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FOREST MANAGEMENT (M WATT, SECTION EDITOR)

Can "Closer-to-Nature" Forest Management Sustain Biodiversity and Ecosystem Services in an Uncertain Future? Lessons from Central Europe

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Abstract

Purpose of Review Forests produce timber, mitigate climate change and provide important habitats; yet their capacity to provide these services under rapid global change is uncertain. "Closer-to-nature" forest management (CNFM) has been proposed by the EU Forest Strategy as a way to reconcile competing demands on forests while enhancing their resilience, but experiences with its implementation remain limited. We synthesized expert knowledge about CNFM in Central Europe, a region with a history of diverse forest management practices that has recently experienced severe impacts of climate change. We used a two-stage Delphi approach (including a questionnaire and a workshop) with experts in forest ecology and management to find a consensus about the effects of specific CNFM tools, and to identify knowledge gaps, barriers, and good practice examples of CNFM.

Recent Findings A wider implementation of CNFM is likely to benefit biodiversity and ecosystem services under climate change, with only one clear trade-off identified between setting areas aside and wood production. However, limited empirical evidence exists for many of the expected effects. Substantial obstacles hinder the implementation of CNFM, including administrative constraints, social barriers, and gaps in knowledge and education. Nonetheless, we identified numerous successful cases of CNFM implementation from local to national scales in Central Europe.

Summary CNFM is viewed as a potent strategy to navigate future social and ecological uncertainties, including large-scale disturbances. However, the implementation of CNFM should be adapted to the local context and ensure landscape-scale heterogeneity. Existing good practices could serve as examples for mainstreaming CNFM in Central Europe and beyond.

Keywords Forest policy · Sustainable forest management · Natural disturbance · Climate change · Forest adaptation · Good practices

Introduction

In the face of the global climate and biodiversity crises, there is a growing recognition of the key role of forests in mitigating climate change and biodiversity loss [1, 2]. In addition, there is a wide variety of demands for forest ecosystem services from society [3, 4]. These demands include providing material, energy, and income for forest owners and wood-based industries [5], regulating erosion and reducing the risk of natural hazards [6], as well as a growing emphasis on the forests' role as recreational spaces for an increasingly urban population [7]. These diverse and sometimes conflicting demands are reflected in policies such as the European Union's Forest Strategy, which aims to simultaneously improve biodiversity, strengthen the bioeconomy, and leverage carbon sequestration for climate

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change mitigation [8–10]. However, the ability of forests to meet these demands in the future is increasingly uncertain.

Globally, forests face mounting pressures from land use and climate change [2]. Rising temperatures and droughts are threatening the growth and survival of ecologically and economically important tree species [11–15]. Forest disturbances, such as wildfires and pest outbreaks, are increasing in frequency, severity, and extent [16–18], and can impair the capacity of forests to effectively provide ecosystem services [19]. In many regions, "conventional" forest management has focused on ensuring a sustained yield of timber by exerting a strong control over forest development [20], e.g., through rotation forestry, promoting a limited number of highly productive tree species and even-aged structures. By simplifying and homogenizing forest structure and composition [21], this type of management has resulted in forests that provide fewer ecological niches [21], are more susceptible to natural disturbances [22–24], and less adapted to a changing climate [25].

To cope with these challenges, a variety of other alternative strategies have been developed based on an understanding of forests as complex ecosystems, and with the aim of providing multiple services to society [20]. These range from continuous cover [26, 27] and retention forestry [28], which aim to strengthen forest diversity and multifunctionality, to climate-smart forestry [29] and the functional complex network approach [30], which focus on strengthening forests' resilience and adaptive capacity. One of these approaches is "close-to-nature" silviculture, which has a long tradition in Central Europe [31–37]. Close-to-nature silviculture typically relies on uneven-aged silvicultural systems [38], such as group and single tree selection, and varying thinning intensities, while avoiding clear-cuts. It also emphasizes the importance of natural regeneration and promotes mixtures of site-suitable tree species as well as complex within-stand structures [37]. Forests managed through this type of silviculture are expected to be better adapted to local site conditions [39, 40] and less susceptible to disturbances than forests managed through rotation forestry [41]. In addition, by giving space to natural processes and fostering diversity [42], "close-to-nature" silviculture is expected to support the adaptive capacity of forest ecosystems [39]. However, this approach usually focuses on the stand level, placing less emphasis on fostering landscape-level heterogeneity [43] and potentially disregarding the diversity of species between habitats (i.e., beta-diversity) and cross-scale forest dynamics [39, 44–46].

More recently, the broader concept of "closer-to-nature" forest management (CNFM) has emerged [46, 47]. Building on experiences with "close-to-nature" silviculture, CNFM aims to learn from and give space to natural processes, mainly focusing on uneven-aged management and natural regeneration, while also increasing deadwood retention. Beyond stand-level silviculture, CNFM also aims to foster biodiversity, promote landscape heterogeneity, and integrate a variety of forest ecosystem services at different spatial scales [48]. Recently, EU policymakers have identified CNFM as a promising approach to reconcile the trade-offs among the sometimes-conflicting goals of the EU Forest Strategy [49], including climate mitigation, biodiversity conservation, and bioeconomy [48]. In spite of European-level policy promoting CNFM, uptake of this strategy across Europe remains limited [43, 47, 50]. Consequently, there are ongoing discussions about how to achieve a wider implementation of CNFM in the EU, especially through voluntary measures [48]. There are also concerns among forestry stakeholders that a wider implementation of CNFM could lead to increases in production costs or reductions in timber production [51], which could challenge bioeconomy goals and the livelihoods of forest owners [52], potentially resulting in leakage effects in other regions [53]. Both proponents and opponents of CNFM tend to have strong beliefs about its benefits or costs for ecosystems and society, but evidence is often lacking in these discussions.

To inform ongoing discussions about the broader implementation of CNFM, we aimed to synthesize current expert knowledge about CNFM in Central Europe. In order to integrate not only published studies but also ongoing research, and to evaluate the level of confidence and consensus (or lack thereof) about CNFM among experts, we employed a two-stage Delphi approach [54]. In particular, we addressed the following questions:

(1) how does CNFM affect biodiversity and ecosystem services under climate change?
(2) does CNFM help in dealing with future uncertainties and large disturbance events?
(3) where has CNFM been implemented successfully, and what are key barriers to its wider implementation?

