase: keep a lower density than «recommended» according to maximum volume.
Production forest phase: no thinning or fertilisation.
Mature forest phase: clear-cut before economic harvest age.

Maximise profitability
Regeneration phase: plant spruce with «recommended» density according to volume production.
Young forest phase: keep «recommended» density according to volume production.
Production forest phase: apply thinning and fertilisation.
Mature forest phase: clear-cut at optimal economic harvest age.