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FOREST ENTOMOLOGY (B CASTAGNEYROL, SECTION EDITOR)

Strategies and Barriers to Reconcile Pest Management with Insect Conservation in Temperate and Boreal Forests

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Abstract

Purpose of Review To describe how general prescriptions to protect temperate and boreal forests against pests have been affecting the conservation of insect diversity, (2) to identify potential conflicts between biodiversity conservation actions and pest control, and (3) to provide future directions to reconcile forest pest management with insect conservation.

Recent Findings Despite dealing with the same habitats and organisms, forest pest management and insect conservation have been separate disciplines, often pursuing conflicting goals. However, there is a large intersection between the two, as interventions to control pests can have repercussions on biodiversity and vice versa. In several regions, forest pest management is shifting from reactive measures to contain on-going outbreaks to proactive strategies to create forest landscapes that are more resistant and resilient against pests in the long-term. These developments suggest a possible convergence between pest management and insect conservation objectives.

Summary Several reactive measures adopted to control pests can cause negative impacts on non-target insects, although effects are sometimes localized and often context-dependent. Following ecological, economic, and social considerations, pest management has been evolving towards diversifying forests across multiple spatial scales to reduce the severity of outbreaks and the risk of damage. Such strategies concur with multiple conservation goals to increase insect diversity across intensive forest landscapes. Insect conservation has traditionally targeted saproxylic organisms, neglecting the conservation of other insect guilds and seldom assessing side effects on pests. Despite some important knowledge gaps, we propose complementary approaches to combine multiple diversification strategies at the landscape scale to reconcile pest management with insect conservation.

Keywords Disturbances · Landscape diversification · Multifunctionality · Pest outbreak · Protected areas

Introduction

In the Anthropocene, insect-related forest disturbances have strongly increased in severity and frequency [1, 2]. On the one hand, global change is causing faster insect development rates and lower mortality under a warming climate, providing higher amounts of breeding substrates for wood-boring insects after abiotic disturbances, and reducing the overall forest adaptive resistance to attacking organisms [3, 4]. On the other hand, modern forestry has often created homogenous landscapes of productive forests [5], which are becoming more and more sensitive to insect outbreaks and to other biotic and abiotic disturbances [6]. Against this background, forest pest management has been playing a key role in controlling or preventing damage caused by native and non-native insects attacking boreal and temperate forests. Historically, the central objective of pest management has been to provide effective solutions to reduce timber losses when insects competed with humans for the forest goods, often ignoring the consequences of these interventions on other organisms [7]. Insecticides constituted the earliest and predominant management option, and their application still persists in some regions [8]. However, in the last decades, applied forest entomology has started to focus on proactive actions to reduce the risk of pest damage [9, 10••]. Despite several paradigm shifts, from reactive interventions to more ecosystem-based solutions, new approaches for the management of forest pests are continuously needed to face new threats and to meet changing needs of multiple stakeholders

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[11, 12••]. This is because the social perception of forests has dramatically changed with forests no longer seen as a sole source of timber, but rather as diverse and dynamic ecosystems harbouring high biodiversity, and thus sustaining a wide range of ecosystem functions and services [13]. Since many such functions and services are delivered by insects, there is an increasing awareness of their ecological importance, and insect conservation is slowly entering the global biodiversity conservation agenda [14].

Besides the anthropocentric definition of plant pests, insects underpin pivotal ecosystem functions, such as pest control, nutrient cycling, plant pollination, and herbivory, and they are key components of food webs transferring large amounts of energy from primary producers to higher trophic levels [15, 16]. However, most forests in temperate and boreal regions have been subjected to habitat loss and fragmentation or have been heavily altered and simplified to increase timber production of a few economically important tree species [17]. Hence, a large body of conservation research has focused on saproxylic arthropods or other groups associated with old-growth conditions, while the conservation status of many taxa belonging to other feeding guilds such as canopy-, ground-, and soil-dwelling taxa remains largely unknown [18, 19, 20•].

Forest entomology is now facing the urgent challenge to provide practitioners and owners guidelines to protect existing forests from pest damage and to design more resistant and resilient forests against future known and yet unknown threats, while creating habitat conditions suitable for maintaining high species diversity and associated ecosystem services. Against this background, we aim (i) to describe how forest pest management has historically changed and to identify the consequences of the different pest control approaches on insect conservation, (ii) to identify potential risks for pest control deriving from actions aimed at increasing insect diversity, (iii) to propose strategies to reconcile forest pest management and insect conservation, identifying barriers and knowledge gaps that prevent the implementation of the proposed strategies. The review focuses on temperate and boreal forests because of the large body of research available. We excluded intensive artificial monoculture plantations, such as short-rotation poplar or *Eucalyptus* plantations where pest control relies routinely on insecticides and ecosystem multifunctionality is never considered among the management objectives.

