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Forest protection under climate change – preventing the downward spiraling of forests into climate change-driven damage and decline

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Forest protection comprises measures to avoid or reduce damage from biotic (insect pests, diseases, game) or abiotic (storms, fire, heat, drought, frost etc.) stressors in commercial and natural forests (Reisch, 1974). Such measures can be preventive by reinforcing forest resistance against stress in the long-term, or involve immediate curative actions that seek to reduce or halt occurring damages.

The history of forest protection dates back to the 18th and 19th centuries, when systematic measures were first developed to protect forests from damage caused by insect pests, diseases and competing vegetation. One of the earliest known plant protection applications was the use of mechanical measures and simple chemical agents, such as oil or soap applications, to combat insect infestations (Miller, 1989). The 20th century saw the introduction of modern insecticides and herbicides that enabled large-scale pest control. In the 1920s, for example, the first synthetic substances were used to control insect pests such as the nun moth, which repeatedly caused extensive damage, particularly in Central Europe (Wallner & McManus 1989). Over the years, the importance of using a combination of preventive and curative measures against biotic stressors was recognized, for example through the promotion of mixed forests that are less vulnerable to attack and the removal of infested trees in cases of attack (Milnik, 2007). These developments formed the basis for the concept of integrated forest protection, which is a combination of measures in which the use of plant protection products (PPP) is limited to a strictly necessary level, with priority given to biological, biotechnical and silvicultural measures, and plant breeding. Today, all users of PPP within the EU are obliged to work in compliance with the general principles of integrated pest management, as defined in Annex III of the EU-directive 2009/128/EC.

For several decades, silvicultural measures have been considered a viable long-term approach for preventing large-scale biotic disturbances, for example by establishing uneven-aged and species-rich forests that are composed of site-adapted and mostly native tree species. Mechanical or technical interventions, like removal of infested trees and debarking of harvested logs (e.g. in the case of bark beetles), play an important role when preventive silvicultural measures are not successful in keeping pest infestation rates and population densities low. The use of PPPs in forests is restricted to few unavoidable cases (Bräsicke et al., 2025a; Lemme et al., 2025; Otto & Bandau, 2025, this issue).

Since the onset of rapid climate change, the effective use of preventive silvicultural measures for forest protection and risk management has become increasingly difficult (Fig.). Because recent legislative processes stipulate to reduce the use of PPPs in agricultural and forestry applications (e.g., EU Green Deal, Farm to Fork), integrated plant protection strategies limit the application of PPPs to a strict minimum and to situations where other measures do not allow the conservation of the forest cover (ultima ratio). However, as forest damages are increasing at an unprecedented rate an severity during the last decades, it is difficult for forest protection agencies to implement integrated plant protection strategies without PPPs, as they allow “buying time” that is required for converting existing forests to more climate-resilient forest types and structures.

In the long term, however, progressive forest protection strategies are needed to address the enormous challenges that global change imposes on forest health and survival (Hartmann et al., 2025, this issue), and to increase adaptability to strengthen resistance and resilience of forests for the coming decades. Ongoing climate change increases the vulnerability of forests to biotic stress, but also impacts insects and pathogens, sometimes in unpredictable ways. Forests across Europe are currently exposed to a new spectrum of harmful organisms that occur at higher frequencies and spread with unprecedented speed, yielding often very high population densities of pests (Mundhenk & Wenzel, 2025; Langer et al., 2025a; Warlo et al., 2025, this issue). At the same time, problems arise when invasive species migrate into regions where they did not occur before, leading to new risks for both native and introduced tree species (Hartmann et al., 2025; Schmidt

