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Bark beetle outbreaks in Europe: State of knowledge and ways forward for management

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TH, RS, KFR, JM, PK, CMH, HQ – Conceptualization and Methodology; M-JS, LK – Formal analysis and Data curation; ML, MS, HV – Review & Editing

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Abstract

Purpose of review: Outbreaks of tree-killing bark beetles have reached unprecedented levels in conifer forests in the northern hemisphere and are expected to further intensify due to climate change. In parts of Europe, bark beetle outbreaks and efforts to manage them have even triggered social unrests and political instability. These events have increasingly challenged traditional responses to outbreaks, and highlight the need for a more comprehensive management framework.

Recent findings: Several synthesis papers on different aspects of bark beetle ecology and management exist. However, our understanding of outbreak drivers and impacts, principles of ecosystem management, governance, and the role of climate change in the dynamics of ecological and social systems has rapidly advanced in recent years. These advances are suggesting a reconsideration of previous management strategies.

Summary: We synthesize the state of knowledge on drivers and impacts of bark beetle outbreaks in Europe and propose a comprehensive context-dependent framework for their management. We illustrate our ideas for two contrasting societal objectives that represent the end-members of a continuum of forest management goals: wood and biomass production and the conservation of biodiversity and natural processes. For production forests, we propose a management approach addressing economic, social, ecological, infrastructural and legislative aspects of bark beetle disturbances. In conservation forests, where non-intervention is the default option, we elaborate under which circumstances an active intervention is necessary, and whether such an intervention is in conflict with the objective to conserve biodiversity. Our approach revises the current management response to bark beetles in Europe and promotes an interdisciplinary social-ecological approach to dealing with disturbances.

Key words: bark beetle outbreaks, climate change, forest disturbances, societal objectives, forest ecosystem services

1. Introduction

Disturbances by tree-killing bark beetles have strongly increased in conifer forests in the northern hemisphere over the last four decades [1,2]. Available projections indicate that this trend will continue [1], mainly due to warmer temperatures and the increasing frequency of drought events [3,4]. It is estimated that the European spruce bark beetle *Ips typographus* has caused as much as 8% of all tree mortality due to natural disturbances in Europe between 1850-2000 [5], and this proportion has increased since 2000 [*6]. A similar trend is observed in western Canada and the United States, where recent tree mortality due to the mountain pine beetle *Dendroctonus ponderosae* has exceeded 28 million ha [7,8].

Bark beetle outbreaks have manifold impacts on ecosystems, affecting water, climate, and nutrient cycles [9–11]. Outbreaks increase net carbon fluxes from the land to the atmosphere and thus provide a positive feedback to climate change [12]. For example, the *D. ponderosae* outbreak in British Columbia changed forests from a net carbon sink to a carbon source, and increased net carbon emissions by 270 megatons over the period 2000-2020 [13]. Outbreaks may also affect regional economies and markets via a range of cascading impacts [*14,15]. These include short-term negative impacts on timber markets (e.g. oversupply, declining timber prices) and non-market values such as tourism, but also increased demands for forestry workers with short-term positive effects on regional labour markets [16,17]. Outbreaks often result in large-scale transformations of forest landscapes and may have profound social consequences, such as reduced life quality and economic well-being of forest owners, loss in aesthetic qualities, reduced trail access, land use conflicts, or loss of community identity [18–21]. A manifestation of the potentially high social impacts [22] are political conflicts that have recently emerged after bark beetle outbreaks in European countries such as Germany, Czech Republic, Poland and Slovakia [e.g. 23–25].

While most forests affected by bark beetle outbreaks in Europe are managed for timber production and economic values, outbreaks occurring in ecosystems managed for biodiversity and nature conservation likewise have received much recent attention [24,26–28]. In such forests, bark beetle disturbances are often valued because they contribute to ecosystem functioning and create more heterogeneous tree cover patterns, leading to more complex forests in the future [29–31]. Furthermore, bark beetle outbreaks have generally positive effects on biodiversity [32–35], and thus contribute to the primary management objectives of these areas. However, outbreaks can also have negative effects in forests managed for biodiversity and nature conservation, such as reducing populations of some endangered species, reducing the quality of the recreational experience of visitors, and compromising the provisioning of ecosystem services such as clean drinking water [32,36,37].

The many different perspectives on bark beetle outbreaks highlight the complex roles these mostly native insects play in forest ecosystems. Depending on what values we primarily derive from forests these roles can be regarded as highly positive, such as fostering biodiversity, or highly negative, such as reducing economic returns and ecosystem services (e.g. carbon storage, water purification), and disrupting a continuous timber supply to the forest-wood-chain [26,38,39]. The context-specific role of bark beetles suggests that differentiated management approaches are required beyond current practices. Currently, the most widely practiced responses to bark beetles in Europe are (i) to employ measures minimizing the outbreak risk, such as clearing of freshly windthrown trees [40,41], and (ii) to contain an outbreak once it is ongoing, for example by using sanitation logging, trap trees or pheromone traps [42–44]. Current management strategies often do not adequately incorporate proactive measures to control beetle outbreak dynamics, fail to consider diverse local contexts and the role of natural disturbances in ecosystem dynamics, lack adequate empirical support, and thus can devolve into what has been termed ‘command-and-control’ management [45]. Such a centralized, unidimensional and disciplinarily isolated approach is unlikely to adequately address the complex, multidimensional, and rapidly changing social-ecological challenges that typify disturbance management [46].

The recent *I. typographus* outbreaks in Europe and their management have precipitated often contradictory reactions among forest professionals, scientists, the general public and other stakeholders [23,28,34,47]. Concerns have been raised about the ability of ‘command-and-control’ tactics [48] to stop outbreaks that largely are driven by extreme weather [49], about the ecological impacts of large-scale salvage felling [50], and about how to promote the economic and environmental recovery of disturbed forests [27,51]. Recent events have also revealed a limited degree of social capacity to address bark beetle outbreaks in parts of Europe, e.g., concerning technical and human resources, legislation and other aspects. More broadly, recent outbreaks have also revealed that control measures in some regions are often applied as a somewhat ‘knee-jerk’ reaction rather than being based on sound evidence on their efficacy, public perception, or effects on ecosystem services [49,52–54]. The unprecedented size of some recent outbreaks has also revealed new challenges, such as the need for coordinated international actions, recognition of the social dimension of forest disturbances, and impacts on international timber markets [16,22].

In this paper, we address these challenges by (i) synthesizing the state of knowledge on bark beetle outbreaks, and (ii) proposing a novel holistic and context-dependent management framework. Our framework combines ecological knowledge about the role of bark beetles in ecosystem dynamics with tactical management tools that consider a broad suite of potential management objectives such as biodiversity, timber production, or recreation. We acknowledge that efficient management systems need to provide solutions tailored to specific places and situations by addressing the complexity and uncertainty of transforming social-ecological systems [55]. We here focus mainly on *I. typographus* outbreaks in Europe`s Norway spruce *Picea abies* forests, but we also draw on notable examples from North America where applicable. We note, however, that the framework proposed here may likewise have implications for the management of other insect-induced disturbances worldwide.

2. Bark beetles and their impacts

2.1 Bark beetle ecology and outbreak dynamics

Bark beetles belong to a diverse subfamily of weevils (Coleoptera: Curculionidae, Scolytinae) with a worldwide distribution. Most of the world’s roughly 6,000 bark beetle species breed only in dead trees and tree parts, and thus play important ecological roles in nutrient cycling and as food for other animals [56]. However, a few species colonize stressed and dying trees when their populations are low, but then successfully mass-attack and kill large numbers of healthy trees once their populations are high [57–59, **58].

Adult bark beetles locate and enter suitable trees, then mate and lay their eggs under the bark; the larvae feed and develop to maturity in the phloem and the brood adults emerge to locate new hosts. This lifestyle can lead to economic losses because bark beetles and humans essentially compete for the same resource [56]. Successful beetle colonization is typically fatal to trees, because hundreds of simultaneously attacking beetles destroy the inner bark and disrupt nutrient transport to the roots. The beetles also infect the trees with moderately phytopathogenic fungi that eventually metabolize tree defence chemicals and block water transport in the sapwood [60]. Species of tree-killing bark beetles are commonly able to breed in only one genus of trees and can exploit a tree for only one or two generations before the resources in the bark are exhausted.

Trees have elaborated chemical, anatomical, and physiological defences that enable them to resist attack by bark beetles most of the time. Examples of tree defences include necrotic lesions that form around beetle attacks in the phloem, production of terpenes and other toxic chemicals, and resin flow [60,61]. These defences can be lethal to adult beetles, their offspring, and the beetles’ fungal associates [56].

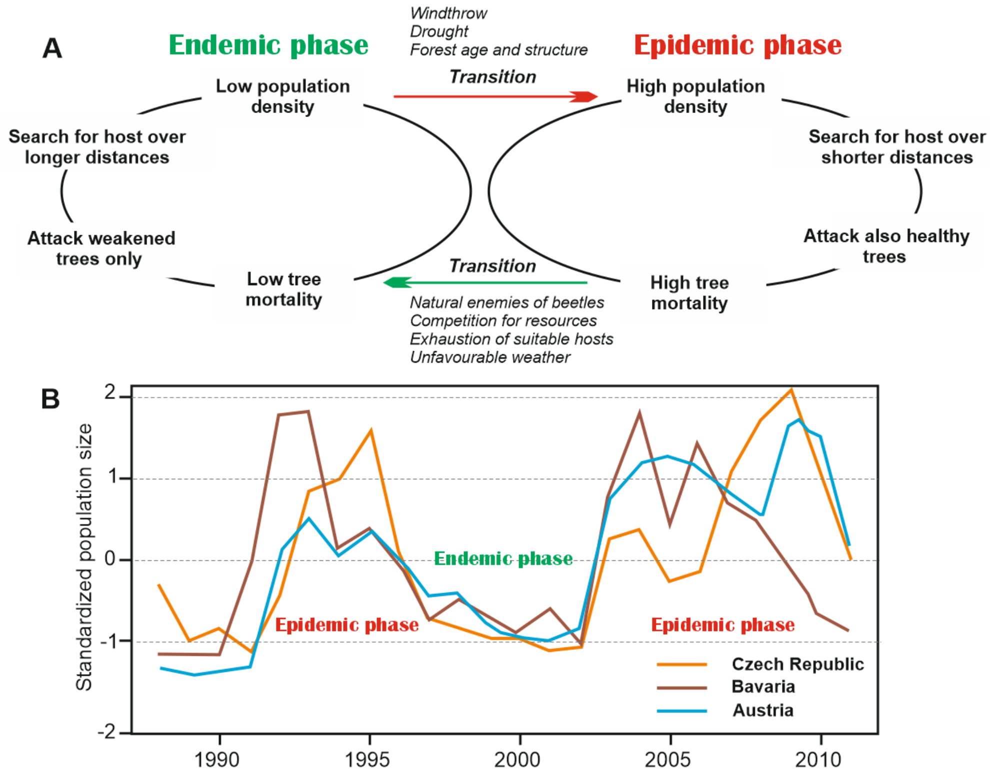

Fig. 1 Scheme of bark beetle population dynamics. A) Low and stable bark beetle populations (endemic phase) can be periodically disrupted by external factors such as droughts and windthrows, which trigger a transition to the epidemic phase (upper panel, adopted from [62]). For *Ips typographus,* the epidemic phase may typically last several years. B) The transition between endemic and epidemic phases over time during synchronous *I. typographus* outbreaks in the Czech Republic, Bavaria (Germany) and Austria. Population values have been standardized for comparison across regions (adopted from [30]).