Historical Development of Forest Pest Management and Consequences for Insect Conservation

The need for applied entomology to be integrated into forest management has emerged at the end of the previous century, after growing concerns on the major threats posed by insects to the provision of timber [11]. Over time, forest pest management deeply rooted within the academic education of forest sciences and the forestry sector, where it continues to provide knowledge support for the control of pests in productive forests [7]. Forest entomologists have historically prioritized pest control, paying very little attention to insect conservation, apart from a few flagship species [21]. Thus, despite dealing with the same habitats, forest pest management and insect conservation have been separate disciplines, often pursuing conflicting goals [22]. However, the interventions to fight pests are expected to have repercussions on multiple taxa of conservation concern, and, vice versa, interventions aimed at protecting insect diversity could affect pest population dynamics and related timber losses [23, 24]. As the attention for forest biodiversity conservation is increasing, traditional pest management is losing ground in the forest sciences and forest entomology has started adopting a holistic approach with substantial inputs from ecology and conservation biology [25]. In the following sections, we provide a general overview of the response of non-target insects to the most common control interventions proposed to reduce pest damage [9, 10••]. As the availability of studies testing simultaneously the response of both pests and non-target taxa is very limited, we will qualitatively review studies considering either pests or taxa of conservation concern starting from reactive measures to contain on-going pest outbreaks to more proactive strategies to increase the resistance and resilience of forests.

Reactive Control Measures

Chemical and Biological Insecticides

Applications of insecticides have a long history in forest pest management. Inorganic chemical compounds containing lead arsenate were used to control spongy moth (*Lymantria* dispar) in North America already in 1893, with ground and aerial application equipment gradually adapted from agriculture to reach large and remote areas [26]. A significant leap in insecticide use was represented by the development of organochlorine insecticides, such as DDT in the 1940s. For over 20 years, spray programmes were routinely conducted against the spruce budworm (*Choristoneura fumiferana*) and other defoliating insects in North America [8] and against various pine and oak moths in Europe [27]. Starting from the mid-1960s, evidence on insecticide resistance [28] and alarming environmental concerns over the toxicity on fishes, birds, aquatic invertebrates, and pollinators [29] fostered the development of more specific chemical compounds and alternative pest control approaches. The development of more specific insecticides with lower side effects has continued since then, and several reviews on such developments are available for North America, Europe, and Australia [8, 30, 31].

It is hard to generalize the effect of insecticides on non-target organisms, as their impacts depend on the chemical and microbial compounds used, context, and spatial scale of application. Overall, broad-spectrum insecticide formulations are highly effective against most pests, but have often severe and persistent negative impacts on non-target organisms. Conversely, recent chemical and biological formulations have shown mixed responses both on their efficacy against pests and their impact on non-target organisms [7, 31, 32]. Surprisingly, there are few studies on the topic in the recent literature, and many only deal with short-term effects on single taxa finding mixed responses depending on the selected group [8, 33–35]. Due to their sometimes long-term inefficacy [36], their controversial effects on non-target organisms, and society concerns on impacts on human health, the large-scale application of both chemical and biological insecticides is now considered as a last-resort emergency measure to contain large pest outbreaks [30, 37]. However, they are commonly used at the local scale, for example to protect felled stands [38], seedlings [39], or in urban forests, for instance against pine and oak processionary moth caterpillars with urticating hairs [40]. Despite the potential risks for biodiversity, the application of insecticides might still be considered an option, in particular when highly destructive non-native pests critically endanger the capacity of forest ecosystems to persist. Notable examples are the potential long-term negative effects of a no-intervention strategy to control the invasive spongy moth [41] or the emerald ash borer (*Agrilus planipennis*) in North America [42, 43]. Although large-scale applications of insecticides will likely be even more restricted in the future, thorough research is needed to evaluate the potential cascading effects of chemical and biological insecticide applications to fight on-going native and non-native pests in multipurpose forests.

Semiochemicals

Besides their application in pest monitoring, semiochemicals are also used as pest management tools, with mass trapping, anti-aggregation, and mating disruption as the most common approaches [7]. While some authors question the efficiency of trapping performance for reducing bark beetle populations [44], most studies on the topic conclude that semiochemicals have good potential in locally suppressing low to moderate pest population densities [45] and reducing damage to healthy trees [46]. Notable case studies include the local eradication of small isolated spongy moth populations [47] and the local containment of bark beetles across western North America and Europe [46, 48]. Being highly selective to the target pest species, semiochemicals are considered relatively safe for vertebrates and beneficial insects [45]. In addition, several strategies exist to reduce potential negative effects, such as using trap designs to physically exclude non-target taxa or identifying more species-specific lures that reduce the attractiveness for non-target organisms [49]. As semiochemical-based pest management is usually applied at small spatial scales, the potential negative impact on predators and parasitoids responding to the same cues as the target pest is limited [50] and likely does not cause strong impacts at the ecosystem level.