Methods

We employed a two-stage wideband Delphi process [54], including a questionnaire and a workshop, with experts in forest ecology and forest management from Central Europe to synthesize insights on the anticipated impacts of closer-to-nature forest management (CNFM) on biodiversity and ecosystem services under climate change, particularly in comparison to conventional forest management. Since biodiversity is a broad concept with many different aspects, we differentiated effects on specific taxonomic facets of biodiversity, i.e., plants, invertebrates, vertebrates, and fungi. Among ecosystem services, we focused on those emphasized in the European Forest Strategy, including the forest carbon sink, wood production, water provision, and recreation. We also included protection from natural hazards, as this is an increasingly important ecosystem service, particularly in mountain regions such as the Alps.

We focused on Central Europe since it has a history of diverse forest management practices and recently experienced severe disturbances [55, 56], both of which can offer valuable lessons for forest management under climate change that could be applied in many regions worldwide. Traditionally, forest management in Central Europe emphasized timber production, often relying on even-aged silviculture and the cultivation of a limited number of productive tree species, such as Norway spruce and Scots pine [43, 57]. However, other management systems have long been used in specific areas, from individual communities and estates practicing plenter management [58–61], to Slovenia's national-scale adoption of "close-to-nature" forest management [35, 62]. Although uneven-aged and mixed forests have been promoted more broadly in recent decades [63], legacy even-aged spruce and pine monocultures remain widespread [50]. In recent years, the region has faced severe disturbances from drought and bark beetles [64, 65], providing a possible preview of the increase in disturbances that is expected under climate change across many parts of Europe [16, 66].

Our expert panel was composed of scientists with extensive expertise in forest ecology and management across Austria, Germany, Czechia, Slovakia, Slovenia, and northern Italy. In selecting participants, we aimed for a broad geographical representation, a balance between senior and early-career researchers, and a group size conducive to focused and productive discussions within the available time. A total of 18 experts contributed to the Delphi process, including nine university professors, a senior researcher, and eight early career researchers, all working in the field of forest ecology and management, forest disturbances and ecosystem services. In addition, five policy experts involved in the implementation of the EU Forest Strategy participated in the workshop discussions to ensure a connection to policy-relevant questions.

Definition of "Closer-to-Nature" Forest Management

We focused on specific tools of CNFM as defined by the European Commission's Guidelines on Closer-to-Nature Forest Management (European Commission 2023). These tools are (1) promoting natural regeneration, (2) ensuring respectful harvest conditions, (3) minimising other management interventions, (4) preserving and restoring forest soils and water ecosystems, (5) optimising deadwood retention, (6) setting areas aside, (7) managing ungulate species at natural carrying capacity, and (8) taking a scale-specific approach. During the Delphi process, we provided the experts with the definitions of each tool as described in the Guidelines (Table 1).

Delphi Process

The Delphi process is a structured group technique often used to elicit expert knowledge and converge towards a consensus among expert panelists [54]. In the first step of the Delphi process, experts filled in a questionnaire, where they were asked about how the four facets of biodiversity and five forest ecosystem services would be affected by the implementation of each CNFM tool under climate change. For each facet of biodiversity or ecosystem service, they were asked to estimate the effect of the CNFM tool on a scale from −10 (strong negative effect) to + 10 (strong positive effect). On the same scale, the experts were also asked to estimate the degree to which each CNFM tool would help or hinder dealing with large-scale disturbance events (i.e., those that deviate from the typical historical disturbance regime in terms of frequency, extent, and/or severity) and with uncertainties (both social and ecological) in forest management decision-making.

In the second step, the results of the survey were visualized and discussed with the experts in a world-café-style workshop. Experts discussed questionnaire results for each CNFM tool in groups of 3–4, which then rotated so that each expert contributed to the discussion of each measure, and groups were mixed in each discussion round. In the discussion, priority was given to effects with a higher level of disagreement between experts in the questionnaire, and the main arguments for each positive or negative effect were recorded. In practice, when asked about the effects of CNFM on biodiversity and ecosystem services, experts often responded with "it depends…", reflecting the strong context-dependency of ecological processes [67]. Consequently, we discussed how specific local conditions influence expected outcomes, and how the effects of each tool depend on its specific implementation. During the workshop, moderators for each tool recorded the main context factors that modify the effects of a CNFM tool. Through the discussion, experts often converged towards a consensus about the strength and direction of each impact. The consensus emerging from the discussion was recorded (see Fig. 1), as were any remaining disagreements.

To assess confidence, we used an approach adapted from the IPCC reporting guidelines, where confidence is defined as a combination of agreement and evidence [68]. Evidence was estimated by each participating expert in the questionnaire, on a scale from 0 (limited evidence) to 20 (robust evidence), then averaged across all experts and categorized

Table 1 Description of CNFM tools based on the Guidelines on Closer-to-Nature Forest Management [48]. More detailed descriptions of each tool, as provided to the experts during the questionnaire, are provided in the Supplement (Table S1)