Beetles have two major ways of reproducing despite these defences; they can avoid defences or they can exhaust them. Beetles can avoid most defences by only entering trees that have recently died, such as windfelled trees, or trees that are under severe physiological stress from drought or other factors [63]. This is the strategy used by so-called non-aggressive or semi-aggressive species (such as *I. amitinus* and *Pityogenes chalcographus* in Europe, and *I. pini* and *Scolytus ventralis* in North America) that can only sustain outbreaks in stressed stands [57]. Alternatively, beetles can exhaust tree defences through mass-attacks coordinated by powerful chemical signals (aggregation pheromones) that rapidly direct hundreds of beetle attacks to a single tree. A tree can resist a certain number of attacks, but beyond this threshold the tree can no longer fend off the attackers [60]. This ability to mass-attack trees is a key adaptation that enables outbreaking bark beetle species to kill healthy trees once their populations have risen and to sustain outbreaks in relatively healthy stands even after the inciting stress is relaxed [57].

Bark beetle outbreaks are intermittent events separated by lengthy non-outbreak periods during which the beetles' reproductive gains are offset by population losses [**58]. During this 'endemic phase', beetle populations are constrained by tree resistance, certain forest structural features (young age, high diversity, low competitive stress), weather, competitors and natural enemies, and the beetles breed only in sparsely distributed dead or severely weakened trees [57,64]. Region-wide disturbances and climatic events, such as windstorms, drought or heatwaves, can raise populations by reducing tree resistance and/or increasing beetle numbers [3,65]. If the reproductive increase is great enough, beetle populations surpass a critical threshold and become capable of overcoming healthy, well-defended trees via their aggregation mechanism. During this 'epidemic phase' beetles no longer focus solely on weakened trees, which tend to support low brood production, but also include healthy trees which tend to support higher brood production, thus releasing strong positive feedback [59,66,67].

2.1.1 The European spruce bark beetle as a model system

The European spruce bark beetle *I. typographus* is the primary outbreak species of bark beetles in Europe (Fig. 2). This small (~5 mm long) beetle is widely distributed across Eurasia where its range largely corresponds to that of its major host, Norway spruce. The total growing stock of Norway spruce in Europe is currently estimated to be 7.0 billion m^3, suggesting that more than a quarter of Europe`s total growing stock of 27.4 billion m^3 is potentially exposed to *I. typographus* outbreaks (Fig. 3, Appendix A).

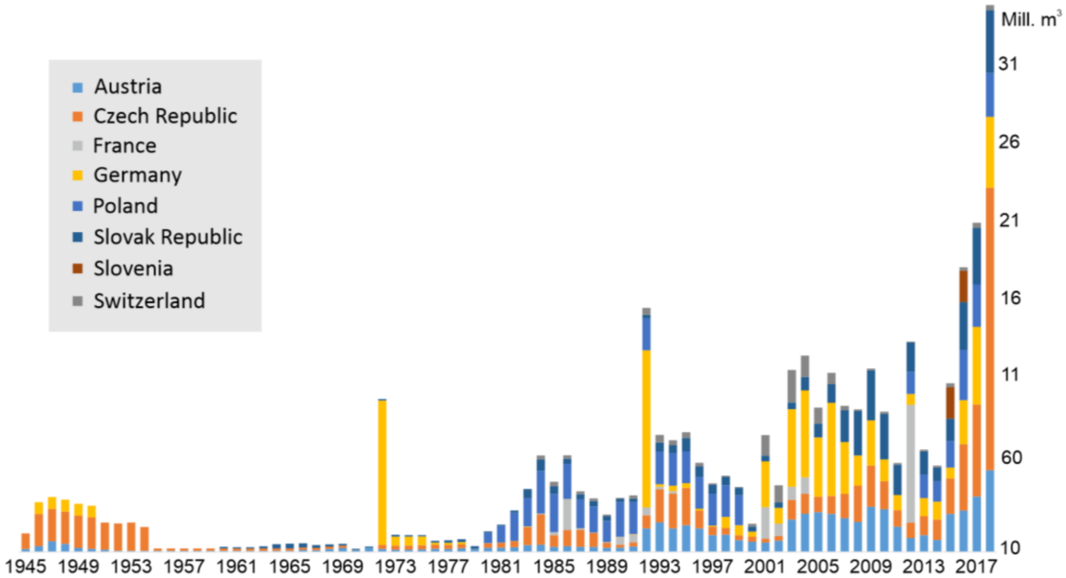

Fig. 2 Volume of Norway spruce killed by *Ips typographus* (and other bark beetles) in selected countries in Europe since 1945.

Like other tree-killing bark beetles, *I. typographus* needs fresh spruce phloem for brood development. It typically favours trees older than 60 years that have a diameter at breast height larger than 20-25 cm, but at high population levels beetles may also attack and reproduce in smaller and younger trees. *Ips typographus* has large phenological plasticity in thermally-regulated traits and this allows it to adjust its number of annual generations and generation timing to local climates [68]. Depending on the annual heat sum, *I. typographus* can thus complete more than one generation per year in large parts of Europe [69], a typical trait for bark beetles that are economic pests in Europe [70].

Outbreaks of *I. typographus* are often triggered by windstorms. Storms can provide large amounts of mechanically damaged trees, which is a less well defended breeding substrate than healthy standing trees [**58,63]. Outbreaks can also be triggered by other factors that compromise tree vigour and support the build-up of bark beetle populations, particularly hot and dry weather [3,71,72]. The mechanisms by which outbreaks collapse are not fully understood [**58], but include depletion of remaining suitable breeding substrate, cold temperatures, density-dependent build-up of natural enemies, and various interactions among these factors.

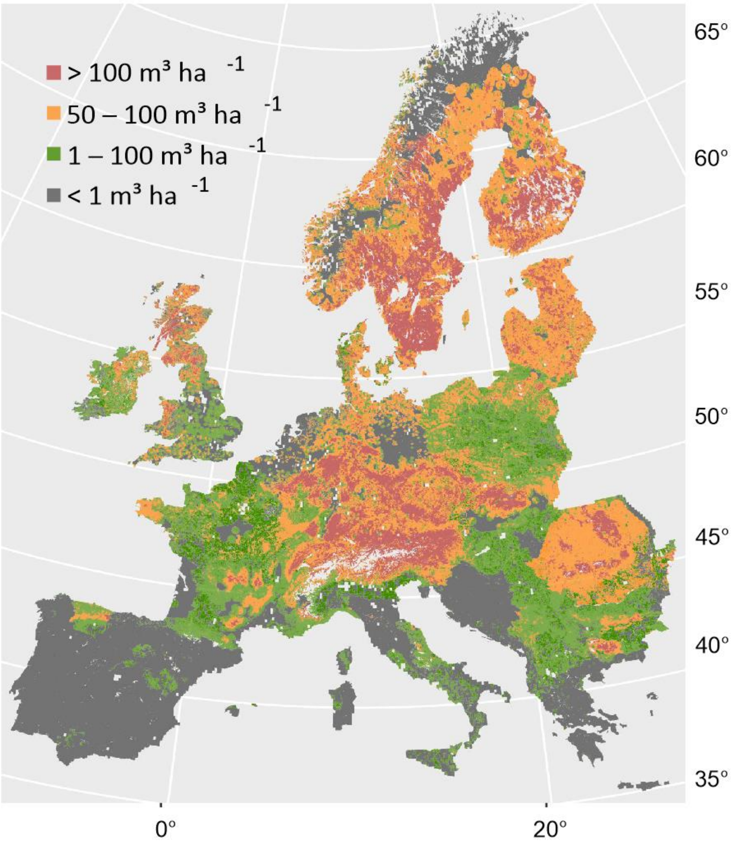

Fig. 3 The current geographical distribution and growing stock of Norway spruce, the main host of *Ips typographus*. Description of used data and methods is in Appendix A.

Management of *I. typographus* either aims to directly reduce beetle populations (immediate control responses) or to modify forest structure and composition to create environments less conducive to outbreaks (long-term preventive management) [42]. Immediate control mainly endeavours to reduce the amount of breeding substrate for beetles by removing trees damaged by wind, snow, rime and other predisposing agents, removing infested trees from the forest before the new beetle generation emerges, and reducing beetle populations using insecticide application or various trapping devices [41,43,44,73]. Preventive management includes different silvicultural practices such as thinning to support tree vigour by reducing tree competition for resources [74], reducing the amount of host trees by changing species compositions [75,76], or shortening rotation periods to reduce the share of mature, vulnerable trees [74,77].

2.2 Effects of climate change

Climate change has a strong amplifying effect on bark beetle population irruptions [57]: (1) it facilitates bark beetle survival and development (e.g. by reducing winter mortality and allowing the completion of additional beetle generations per year [69,78]; (2) it increases potential beetle habitat by allowing beetles to spread into higher altitudes and latitudes [79,80]; and (3) it increases the probability of extreme, region-wide weather events such as drought, which reduces tree resistance [63,81]. Due to these mechanisms, disturbances caused by bark beetles are projected to increase in Europe in the coming decades. Based on statistical models parameterized with past disturbance data and data on forest structure and composition [82], the strongest relative short-term increase in bark beetle irruptions is expected in the Sub-Atlantic region of Europe, i.e. Germany, France, Denmark, the Netherlands, Belgium, and Luxemburg. The average annual damage caused by bark beetles in this region is for 2021-2030 projected to be almost six times higher than during 1971-2010 [1]. These trends are expected to continue throughout the 21st century. Under a warming of +4 °C virtually all spruce forests in temperate Europe will be at high or very high risk from bark beetle infestation (Fig. 4, Appendix B). In general, areas and/or time periods that experience a combination of warmer and drier conditions will undergo particularly strong population irruptions [59,83]. These increases will not occur at a consistent rate, but rather are expected to come in waves that are synchronized across several hundred kilometres and will be triggered by climatic extremes such as cyclonal storms and large-scale droughts [**84].