Classical Biological Control

Invasions of non-native insects are a major impact on forests globally, particularly in temperate regions [51]. Because forests are complex, long-lived ecosystems, managing non-native pests has often successfully relied on classical biological control [52]. Looking at the past, classical biological control has led to the control of at least 226 invasive insects worldwide since 1888, with only a few cases of documented negative impacts [53, 54]. The risks for non-target organisms are generally considered limited as there is an increasing emphasis and legal requirements on the selection of biocontrol agents that are highly host-specific [55]. While some authors warn of potential apparent competition between specialist control agents and non-target native organisms [56], most of these interactions remain hypothetical rather than realized [54, 57, 58] and classical biocontrol is considered an effective, safe, and sustainable method for the long-term management of non-native pests [59]. While in Europe new releases are expected due to the increasing number of non-native species invading temperate forests [55], North America faces a decreasing trend in the adoption of classical biocontrol [60], leading to likely opportunity costs. Provided that a zero-risk scenario is unrealistic in all pest management approaches, recent decision models already adopted in some countries, such as New Zealand, carefully balance the magnitude of social and environmental benefits of classical biological control against the degree of risk that can be accepted [54].

Salvage and Sanitation Logging to Control Wood-Boring Insects

The potential impact on biodiversity of removing damaged and susceptible trees with salvage and sanitary logging to lower the risk of spread of wood-boring pests has been long debated in the academic and policy arena [61]. On the one hand, while it is still common practice to salvage as much timber by logging before it deteriorates, solid scientific evidence of its efficacy in preventing outbreak spread is still doubtful [62]. Recent simulation models show that high effectiveness in preventing bark beetle outbreaks can be achieved only with very high removal intensities [63], while empirical studies sometimes found the contrary [37]. On the other hand, the intensive logging of damaged trees has a clear negative impact on biodiversity and multiple ecosystem services [64]. The insects most likely to be affected are forest specialists such as saproxylic species [65], but also ground- and soil-dwelling species [66], that can benefit from microhabitat and climate heterogeneity related to unlogged disturbed areas. This impact is of particular concern for conservation when logging is carried out in protected areas, besides generating social protests and heated debates among stakeholders [67, 68]. A recent global study indicated that at least 75% of a naturally disturbed area needs to be left unlogged to maintain 90% of its unique species, whereas retaining 50% of a naturally disturbed forest rapidly decreases its unique species richness by one-fourth [69•]. As a result, there is an increasing consensus among ecologists and conservationists that several major pests are in fact keystone species regulating forest disturbance dynamics [11, 70]. However, experiments successfully comparing salvaged and unlogged disturbed areas indicate that some non-saproxylic beetles and pollinators are not reduced by salvage logging operations [71–73] and that salvage logging might even create more diverse communities of saproxylic taxa, likely due to the diversity of deadwood found in salvaged plots [71].

Proactive Management

Forestry Interventions

Since the early 2000s, advances in forest pest management have proposed a shift from directly managing pests and their impacts to a proactive management to indirectly control pests by creating ecosystems that are more resistant and resilient to multiple disturbances [9]. These interventions can be implemented at both the local and landscape scale [10••]. However, at the local scale, it is often impossible to identify a single optimal management due to the variety of practices carried out in one rotation cycle that often cause complex non-linear effects on pests depending on the environmental context and the focal pest species. Similarly, insect diversity responses are expected to be mixed depending on the feeding guilds and species-specific habitat and resource requirements [19]. However, there are some interventions proposed by pest managers that are expected to have more predictable effects on both target and non-target taxa according to the available empirical evidence.

First, increasing tree diversity is generally acknowledged as a winning strategy for reducing pest damage across several forest types through associational resistance (i.e. heterospecific neighbours reduce the risk of a focal tree being attacked by herbivores) [74] and improved pressure from natural enemies [75]. This strategy also concurs with the general conservation goal to increase insect diversity as predicted by the habitat heterogeneity hypothesis, i.e. an increase in the number of niches leads to an increase in species diversity [76]. The effects should be more evident for tree and canopy-dwelling species that profit from higher host plant diversity, structural complexity, and micro-climatic variability [77], but similar effects are expected for ground- and soil-dwelling species due to the increase in biotic and abiotic heterogeneity [78]. Examples in the literature report promising results in replacing Norway spruce monocultures with spruce and birch or spruce and Scots pine plantations in Sweden [79] and in larch-birch mixtures in Chinese boreal forests [80]. However, converting monocultures to mixed-species stands is a social as much as a technical choice and cannot always be achieved in commercial forestry [81]. Under these circumstances, the most adopted alternative is increasing forest structural diversity by applying uneven-aged silvicultural treatments. For instance, shelterwood and selection systems have been shown to promote invertebrate predators while reducing the abundance of bark beetles in Sitka spruce plantations in the UK [82, 83].

Second, the positive effects of tree diversity on insect herbivores at the stand scale suggest that increasing forest heterogeneity could also work at larger spatial scales through landscape diversification [84•], although this strategy has received less attention. For instance, the presence of forest patches belonging to different forest types can reduce successful colonization of suitable stands by pests at the landscape scale [85] or at least reduce the overall timber loss due to the co-occurrence of multiple host species [10••], although exceptions for polyphagous species potentially occurring as metapopulations exist [86]. Again, landscape diversification is often suggested as the key strategy also to boost insect diversity across different taxa and feeding guilds through increased habitat diversity [87••, 88]. However, while there is a strong emphasis on landscape diversity to protect insects in agriculture-dominated landscapes, research in forest-dominated landscapes is limited due to the disproportionate attention to forest-interior organisms relying on deadwood and old-growth conditions [89, 90]. However, it is well known that many forest generalist species are also favoured by a mixture of forests and open habitats such as wetlands, grasslands, clearings, or regenerating stands [91, 92]. For habitat specialists, we should consider that increasing habitat diversity can lead to habitat area limitation and dispersal limitation causing unimodal and even negative relationships between species richness and habitat heterogeneity [93].