Tool	Description
Promoting natural regeneration	Natural regeneration should be the prevailing approach to regenerate forests, particularly when the residual stand is characterized by features desired in the next generation (e.g., native and/or climate-adapted pioneer species, inter-species and intra-species genetic diversity, local provenance, quality, resistance, and vitality) Artificial regeneration can complement natural regeneration in specific situations (e.g., reduced genetic diversity, unsuccessful natural regeneration, need for assisted migration, or focus on habitat restoration for specific species) and should be based on reproductive materials obtained from natural stands or native trees of local provenance deployed in seed orchards mimicking natural pollination and reproduction. The use of non-native species adapted to future climatic conditions may be considered in very specific cases
Ensuring respectful harvest conditions	Harvesting should be partial (i.e., single-tree selection, group selection, or gap cuts (max. 0.2–0.5 ha)) mimicking natural disturbance patterns, as opposed to 'clear-cutting' larger areas. Small clear-cuts might be needed as part of restorative forest management to temporarily mimic natural disturbances During harvest, buffer zones along streams, primary and old-growth forests, and potential habitat trees should be protected. During ecologically sensitive periods such as nesting or breeding periods, harvesting should not take place or minimise disturbance to birds
Minimising other management interventions	External inputs, such as fertilizers and pesticides, should be kept to a minimum. Some exceptions can be made for limited organic fertilisation, liming, and, under exceptional conditions, targeted use of biological pesticides in the absence of other possible measures
Preserving and restoring forest soils and water ecosystems	The health of forest soils and aquatic ecosystems must be protected. Negative impacts on soils must be avoided as much as possible by promoting minimal intervention techniques. Light or low-bearing machines (or, in general, machines with a large and light footprint) must be preferred. Removal of riparian vegetation should be avoided
Optimising deadwood retention	Leaving enough deadwood in the forest in all stages of decomposition is essential for biodiversity. Establishing forest stands with deadwood amounts of more than 20 m^3 ha^{-1} in a network of forest landscapes, rather than a lower mean in all stands, is recommended Removing all deadwood (for example, as part of sanitary logging to address extreme events) should be seen as a last solution
Setting areas aside	Voluntary set-asides are areas where no management takes place. The selection and establishment of set-aside areas should aim to preserve tree-related microhabitats, veteran trees, and forest biota representative of the different forest development stages, help protect threatened species, facilitate biodiversity networks and corridors across scales in coordination with adjacent forest owners/managers, ensure the diversity of associated habitats and species linked to the forest (e.g. water ecosystems, rocky areas, and grassland), maintain or improve remarkable or heritage trees and landscape elements (viewpoints, remains, etc.)
Managing ungulate species at natural carrying capacity	A balanced hunting policy, in combination with barriers or protective measures (e.g., stem fencing or temporary and small-scale plot fencing), should facilitate regeneration, and at the same time, make it possible to maintain healthy populations of ungulate species. The search for the right balance requires the cooperation of all relevant stakeholders (e.g., regulatory authorities, forest owners, and hunters) reflecting on the distribution of ungulate populations concerned. It is often necessary to consider and analyse the wider landscape context to understand the sources of – and reasons behind – browsing damage in a forest stand
Taking a scale-specific approach	Forest management needs to take account of three levels: (i) the level of individual trees and groups of trees (where the role of each tree or group of trees should be considered during forest management operations); (ii) the level of the stand (where the delineation of stand boundaries should be flexible to adapt to changes in natural dynamics, forest-ecosystem dynamics or landscape planning), and (iii) the level of the landscape (to promote diversity at the landscape level)

(robust evidence: mean evidence scores ≥ 15, medium evidence 10–15, limited evidence: < 10). Agreement was estimated based on the directions of effects estimated through group consensus during the workshop (high agreement when all experts agreed on the direction of effects; medium agreement when experts agreed on effects being either in one direction or neutral; low agreement when the experts did not agree on the direction of effects).

Implementation of CNFM

Besides the Delphi process on the effects of CNFM, we also addressed the potential for a wider implementation of CNFM in the Central European context. In particular, the participating experts were asked to identify the main barriers that hinder a wider implementation of CNFM, and to list examples of good practice in CNFM in Central Europe. Finally, we discussed appropriate spatial scales for defining targets and criteria for the implementation of CNFM, such as those that could be used in regulation or incentive schemes.

Results

Effects of CNFM on Forest Biodiversity and Ecosystem Services

CNFM tools were identified by experts as having largely positive effects on biodiversity and ecosystem services (see Fig. 1), with over 60% (45 out of 72) estimated effects showing high agreement and medium to high evidence. Experts were largely confident in positive effects of CNFM on biodiversity, with set-aside areas and deadwood retention having the strongest positive effects across all addressed taxonomic groups (i.e., plants, invertebrates, vertebrates, and fungi). CNFM was also seen to be beneficial for carbon sequestration, water provision, protection from natural hazards, and recreation, although effects on these forest ecosystem services were estimated with a lower confidence than effects on biodiversity. A distinct trade-off was identified with wood production, which is expected to decrease if more areas are set aside. Other CNFM tools, such as preserving forest soils and water ecosystems, and natural regeneration were identified to have more ambiguous or positive effects on wood production.

Although experts mostly agreed on the effects of CNFM, they most often estimated the supporting evidence as medium. The effects of deadwood retention and set-aside areas on biodiversity were estimated to have the most robust evidence, while the evidence was more limited for more vaguely defined tools, such as “minimising other management interventions” and “managing ungulate species”, where the effect on tree regeneration is evident, but remains unclear for other taxonomic groups. Across all tools, the medium level of evidence reflected the strong context-dependency, with effects of specific silvicultural approaches often documented for specific case studies but difficult to generalize. Important contextual factors that modify the expected effects of CNFM include the spatial scale of implementation, the temporal scale over which effects are evaluated (often contrasting short- vs. long-term effects), issues of product substitution and leakage (i.e., the displacement of negative effects of forest use to other regions), public perception, and economics of wood production.

Local Context The impacts of CNFM depend on local social-ecological conditions. For example, the impact of establishing set-aside areas depends on the current forest conditions (i.e., species composition, age distribution, vertical structure and spatial heterogeneity, etc.) and the level of biodiversity of the area. In monospecific stands with homogeneous structure, management that increases species and structural diversity may enhance biodiversity more than strict protection [21]. Next, the effectiveness of natural regeneration depends on the locally available species pool. Local species and provenances may not always be best adapted to a rapidly changing climate, so enriching their gene pool through artificial regeneration of non-local provenances can strengthen adaptive capacity [69].

Spatial Scale Spatial heterogeneity of management approaches is essential for biodiversity, since different species and life stages require different conditions and management types. Applying the same silvicultural approach across stands can lead to increased local diversity but also to homogenization at the landscape scale [46]. Considering landscape-level heterogeneity in management planning is therefore important for fostering biodiversity [70], although heterogeneity is also expected to increase through increasing natural disturbances even without human interventions [71]. In the case of set-asides, their effects strongly depend on their location, size and spatial distribution. Several small set-asides can harbor a higher species richness than single large reserves [72, 73], although landscape-level diversity is higher in larger, connected landscapes [74], which are also required as habitats for forest specialist species. In addition, larger areas are required if the set-asides are to be used as a reference for natural landscape dynamics [75].