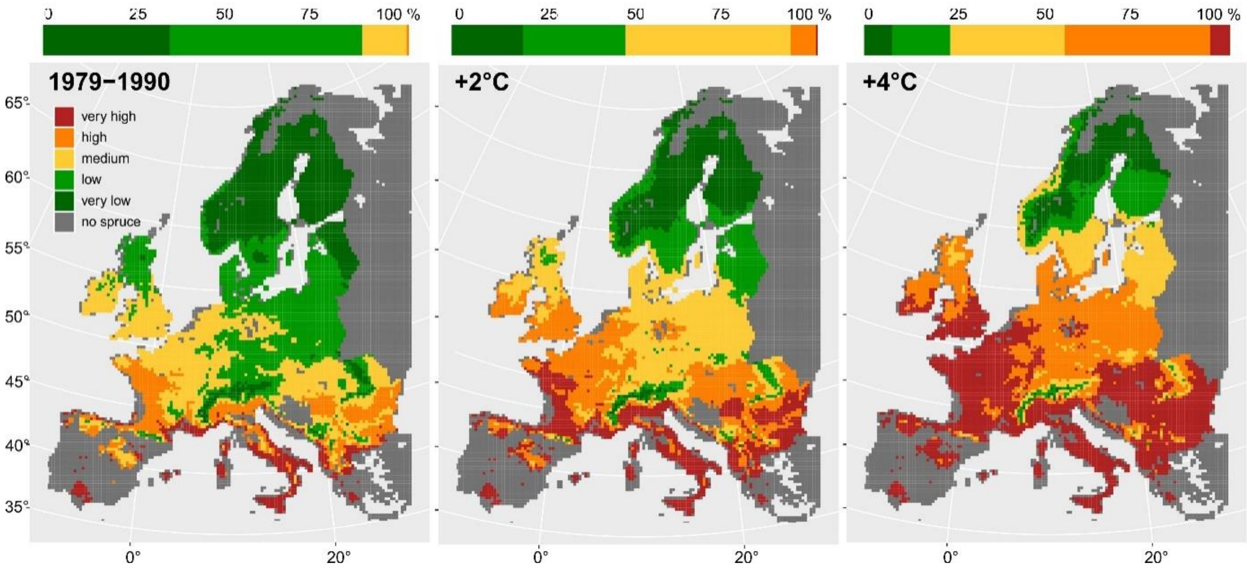

Fig. 4 Probability of a model Norway spruce stand (fully stocked, 100-year-old) being disturbed by bark beetles under historical temperature conditions (1979-1990), and under +2 °C and +4 °C temperature scenarios. Drought conditions were assumed to remain unchanged at the level of 1979-1990, the maps therefore present a conservative estimate. Bars on the top show the relative share of Norway spruce growing stock in Europe in different risk classes. For description of data and methods, see Appendix B.

2.3 Impacts of bark beetle outbreaks

Bark beetle outbreaks affect forest ecosystems and societies in multiple ways, ranging from altered element cycles, to shocks in the provisioning of ecosystems services, to diverse economic and social impacts. We here provide a short synthesis of these diverse impacts as background for the bark beetle management strategy formulated in the following sections.

Element cycles

Large-scale bark beetle outbreaks can have substantial impacts on the biogeochemical cycles of forest ecosystems. Outbreaks reduce the amount of carbon stored in forest ecosystems because of reduced carbon uptake due to a mortality-related reduction in leaf area [85] and increased carbon loss from litter and soil due to increased activity of decomposers [9]. Even though the young forests that emerge after an outbreak may act as sinks for atmospheric carbon [86], a Central European landscape heavily disturbed by bark beetles may require 30 years to reach carbon parity with undisturbed forests [12]. Outbreaks can also result in increased nitrogen mineralization rates and a better nitrogen supply to the foliage of regenerating trees [87]. However, outbreaks might also induce short-term nitrogen losses from the system, for example in the form of nitrate leaching [88]. Due to a reduction in the water use of attacked trees, both water availability in the soil and water runoff increase after a bark beetle outbreak [10]. Also the timing of water runoff can change, as canopy interception is reduced and snowmelt is accelerated in beetle-disturbed systems [11].

Biodiversity

Bark beetle outbreaks strongly alter forest structure [85,89], reset forest succession [90], and create heterogeneous tree cover patterns that lead to more complex forests in the future [29,30,64,91,92]. Outbreaks also increase light availability and the amount of dead wood in forest stands, which is beneficial for many forest-dwelling species [93]. Consequently, many species, including some important red-listed species, respond positively to bark beetle disturbances [32]. The complex post-outbreak landscape patterns can provide habitat for species such as the small hazel grouse *Tetrastes bonasia* and important flagship species of conservation, such as capercaillie *Tetrao urogallus* [94,95]. Nonetheless, the effect of outbreaks on individual species strongly depends on their particular habitat requirements and life history strategy, with both positive and negative effects being reported [54,96]. Stand-replacing tree mortality from bark beetles can cause a decline in endangered species, particularly species that have a limited distribution area. Such examples have been reported after mountain pine beetle and southern pine beetle *Dendroctonus frontalis* outbreaks in the USA [97–100], but there are no cases reported to date in Europe.

Ecosystem services

A meta-analysis has shown that all categories of ecosystem services, i.e. provisioning, regulating, cultural and supporting services, are negatively impacted by bark beetle outbreaks [39, Fig. 5]. The provisioning of timber is affected by bark beetle outbreaks through the need to harvest stands prematurely and a quality reduction of harvested timber caused by beetle-associated blue-stain fungi [101]. Impacts on regulating ecosystem services include an increasing risk of natural hazards such as mudslides and debris flows [102,103]. Also, changes in N cycling can temporarily reduce water quality after bark beetle outbreaks at the local scale, whereas effects at larger scales and over longer time periods are minor [32,104]. Impacts on cultural ecosystem services are manifested by decreased recreational value of bark beetle-affected landscapes [37,105].

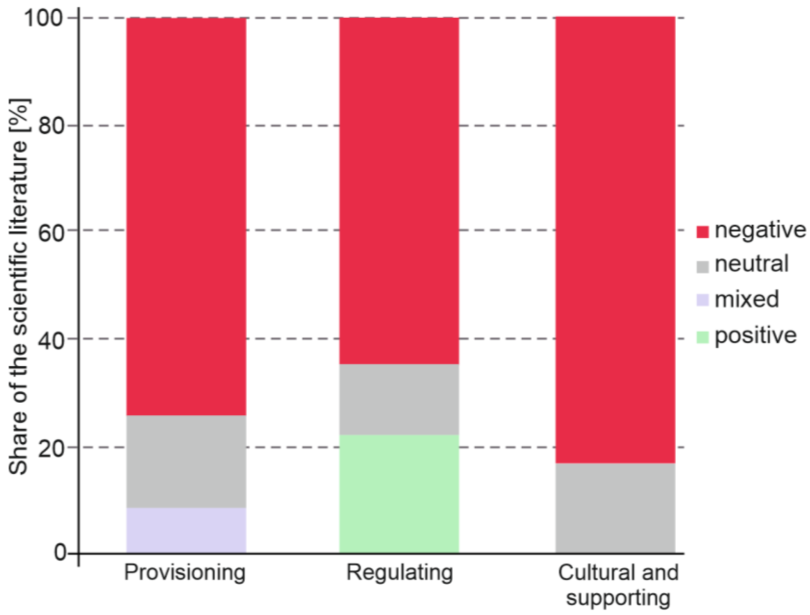

Fig. 5 Impacts of bark beetle outbreaks on ecosystem services. The figure shows the distribution of the evidence of bark beetle impacts collected from 41 scientific papers over different categories of ecosystem services. Source: [39]

Economic impacts

Economic consequences of outbreaks arise from both the direct losses of trees and the market impacts of resulting massive, synchronous salvage and sanitation harvesting [106,107]. Outbreaks result in a pulse of timber supplied to the market and this can lead to positive short-term market dynamics, including a temporary increase in employment, activity (logging, transportation, sawing, wood processing, etc.) and timber exports. However, markets may eventually become saturated with wood, as market participants increasingly attempt to liquidate beetle-killed timber, or even harvest healthy stands in anticipation of decreasing timber prices or future expansion of outbreaks [106]. For example, in 2005 the storm Gudrun and a subsequent bark beetle outbreak caused a temporary decrease in Swedish timber prices from 40 to 25 €/m^3, though prices recovered in the next years [108].

In the short-term, timber-processing companies tend to benefit from the cheap timber generated by bark beetle outbreaks. Timber producers are negatively impacted by reduced timber prices and increased logging, sanitation and regeneration costs. For example, the southern pine beetle caused a short-term economic loss of about $375 million from 1977 to 2004, (in 2004 constant dollars) to the timber market in the southern US. Timber producers lost about $1,200 million, while timber-processing companies gained about $837 million from lower roundwood prices [16]. Similar data for Europe are not available. In the longer-term, as the forests recover, timber supplies and exports are expected to decline and timber prices to rise due to a reduced availability of timber on the market.

However, this increase in timber prices typically does not compensate for the initial price decline, and thus also the long-term economic effect of outbreaks for forest owners is negative [16,107].

Economic consequences of bark beetle outbreaks also include reduced property values [109] and reduced income from tourism [110]. For example, tree mortality caused by the mountain pine beetle in Colorado, USA, induced a 5-22% loss in home values depending on county, timing and severity of the outbreak. By comparison, there was a general increase in home prices in areas not affected by beetle outbreaks during the same period [109]. Effects on recreation values are not so clear; for example, Rosenberger et al. [110] reported that moderate to severe mountain pine beetle outbreaks in the Rocky Mountain National Park (USA) caused important losses in total recreation value. Conversely, Dhar et al. [111], found that overall visitation and revenue earnings were not affected by beetle outbreaks in Canadian national parks. Similar research is currently lacking in Europe and constitutes a major knowledge gap regarding the impacts of bark beetle outbreaks.

Social impacts

Despite the importance and scale of bark beetle outbreaks in Europe now and historically, there is surprisingly little empirical research on the social aspects of outbreaks in the European context. When we did a systematic review of the social dimensions of bark beetle outbreaks, we identified 41 case studies from North America, but only six from Europe during 1978 – 2018 [18,24,37,112–114]. The major social impacts identified in the literature are due to falling trees, fire hazard, aesthetic loss, reduced trail access, land use conflicts, loss of community identity, and affected park visitor experience [e.g. 18–20,24,115,116]. In parts of Europe, bark beetle outbreaks have even triggered social unrests and political instability. In Poland, for example, efforts to control the outbreak in the Bialowieza Forest led to public demonstrations of disagreement with forestry policy, resulting in the involvement of EU authorities [117]. Contrary to these negative impacts, some studies suggest that impacts such as emergent views for tourists and increased ecological awareness of some social groups are positive societal effects [19,37].