Third, thinning is frequently encouraged to increase vigour of remaining trees and reduce infestation levels [94]. For instance, early thinning was strongly recommended in the National Strategy for control of sirex woodwasp (*Sirex noctilio*) in Australia [95] and for increasing resistance to bark beetle outbreaks [96]. However, the effects of forest thinning on other invertebrates are not well understood, and the literature on this topic is mostly anecdotal. The few available studies found that the distribution of insect biomass between thinned and unthinned pine stands varied among taxa, indicating that the response is highly species-specific [97]. However, canopy opening in thinned stands may allow for higher light penetration, which may favour organisms depending on understorey vegetation such as pollinators [91] and soil arthropods [98].

Last, reducing the length of rotation cycles is often suggested to reduce the impacts of several wood-boring species, in particular bark beetles that usually prefer to attack large-diameter trees [10••, 99]. Besides climate change, a key trigger of recent major outbreaks of pests, such as eastern spruce budworm, mountain pine beetle, and Eurasian spruce bark beetle, was the creation of large areas of mature or over-mature forests [84•]. Here, there is a clear conflict with the conservation of species related to deadwood, old trees, and in general to more mature conditions [100]. The risk of increasing forest age, however, depends critically on the spatial scale and on the existing age heterogeneity. Most of the work done in insect conservation has focused on this driver suggesting to either increase tree age and forest continuity within protected areas or to promote old-growth conditions within intensive managed forests. There are also some indications that the protection of remnant old-growth forests within the landscape matrix may be valuable for maintaining the diversity of plant and arthropod predators that can minimize future outbreaks through improved natural biocontrol [101].

Insect Conservation Actions and Potential Risks for Pest Control

Intensive forestry has highly modified natural forest ecosystems, causing alarming impacts on insect diversity [102]. To counteract such negative effects, several habitat enhancement and restoration practices to protect biodiversity have been increasingly implemented, both in semi-natural secondary forests and in commercial plantations. One question that can arise from forest owners, foresters, and applied forest entomologists is whether these measures could also favour pest populations and cause economic losses. The literature on the topic is surprisingly poor, and there are only a few studies that explicitly tested this idea, mostly in boreal forests [23, 103]. In the following sections, we describe the potential pest risks related to the major conservation actions implemented to increase insect diversity.

Promotion of Old-Growth Conditions

In structurally simplified managed stands, such as commercial plantations or intensive forests, the development of many components of old-growth forests to benefit biodiversity can be accelerated through several silvicultural interventions. A wide array of uneven-aged silvicultural treatments [104], retention forestry [105], habitat restoration [18], extended rotation [106], and set-aside [107] have been proposed, with the general aim of enhancing stand structural and compositional diversity. In secondary forests, increasing the availability and diversity of deadwood is among the most common interventions to increase insect diversity. A recent meta-analysis on the impacts of deadwood manipulation on saproxylic insects where also the response of pests was evaluated indicates little-to-moderate risks in restoring larger availability of deadwood for managed forests [20•]. However, these results are related to small-scale interventions such as creation of deadwood from live trees, addition of existing fresh deadwood, or prescribed burning. When the spatial scale of these interventions increases, for instance resulting in the creation of large areas of mature stands belonging to a single forest type, the risk of pest outbreaks could possibly be of legitimate concern [108]. Although these practices can help managed forests to increase their old-growth attributes, true old-growth forests generally host higher insect diversity than improved managed forests [109].

Protected Areas and Natural Disturbance Dynamics

The ecological benefits of natural disturbances in increasing forest complexity across spatial scales have long been recognized [110]. Against this background, many recent conservation studies call for creating permanent protected areas where natural forest disturbance dynamics—including insect pest outbreaks—are retained [111]. Particularly in large disturbed areas, it is essential to limit post-disturbance logging in refugial areas, such as unburned patches in a post-fire landscape or stands surviving bark beetle attacks. Indeed, many authors suggested that logging under these circumstances homogenizes landscapes and should be avoided, particularly in areas with high ecological values [64, 69•]. However, a non-management strategy is often seen as an opportunity for pests to build up their populations and to spread to neighbouring areas [37]. These contrasting understandings of post-disturbance dynamics result in disputes about land management options and often generate political and social conflicts, particularly in Europe, where there is a large extent of land-sharing between forestry and conservation [61].