Temporal Scale Since forests are dynamic systems, the effects of implementing CNFM may vary across time. For example, the cessation of management in set-aside areas is expected to increase their carbon stocks [76, 77], but sequestration rates are likely to slow over time as these forests age [78, 79], although research suggests that old forests can remain carbon sinks [78, 80]. Similarly, the biodiversity benefits of set-asides also depend on the time since cessation of management, and the development stage of the forest. Setting aside forests that are close to old-growth conditions or recently disturbed forests with high deadwood levels can be particularly effective for fostering biodiversity. In managed forests, a transition to CNFM may reduce wood

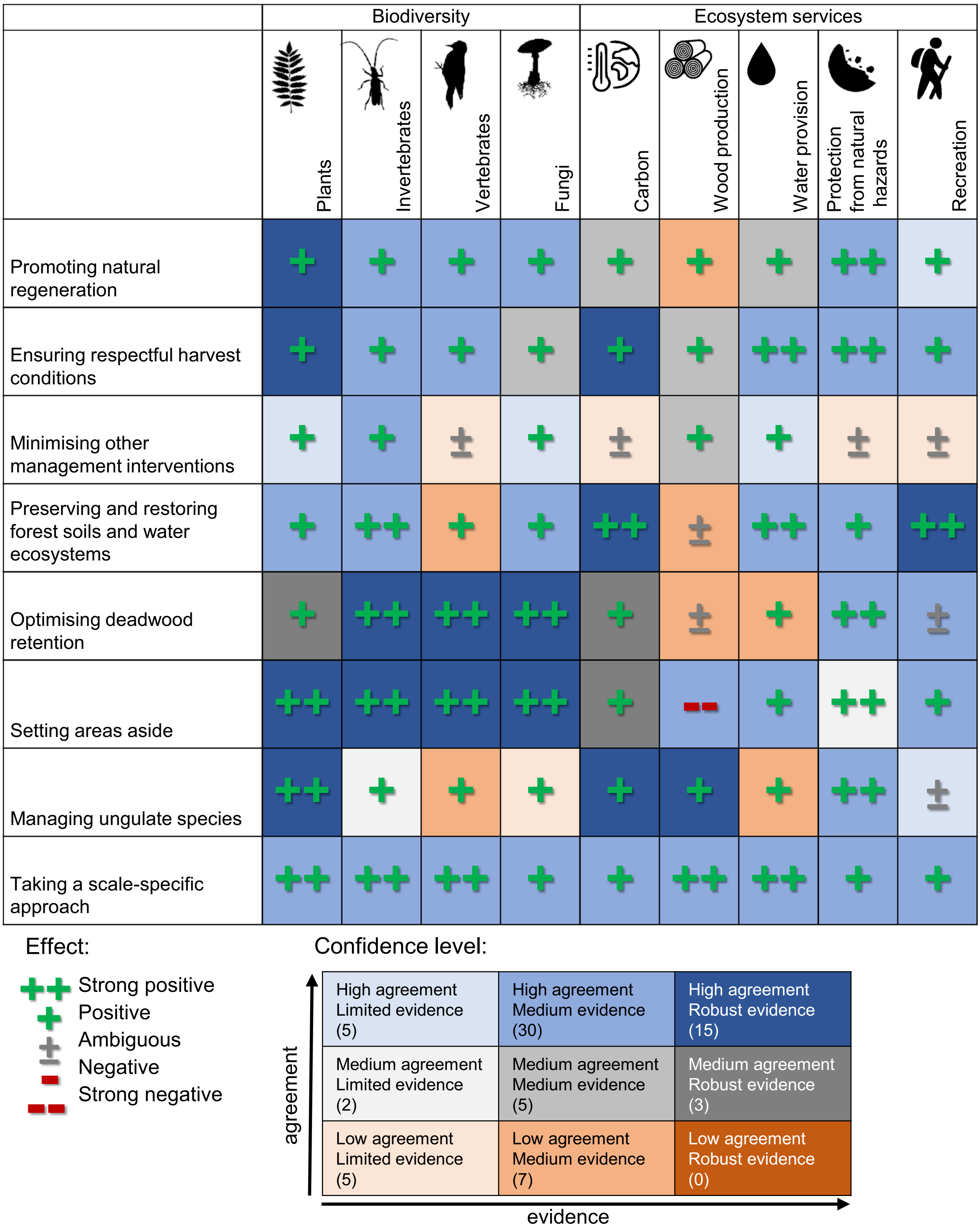

Fig. 1 Summary of expert assessments from a two-stage Delphi process evaluating the effects of closer-to-nature forest management tools (rows) on facets of biodiversity and ecosystem services (columns), showing the estimated effects and the level of confidence in the assessment. The effect is defined as strongly positive when all experts agreed on effects > 5 on a scale from −10 to 10; positive when all experts agreed on positive effects (0–10); ambiguous when effects were estimated around 0; negative when effects were < 0, and strong negative < −5. The confidence level combines expert agreement (after the expert workshop) and the strength of evidence as estimated by the experts. The number of cases for each confidence level is shown in parenthesis. For the full results of the Delphi process, see Supplementary Table S2

production in the short term, although more diverse and potentially more resilient forests are more likely to avoid severe disturbance impacts and enhance the stability of production on the long term [81, 82].

Economics of Wood Production Compared to rotation forestry systems that produce homogeneous products in uniform stands, CNFM may generate higher management costs due to higher labor intensity of harvesting in structurally complex stands with a limited use of heavy machinery, higher costs of marketing a broader mix of log assortments into different market segments, a higher road density, etc. [83]. Small-scale, uneven-aged silvicultural systems are sometimes economically unfeasible, particularly where safe and environmentally sound harvesting operations require the use of expensive technology, such as cable yarders in steep, mountainous terrain [84]. On the other hand, natural regeneration may substantially lower regeneration and tending costs compared to relying on artificial regeneration [85, 86]. In addition, CNFM can produce high-value timber that can be harvested according to the financial maturity of individual trees or when market price fluctuations offer positive returns. Overall, CNFM is therefore expected to be economically competitive with rotation forestry systems in the long term, especially when accounting for disturbance risks [81, 87]. Nonetheless, the transition to CNFM can be costly in the short-term for enterprises currently practicing even-aged forestry [88, 89].

Product Substitution and Leakage While CNFM is generally expected to be beneficial for carbon stocks within forests, reduced timber production (i.e., in the case of set-asides and dead wood retention) could lead to unwanted leakage effects through higher timber harvest in other regions [53, 90, 91], given stable or increasing levels of demand for timber [92]. In addition, it may limit the potential to substitute more carbon-intensive materials with wood.