When formulating management strategies, it is important to understand the sociological factors that affect how people perceive and respond to natural disturbances. For example, Müller [24] showed how political conflicts over the management of bark beetle disturbance in Germany's Bavarian Forest National Park were rooted in opposite sociocultural attitudes toward the disturbed landscape. Different social groups often perceive and respond to outbreaks in distinct ways. For example, park visitors from local areas often have a more negative view of bark beetle impacts than tourists traveling a longer distance to visit a park [37,116]. Compared to longer-time residents, newcomers report lower satisfaction with land management entities and are less likely to act in response to forest disturbance [118,119].

As human responses to beetle disturbance are directly influenced by the socioeconomic and biophysical characteristics of local communities [120], it is essential to maintain a good balance between diverse community contexts and landscape-scale forest management by incorporating local perspectives into risk mitigation strategies. Perception of threat also varies with time and proximity. For example, research on community responses to a North American spruce beetle *Dendroctonus rufipennis* outbreak on the Kenai Peninsula, Alaska showed that although local residents' perception of beetle-related risks generally decreased over time, concerns remained high about immediate threats to personal property and safety (e.g., forest or grass fire). This suggests the social ramification process of forest risks related to insect disturbances is much more complicated than usually assumed [121].

3. A context-dependent framework for managing bark beetles

Currently applied disturbance management in Europe has emerged based on experiences acquired over the last two centuries. Most European countries have adopted legislations on the management of natural disturbances that require monitoring, control and interventions to mitigate negative impacts on forest resources and economies [122]. Though the level of obligation and details of the prescribed procedures differ among countries, top-down approaches that strive to exert control over the disturbance and the post-disturbance vegetation development prevail. In the case of *I. typographus,* for example, the concept of 'forest hygiene' [e.g. 123] has been broadly advocated. The current disturbance management approach in many parts of Europe thus exhibits features of the *command-and-control pathology* originally described by Holling and Meffe [45] and recently summarized by Cox [48]. This concept describes a problematically large degree of authoritative centralization and control in a governance system. It is characterized, for example, by an inadequate analytical simplification of the problems in question, a preference for 'one-size-fits-all' solutions (the panacea approach), and a lacking acknowledgement of local social and ecological knowledge and practices. The command-and-control approach can lead to deterioration of social-ecological systems and loss of resilience. Recent events have demonstrated the inefficiency of current management approaches to address the intensifying bark beetle outbreaks and an increasing desire of the general public to participate in forestry policy decision-making.

Here we propose a context-dependent management framework that incorporates emergent understanding from disturbance ecology, population dynamics, economics, social sciences, and other research fields. The context-dependency of the proposed approach means that we differentiate between forests managed for different societal objectives. Our approach emphasizes tailor-made solutions for different social-ecological contexts rather than any uniform solution. In particular, we begin with the recognition that effects of bark beetles range from highly positive (fostering biodiversity and contributing to nutrient cycling) to highly negative (reducing desired ecosystem services), depending on site-specific management objectives and the human values that are emphasized. Accordingly, management responses should span the full range from non-intervention (in environments where conservation of natural ecosystem processes is the main management objective) to active prevention and mitigation of excessive population levels (in environments where the main objective is to create economic value from timber production). For the sake of clarity, we first present our ideas for two contrasting societal objectives that represent the end-members of what is actually a continuum of forest management goals:

1. Wood and biomass production to generate economic values: forests managed under this objective dominate in Europe, and a large share of them is stocked with Norway spruce and thus may be affected by *I. typographus* outbreaks (Appendix E). Because bark beetles directly threaten economic values and because the timber industry is an important part of many national economies, interventions against bark beetles are typically legally required in these systems.
2. Conservation of biodiversity, natural processes and other conservation values: forests managed under this objective (henceforth referred to as High Conservation Value Forests; HCVF) include national parks, biological reserves, and wilderness areas. A restricted range of management measures is allowed in these forests, which are designated to conservation by law. Most HCVF are categorized as Wilderness Areas (categories Ia and Ib) or National Parks (category II) according to the International Union for Conservation of Nature (IUCN). Other HCVF include small, strictly protected reserves embedded in production forest landscapes. In Europe, 3.6% of spruce growing stock is located in the IUCN categories I and II, while 23.5 % of the growing stock is located inside protected areas in general. At the same time, 88.9 % of the IUCN categories I and II are estimated to contain spruce and may thus face infestation of *I. typographus* (according to the World Database of Protected Areas; Appendix E).

We do, however, recognize the fact that a large share of Europe's forests is managed for multi-functionality, generating finer-scale trade-offs between the two end-member categories described above. After developing management approaches for production forests and HCVF we therefore elaborate on how management principles may be integrated also into the context of multi-purpose forest management.

3.1 Forests managed for timber production and economic values

A growing body of evidence suggests that many of the present-day production forests stocked with Norway spruce in Europe cannot be sustained under climate change [82,*124]. Still, active management of bark beetles will remain an important task for the coming decades, in parallel with an overall transition of forest management to different tree species and management systems. Effective outbreak management needs to be embedded into a broader agenda of climate change adaptation and a comprehensive risk management framework for the entire forestry sector. To facilitate an integration of the ideas presented here into such efforts we present a framework for comprehensive bark beetle management that includes four complementary components: preparedness, prevention, response, and recovery (Table 1). These phases incorporate infrastructural, legislative, ecological, and social components in a structured but overlapping progression. Some overlap between phases is inevitable, as some specific practices can achieve multiple functions.

We deliberately deviate from the traditional sequence of management phases by placing preparedness before prevention. This allows us to first address numerous legislative, infrastructural and other aspects that operate at largely national and regional scales, thereby facilitating activities in the remaining phases. Preparedness differs from prevention, as prevention mostly addresses bark beetle and vegetation management measures at a scale of forest management units, yet its efficiency is contingent on the level of preparedness. Moreover, management of bark beetle populations often differs from management of other pulse disturbances such as floods and wildfires [125,126], because biotic systems are often characterized by unique density-dependent sources, rates, and degrees of internally generated positive and negative feedbacks [57,64].

Preparedness

From an ecological perspective, preparedness addresses a complex set of measures fostering forest resilience, i.e., the ability to swiftly recover from disturbances caused by population irruptions [51,127,128]. Resilience-oriented management focuses, for example, on maintaining a vital layer of advanced regeneration in the forest, management of disturbance legacies, and maintaining a balanced distribution of late- and early-seral species in the forest to facilitate fast recovery after future disturbances [92,129]. Resilience is an overarching concept that helps to cope with the high level of uncertainty related to future disturbance dynamics and shifting social objectives, and thus underlies all the remaining phases.

The *social aspects* of the preparedness phase includes a number of factors, such as improved education about disturbance management and bark beetle ecology, maintaining sufficient levels of trained professionals on site, strengthening international cooperation in population monitoring and management, developing communication platforms that increase the awareness of all relevant social groups about the multiple roles of forest disturbances, and building relationships with local stakeholders and communities [130]. Involving local communities in the designation of management objectives is a key element in developing a shared understanding of natural disturbances in forests. Such a shared understanding is, in turn, a prerequisite for successful disturbance management [131].

Preparing forest *infrastructure* for bark beetle outbreaks includes the provisioning of ample timber storage capacities to cope with large amounts of salvaged timber and buffer negative impacts on timber markets [132]. Improved forest road networks allow the timely implementation of management responses (including salvage and sanitation fellings) throughout the landscape [133], and sufficient nursery capacities provide enough seedlings of diverse genetic stock of desired tree species for (partial) replanting of disturbed sites [134]. Development of early-warning and hazard rating systems that combine near-real time meteorological data, remote sensing and field surveys can help to identify vulnerable stands and better target scarce management resources [135–138].

Finally, *adaptive legislative frameworks* are an important component of preparing for bark beetle outbreaks. These frameworks should contain evidence-based guidelines for conducting salvage and sanitation operations, and for when it is necessary to plant in order to aid post-disturbance recovery. Legislative frameworks should also provide guidance on the geographical transfer of reproductive material [139] and could be complemented by incentive schemes that support efficient disturbance responses and recovery operations [140]. These instruments also need to be supported by a certain level of international harmonization. Each of these legislative elements must be put into place well in advance of an outbreak so that they can take effect once a disturbance occurs.

Prevention

Prevention mainly focuses on *ecological aspects* and includes population-based measures aimed at preventing the build-up of bark beetle populations, as well as stand-/landscape-based measures that manipulate forest conditions to create environments that reduce the probability of outbreak initiation and spread [30,141]. Prevention addresses a complex set of measures aimed to reduce the likelihood and extent of outbreaks. For example, resistance to outbreaks can be improved by increasing tree species, age, and genetic diversity, by judicious site selection (i.e., planting on sites for which a tree species is well adapted and that has water retention and soil nutrient properties supporting tree resistance to attack), and by promoting natural enemies of bark beetles. By increasing forest diversity, beetle population increases and decreases are distributed more evenly over space and time, thus making large-scale outbreaks less likely. Furthermore, a key element of prevention is quantitative monitoring, tracking changes in populations of native bark beetles and their natural enemies, as well as changes in host tree resistance to attack. In addition, monitoring can track the occurrence and tree-killing capacity of emerging invasive or native pests [142–144].

All these preventive measures include elements such as timely detection and removal of infested trees [41], maintaining compositionally and structurally diverse stands [75,76], increasing host tree resistance by e.g. thinning [74], creating habitats for natural enemies of bark beetles [145], and decreasing landscape-scale host connectivity [30,146]. As these measures are largely consistent with broader objectives of climate change adaptation in Europe’s forests they are likely beneficial beyond the specific aim of bark beetle management [147].

Social aspects of prevention include the coordination of preventive measures across the landscape, particularly when there are multiple owners and when forest lands are managed for different objectives. For example, small-scale owners may not be able to manage scattered windthrows or implement plans on large-scale transformation of forest species composition in an efficient manner without established coordination platforms. Ongoing prevention measures must be effectively communicated to reach wide acceptance of the applied management among forest owners and other stakeholders, although measures included in the prevention phase are typically not a subject of public outcry.