Increasing Forest Amount and Connectivity Across Mixed Landscapes

Most of the world's forests are interspersed with productive lands [112]. For instance in Europe, 40% of the forests have in their close surroundings a mosaic of other semi-natural, agricultural, and urban areas [113]. It is well known that there are strong and rapid negative responses of forest biodiversity to fragmentation arising from decreased habitat area, reduced connectivity, and the creation of disturbed habitat edges [112]. Recent empirical studies confirmed that habitat amount appears fundamental for the conservation of forest insect specialists at the local [114] and landscape scale [87••]. However, smaller habitat patches can cumulatively sustain higher levels of species richness at the landscape scale and should not be neglected in conservation [115]. Additionally, there is increasing evidence on the importance of connectivity to support specialists with low dispersal ability both at the local and at the landscape scale [116]. Since many insect organisms providing key ecosystem services to crops, such as pollination and pest control, critically depend on forests [117, 118], there is also a strong interest by agroecologists and agricultural entomologists in protecting, conserving, or restoring forests across mixed landscapes [119–121]. However, outbreaks of destructive insect herbivores might also be facilitated by high connectivity among forest patches [122, 123], although pest responses are often non-linear and context-dependent [124]. Understanding the positive and negative effects of increasing forest amount and connectivity across mixed landscapes is needed to help land managers anticipate trade-offs among forest-associated insect conservation, increased risk of pest herbivory, and potential negative spillover between habitats [125].

Knowledge Gaps

In reviewing the available literature about the potential conflicts and synergies between pest management and insect conservation, we identified several knowledge gaps. First, very few studies tested at the same time the effects of conservation measures or pest management strategies on both biodiversity and pests. Similarly, some species that are considered pests in a particular context might be endangered species in others (see for instance ref. [126]), and more research should acknowledge this when suggesting different management actions. Second, because conifers are the most dominant and valuable tree species in current temperate and boreal forest production areas, pest control management and research have focused almost exclusively on these forest types. However, broadleaved forests can host several species of conservation concern and have several highly destructive pests [43, 127], which are not being adequately represented in the literature. Third, insect conservation has largely focused on saproxylic arthropods, while canopy, soil, and water arthropods are still underrepresented in the literature, and insect conservation and pest management might have contrasting effects depending on the guilds considered. Fourth, potential interactions between local (e.g. tree diversity, stand age) and landscape factors (e.g. connectivity, landscape complexity) have been seldom tested. Fifth, while there is much evidence supporting the movement of organisms from forests to other managed land uses in mixed landscapes, very little attention has been given to the potential spillover in the opposite direction [125]. Last, experimental and observational studies are often carried out at small spatial scales and over the short term. Landscape management is increasingly considered a promising frontier for improving forest resistance and resilience to large-scale outbreaks [10••], and more research should focus on multi-actor approaches to land management and explore its long-term cascading effects. To this end, integration of social science with landscape planning and forest management is crucial for understanding where conflicts between policy and practice lie and for overcoming barriers to implementing strategic solutions in forestry.

Reconciling Pest Management and Insect Conservation

One way to cope with increasingly frequent and severe biotic stressors while preserving unique forest insect biodiversity is to promote forest resistance and resilience at multiple spatial and temporal scales [128]. In this section, we combine the principles with empirical support described above to outline complementary operational strategies to reconcile protection from pests and conservation of insect diversity.

Strategy 1: Forest Diversification at Multiple Spatial Scales

There is now a general consensus among forest entomologists that higher genetic, specific, functional, and structural diversity increases the probability of forest ecosystems to resist to damaging insect attacks and to functionally persist after the disturbance [128, 129]. While forest managers and policymakers are increasingly acknowledging the benefits of tree diversity at the stand scale [5, 74, 130], this strategy has been recently proposed also at the landscape scale [10••, 84•]. Forest diversification at the stand scale is expected to support also a wide range of species associated with multiple habitats, thus being key to insect conservation [131–133]. Similarly, conservation synthesis studies have concluded that the best overall biodiversity outcome can be achieved through a mosaic of different forest types within the same landscape [134, 135]. Despite increasing evidence of multiple benefits, planning the diversification of productive forests is a complex task, and several open questions still remain.

First, a major knowledge gap is the operational resolution of the forest landscape mosaic. Global analyses suggest that multiple ecosystem functions increase synergistically with plant diversity at higher spatial scales [136]. However, since managing landscapes for resilience becomes more challenging as the scale of interventions increases, it is essential to find compromises between the highest opportunities to reduce pests and an optimal achievement of insect conservation goals. Solid scientific knowledge on ecosystem diversification and the associated costs of transforming a pure forest into a mixed forest is available only for a few systems [137] and at the local scale [138]. Additionally, even at the local scale, many diversification aspects still need further clarifications, for instance the choice of the best species identity and the proportion of each mix component to simultaneously decrease stand vulnerability to pests and to increase insect diversity [139, 140]. Finally, despite the positive general trend for pest control, it is important to consider that tree diversity has highly variable outcomes depending on taxa and study systems [75], with some authors reporting even associational susceptibility [141].

Second, the underlying forest ownership structure and the regulatory system in place within a country are key elements for the implementation of any kind of landscape diversification interventions. For instance, the achievement of large-scale conservation designs will occur more readily in landscapes containing large blocks of public or former timber industry forestlands [142]. Conversely, landscapes dominated by small-scale private owners have greater potential to strengthen sustainable development in forestry that integrates nature conservation and timber production, due to increased variability in scope, management, and practices at finer spatial scales [143, 144]. Recent outbreak events and post-disturbance management approaches have readily demonstrated the increasing desire of the general public to participate in decision-making [12••]. Participation of different forest owners coupled with inclusive policy instruments and supported by effective governance systems may foster the development of novel management solutions addressing forest multifunctionality [145]. Despite the profound impact of public engagement on the sustainability of actual and future forest management and of the fulfilment of national policy goals, this socio-ecological aspect is seldom included in research on forest management.

