Managing Forest Health in Connected Landscapes

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Forest of dead trees. Forest dieback in the Harz National Park, Lower Saxony, Germany, Europe. Dying spruce trees, drought, and bark beetle infestation, late summer of 2020. (Photo: K I Photography)

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Abstract

Managing forest health is a critical challenge for forest managers and policymakers worldwide, especially in connected forests where ecological and socio-economic linkages are tightly intertwined. Conservation and sustainable management of forest ecosystems require the development and implementation of comprehensive strategies that address the complex interactions between natural and human-driven stressors affecting forest health. In this chapter, we review the main drivers of forest health degradation and provide an overview of the approaches and tools that can be used to monitor and manage forest health. We highlight the importance of integrating practical knowledge with scientific information to enhance the resilience of forest ecosystems to global environmental changes. Finally, we discuss the challenges and opportunities associated with managing forest health in connected forest landscapes, and we suggest possible strategies to improve forest health management.

Keywords

Pests · Fungal pathogens · Invasive species · Climate change · Plant protection · Tree health

Introduction

Forest health refers to the overall well-being and functionality of a forest ecosystem. This includes the physical, chemical, and biological processes that occur within the forest as well as the relationships between various components of the ecosystem such as trees, other plants, animals, fungi, soil, and water. Definitions of forest health should combine ecological and utilitarian aspects (Kolb et al. 1994). A healthy forest thus sustains the complexity of the ecosystem and provides ecosystem services for human needs. In the context of ecological connectivity, forest health is closely linked to the ability of the forest ecosystem to support biodiversity and maintain ecological processes across spatial scales (Pautasso et al. 2015). Ecological connectivity refers to the connection between different forest habitats by corridors or stepping stones and allows for the movement of species and the exchange of genetic material between them. Forest health and connectivity are linked in various ways. A decline in forest health may negatively affect connectivity; on the other hand, high connectivity may not only facilitate species movement but also the spread of pests and pathogens—particularly invasive alien ones (see also Chap. 17).

Forest health must be distinguished from tree health. Individual trees are generally attacked by numerous parasitic organisms such as herbivorous insects or pathogenic fungi. Some act as primary pests, attacking and damaging a vigorous tree without other predisposing factors. Defoliators such as leaf/needle-feeding caterpillars are typically primary pests. Others function as secondary pests that attack weakened trees. Bark beetles, long-horned beetles, wood wasps, and other insects that develop under the bark or in the wood of living trees are examples. Their degree of aggressiveness can vary; some species may switch to primary attack once they reach very high population levels, as is the case with a small number of bark beetle species (e.g. from the genera *Dendroctonus* or *Ips*). Overall, damage to individual trees will always occur in forest ecosystems and impair tree health. While this damage will remain innocuous most of the time, certain conditions may trigger the mass proliferation of a pest or pathogen species, leading to an outbreak damaging large numbers of trees. Whether such an outbreak will also impair forest health depends on the amount or degree of damage as well as the constitution and the resilience of the affected forest ecosystem. Forest stands suffering insect or disease outbreaks must be viewed in their specific landscape and societal context. There may be interests of neighbours that need to be protected, for example, by preventing spillover of a pest from an affected stand or legal requirements to control certain pests and diseases. Forest managers therefore will not always have a choice whether to implement forest protection measures or which ones to apply. These measures should ideally be proactive by controlling conditions that can trigger pest or disease outbreaks. When curative measures are necessary, they will often be limited to cutting and removal of infested trees.

A healthy forest ecosystem is one that is resilient to environmental stressors and can recover from disturbances caused by pathogen or insect infestations and abiotic stressors such as drought or windthrow (Trumbore et al. 2015). This resilience is closely tied to the connectivity of the forest as the latter facilitates the movement of species and the exchange of genetic material between different patches of habitat, thereby increasing genetic diversity and promoting ecosystem resilience (Pearson et al. 2021). Therefore, maintaining and enhancing ecological connectivity can be critical for promoting forest health and resilience.