Response

The aims of responding to bark beetle outbreaks are to mitigate outbreak impacts and prevent negative effects on management objectives. *Ecological aspects* include the removal of freshly killed and infested trees to reduce the amount of available breeding substrate and prevent deterioration of timber quality and further reduction of timber value [107,148,149]. The latter aspect is particularly important in Europe's production forests where management decisions are chiefly driven by economic considerations. However, an important management response to outbreaks that should be considered more often is the deliberate decision to make no intervention. This can be the most efficient option when tree removal is likely to have little effect on bark beetle populations, may compromise the provisioning of ecosystem services, and interferes with post-outbreak recovery [49,52,150]. *Infrastructure* supporting evidence-based responses to bark beetle outbreaks includes the development and application of formal models that help decision makers evaluate the inherent trade-offs of various response measures [151,152]. *Social responses* to bark beetle outbreaks include the decision to reduce planned harvests elsewhere (in order to compensate for high levels of salvage harvesting in disturbed parts of the landscape), and the temporary storage of salvaged timber to buffer market impacts. Preventing injuries by falling dead trees, e.g. along hiking routes, is another important response measure. Finally, maintaining an open dialogue with stakeholders can reduce the risk of negative reactions towards the applied response measures [23].

Recovery

Recovery measures aim to support the establishment of a new tree cohort on disturbed sites and the recovery of forestry economies affected by a disturbance. Recovery measures thus focus on creating forest structures that are consistent with management objectives and are resilient to future changes in climate and disturbance regimes [51,153]. Measures include silvicultural approaches to foster diverse stands [154,155], maintain sufficient early-successional species across the landscape (due to their ability to swiftly recolonize disturbed patches), and integrate disturbance legacies (e.g., individual surviving trees, standing and downed deadwood) into the recovering forest [156]. In order to enable natural regeneration, ungulate populations should be kept low, particularly during the initial recovery phase. A *social aspect* of disturbance recovery includes subsidies for recovery measures. Such subsidies could, for instance, support the planting of new species that are better adapted to future conditions, or distribute economic risks among forest owners via forest insurance schemes [157]. Still, negative aspects of subsidy policies, such as a reluctance of forest owner to insure and invest in prevention, need to be considered [17]. Maintaining a dialogue with all stakeholders allows tracking changes in risk perceptions. We note that many recovery measures are contingent on measures taken to increase the preparedness to bark beetle outbreaks (e.g., an increased capacity of nurseries, the presence of a vital cohort of advanced regeneration, an adapted density of ungulates), illustrating the interconnectedness of measures taken along the four steps proposed here.

	Preparedness	Prevention	Response	Recovery
Objectives	Revise forestry education	Reduce the risk of outbreaks	Prevent outbreak expansion	Secure regeneration of disturbed stands
	Strengthen international collaboration in disturbance management and monitoring	Keep high level of awareness about forest conditions and pest populations	Mitigate social, economic and environmental impacts	Foster climate-adaptedness and resilience of the new forest generation
	Build relationships with local communities	Maintain a high level of forestry infrastructure	Monitor and forecast outbreak development	Monitor recovery dynamics
	Establish forest and pest monitoring systems and data dissemination protocols	Reduce the risk of negative public response to preventative measures	Reduce the risk of negative public perception of applied response measures	Consolidate affected forestry economies
	Support advanced regeneration		Secure coordination of disturbance management in multi-owner landscapes	Inform the previous management phases about the effect of measures taken
	Secure coordination of disturbance management in multi-owner landscapes			
	Monitor forest conditions and pest populations			
	Maintain and enhance the level of forestry infrastructure			
Measures	Develop new curricula for education and training at all levels of forest policy- and decision-making.	Quantitatively sample populations of bark beetles and predators using pheromone traps and remote-sensing systems, and disseminate data	Apply knowledge-driven sanitary operations	Maintain high nursery production of seedlings of desirable species and provenances
	Develop communication platforms for multi-stakeholder dialogue, and engage social scientists and professionals	Apply knowledge-driven sanitary operations	Apply salvage operations addressing trade-offs between the mitigation of economic impacts, and collateral impacts on the environment and the recovery process	Subsidize recovery measures

	Develop data-driven crises plans for managing large-scale forest disturbances	Maintain tree vitality using silviculture operations	Reduce regular harvests and exploit storage capacities for salvaged timber to buffer impacts on the market	Support affected forest owners and economies to speed-up their recovery
	Develop high-level timber storage, nursery, and transportation infrastructure	Foster complex forest structures and diverse species compositions, reduce the share of spruce	Subsidize response measures, including tax reductions and other indirect measures	Keep density of ungulates low to protect forest regeneration
	Develop decision-support systems to guide salvage and sanitation operations with regard to multiple objectives	Create forest landscapes that prevent a large-scale spread of outbreaks	Communicate response measures to the public to prevent undesired responses	
		Communicate preventative measures to the public via diverse dissemination platforms		
Tools	Modern teaching materials	Improved monitoring tools and protocols	Models for spatial and temporal optimization of disturbance management operations	Tree species distribution models to optimize planting for future climate conditions
	Improved monitoring tools, such as intelligent pheromone traps, semi-automatized detection algorithms for remote sensing data, etc.	Hazard-rating models to target preventative measures to high-risk stands	Wood cycle models to identify the bottlenecks in the disturbance-affected forestry sector	Sampling design and protocols to permanently monitor forest recovery
	Models to optimize regional-to-national disturbance management infrastructure	Improved silviculture practices	Targeted subsidy systems	Targeted subsidy systems
	Decision support systems optimizing multi-objective disturbance management operations	Targeted communications platforms and channels	Targeted communications platforms and channels	New repellents and other technologies to manage ungulates
	Preparedness	**Prevention**	**Response**	**Recovery**

Tab. 1 Main elements of a framework for comprehensive bark beetle management distributed along four management phases: preparedness, prevention, response, and recovery. The included elements are representative of a broader set listed in Appendix F. ‘Measures‘ indicate specific actions needed to reach different objectives. ‘Tools‘ indicate specific technologies, materials, legislation and other means that support individual measures.

3.2 Forests managed for biodiversity and nature conservation

The default approach to managing HCVF is to conserve natural processes and not intervene with ecosystem dynamics [38]. The key question related to the management of natural disturbance in HCVF is thus, under which circumstances an active intervention is necessary, and whether interventions are in conflict with the main management objective for these forests, i.e. the conservation of biodiversity [25]. Important considerations include (i) whether a particular disturbance falls within the historical range of variability of a given forest and thus should be treated as part of the natural forest dynamics; (ii) what the social and economic implications of non-intervention are, including a potential loss of recreational value; (iii) concerns about outbreak expansion to adjacent production forests; and (iv) threats to focal species of conservation in a given territory, from both the disturbance itself and the potential management response.

In Europe, most insect outbreaks in HCVF have been and still are caused by native bark beetles. In these cases, bark beetles and the disturbances that result from their colonization of trees are part of the natural system, contribute to natural ecosystem dynamics and often increase biodiversity [158]. A long history of co-evolution between host tree, bark beetle and associated species [159] ensures that a „correction“ by management is rarely required [17,56]. As a consequence of their co-evolutionary history with disturbance, many species in Europe (including threatened ones) are adapted to the early stages of forest succession following bark beetle outbreaks [32,93]. Even some species that were previously considered specialists dependent on the presence of mature stands (e.g., *Tetrao urogallus*) have been found to thrive in the heterogeneous landscapes that emerge after bark beetle disturbances [160]. Consequently, the early successional habitats resulting from an outbreak of a native bark beetle are valuable for conservation [54].

There are, however, situations when active intervention against bark beetles is a justifiable option in HCVF. These mainly include (i) invasions by non-native pest species, (ii) a range expansion of native bark beetles into habitats that have not been occupied by them previously (e.g., due to climate change), (iii) threats to trees or stands of exceptional conservation value (e.g., the last old-growth remnants of a certain area), and (iv) threats to focal species of conservation. We elaborate below the conditions under which active management interventions might be justifiable in HCVF and how such interventions might differ from those made in commercial forests.

Risk from non-native pests

Invasive species, i.e. the most damaging introduced species, can have severe impacts on HCVF and cause dramatic changes to their historical disturbance regimes [161]. In Europe's Norway spruce forests, no invasive bark beetle species have emerged to date. However, at least 18 non-native bark beetle species have established in Europe already, and introductions occur at an accelerating rate [162]. Because most invasions take place at large spatial scales (i.e., beyond the boundaries of individual conservation areas), management options in HCVF are limited. The most efficient means to halt species invasions are coordinated nationwide or international actions [e.g. 163].

Expansion of native bark beetles into new territories

An emergent situation in some HCVF is that native bark beetle species expand their outbreak range into higher altitudes or latitudes in response to climate change. This might critically impact conservation values and disrupt natural ecosystem dynamics in HCVF. The beetles may encounter evolutionarily naïve or semi-naïve host trees, i.e., trees with no or little prior contact with the beetle over recent evolutionary history, and which therefore lack effective defences [164]. One well documented example is the elevational shift of mountain pine beetle in North America into high-elevation whitebark pine *Pinus albicaulis* forests, which have relatively low resistance against attacks [165]. This has resulted in high tree mortality that reduces the availability of whitebark pine cones as food for grizzly bears (*Ursus arctos horribilis*) and other endangered wildlife, and has created multiple other adverse environmental impacts [166]. In Europe, *I. typographus* expands its range into northern Europe in response to relaxed temperature limitation [167] and its outbreak range into higher elevations in protected areas of the Alps [80]. Further south, the northern bark beetle *Ips duplicatus* is expanding its range southwards in Eurasia, causing considerable damage to spruce forests in some locations [168]. Range expansion of native species needs to be continuously monitored and containment actions could be considered. However, currently no immediate conservation threats are known from range expansions of native bark beetles in Europe [24]. Furthermore, these expansions could conceivably help forests in high latitudes and elevations adapt more quickly to the emerging climatic conditions [169].

Risk to trees and stands with high conservation value

Old-growth forests are rare in most parts of Europe [170]. They typically have forest structures that are associated with high resilience to disturbances and have high biodiversity. Moreover, old-growth forests show lower climate sensitivity than younger forests [171]. Relict stands of old trees are thus highly valued by conservation managers and the general public, and are frequently under strict protection [172]. Because these stands are usually small, active management tools such as antiaggregation pheromones or sticky traps can be considered in efforts to sustain such stands in the face of a bark beetle outbreak. However, whether such relict stands can be protected from bark beetles in the long run remains uncertain.

Risk to focal species of conservation

Large stand-replacing bark beetle outbreaks can threaten local populations of species of conservation concern, particularly if their remaining habitat is small. To date, no threats from bark beetles to species of conservation concern have been reported for Norway spruce forests in Europe. However, examples from North America illustrate the potential for negative effects of bark beetle outbreaks. Populations of the endemic squirrel *Tamiasciurus hudsonicus grahamensis* declined sharply in response to an extensive mountain pine beetle outbreak [97], and the endangered red-cockaded woodpecker *Leuconotopicus borealis* suffered from the loss of cavity trees after bark beetle attacks [100].