Third, when designing diversified forest landscapes, it is necessary to consider also the contribution of non-forest habitat patches in determining the dynamics of both pests and insects of conservation concern (Fig. 1). Besides forest diversification at the landscape scale, recent syntheses have proposed to decrease the matrix contrast with forest habitats through increasing tree cover, promoting semi-natural elements and agroforestry [87••, 146]. This is likely to promote forest habitat connectivity, supporting beneficial forest insects and related ecosystem services to non-forest habitats. Moreover, forest patches embedded in a high-quality matrix could boost forest-dwelling natural enemies across heterogeneous landscapes, potentially minimizing the spread of insect pests to the forest interior. While increasing landscape

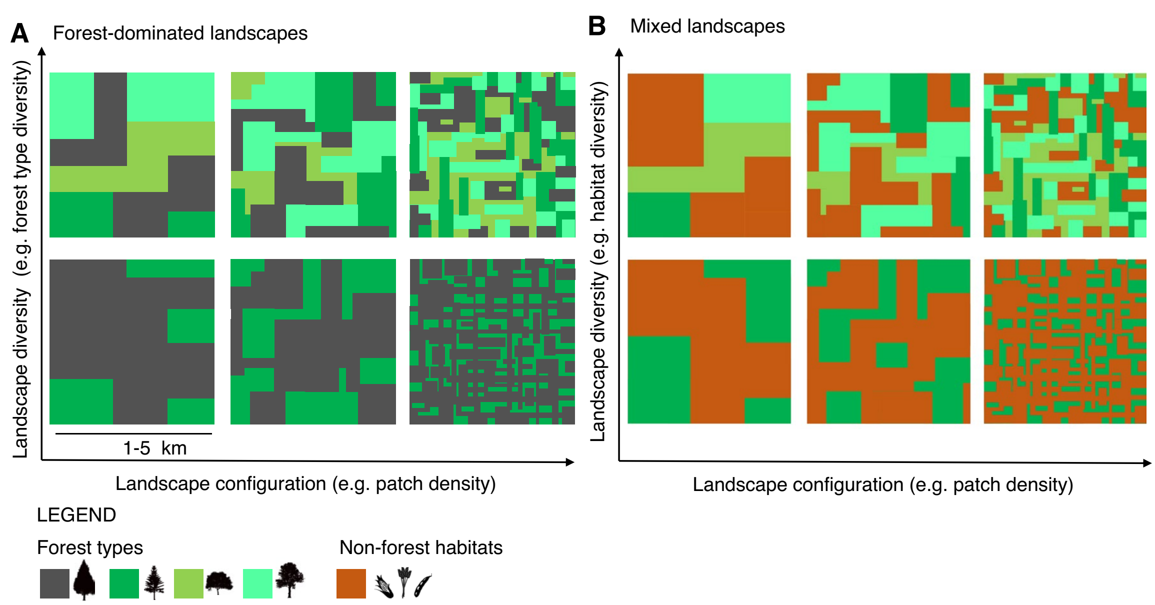

Fig. 1 Different scenarios of landscape diversification where both landscape composition and configuration vary in A forest-dominated landscapes and in B mixed landscapes where forestry co-exists with other land uses (e.g. agriculture or urban areas)

diversity appears as a promising approach to improve conditions in intensive and homogenous forest landscapes, we should not neglect the need to protect entire landscapes of old-growth forests where natural dynamics can be allowed at large spatial scales. To inform forest managers and land planners with sound evidence on how to best improve forest resilience with diversification, it is fundamental to set up real-world experiments integrating concepts of biodiversity and multifunctionality, including multiple spatial scales and multiple aspects of structural diversity of forests [147•]. Although agricultural entomology, forest entomology, and forest insect conservation would benefit from sharing knowledge and perspectives, the delivery of agriculturally relevant ecosystem services should not be the primary argument for the conservation and restoration of forests, that have important values per se.

Strategy 2: Explicitly Incorporate Insects in the Design and Management of Protected Areas

Although 18% of global forests are currently included in protected areas, only c. 10% of boreal and temperate forests are under protection [17]. Because of their major role both as forest disturbance agents and taxa of conservation concern, insects should be explicitly considered in the design and management of protected areas [14]. Due to the relatively low requirements in terms of habitat amount and resources of many insect species, these protected areas could be sometimes smaller than those designed to protect vertebrates [89, 115, 148]. In mixed landscapes, the pest-related risks connected to protected areas are unknown [109], while they can be more substantial if landscapes are dominated by single tree species in former productive forests [149, 150] (Fig. 2A). One key question to design protected areas for insects and to tailor management to meet their habitat and resource requirements is whether there is a good cross-taxon congruence with other groups of conservation concern. Here, most of the available data come from saproxylic insects, which usually exhibit weak, positive correlation with other taxa such as fungi, bryophytes, plants, or birds [151]. As in many other ecosystems, the lack of data on species occurrence, population trends, and level of threat are still the major constraints in insect conservation.