Changing Environmental Conditions Challenging Forest Health

Two drivers of global environmental change can have severe impacts on forest health: climate change and invasion by alien pests and pathogens. Even forests adapted to certain levels of disturbance will be challenged by novel stressors caused by global environmental change (Trumbore et al. 2015). Forests exhibit varied responses to climate change and the associated abiotic challenges including wildfires, storm damage, drought events, and changes in precipitation patterns. Climate predictions for Europe show regionally diverse changes, including an escalation in high-temperature extremes, drought events, and heavy precipitation events, all of which will negatively impact forest productivity and vitality (Martinez et al. 2022; Lindner and Verkerk, 2022).

Increasing temperatures can have significant impacts on forest health. Higher temperatures can lead to increased stress on trees, making them more susceptible to disease, insect infestations, and other types of damage. High temperatures can also increase the frequency and intensity of forest fires, which can further exacerbate forest health problems. One of the primary impacts of increased temperatures on forest health is drought stress (Hayden et al. 2011). As temperatures rise, evapotranspiration rates increase, which can cause soil moisture to decrease rapidly. This can lead to water stress in trees, which can cause wilt, reduce growth rates, and increase vulnerability to pests and diseases (Netherer et al. 2021). Greater damage from secondary pests or pathogens, such as species of bark beetles or fungi infecting woody organs, following severe drought (Jactel et al. 2012a, b) is a likely consequence (Fig. 16.1).

Trees experiencing physiological stress are more susceptible to potential pests, which can lead to increased occurrence of pest outbreaks as a result of climate change. In addition, previously insignificant pests or pathogens that were not considered harmful may cause more damage due to the predisposition of trees to diseases. The spread of new harmful organisms through immigration or introduction is also contributing to an increase in tree damage. Drought and high temperatures can have a direct detrimental impact on trees. Under extreme drought conditions, the hydraulic collapse of a tree can lead to its fast death (Arend et al. 2021). Carbon starvation can be another consequence of drought damage (McDowell, 2011). Following the extreme drought in the summer of 2018 in Western and Central Europe, high mortality was recorded among beech as well as other trees (Schuldt et al. 2020). Higher temperatures can also lead to changes in the timing and severity of insect outbreaks. Insects are poikilothermic animals, meaning that within species-specific limits, warmer temperatures speed up their development, leading to larger populations and more severe outbreaks. Insect species with flexible numbers of generations per year (e.g. the European spruce bark beetle, *Ips typographus*) can further increase population growth at higher temperatures. Exacerbated by the weakening of host trees due to climatic extremes, bark beetle outbreaks have reached unprecedented levels during the past decade (Hlásny et al. 2021a). The emergence of diseases such as sooty bark disease of maple (caused by the fungus *Cryptostroma corticale*) or pine dieback (caused by *Diplodia sapinea*) is likewise driven by high temperatures and drought (Brodde et al. 2019; Muller et al. 2023).

Another impact of increased temperatures on forest health is the expansion of the range of species and the subsequent proliferation of pests that have always been present but only in low populations causing little damage. As temperatures rise, some species may be able to expand their ranges into areas previously considered unsuitable for their survival. This has been demonstrated, for example, for the pine processionary moth (Battisti et al. 2005). In addition, the establishment of alien pests or pathogens can be supported by climate change. Invasion can lead to increased competition with native species and further stress on already vulnerable forest ecosystems. Climate warming can also increase the detrimental impact of invasive harmful organisms, for example, as increasing the likelihood for expression of lethal wilt in trees infested with the pine wood nematode, *Bursaphelenchus xylophilus* (Gruffudd et al. 2016) or allowing faster population growth (Fig. 16.2). Overall, the impacts of increasing temperatures on forest health are complex and multifaceted. Addressing these impacts will require a combination of approaches including reducing greenhouse gas emissions to mitigate climate change,