Public Perception Public perception plays a crucial role in the context of CNFM effects on cultural ecosystem services, particularly regarding deadwood retention. Perceptions vary based on factors such as culture, tradition, education, and demographics [93, 94]. In line with the concept of "forest hygiene", a forest with little to no deadwood has traditionally been viewed positively in Central Europe, with deadwood often regarded as a waste of resources [95], detrimental to landscape aesthetics [96], and as a source of pests and pathogens, notably spruce bark beetles [65]. However, deadwood is perceived more positively with growing awareness about its biodiversity benefits, especially by younger generations [94].

Role of CNFM in Dealing with Future Uncertainties and Large Disturbances

In the questionnaire, the experts provided a wide range of responses regarding the role of CNFM in dealing with uncertainties and disturbances (see Fig. 2), but in most cases, a clear consensus emerged during the workshop. CNFM is expected to help forest management deal with an uncertain future in terms of unknown magnitude and manifestations of climate change, novel disturbance regimes, and changing societal demands on forests. Most CNFM measures are expected to contribute to more diverse forests resilient to the impacts of climate change [97], even if some of these impacts cannot be anticipated [98]. Compared to even-aged systems, forests managed through CNFM are less susceptible to disturbances [41] and provide a wider range of ecosystem services that may be valued by society in the future [99, 100]. In addition, CNFM often involves more frequent, smaller-scale interventions in the same stand than other types of forestry, which can provide more frequent opportunities to re-assess the management strategy and adapt management measures to changing conditions, thus enabling more flexible and adaptive management [101]. However, more frequent interventions are also associated with higher costs.

Promoting natural regeneration, respectful harvest conditions, managing ungulate populations, and scale-specific approaches are expected to play a critical role in dealing with large disturbance events in the future [102]. Advanced natural regeneration is a cost-effective way to ensure a seamless forest recovery after disturbances, but it can be jeopardized by ungulate browsing [103] and salvage logging [104]. Browsing pressure reduces the diversity of woody regeneration in forest gaps [105], so ungulate management is important for ensuring mixed regeneration [106]. Coordinating disturbance management across landscape or regional scales can facilitate an effective response to extreme events [65], and limiting large-scale canopy openings in management can compensate the ongoing trend towards more open forests [107, 108].

There was less agreement on the role of deadwood retention, set-asides, and minimising other management interventions in dealing with large disturbances. On the one hand, the removal of dead and infested trees is a key component of strategies to mitigate disturbances, especially pest outbreaks [65, 109] and wildfires [110]. In some cases, managers also rely on pesticides to suppress pest outbreaks, so minimising such interventions might limit their options in responding to disturbances. On the other hand, recent research suggests that the effectiveness and economic efficiency of sanitary logging may be limited in case of large-scale disturbances under climate change [65, 111]. The effectiveness of salvage