Strategy 3: Management of Natural Disturbances to Benefit Both Biodiversity Conservation and Forest Protection

Disturbances may support insects of conservation concern [152], but simultaneously increase pest outbreaks irrespective of other climatic triggers [153]. As outlined above, the strongest conflict between pest management and insect

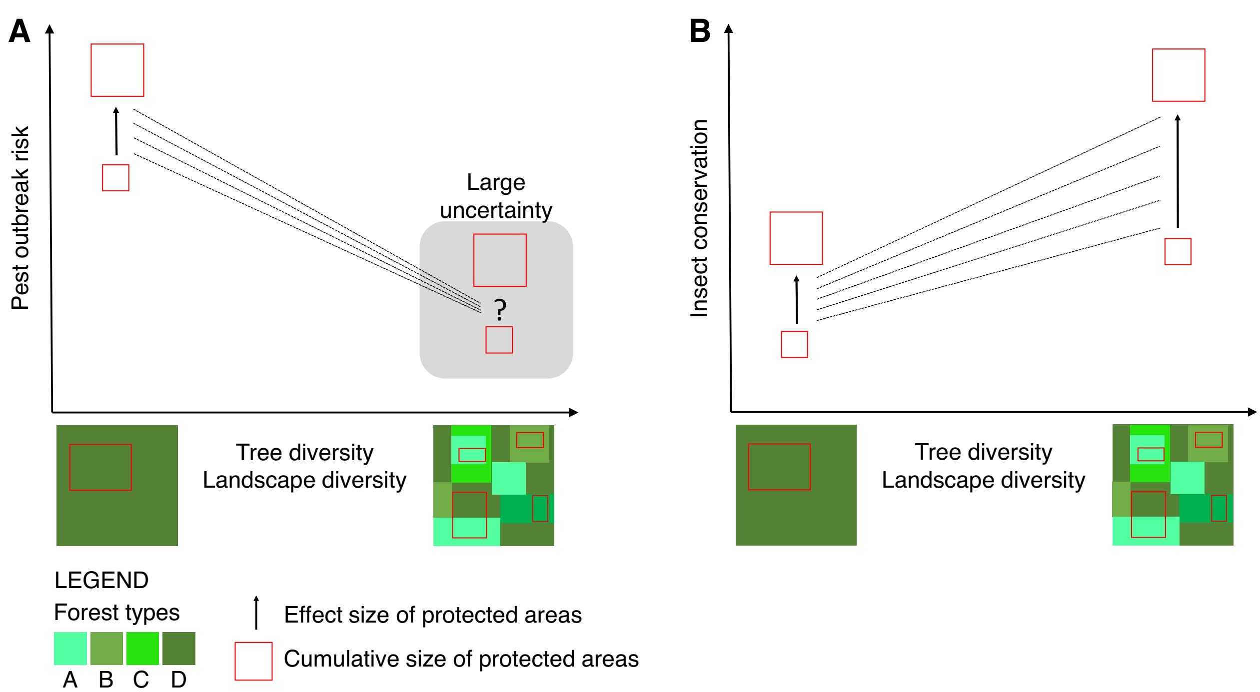

Fig. 2 Schematic representation of the expected effects of increasing forest and landscape diversity in a forest-dominated landscape under scenarios of different degrees of forest protection on A pest outbreak risk and on B insect biodiversity conservation, based on the evidence reported in the literature. Forest and landscape diversification is generally beneficial to reduce pest outbreak risk, while the effects of setting aside land for conservation purposes have a variable outcome in diversified forest ecosystems. Similarly, we expect a strong interdependence between landscape diversification and protected area effectiveness per unit area for the conservation of forest insect biodiversity

conservation lies within the decisions about post-disturbance management. Often large-scale disturbances simultaneously impact both protected and productive areas, creating conflicts between different stakeholders [61]. Forest owners, managers, and conservationists have often different goals and contrasting positions about intervention options. Allowing some forests to be shaped by natural processes is congruent with multiple goals of forest management, even in densely settled landscapes [154]. Indeed, the importance of pests in promoting forest ecosystem successional dynamics and supporting biodiversity and multiple ecosystem services is being increasingly acknowledged [111, 155], although such positive effects might not benefit all insect guilds in the long term. Here, we propose a hybrid approach where intensive post-disturbance management and non-intervention are not mutually exclusive and can be combined within the same landscapes. For instance, small logged areas scattered across a forest-dominated landscape can favour taxa that can benefit from a larger availability of flowers in forest openings and ecotones [91]. At the regional scale, having a fine-scale mosaic of logged and unlogged windthrows within a continuous forest cover can promote insect diversity of multiple taxa by increasing beta diversity between habitats [73]. Despite recent advances in forest ecology and management, there is still strong legal and social pressure to suppress biotic disturbances and control the natural dynamics of disturbed forests (see for instance ref. [156]), and an intensified conversation about how society can coexist with disturbances is timely needed [154, 157].