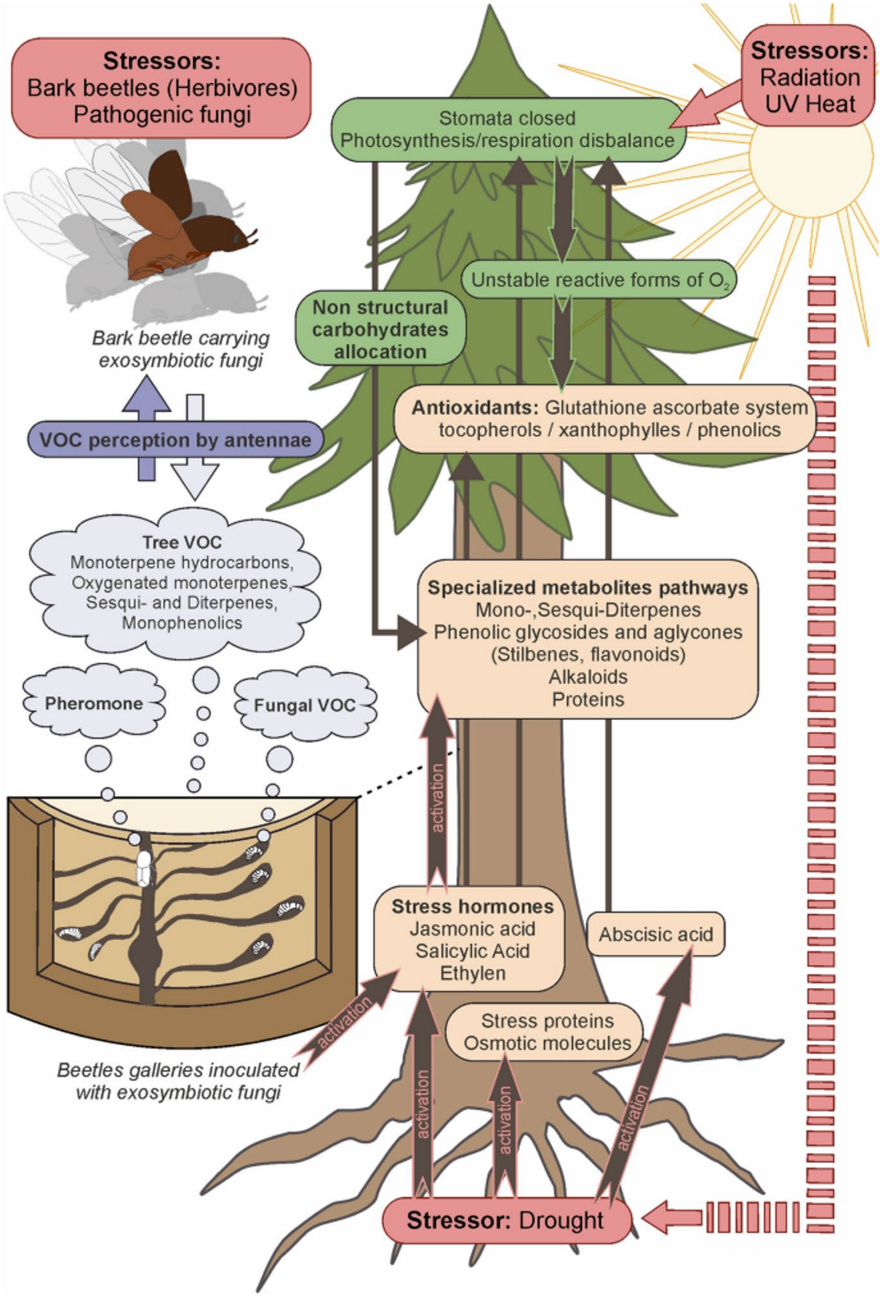

Fig. 16.1 Drought can cause a reduction in water and nutrient flow in plants, which in turn may impact their ability to defend against herbivorous insects and pathogens. In response to drought, plants may reduce the production of chemical defences, making them more susceptible to insect damage and disease. (originally published by Netherer et al. (2021). Journal of Pest Science, 94(3), 591–614; released under a Creative Commons Attribution 4.0 International License (CC BY 4.0))

Fig. 16.2 The oak lace bug, *Corythucha arcuata*, is an example of an invasive pest species that is rapidly spreading and causing damage to forests and urban trees in many parts of Europe. The spread of this insect is supported by human transport activities. Higher temperatures contribute to faster population growth since more generations can develop per year. (Photo: BFW)

implementing forest management practices that promote resilience, and developing strategies to monitor and control the spread of pests and diseases.