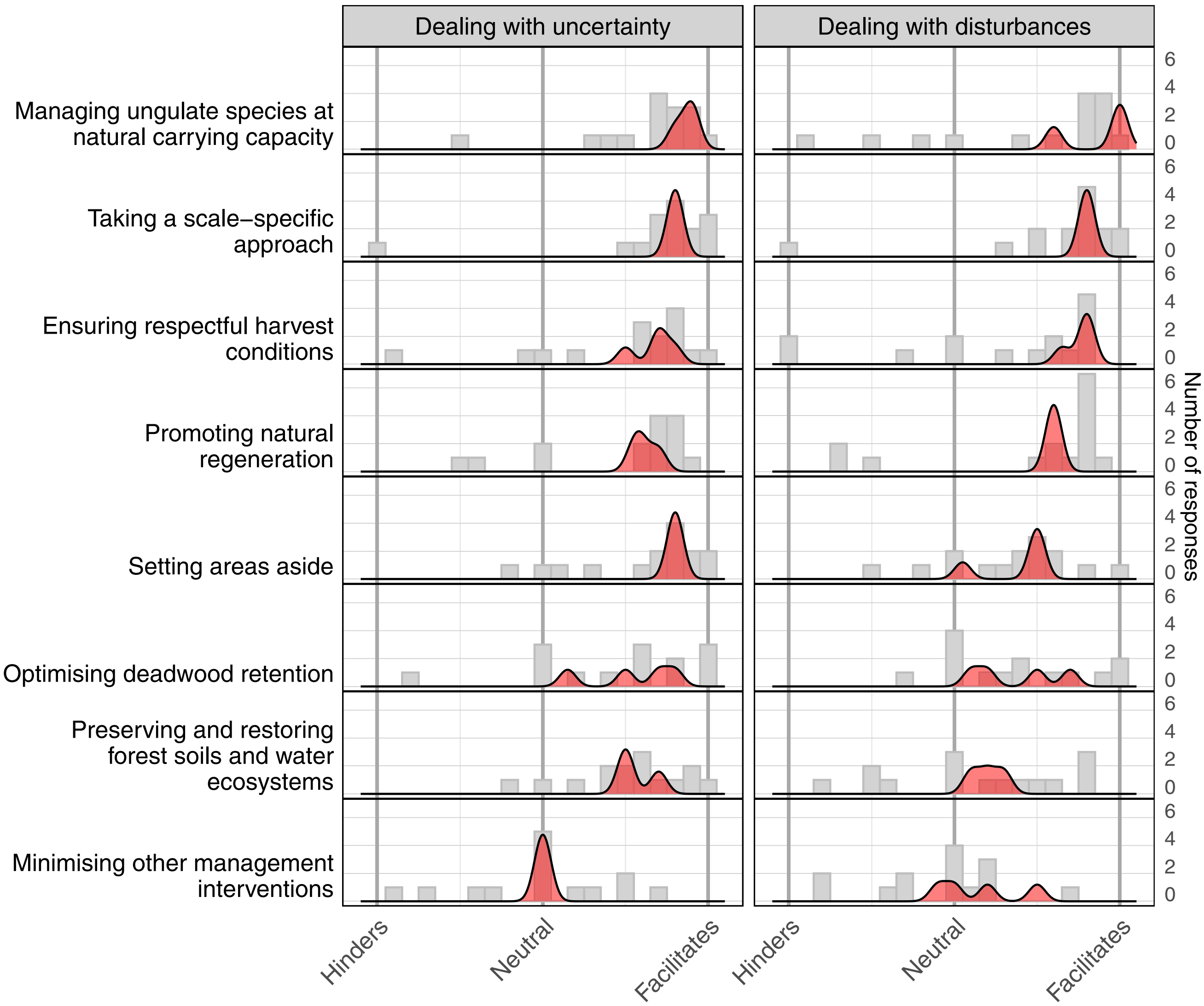

Fig. 2 Expert assessments from the two-stage Delphi approach on whether CNFM facilitates or hinders dealing with uncertainties in general (left), and with large disturbances in particular (right). Grey columns indicate initial expert responses in an expert questionnaire (Delphi stage one), red curves indicate the distribution of consensus points by expert subgroups during the workshop (Delphi stage two). Individual assessments in the first Delphi stage were more variable, but discussions during the workshop led towards a consensus that CNFM overall facilitates dealing with uncertainty and disturbances

logging in preventing wildfires is also ambiguous, as it reduces the amount of coarse fuels, but can increase the amount of fine fuels and exacerbate the drying of fuel [112]. In contrast, deadwood retention can reduce the time and effort needed to clear disturbed sites, facilitate regeneration [113–115], and help maintain essential ecosystem services [116, 117]. More broadly, set-asides, deadwood retention, and minimising other management interventions are largely seen as positive for enhancing forest resilience and biodiversity, with higher biodiversity levels being positively associated with reduced disturbance impacts and faster recovery [118, 119].

Implementation of CNFM in Practice

Most frequently mentioned barriers that hinder the implementation of CNFM were related to existing legislation or administrative constraints, as well as social barriers (Table 2). The fragmented ownership of Central European forests [120] presents a key challenge for landscape-level forest planning and for the creation of larger set-aside areas, as well as for active forest management [121]. While small forest owners often do not actively manage their forests [122], these unmanaged forests are rarely documented as set-asides, making it more difficult to include them in planning or to monitor their development. On the contrary, larger forest estates owned by states, communities, or private enterprises have a higher potential for landscape-level management.

In many European countries, public authorities mandate (and sometimes subsidize) sanitary logging after disturbances [65, 123]. In addition to legal requirements, the enforcement of "forest hygiene" is still viewed as important among forest owners and practitioners in Central Europe. Sanitary and salvage logging are intended to recoup economic losses after disturbances and limit pest outbreaks, but they also reduce opportunities for deadwood retention and set-asides, thus conflicting with conservation objectives. Although recent research suggests that unmanaged forests have a lower rate of disturbance than their managed counterparts [124], and that bark beetles tend to disperse from managed to unmanaged forests rather than vice-versa [125], the negative perception of deadwood can lead to substantial pressure on forest owners who wish to retain deadwood or create set-asides, and even challenge conservation in protected areas [123, 126]. Nonetheless, nature conservation is gaining attention in forest management across Europe [127].

Browsing pressure is perceived as an important barrier to successful natural regeneration [128] and to adaptive changes in species composition [103, 129], highlighting the need for appropriate ungulate management. However, the "carrying capacity" of the landscape for ungulates is often contested between foresters and hunters [130], with hunters typically preferring higher ungulate populations than forest managers. Deeply entrenched conflicts between forestry and hunting stakeholders are common across Central Europe, hindering the development of shared ungulate management strategies. While the expansion of large predators, especially wolves, may benefit natural regeneration [131], it also entails conflicts due to livestock depredation, safety concerns, and limited public tolerance of predators [132], especially in rural areas where predators have previously been extirpated [133, 134].

There are numerous good examples of the implementation of CNFM tools in practice at different scales across Central Europe. At the level of individual enterprises, public forests, such as state forest enterprises in Germany, are setting areas aside, and cities such as Munich and Vienna are managing their forests in line with CNFM principles to help regulate the cities' water supply and buffer high temperatures. There are also existing incentives for private forest owners to implement CNFM approaches, such as Germany's financial reward to private and municipal forest owners for ecosystem service provision through the "Climate Adapted Forest Management Program", which requires site-adapted, mostly native tree species, natural and advance regeneration, and retention of habitat trees and dead wood [141]. Certification schemes that aim to promote sustainable forest management, such as PEFC and FSC, also provide incentives for specific aspects of CNFM, including deadwood retention, although certification standards do not fully align with CNFM and vary between countries [142].

At the landscape scale, associations of private forest owners enable the sharing of knowledge and resources, and could potentially provide opportunities for landscape-scale coordination of forest management even in areas with fragmented ownership [143]. In addition, various EU funding schemes such as LIFE and Interreg have supported specific measures to improve forest biodiversity at local, landscape, and regional scales [144]. At larger scale, CNFM is also implemented in some regional and national institutions. For example, Slovenia's national forest service and Italian regional administrations implement forest management planning across scales in both public and privately-owned forests, from defining priority ecosystem services [145] at the landscape level, to the selection of trees for harvest at the individual tree level.

Discussion

We found a high degree of consensus among experts that CNFM tools are generally beneficial for biodiversity and ecosystem services, especially when facing uncertainties about future climate conditions and changing societal demands for forest ecosystem services. Importantly, these uncertainties should not be a reason for inaction, especially given the accelerating impacts of climate change, where strengthening forests' adaptive capacity is critical [98]. However, the implementation of CNFM is hindered by a variety of barriers, including knowledge gaps, trade-offs between short-term and long-term outcomes, and institutional constraints, such as conflicting regulations [146]. Understanding these barriers can help identify the potential levers for mainstreaming forest management approaches that give space to natural processes and strengthen the adaptive capacity of forests. For example, since many of the identified barriers were related to current legislation and administrative constraints, a wider implementation of CNFM could be facilitated by aligning forestry regulations with policy aims [10, 49, 147].