Management options

The most common tools for controlling outbreaks by native bark beetles in HCVF are similar to those applied in production forests [*173]. However, several recent studies have shown that management measures such as salvage logging can have adverse impacts on conservation goals [174,175]. These impacts include the declines in native species populations [54], a shift in community assembly processes [50], reduced natural regeneration [176], and the loss of key forest structures, such as abundant deadwood and old legacy trees surviving the disturbance [177]. If bark beetle control measures are implemented in HCVF, their benefits need to be balanced against their negative impacts, and measures to minimize negative impacts need to be taken.

Beyond the measures already discussed for production forests, a widespread approach for managing bark beetles in conservation areas of Europe is zoning, i.e. designating a non-intervention zone at the core of a protected area that is buffered by a management zone of sufficient width to prevent bark beetle spread into surrounding managed forests [178]. Typical buffer widths for management zones are between 200m and 500m for *I. typographus*. Zoning also increases the social acceptance of non-intervention in core zones of protected areas, as it dispels the widely held belief that protected areas act as sources or epicentres for bark beetle outbreaks. In fact, recent research indicates that large, unmanaged HCVFs in Europe often attract more bark beetles from surrounding managed forests than they export [179].

Another regularly applied management approach for bark beetles in HCVF areas is “low impact” salvage logging that preserves part of the biologically legacies created by the disturbance. This can be done for instance by debarking infested trees to effectively destroy the beetle brood but retain the deadwood in the forest. This approach is expensive and also has negative effects on a broad community of organisms that depend on the specific microclimate under the bark of beetle-infested trees. In recent years, an equally efficient tree-level approach with lower biodiversity impact has been developed ("bark scratching"), in which multiple longitudinal strips of bark are removed from fallen trees [180]. In addition to benefiting biodiversity, bark scratching has also proven to be economically and aesthetically advantageous compared to complete debarking of beetle-infested trees.

3.3 Multifunctional forests

The two approaches to dealing with bark beetle disturbances described above are representative for the end-members of management objectives along a production – conservation gradient. As such they can be applied in areas where commodity production and conservation are spatially segregated, and where buffer zones between the two categories mitigate undesired interactions. However, in many parts of Europe an integrative, multi-functional approach to forest management prevails. In forests managed for multiple objectives managers usually aim to simultaneously produce timber and maximize the habitat value of the forest ecosystem [181]. Consequently, reconciling the two alternative approaches to dealing with bark beetle outbreaks remains a challenge for multifunctional forest management. No general recommendations for how to address these challenges can be given, as the success of management depends strongly on the specific management objectives and local contexts, which are highly diverse across Europe. Nonetheless, we here formulate some general ideas that can guide the development of a tailor-made bark beetle management strategy within the frame of the end-member approaches described above:

- The spatial scale of integrative, multi-functional forestry should be reconsidered. Traditionally, the stand scale has been the focus of management considerations in Europe, and the goals of multi-functionality have also largely been assessed at this scale. However, achieving multifunctionality at the stand scale might be near impossible in the face of landscape-scale drivers such as bark beetle disturbances. Instead, we propose to adopt a landscape-scale approach in which the benefits of bark beetle containment on forest production can be maximized by focusing on particularly valuable and vulnerable stands, while natural disturbance dynamics can be allowed in other parts of the landscape (with lower importance for the locally relevant portfolio of ecosystem services) [e.g., 182].
- Non-intervention should not be categorically rejected as a management option in multifunctional forests, especially if salvage and sanitation logging are not feasible due to market, logistic and other reasons. In such cases, non-intervention could limit disturbance-induced losses and increase forest biodiversity through deadwood retention. Advanced

planning tools for multi-criterial optimisation of salvaging decision can be used to support such considerations [183].

- Financial incentives should be established that facilitate integration of natural disturbance dynamics into landscapes managed for multiple ecosystem services. These incentives could compensate forest owners for (i) potential losses of marketable ecosystem services due to bark beetles, and (ii) losses due to management restrictions resulting from natural disturbances. As bark beetle disturbances are a potent means to increase the biodiversity of managed forests (e.g., by enriching their deadwood stocks; [158]) funds for biodiversity conservation could be used to incentivize a more balanced disturbance management in multi-functional forests.

- Improved information about the potential roles and effects of bark beetles are particularly needed in multi-functional forest landscapes. Because such landscapes aim to fulfil many functions simultaneously they usually also have a large and diverse set of stakeholders. Raising awareness of the trade-offs involved in bark beetle management and clearly communicating the rationale behind individual management decisions (e.g., salvage logging in some parts of the landscape, no intervention in others) is of paramount importance to increase the local acceptance of bark beetle management in multi-functional forests.

4. Discussion and conclusions

Recent decades have seen a dramatic change both in the dynamics of bark beetle outbreaks and in public attitudes to and perceptions of natural disturbances [26,37,96]. The adaptation of management strategies, however, lags behind these social-ecological changes, eroding the ability of management to address the emerging challenges. Although several synthesis papers on different aspects of bark beetle ecology and management have been published recently [*14,**58,63], Wermelinger [42] – published 17 years ago – remains the latest comprehensive review paper on the management of *I. typographus* in Europe (but see relevant syntheses of bark beetle management by Fettig and Hilszczański [184] and the work of Fettig et al. [141] for *D. ponderosae*). The last decades have seen a remarkable advance in our understanding of outbreak drivers and impacts, principles of ecosystem management, governance, and the prominent role of climate change in the dynamics of ecological and social systems. These advances suggested the need to reconsider previous strategies for bark beetle management. In this paper we have synthesized the current understanding of bark beetle ecology and formulated a new management framework to address the bark beetle outbreaks of the coming period. Cornerstones of the management strategy outlined here are context-dependency, a holistic integration across the entire management cycle, consideration of how ecosystem dynamics are affected by climate change, and recognition of the social-ecological complexity of managing bark beetle outbreaks.

4.1 Context-dependency

Current outbreak or, more broadly disturbance management often applies a unified set of measures across diverse environments and management objectives. Yet such measures can fit some social and ecological conditions better than others. For example, a global survey revealed that salvage felling is frequently implemented in protected areas to control outbreaks and recover economic values [*173], even though this practice contradicts the main management objective in these areas, i.e. nature conservation. Insufficient coordination between societal objectives and management strategies often stems from poor understanding of the role of natural disturbances in ecosystem dynamics and an absence of shared management objectives [*14,131]. In HCVF, for example, efforts to control disturbance dynamics are often motivated by unrealistic expectations of how much mature and old-growth stands there should be on the landscape, and the perception of disturbed forest as a less desirable state [17,56]. This implies that clear formulations of management objectives based on a consensus among relevant stakeholders is a precondition for successful management, an aspect that remains largely underappreciated in the current bark beetle management practices.

Apart from differences in local management objectives, ecological and geographical gradients form another dimension along which management strategies need to be organized. For example, bark beetle management can be more successful in thermally limited environments, such as mountain regions and high latitudes, where a harsh climate keeps bark beetle populations below the eruptive threshold. This, however, may differ at lower elevations and latitudes, where spruce has often been artificially introduced and where biotic risks are generally high [4]. Therefore, while management can succeed in controlling bark beetle populations in harsher climates, management should predominantly focus on transforming forest structure and composition in regions that are more favourable to the beetles. Here, outbreaks can also effectively catalyse forest transformation and provide negative feedback to future disturbances [64,169]. We also note that our Europe-wide projections of bark beetle risks show that the extent of low-risk areas will decrease dramatically with increasing temperature (Fig. 4), and options for active containment of beetle populations will thus likely diminish.

To address the problem of context-dependency, we organized our framework around two contrasting management objectives that represent end points along a management continuum relevant for European forestry: delivery of timber production and economic values versus biodiversity and nature conservation [185]. Still, since much of Europe’s forests are managed for multi-functionality our proposed framework must be adapted to address challenges arising from e.g. conflicts between concurrent management objectives [186,187]) or from beetles migrating between forests with different management objectives [179,188]. Such problems cannot be addressed effectively in the face of an outbreak, but rather require extensive and long-term institutional and legislative adaptation (e.g. improved education, development of compensation payment systems; [189,190]). This highlights the importance of preparedness for effective disturbance management. However, while a firm and evidence-based approach to the two major management objectives should be taken at the sectoral level (forestry vs. nature conservation), there is a range of embedded contexts, which need to be addressed at decision-making and operational levels.

In the case of production forests, active management of bark beetle populations is the default option because outbreaks threaten the desired ecosystem services [39,102]. However, many situations may call for differentiated treatments, such as different bark beetle population levels, the distribution and conditions of host trees, institutional settings and market conditions. Therefore, centralized management that applies a unified set of measures without considering the local context will often be a misguided strategy. Instead, tailored management approaches that include balanced combinations of monitoring and forecasting, preventive measures, salvage and sanitary operations, silviculture and non-intervention need to be formulated. For example, as opposed to the current European practice, we suggest that non-intervention could become an increasingly used response if outbreaks are strongly driven by external factors, such as climate change and if timber prices are depressed by large pulses of disturbed timber. Obviously, formulating management systems tailored to such a broad range of contexts requires new management planning tools. We therefore encourage the scientific community to develop tools coupling process understanding of climate-sensitive disturbance dynamics with decision support systems, and develop a portfolio of management strategies for different contexts. Implementation of such context-specific management will increase the demand on human resources, education and training.

Contrary to production forests, non-intervention is a default management option in HCVF because it is most compatible with efforts to preserve biodiversity and other conservation values [38]. Still, climate change and other anthropogenic processes, such as increasing rates of biological invasion, challenge the current static conservation paradigm [191]. This may shift disturbance regimes from their historical ranges and put conservation values at risk. To date, the management of HCVF only rarely considers challenges due to shifting climate and disturbance regimes, and relevant policies and operational guidelines are missing. To address this gap, we have summarized situations where bark beetle outbreaks interfere with conservation objectives and require active intervention [161,192]. We suggest that Europe`s conservation policies should incorporate the lessons learned in North America and Asia [e.g. 193], where conservation objectives have already been put at risk from altered biotic disturbance regimes in the recent past. Such insights can inform European conservation policies, improve monitoring networks and management guidelines, and help Europe reach its conservation targets.