Considering the effects of global environmental change on forest health, the introduction and spread of invasive alien pests and pathogens play a critical role. These pests and pathogens can severely impair forest ecosystem functioning and, in some cases, even threaten the existence of entire tree species in a region. Examples of devastating diseases caused by fungi are the Dutch elm disease (caused by *Ophiostoma ulmi* and *Ophiostoma novo-ulmi*), chestnut blight (caused by *Cryphonectria parasitica*), and more recently, ash dieback (caused by *Hymenoscyphus fraxineus*). Nematodes and insects can also have threatening impacts on their host tree species: the pine wood nematode has destroyed vast numbers of pines in its invaded ranges in East Asia and on the Iberian Peninsula, and the emerald ash borer, *Agrilus planipennis*, is devastating ash stands in North America. Many other invasive pests and pathogens will not threaten a tree species with extinction but still negatively impact tree and forest health. A significant reduction of resources needed by specialised herbivores can also occur when invasive pests or pathogens do not kill trees but cause, for example, a loss of palatable foliage for leaf-feeders. This is a likely consequence of the extremely high populations of the oak lace bug, *Corythucha arcuata*, that occur every year once the species is established in an area (Paulin et al. 2020). Once established, the organism can begin to spread in the new area. This can occur via natural dispersal as well as with the aid of human activities. The connectivity of the landscape can thus be a factor regarding both establishment and spread.

Habitat Connectivity in the Context of Forest Pests and Diseases

Forest pests and disease outbreaks, on the one hand, may negatively affect connectivity that make it less useful for other native organisms, while on the other hand, connectivity may support the establishment and spread of (invasive alien) pests and pathogens. Pests and diseases can impact connectivity in a number of ways and affect functional as well as structural connectivity. If they cause tree mortality, their presence can lead to the fragmentation of forest habitats, making it difficult for species to move between different areas (Helander et al. 2007). This can result in isolated fragments of habitat that are too small to support viable populations of certain species, thus leading to local extinctions and reduced biodiversity, i.e. negatively affecting forest health. Pests and diseases can alter the structure of forest habitats by killing trees, reducing canopy cover, and changing the composition of plant communities. This can lead to changes in microclimates, soil moisture, and other environmental conditions that can impact the distribution and abundance of species. Pests and diseases can impact the availability of resources such as food, water, and shelter, which can have negative effects on the species that depend on these resources. For example, a disease that kills a particular tree species will reduce the resources for specialised herbivores. Furthermore, it may reduce the availability of habitats for other animals, such as nesting sites for birds that rely on that tree. This is of particular importance in the case of invasive pests or pathogens such as the abovementioned fungus *Hymenoscyphus fraxineus* or the pine wood nematode.

Landscape patterns can significantly affect the probability of pest and disease infestation in forest patches. When forests are arranged in fragmented patches rather than as interior habitats, they may be more vulnerable to the effects of climate change and other stressors. This can further increase their susceptibility to pests and diseases as weakened trees are more vulnerable to infestation. In addition, when forests are located close to other lands or fragmented into smaller patches, they may be more vulnerable to invasion by pests and pathogens from adjacent areas. In the European Union, the fact that 40% of woodlands are located within a distance of 100 m from other types of land means that many forests are likely to be located in areas with a high degree of human activity, such as urban or agricultural areas (Estreguil et al. 2013). This proximity to human activity can increase the likelihood of introduction and spread of invasive species, pests, and diseases that can negatively affect forest health. Typically, invasive pests and pathogens are introduced into new areas distant from previously infested areas by human activities (e.g. transport of infested plants or plant material, hitchhiking on vehicles, etc.). New populations can be established in these areas and consequently spread into adjacent forests. Examples are *Phytophthora* spp., which frequently contaminate nurseries (Jung et al. 2016) and are spread to the soil when reared plants are planted; the bacterium *Xylella fastidiosa*, an EU priority quarantine pest that can be spread with plants for planting and is then transmitted to plants in the vicinity by vectors; or the oak lace bug, which spreads easily as a hitchhiker and often establishes new populations near traffic infrastructure (Csóka et al. 2020; Hoch et al. 2023).