Table 2 Summary of barriers and good practice examples identified during the workshop. The barriers include ecological (), administrative or legal (), social (), and economic barriers (€€), as well as barriers related to a lack of knowledge and/or education (). Please note that the listed examples are not an exhaustive list of good practices

Tool	Barriers	Good practice examples
Promoting natural regeneration	Excessive browsing pressure Availability of seed trees of suitable species for future climate Dominance of undesired species in natural regeneration (e.g., species not adapted to future climate, such as Norway spruce in low elevations) Uncertainty about suitable target species for the future Legal restrictions (e.g., mandatory reforestation shortly after harvest or disturbance)	Establishing advance regeneration (DE, [134,135]) Mitigating selective browsing through ungulate management and regeneration protection [105,136] Subsidies for post-disturbance restoration encouraging planting of species other than spruce (CZ) Training of forest owners (SI) Networks for forest practitioners (e.g., ProSilva, Integrate network)
Ensuring respectful harvest conditions	**€€** Lower efficiency of small-scale harvesting (economy of scale) **€€** Lack of forest roads Traditions, education, and knowledge of professionals	Individual tree marking by forest service (SI, IT) Small-scale gap cuts emulating natural gap dynamics in beech forests (SI) Well-trained forest workers (national vocational qualifications, SI)
Minimising other management interventions	Invasive species [137,138]	Promoting advance regeneration to avoid competition with weeds and reduce the need for herbicides and mechanical removal of competing vegetation [139], ("climate adapted forest management" programme, DE) Limiting the use of insecticides to treat infested logs and using alternative techniques, such as debarking (CZ)
Preserving and restoring forest soils and water ecosystems	**€€** Harvesting logistics and costs Public and local authorities' beliefs about (traditional) flood risk management Limited communication between water and forest managers	Forest functions and ecosystem services mapping (DE, SI, CZ) Cable crane harvesting (AT, CZ) Riparian vegetation restoration (Salzachauen, AT) Cooperation between water companies and rewilding NGO (SK) Community forest management for water supply (Munich, DE; Vienna, AT; CZ)

Table 2 (continued)

Optimising deadwood retention	Perceived disturbance risk Traditions and beliefs ("tidy" forests and "forest hygiene") Safety for recreational users Lack of biodiversity knowledge among practitioners Traditional forestry education Lack of clear indicators Forestry legislation (e.g., mandatory sanitary logging) **€€** Increased wood demand	Habitat trees in national legislation (IT, SI) and in public forests (DE) Regulations on minimum amount per ha (SI, IT, DE state forests) Indicators for deadwood quality and quantity (BioΔ4 Interreg project, AT and IT) Incentives for habitat trees (DE) Certification standards (PEFC, FSC)
Setting areas aside	Legislation (e.g., regarding bark beetle management, firefighting) Lack of documentation and reporting Fragmented ownership Public and neighbor acceptance Set-asides often in marginal areas (not representative of other forests' natural dynamics) **€€** Increased wood demand	Forest planning including areas left to natural development (SI; GoProFor project, IT) Incentives for setting aside 5% in enterprises >100ha (DE) Subsidies for set-asides in private forests ("ekocelice", SI) Wide range of forest types in state forest set-asides (DE) Integrative forest management with habitat tree retention, set aside of special habitats, and stepping stones (Ebrach forest enterprise, DE)
Managing ungulate species at natural carrying capacity	Deeply entrenched conflicts between forestry and hunting actors Public perception of large predators Legislation (e.g., limits of hunting targets)	Administrative integration of forest and game management planning (SI) Regeneration conditions as an indicator for decisions about ungulate population management (SI, DE state forests)
Taking a scale-specific approach	Small-scale and fragmented ownership Lack of monitoring Administrative boundaries Management guidelines focused on stand-scale Lack of knowledge of species dynamics Education focused on stand-scale **€€** Harvesting logistics	Forest planning across scales (IT, SI, CZ) Individual tree marking by forest service (IT, SI) Establishing associations of small forest owners with shared management plans (CZ) Forest functions and ecosystem services mapping (DE) Forest owners' associations (DE, AT) Implementing biodiversity assessments in forest management plans (Veneto, IT)

Implementation of CNFM in Policy and Practice

Although experts agreed on the overall benefits of CNFM, they also expressed a high degree of caution against applying CNFM as a "one-size-fits-all" solution. Forests are inherently dynamic systems, changing over space and time, and this heterogeneity is essential for their biodiversity and adaptive capacity. This can present a challenge for developing policy instruments, such as subsidies, certification standards, or payments for ecosystem service schemes, which have typically been based on quantifiable criteria and target outcomes. To reflect forest diversity and dynamics, such targets must be tailored to local conditions, including forest types and development stages, and should integrate a landscape-scale perspective. For example, different forest development phases are expected to harbor different amounts of deadwood, and deadwood is thus heterogeneously distributed across landscapes. Besides setting a minimum threshold of deadwood amounts at the stand level [148], it is thus important to consider areas with higher deadwood amounts in the landscape [149], such as recently disturbed and regenerating forests [75], while also tolerating areas with below-average deadwood values (e.g., in intermediate forest development stages). Similarly, while the CNFM guidelines emphasize the small-scale harvesting, some canopy openings are important at the landscape level to sustain light-demanding species [140]. Where these are not created through natural disturbances, some silvicultural flexibility is required [62, 150]. Inspired by natural forest disturbance regimes, which create spatial and temporal heterogeneity in forest canopies, "closer-to-nature" targets should not be quantified as single values but rather as a range of desired target conditions [43, 151, 152]. Targets represented through respective ranges of variability would provide some flexibility for forest managers to make decisions tailored to their local context and would better reflect the inherent heterogeneity of forest ecosystems. Beyond targets for forest conditions, policies supporting CNFM could also include process-based targets, such as requirements for landscape-scale planning and forest monitoring, which are essential for context-sensitive and adaptive management.

CNFM can promote forests that are more complex than rotation forestry systems, but this also results in more complex planning and management decisions [83]. Therefore, forestry professionals need to play a key role in the implementation of CNFM. While traditional forestry education often focuses on the stand level, forestry professionals applying CNFM need an appropriate knowledge of their local forest ecosystems and their dynamics across multiple spatial scales, from the single tree to the landscape level. Given the uncertainty of future developments related to climate change, extreme events, and changes in societal demands on forests [153, 154], and the high context-dependency of forest systems, forest practitioners need to make decisions under uncertainty, test and implement measures, observe outcomes, and adapt their management as new information becomes available [155]. Enabling adaptive CNFM therefore requires appropriate education and training for forestry professionals [27, 147], as well as knowledge sharing between practitioners and scientists [47], and comprehensive forest monitoring [156].