4.2 Holistic perception

Centralized and reductionist ‘command-and-control’ strategies for outbreak management are becoming less efficient in the highly complex, uncertain, and rapidly changing conditions that forest ecosystems are confronted with today [133,194]. Therefore, decentralization and development of strategies tailored to the local context is a key premise for sustainable management [195]. By decentralization we mean the transfer of power from central authorities to lower levels of the administrative and territorial hierarchy with the aim to improve efficiency and accountability, and to better address differences in local contexts [e.g. 196]. The need for decentralization is, however, stage specific – while centralized actions are needed in the preparedness phase (e.g. legislative changes and education), a higher degree of context-dependency is required in the remaining phases. At the same time, managing large-scale outbreaks requires a high-level of cross-sectoral mobilization and formulation of roles, institutions and incentives [197] that support individual (decentralized) actions. We have therefore formulated a holistic framework, which strives to address social and ecological conditions related to managing bark beetles and the disturbances they cause. This framework extends beyond existing approaches in several ways.

First, current management of bark beetles in Europe typically emphasizes direct control of beetle populations, while maintaining only a lose connection with fields such as silviculture, economics, monitoring, infrastructure development, and stakeholder interaction. For example, silviculture can be a critical element in the prevention and recovery phases of the management cycle in production forests, but it can also counteract disturbance management objectives. Although there exist systems that consider trade-offs between the quantity and stability of forest production [198,199], they are rarely deployed (but see [200]). Likewise, Integrated Pest Management [201], which strives to integrate considerations and tactics from a range of disciplines and approaches, has never reached broad acceptance in European forestry [e.g. 202]. We therefore propose that different fields of management, including silviculture, monitoring, economics, ecology, education, and transportation, should be integrated into a holistic outbreak management system. Yet, the complexity of such a system may also hamper practical implementation, as often rigid legislative and organisational settings must be overcome. Recent experiences with bark beetle outbreaks of unprecedented intensity, however, is a strong incentive for changing management strategies.

Second, our framework inherently couples social and ecological dimension of disturbances, and this is recognized to be of utmost importance for resolving different social-ecological problems [55]. Large-scale landscape transformations caused by outbreaks and their management affect human communities and may trigger negative responses towards responsible authorities [e.g. 24,175]. At the same time, the degree of institutional development and cooperation (e.g. between forestry, economy, transportation, and nature conservation) determines our capacity to take appropriate precautionary and responsive measures to face outbreaks, particularly if they occur at large spatial scales. The public is increasingly aware of how forests affect the quality of their lives and thus endeavours to participate in decisions affecting the fate of the forests. This increasingly applies even for countries where participatory approaches do not have a long history, such as the former socialist countries of Europe [203], some of which have become epicentres of the recent bark beetle outbreaks. Such bi-directional social-ecological interactions can determine the overall success of outbreak management and should be addressed across all phases of the management cycle, suggesting that current governance systems need to be revised accordingly.

Third, the behaviour of policy-makers and managers is strongly driven by economic considerations, and these may change over the course of an outbreak, depending on market dynamics. Large-scale and persistent outbreaks may saturate international wood markets and reduce the profitability of selling salvaged wood. Therefore, management decisions need to consider a broader economic context and aim to mitigate negative impacts on the market, for example, by increasing timber storage capacities and reducing planned harvesting and salvaging where possible. More strategic anticipatory decisions may include market diversification and adaptation of regional wood-processing industries towards large amounts of salvaged timber.

Finally, advances in different fields of science have not been adequately implemented into management of bark beetle disturbances. This particularly includes advances in bark beetle monitoring and forecasting based on intelligent trapping devices, remote sensing and machine-learning classification algorithms, process-based ecosystem models addressing climate-sensitive disturbance dynamics, governance systems such as ecosystem management and co-adaptive management, as well as decision-support and resource-allocation systems. We suggest that interdisciplinary methods and technologies need to be organized in a consistent framework throughout all phases of the management cycle.

4.3 Final considerations

Bark beetles are not the only risk that is threatening European forests. Our proposed management framework should thus not be perceived in isolation, but be seen as part of a more comprehensive risk management and climate change adaptation agenda. This particularly applies for the management phases of preparedness and recovery, which are the most forward-looking elements in our framework. We here have included several management options that are broadly beneficial for addressing different types of future risks, such as options aiming to increase the ability to take timely actions (via monitoring, forecasting, social acceptance) and fostering social and ecological resilience [51,128].

In many European countries, rigid legislation, institutions, and logistic limitations can hamper the implementation of here proposed framework, and the mismatch between legal and institutional frameworks and the requirements of bark beetle management could increase further as outbreaks intensify. Insufficient infrastructural and legislative preparedness, along with the low resilience of many European forests, will limit the options for mitigation. The framework proposed here can help to facilitate transitions to new management systems and provide a starting point for managing the forests emerging from the current wave of bark beetle disturbance. Moreover, societal awareness of climate change-driven risks is increasing in many parts of Europe as a result of ongoing outbreaks, potentially supporting a shift in the current bark beetle management paradigm.

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Appendix A: Spruce distribution and growing stock map: Methodology

We produced a map of Norway spruce growing stock in Europe by combining the live tree volume map of Moreno et al. [1] and the tree species cover map of Brus et al. [2]. The data and code can be found at figshare (https://dx.doi.org/10.6084/m9.figshare.c.3463902). The species distribution map is freely available at the European Forest Institute (http://dataservices.efi.int/tree-species-map/register.php). We transformed the volume map from a WGS84 projection with a resolution of 0.1333° to the ETRS_1989_LAEA projection of the tree species cover map with a resolution of 1×1km to facilitate further analyses.

We classified the spruce biomass map into the categories ‘low‘ (up to 50 m^3 ha^{-1}), ‘medium‘ (51 to 100 m^3 ha^{-1}) and ‘high‘ (above 100 m^3 ha^{-1}) biomass levels (Fig. 2).

All analyses were performed in ArcMap 10.6.1 [3]. Graphical outputs were produced in R [4] using packages sf [5], ggplot2 [6] and raster [7].

Appendix B: Probability maps of spruce stands being disturbed by bark beetles: Methodology

The annual probability of bark beetle damage (pBB) across Europe was calculated after Seidl et al. [8] on a 25×25 km grid. We used a constant stand age of 100 years, relative stocking density 100%, and spruce share 100%. Climate data was obtained from the Joint Research Centre (http://agri4cast.jrc.ec.europa.eu/). We calculated the base map for historical temperature conditions using climate data for the period 1979-1990, and modelled two climate change scenarios by adding 2 °C and 4 °C. This approach focuses on the sensitivities to temperature as it expects a unidirectional change in this parameter for the coming decades, while precipitation changes remain uncertain and will likely differ regionally.

$$pBB = \frac{e^{Z_{ijklm}}}{1 + e^{Z_{ijklm}}}$$

$$Z_{ijklm} = \mu + a_i + b_j + c_k + d_l + e_m + (a \times b)_{ij} + (a \times c)_{ik} + (a \times d)_{il} + (a \times e)_{im} + (b \times c)_{jk} + (b \times d)_{jl} + (b \times e)_{jm} + \varepsilon_{ijklm}$$

pBB	probability of bark beetle damage
Z_{ijklm}	linear combination of predictor variables
μ	intercept
a_i	logarithmic mean annual temperature (i = 2-15°C)
b_j	logarithmic mean annual precipitation (j = 500-2 000 mm)
c_k	stand age (k = 100)
d_l	relative stocking density (l = 1.0)
e_m	host tree share (m = 100 %)
ε_{ijklm}	error term

Class width in the presented maps (Fig. 3) was calculated as the difference between maximum and minimum pBB over all maps divided by the number of classes. The resulting probability categories were: 'very low' (pBB 0.3-1.96), 'low' (pBB 1.97-3.63), 'medium' (pBB 3.64-5.29), 'high' (pBB 5.3-6.95) and 'very high' (pBB 6.96-8.63).

Appendix C: Biomass of spruce at risk in Europe

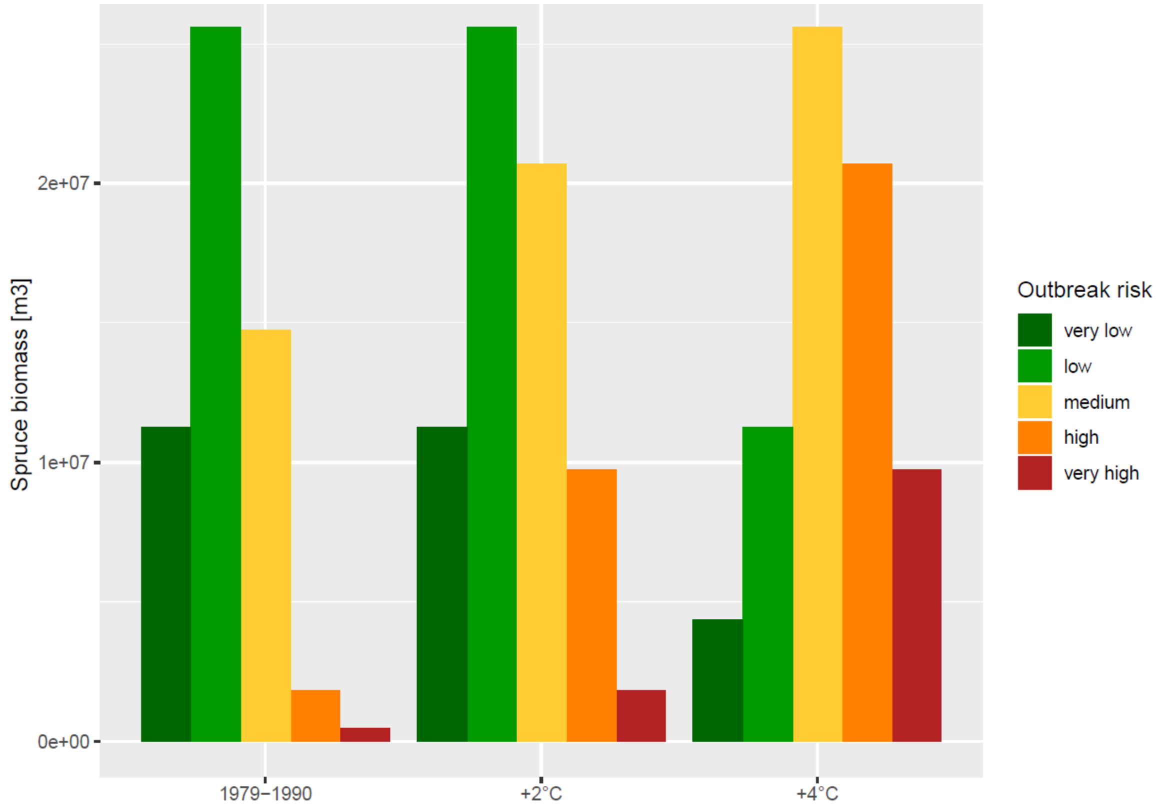

Fig. C1 Absolute volume of Norway spruce in different outbreak risk classes across different temperature conditions. The graph is complementary to Fig. 3 in the main text.