On the other hand, landscapes with high connectivity and a higher percentage of suitable host tree species may support the spread of an invasive pest or pathogen over a larger area following its establishment. The presence of suitable hosts can function as stepping stones for newly introduced harmful organisms, as has been shown, for example, for the pine scale *Matsucoccus feytaudi* (Rigot et al. 2014). The effect of connectivity depends on the biology and dispersal capacity of the specific invasive pest or pathogen. For example, the spread of a slowly dispersing, relatively large beetle like the Asian long-horned beetle, *Anoplophora glabripennis*, will most likely be aided by a continuous availability of suitable host trees. The oak lace bug with its notorious hitchhiking abilities, on the other hand, can easily utilise human transportation for dispersal; host tree availability will nevertheless be important for the success of the species. Root pathogens of the genus *Phytophthora* depend on water bodies for dispersal; when infested planting material is introduced near a river or a creek, a quick regional spread is likely.

Prevention and Mitigation Strategies

To address the issue of tree diseases and response to symptoms, it is important to identify the disease and determine the pest insect or pathogen responsible for the outbreak. Studying the causes of disease processes can also help prevent and manage outbreaks in the future. This includes identifying factors that contribute to the spread of pest insects and pathogens, such as environmental conditions, host susceptibility, and the presence of vectors or carriers. By understanding the underlying causes of tree diseases, we can develop more effective management strategies to mitigate the impact of outbreaks and protect forest health.

Analysing the effects of pathogenic organisms or pest insects is important to understand how they interact with both biotic and abiotic factors in their environment. This helps identify the key drivers of disease outbreaks such as environmental stressors or host susceptibility and develop effective management strategies to mitigate their impact. To better understand the threat posed by important pests and pathogens, it is essential to study their life cycles including the different stages they undergo, host preferences, and modes of transmission. This information can help identify potential pathways for pathogen introduction, transmission, and spread as well as ways to disrupt them. Corridors and stepping stones can be of particular importance for surveillance in order to detect a spreading (invasive) pest or pathogen early. Surveys should therefore consider such sites since detecting invaders there may allow for the control of the pest at an early stage or disrupt the connections, thereby contributing to stopping or at least slowing their spread.

Considering the possible harmful effects of pathogenic organisms is critical. This includes assessing the economic and ecological impacts of disease outbreaks on plant health, biodiversity, and ecosystem services. Understanding the impacts of pathogenic organisms can inform decision-making processes for the development and implementation of management strategies.

To reduce the impact of insects and pathogens on trees and on forest health, it is important to develop suitable transnational strategies and processes to prevent or manage pest insect and pathogen outbreaks (Wingfield et al. 2015). This includes the establishment of monitoring programmes to identify potential outbreaks and the use of preventative measures to reduce the spread of pathogens. Effective management strategies may involve a combination of approaches, including the use of biological control agents, cultural practices, chemical treatments, and quarantine measures to prevent the introduction and spread of pathogens. Additionally, education and outreach programmes can help increase awareness regarding tree diseases and encourage the adoption of best management practices. Well-informed professionals and interested citizens can also play a crucial role in the early detection of emerging pests or pathogens and introduced aliens. Early detection followed by rapid response is typically key to successful control. Experts can provide advice on countermeasures and management strategies for specific pathogens, including guidance on the most effective control methods and treatment options. This can include recommendations on tree species selection, cultural practices, and chemical treatments as well as advice on the potential ecological and economic impacts of different management strategies or the implementation of quarantine regulations. By taking a holistic approach to pest and pathogen management, we can help reduce the impact of diseases on trees and protect the health and biodiversity of forests.

Adaptive Forest Management and Forest Pest Management

Forest managers can take various measures to control pests and diseases and protect the connectivity of forest ecosystems. These measures include prophylactic, silvicultural approaches, such as an increase in tree diversity, use of resistant tree species, or proper sanitation measures. Measures can be curative and aim to prevent the spread of pests and diseases, like the removal of infected trees. Measures can also be taken to block the infectious process by preventing the introduction and spread of pests and diseases. This may involve implementing quarantine measures like buffer zones around infested areas (thereby reducing connectivity), monitoring the spread of pests and diseases, and restricting the movement of potentially infected plant material or the pest itself. Important pathways for this movement are living plants, wood and wood products, seeds, and hitchhiking (Liebhold et al. 2012; Meurisse et al. 2019). The most likely pathways depend on the biology of the respective species.