Strengthening the Evidence Base

Although expert agreement on the effects of CNFM was often high, the evidence base for many of these assessments remains limited. This reflects the challenges of empirical research in forest ecology, where long timescales of forest development make experimental studies particularly difficult. Although challenging, large-scale experiments testing the effects of forest management regimes on biodiversity, ecosystem services, and adaptive capacity are urgently needed [27, 157]. One of the rare examples are the German Biodiversity Exploratories, a long-term research programme investigating the impact of forest management on biodiversity [158]. In addition, data on forest structure, biomass, and dynamics is becoming increasingly available through remote sensing [159] as well as networks of ground-based observations, such as forest inventories. When combined with information on forest management, these observations allow for comparative studies on the effects of specific forest management approaches [41, 42, 115, 124]. However, in complex systems such as forests, inferring causal effects from observational data can be difficult [160]. To test the effects of different management approaches in a controlled setting and over longer time scales, process-based forest modelling tools are often used [161–163]. Together, observational and modelling studies can contribute to a more robust evidence base to support decisions about forest management.

Reconciling Trade-offs Between Ecosystem Services

While CNFM is expected to benefit society through its positive effects on biodiversity and ecosystem services, expected trade-offs with wood production and higher production costs remain key barriers to its implementation. These trade-offs are expected to be temporary (except in the case of set-aside areas), but they are important for the decisions of forest owners whose income is derived from wood production [52]. Therefore, a wider implementation of CNFM would require incentives for forest owners, such as payments for ecosystem services [164]. Such incentives would challenge traditional norms among forestry practitioners, where forest managers should ensure the economic self-sufficiency of forest enterprises through wood production [165, 166]. Nonetheless, many forest owners are interested in managing their forests for a variety of ecosystem services [167, 168] and have positive attitudes towards payment schemes that would promote environmental goals [164], such as those foreseen in EU policy [8].

CNFM is often associated with lower management intensities than conventional even-aged forestry and is therefore seen as a land-sharing approach to reconcile the trade-offs between biodiversity and wood production. However, it is important to note that CNFM can have variable harvesting intensities, which shape its effects on forest structure [169] and biodiversity [170]. Forest management, even with "close-to-nature" forestry, has been shown to lead to a decline of old-growth-like structures [171] and the species that rely on them [149]. Although old-growth-like structures can be enhanced through targeted silvicultural measures [172, 173], unmanaged set-asides are expected to play a critical role in preserving forest biodiversity. At the European scale, a recent simulation study suggests that reductions in forest harvesting due to set-asides would likely be compensated by an increasing intensity of harvest in other areas [91]. Planning approaches such as triad zoning [75, 174] have been suggested as a way to efficiently allocate areas for set-asides, extensive management, and intensive management (e.g., high-yield plantations), and to minimise trade-offs between biodiversity and wood production [163]. However, the fragmented ownership structure of Central European forests makes it difficult to balance different forest management intensities among forest owners through top-down planning [75]. In addition, in the small-scale mosaic of Central European landscapes, forests are also used and valued for recreation and other ecosystem services [7, 175], which means that forest management decisions need to balance additional objectives beyond biodiversity and wood production [145]. At the same time, the diversity of forest owners with various priorities and objectives provides opportunities for diverse forest management at the landscape scale [176]. In this context, incentives for forest owners interested in CNFM, together with guidelines that can be applied locally in a context-specific manner, could help increase the proportion of forests managed through CNFM and improve biodiversity and ecosystem services in European forests.

Limitations

In this study, we synthesized the knowledge of academic experts in forest ecology and management with broad expertise on topics including silviculture, ecosystem services, and disturbance ecology, as our aim was to identify the consensus (or lack thereof) about CNFM among experts in the field. While the panel reflected a range of forestry backgrounds from a range of countries in Central Europe, it was not comprehensive. Perspectives from countries such as Poland and France, which have distinct management traditions, were not represented, which may have limited the scope of examples discussed. Furthermore, as a result of the regions represented, the focus of the discussion was on temperate forests with strong legacies of conifer-dominated management. In addition, our panel did not encompass all disciplines intersecting with forest management, such as economics, technology, ecology of specific taxa, recreation, or hydrology. A broader group of experts could offer further insights into how management influences specific ecosystem services, but would also make achieving a consensus among experts increasingly difficult. Moreover, relationships between society and forests go beyond the instrumental perspective that can be described through ecosystem services, and include intrinsic [20] and relational values [177]. For example, many forest owners and managers are motivated not only by profit from timber production, but also by a sense of stewardship and care for the forests they manage [127, 177]. This diversity of perspectives means that decisions about forest management cannot be guided by forest science alone, but should integrate the knowledge and values of a broad range of stakeholders.

Conclusions

Experience from Central Europe suggests that CNFM can help sustain forest biodiversity and ecosystem services in a future characterized by rapid environmental and social change. Among specific CNFM tools, set-aside areas and deadwood retention are seen as particularly beneficial for biodiversity across different taxonomic groups. However, set-aside areas also cause substantial trade-offs, as setting more areas aside for conservation reduces wood production. Other CNFM tools have either positive or ambiguous effects on timber production and are largely seen as beneficial for other ecosystem services under climate change. Nonetheless, the impact of CNFM is often context-dependent, and while we found a high level of agreement among experts on most of the expected effects, the available empirical evidence base remains tenuous, highlighting the need for further research on the effects of specific forest management approaches on biodiversity and ecosystem services.

By increasing forests' diversity and adaptive capacity, CNFM is a promising avenue to address uncertain future conditions and respond to large disturbance events. To achieve these benefits, the implementation of CNFM should be tailored to local conditions, while also considering landscape-scale heterogeneity. Taking a landscape-scale perspective is a key challenge for the implementation of CNFM in practice, where many forest management decisions take place at the level of forest stands or smaller forest properties. However, even in Central Europe's fragmented forest ownership landscape, numerous examples demonstrate the potential to implement CNFM in practice from local to national scales. These examples provide valuable models for overcoming barriers to CNFM adoption, and offer opportunities for further empirical research on the effects of CNFM and for accelerated knowledge exchange with and among practitioners. Lessons from these experiences in Central Europe can also inform forest management in other regions, supporting the global transition toward more resilient and sustainable forestry practices.

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Declarations

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