Appendix D: Spruce growing stock in Europe`s protected areas

Proportions of spruce growing stock inside and outside protected areas were calculated by overlaying the spruce distribution map (Appendix A) with the World Database on Protected Areas (WDPA) acquired from the Protected Planet network [9]. Protected areas included in the analysis had the following statuses: designated, inscribed, adopted and established. Further, we selected only those areas that were predominantly or entirely terrestrial. We calculated spruce growing stock for two different categories of protected areas:

1) Highly protected areas: IUCN categories Ia Strict Nature Reserve, Ib Wilderness area, and II National Park

2) Protected areas: IUCN categories Ia Strict Nature Reserve, Ib Wilderness area, II National Park, III Natural Monument or Feature, IV Habitat/Species Management Area, V Protected Landscape/Seascape, VI Protected area with sustainable use of natural resources

Table D1 Spruce growing stock inside and outside protected areas

	Spruce volume (million m^3)	Spruce volume (%)
Total spruce volume	6 987	100
Spruce volume inside protected areas	1 645	23.5
Spruce volume inside highly protected areas	250	3.6
Spruce volume outside protected areas	5 342	76.5

Further, we calculated the number and area of protected areas in Europe falling into the distributional range of spruce in Europe (Appendix A). To identify the distributional range of spruce, we selected areas containing more than 1 m^3ha^{-1} of spruce.

Table D2 Number and area of protected areas inside and outside spruce distribution range

	Total number	No. within spruce range	Total area (km^2)	Area within spruce range (km^2)	No. %	Area %
Highly protected areas	7 134	6 341	179 345	131 593	88.88	73.37
Protected areas	63 463	47 723	696 816	535 902	75.20	76.91

Appendix E: Main items of the comprehensive outbreak management framework

PREPAREDNESS		
#	**Tools & Measures**	**Description**
1.1	Improving education	Development of new curricula, and intensive education and training at all levels of forest policy- and decision-making.
1.2	Strengthening international collaboration	The transboundary scale of outbreaks and the potential introduction and spread of invasive pests require strengthened international collaboration on data and knowledge sharing, pest monitoring and crises management.
1.3	Increasing knowledge transfer and evidence-based decision making	Intensifying outbreaks are increasingly questioning the efficiency of traditional approaches to controlling outbreaks. There is a need for improved knowledge transfer from science to policy, legislation and practical management, as well as the development of best practice examples, to improve management of bark beetle populations.
1.4	Developing effective crises management programmes	Outbreaks occurring at national or supranational scales require well-prepared cross-sectoral responses (forestry, environment, finance, transportation, public security, etc.).
1.5	Developing zonation for nature conservation areas	Landscape-level planning in nature conservation areas should include adequate buffer zones to prevent dispersal of beetles into adjacent managed forests.
1.6	Maintaining multi-stakeholder dialogue	Dialogue should be maintained with all stakeholders involved in outbreak management or otherwise concerned with the forest and its development to increase the efficiency of measures, acceptance of the final outcome, and mitigate the risk of societal conflicts.
1.7	Building relationships with local communities	Building relationships with local communities and clearly communicating risks and potential countermeasures prior to outbreaks lends legitimacy to outbreak management and reduces the risk of societal conflicts.
1.8	Improving and/or establishing systems for monitoring forest susceptibility to disturbance and the dynamics of pest populations	Timely and efficient implementation of management actions require early detection of highly susceptible forest conditions, climatic extreme events that could trigger pest outbreaks, quantitative modelling and sampling of pest densities, and detecting the appearance of new pests.
1.9	Maintain sufficient levels of well-trained professionals	Employment levels in forestry are going down, yet challenges - such as dealing with bark beetle outbreaks - are increasing. In order to be prepared to deal with these challenges it is important to have well-trained forestry personnel on site that knows the local conditions.
1.10	Supporting advanced regeneration	Maintaining a vigorous advanced spruce regeneration facilitates a faster recovery of forest cover after a disturbance event.
1.11	Maintain sufficient nursery capacity	Greatly increased demands on reproductive material of suitable species and provenances after large-scale bark beetle

		disturbances may exceed the existing capacity of nurseries and could result in insufficient regeneration of disturbed areas.
1.12	Developing and maintaining an adequate forest road network	A sufficient forest road network is needed for small-scale interventions, resilience-oriented management, as well as efficient detection and removal of infested trees.
1.13	Increasing timber storage capacities	Sufficient facilities for wet storage of timber function as a supply buffer after windthrows and bark beetle outbreaks by preventing large quantities of timber to flood the market.

PREVENTION

#	Tools & Measures	Description
2.1	Developing early-warning systems and integrating them in outbreak management	Development and maintenance of early-warning systems based on near-real time weather data, automated beetle monitoring, and/ or remote sensing data helps to identify areas with a high risk of bark beetle attacks, and to implement targeted prevention measures.
2.2	Coordinating beetle management across the landscape	Effective management of outbreaks is often complicated in multi-owner landscapes. Plans for coordinated management actions across property boundaries is needed to prevent outbreaks to spread.
2.3	Decreasing landscape-scale host connectivity	Aim to reduce the landscape-scale connectivity of susceptible hosts by implementing targeted landscape management measures that contain the spread of beetles from individual attack spots.
2.4	Use pheromone traps to monitor beetle populations and potential invasions	Pheromone traps can be efficiently used to monitor beetle populations and inform management decisions on timing and intensity of control measures.
2.5	Maintaining compositionally and structurally diverse stands	Mixed stands with a complex vertical and horizontal structure tend to be less likely to generate outbreaks and generally exhibit a higher survival rate under compounding disturbances than monospecific stands of homogeneous structure.
2.6	Reducing the rotation period	Tree vulnerability to wind and bark beetle damage increases with age and tree size. Reducing the area of susceptible age classes reduces the overall outbreak risk.
2.7	Increasing host tree resistance by thinning	Silvicultural treatments that reduce competition between trees can increase tree vigour and resistance against bark beetles.
2.8	Early detection of infested trees	A prerequisite for efficient sanitation felling is the ability to detect infested trees early (in the green attack stage) using a range of terrestrial and remote sensing approaches.
2.9	Reducing outbreak risks by sanitation felling	Removing infested trees from the forest while the beetle brood is still inside can reduce beetle populations, maintain forest health, and decrease outbreak risks. Sanitation harvest of windfelled trees to prevent build-up of beetle populations is also effective.
2.10	Preventing beetle spread from felled trees and logs	Mechanical or chemical treatment of infested windfalls and logs can prevent beetles from leaving the trees and infesting live trees. Another option is the timely removal of infested trees from the forest.
2.11	Creating habitats for the natural enemies of bark beetles	Bark beetles have a number of natural enemies (birds, predatory beetles, etc.). Creating diverse stands with favourable habitat conditions for natural enemies can reduce beetle populations and reduce outbreak risks.

RESPONSE		
#	**Tools & Measures**	**Description**
3.1	Salvage logging	Salvage logging is the removal of infested, windfelled or otherwise damaged trees with the primary intention to recover economic losses. Salvaging needs to take place before timber quality deteriorates. Potential negative impacts of salvage logging on biodiversity should be considered.
3.2	Reducing planned harvests	A reduction of planned harvests can free up capacities for logging of beetle-killed timber and mitigate adverse effects of a temporary timber surplus on the market.
3.3	Subsidising response measures	Responses to a large-scale bark beetle outbreak may require substantial investments, which could exceed the capacity of forest owners. Subsidizing timber transport, storage, and other components of outbreak management can mitigate economic impacts and increase the efficiency of the response actions.
3.4	Considering “no management” as a possible response option	No management needs to be considered as a possible response option in situations where salvaging is not economically viable and extensive sanitary felling, mass-trapping or other measures do not hold promise of containing the outbreak. In such situations, benefits from the retention of biological legacies should be exploited.
3.5	Sanitation logging	Detection and removal of infested trees can be applied to prevent the spread of infestations, particularly for small infestation spots. Trees damaged by wind or other abiotic factors should be prioritized because they have weakened defences against bark beetles and serve as multipliers for beetle populations. Hazard-rating and other types of models can be used to optimize sanitation felling and reduce the connectivity of host trees and beetle populations.
3.6	Increasing multi-stakeholder dialogue and communicating response strategies to the public	Maintaining a good dialogue with all stakeholders involved in outbreak management will improve the efficiency of control measures and the acceptance of final outcomes. Use of the media to communicate management strategies and progress to the general public will raise awareness and reduce the risk of negative responses towards management actions.

RECOVERY		
#	**Tools & Measures**	**Description**
4.1	Fostering diverse stands	During the recovery phase there are excellent opportunities to influence the tree species composition of the regeneration, thereby reducing the vulnerability to future outbreaks.
4.2	Supporting advanced regeneration	Advanced regeneration present on site should be spared during logging operations, as it facilitates a faster recovery of the forest canopy and restores the microclimate.
4.3	Harnessing early-successional species	Regeneration of early-successional species such as birch, poplar, and larch can swiftly establish a new canopy. Commercially more important species can later be planted under this canopy.
4.4	Considering natural recovery processes	Forests have a high capacity to naturally recover from disturbances. Low-cost natural stand recovery options can be considered in areas where a speedy recovery of spruce forests is not of paramount importance and where locally relevant ecosystem services are also provided by naturally regenerating tree species.
4.5	Planting seedlings on disturbed sites	Planting seedlings leads to a quicker recovery of tree cover and gives more control over the future tree species composition.
4.6	Protecting the regeneration against adverse effects	Protection of seedlings against animal browsing and competing vegetation improves the growth rate and quality (shape) of the trees.
4.7	Integrating disturbance legacies into the recovering forest	Disturbance legacies, such as remaining live trees and standing and downed deadwood, can be integrated into the recovering forest rather than being completely removed. Such legacies support the regenerating tree cohort and increase the structural diversity of the recovering stand.
4.8	Reducing browsing by ungulates	Browsing by ungulates is a key limiting factor for regeneration of disturbed forests in many parts of Europe. Ungulate densities should thus be regulated to levels where they do not hamper a successful and swift regeneration of desired tree species.
4.9	Maintaining multi-stakeholder dialogue	Maintaining the dialogue with all stakeholders involved in outbreak management makes it possible to track changing risk perceptions and responses.
4.10	Forest insurance	Forest owners can be insured against certain kinds of forest damage and loss of future income in some countries (e.g. Finland and Norway). This provides an effective distribution of economic risks from disturbances among forest owners.
4.11	Subsidising recovery measures	Recovery from large-scale bark beetle outbreaks may require substantial investments, which may exceed the capacity of forest owners. Recovery actions can be made more efficient by subsidizing afforestation with tree species mixtures, tree species that are well adapted to local climates, protection measures against browsing, etc.

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