Many countries have clear regulations on how outbreaks of invasive quarantine pests and pathogens are to be managed (e.g. EU Plant Health Law: Regulation (EU) 2016/2031). Measures to eradicate or contain newly introduced pests or pathogens will often involve extensive removal of host trees to prevent further dispersal and spread. Deliberate interruption of connectivity can thus be an effective pest management strategy and, in some cases, necessary to prevent further negative consequences for forest health or biodiversity. It is also important to develop and expand a practical training concept for forest managers to increase their awareness of forest pests and diseases and equip them with the skills and knowledge necessary to identify, monitor, and manage outbreaks. In addition, modernisation of the forest protection monitoring system, including the use of GIS and remote-sensing technologies (Dillon et al. 2014), can help forest managers better understand complex damage events and make informed decisions about management strategies.

Box 16.1 Lessons Learnt from Bark Beetle Outbreaks

The European spruce bark beetle, *Ips typographus*, is one of the most important native tree–killing insects in European forests (Fig. 16.3). It can switch from the endemic to epidemic phase driven by the availability of suitable material for breeding (weakened trees, trees broken by storm, etc.), allowing the build-up of beetle populations. Large numbers of living Norway spruce trees can be attacked and killed in the epidemic phase. The population dynamics of *I. typographus* is strongly influenced by the volume and height of available Norway spruce trees, as well as by the distance to the nearest harvested area in the previous 4 years. The effects of tree diversity only become noticeable in Central Europe when the spruce percentage is below 40% (De Groot et al. 2023). Climate variables also influence the speed of infestation and population increase (e.g. Hlásny et al. 2021b, Kärvemo et al. 2023). The effects of climate change, including higher temperatures and increased storms, have become increasingly important since the 1990s; consequently, damage by *I. typographus* has been steeply rising in Europe (Hlásny et al. 2021a).

Fig. 16.3 Adults and larvae of the European spruce bark beetle, *Ips typographus*, the major pest in Europe for Norway spruce, *Picea abies.* (Photo: BFW)

(continued)

Besides long-term silvicultural measures such as changing forest structure and tree species composition, the most important tool for managing the spruce bark beetle is the removal of suitable breeding sites like wind-felled trees or their treatment, for example, by debarking or bark-scratching to avoid the build-up of bark beetle populations, as well as cutting and timely removal of newly infested trees. Once an outbreak starts and the attack on standing trees begins, the loss of large numbers of mature spruce trees is inevitable, and the pest may spread to other stands.

The current extent of outbreaks of *I. typographus* is exceptional (Hlásny et al. 2021a). However, following drought conditions, outbreaks of bark beetles specialising in other tree species can cause significant tree mortality as well, e.g. fir bark beetles, *Pityokteines* spp., or pine bark beetles like *Ips acuminatus*.