Implementation of Multiple Strategies

To build multifunctional and resilient forest landscapes, the three proposed strategies could be simultaneously adopted after regional adaptation. In particular, it is necessary to consider first the predominant land planning approach, i.e. land-sharing or land-sparing [158], and to assess the underlying heterogeneity of the working landscapes. Then, when implementing pest management, land planners and stakeholders should consider the interdependence between the amount and configuration of land under protection needed and the general level of forestry intensity outside protected areas [159]. The implementation of multiple forest diversification strategies at the local and landscape scale is expected to synergistically increase the protection efficiency per unit area, thus achieving maximized biodiversity conservation due to the habitat diversity effect (Fig. 2B). However, setting aside also entire forest landscapes for conservation is strictly non-negotiable [87••], and policies to improve landscape diversity should not work antagonistically with the creation of large protected areas. Small-scale conservation interventions could also be implemented without a formal protection, for example by retaining veteran trees or small set-aside areas within productive landscapes [159]. Although even the implementation of small conservation interventions within productive stands is not straightforward due to different perspectives between foresters and conservationists [160], such management measures are expected to have positive effects on a large spectrum of species of conservation concern. On the contrary, conservation actions do not seem to impose significant economic costs or phytosanitary risks, although there is large uncertainty in mixed landscapes (Fig. 2A).

For forest-dominated landscapes, several management approaches targeting resilience have been proposed [161••], among which triad forestry represents an interesting framework to promote forest multifunctionality at the landscape scale. Triad forestry refers to a landscape-scale management regime that combines forests with contrasting functions, such as intensive plantations for timber production, forest reserves for biodiversity conservation, and a dominant forest matrix extensively managed for multiple uses [158, 162••] Several local and regional examples already exist in North America [163, 164], in Europe [165], and in Oceania [166, 167]. We propose to expand this idea by allowing natural disturbance dynamics to help increase structural and compositional heterogeneity at the landscape scale [168]. Again, careful planning and participation of multiple stakeholders is needed to identify areas where natural disturbance dynamics is compatible with other desired ecosystem services [154].

In mixed agricultural-forest landscapes, the triad forestry system should ideally also consider the composition and configuration of non-forest patches. Additionally, forest edges represent important habitats, possibly sustaining a high proportion of insects acting beneficially both in the forest interior and in non-forest habitats [169]. However, the application of such a multifunctional approach in the management of forests in mixed-used landscapes requires a deep understanding of the social, economic, and cultural factors that influence private land uses. When forest is the natural land cover in anthropogenic landscapes, priority should be given to conserving primary forest patches and their non-forest features. By contrast, in mixed landscapes where forests have a long history of human disturbance, it is essential to find a compromise to preserve both such forests and other habitats with contrasting land use goals. It is particularly challenging to maintain a high diversity of habitats across landscapes and simultaneously to maintain a sufficient degree of habitat connectivity and amount. Increasing habitat diversity increases the potential number of species that may exist in a given area but simultaneously reduces the amount of habitat area and connectivity available for specialists and, thus, increases the likelihood of stochastic extinctions [93]. In this context, recent integration of landscape and network ecology could help in understanding how insect species move and use forest and open habitats across heterogeneous landscapes [170, 171].

Conclusions

Scientific evidence for a positive diversity-functioning relationship in pest control is emerging across different research fields from agroecology [172], to landscape ecology [173] to forest pest management [130, 174, 175•]. Since conservation research has also proposed this strategy to boost multi-taxa diversity at large spatial scales [176], the times are ripe to join forces by specialists from forest pest management and conservation biology. Although forests often possess two major contrasting management objectives, i.e. either timber production or biodiversity conservation, diversifying forest landscapes appears as the most effective way to reduce conflicts between contrasting objectives in forest uses [177]. Recent simulation studies suggest that this forest resilience-oriented management can also overcome the threats of climate change and provide multiple ecosystem functions and services [178]. However, we should not neglect to maintain a high conservation priority for the few remaining areas where large primary forests are under threat [12••, 179]. While there are now several economic and legislative tools to implement diversification in agriculture, particularly in Europe (e.g. European Green Deal), the forest sector is still struggling with the adoption of similar policy frameworks. Major barriers include the lack of a long-term policy or management plans reflecting the long-lived nature of trees, the current wood-market demands, and a lack of tailored policy instruments that hamper the integration of pest control and conservation measures [84•]. Other barriers include the availability of relevant scientific knowledge and related knowledge gaps, complex relationships between multiple stakeholders, and the legal framework in which forest management operates [180•]. We acknowledge that the higher the variability in environmental conditions, ownership structure, and economic and socio-cultural conditions, the more complex is to develop strategies adapted to the local and regional needs [181]. However, there are emerging signs indicating the feasibility of maintaining both high timber production and structural elements of importance for biodiversity at a relatively minor economic cost and to the benefit of many species of conservation concern [182, 183]. Insect conservation and pest management do not appear to be in strong conflict when a modern proactive management based on forest diversification is preferred over reactive emergency measures. Achieving this requires context-dependent changes in management at the landscape scale, long-term monitoring, and evidence-based adaptation plans that need to be harmonized with rapidly evolving socio-economic systems.

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Declarations

Competing interests The authors declare no competing interests.

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- • Of importance
- •• Of major importance

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