Biological Control

Biological control can be one effective and environmentally sound technique for managing pests, both native as well as alien species. Biological control refers to managing pest species by using living organisms like parasitoids, pathogenic microorganisms, or herbivores. Eilenberg et al. (2001) list four strategies of biological control: inoculation biological control, inundation biological control, classical biological control, and conservation biological control. Inundation biological control is based on the mass release of living organisms to immediately suppress pest populations. Preparations of the bacterium *Bacillus thuringiensis kurstaki* have been successfully used against leaf-feeding caterpillars for many years, and preparations based on insect viruses such as the *Lymantria dispar* nucleopolyhedrosis virus (against the spongy moth, *Lymantria dispar*, an invasive pest in North America) have proven to be highly specific and effective biopesticides. But in general, the methods available for forest protection are few. Inoculation biological control works by releasing smaller numbers of the living biocontrol agent, which is supposed to proliferate in the environment and achieve control of the pest with some time delay. The most successful strategy in forest protection featuring the release of living organisms has been classical biological control. This method employs inoculative releases of natural enemies of an alien invasive pest collected in its native range (see also Chap. 17). Current examples are the release of the parasitic wasp *Torymus sinensis* against the chestnut gall wasp, *Dryocosmus kuriphilus,* in Europe and the release of several parasitic wasps from East Asia against the emerald ash borer in North America. Increasing connectivity would increase the dispersion of the biocontrol agent and therefore improve the impact on the target organism. However, a parasitoid or predator with a wide host/prey spectrum could become an invasive alien species itself. A prominent example is the Asian lady beetle, *Harmonia* *axyridis*. This species was introduced in greenhouses against aphids but is now also predating on native lady beetles, hoverfly larvae, and other species (Roy and Brown 2015). Therefore, thorough testing of the host specificity of the biocontrol agent prior to release is a crucial element of such classical biological control programmes to avoid negative effects on non-target organisms. Measures to increase connectivity will likely be useful to support the establishment and spread of released natural enemies just like they supported the alien pest to be controlled. The fourth method, conservation biological control, does not release natural enemies against target pests but instead attempts to protect and enhance already-present natural enemies in order to suppress the target pests. This is done by using appropriate cultural and silvicultural practices, supporting plants that serve as food, providing habitats for natural enemies, and supporting a continuous supply of hosts for parasitic insects or insect pathogens. Increasing structural and species diversity in a forest and maintaining a certain amount of deadwood can form a part of strategies to support natural enemies of forest pests. For this biocontrol strategy, an increase in connectivity for the natural enemies of concern will also be beneficial. Close-to-nature forestry, a management practice applied in Slovenia for decades with the goal of developing mixed and uneven-aged forests with high structural diversity (Diaci 2006; Diaci et al. 2017) can also be seen as a method of conservation biological control.

Implications for Managing Forest Health in Connected Forests

Effective forest management requires a multi-criteria approach that takes into account the various ecosystem services that forests provide (Jactel et al. 2012a, b), including carbon sequestration, water regulation, biodiversity conservation, and recreational and cultural benefits. In order to ensure that forest management decisions are sustainable and effective, it is necessary to conduct multi-criteria risk analyses that assess the potential impacts of various forest management scenarios on these ecosystem services. This involves considering a range of factors including the potential impact of management practices on soil health, water quality, and biodiversity as well as the potential trade-offs and synergies between different ecosystem services. Pest or disease outbreaks of native species can be considered natural processes in the forest ecosystem. It may be appropriate to rely on the resilience of the disturbed system when it is adapted to the occurring disturbance. Significant loss of mature trees can still be the consequence. Climate change impacts will likely impair this resilience. By taking a holistic approach to forest management, we can aim to maintain forest health and ensure that our forests continue to provide a wide range of ecosystem services and meet the needs of both current and future generations (Bakhtiyari et al. 2019).

In connected forests, corridors and stepping stones must be treated as integrated parts of forest health management. Therefore, we suggest the following measures to improve corridors for biodiversity management but not allowing the propagation and dispersion of invasive alien pests, emerging pests, and native pests:

A. Recognise and implement corridors as an integrated part of the forest complex and integrated forest pest management.
B. Increase tree species diversity in the corridors to reduce its vulnerability to outbreaks. Moreover, this will prevent deterioration of the corridor after a pest or disease outbreak.
C. Carry out sanitary measures to mitigate moderate disturbances, for example, by cutting and removing infested trees.
D. Consider using semiochemicals for mass trapping or repelling pests from the corridors when appropriate systems are available.
E. Manage corridors to support the establishment and dispersion of biocontrol agents (natural enemies) by providing habitats and nutritional resources to suppress pest populations in corridors and in other fragments.
F. Focus surveillance for invasive alien pests on corridors to allow early detection. Use appropriate measures to eradicate or suppress detected infestations to avoid their spread to other forest complexes or a decrease in the quality of the corridors as a dispersal structure for biodiversity.
G. Massive tree removal can be an appropriate measure to break connectivity. This may be necessary to contain or eradicate newly introduced invasive pests or pathogens in order to prevent unacceptable damage to forest health or biodiversity.

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