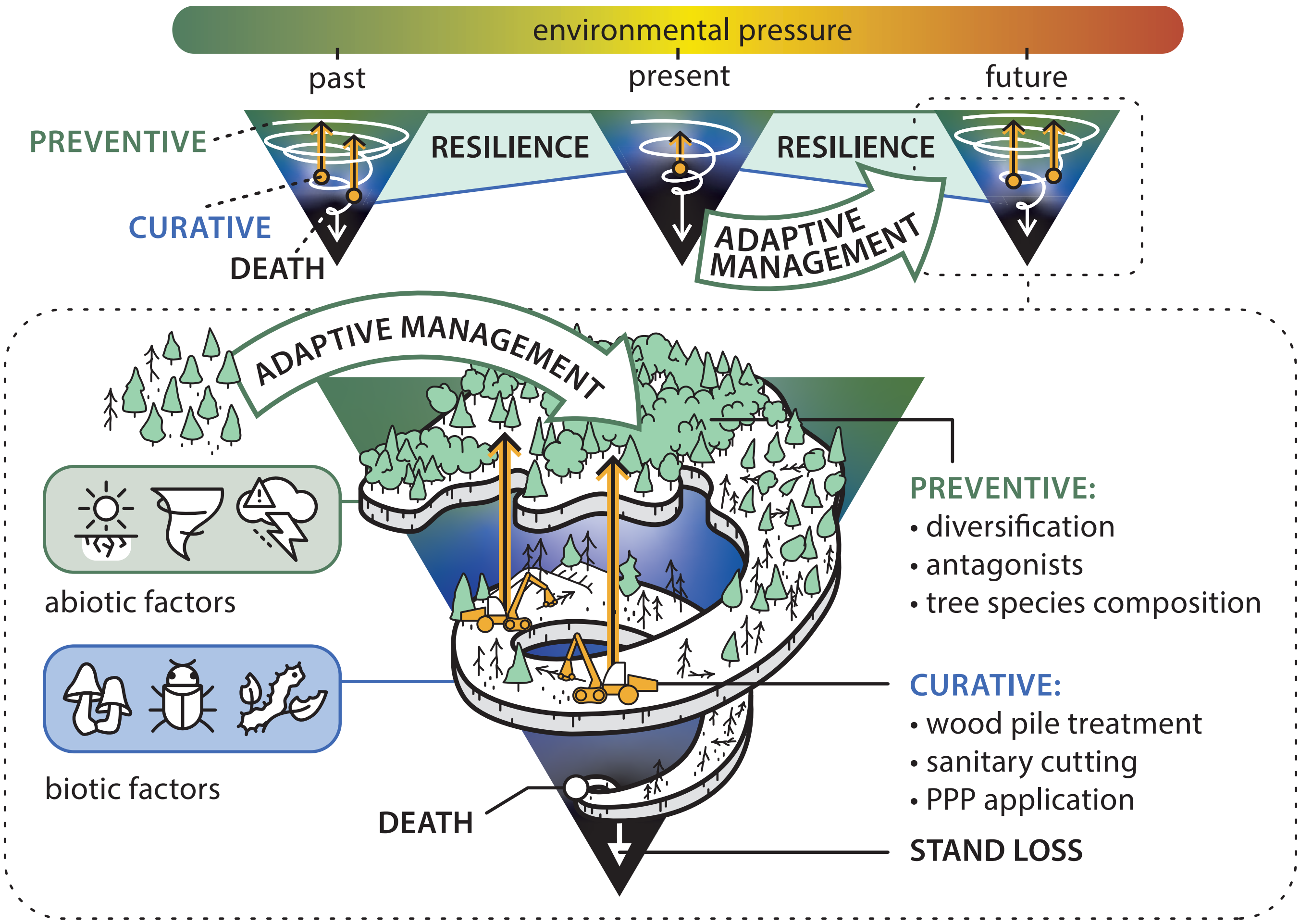

Fig.: The downward spiral of tree death and stand loss (inspired by Manion 1991 "tree disease concept") in the context of forest protection. In the past, preventive management measures was often sufficient for maintaining forest vitality (green shading), occasionally relying during biotic attacks on curative measures (blue shading) to prevent the downward spiraling of forest vitality towards stand loss and to regain forest vitality (orange arrows). Increasing environmental pressure via abiotic and biotic stressors has decreased the effectiveness of both preventive and curative measures, resulting in reduced resilience and more severe forest damage in the recent past. Adaptive management, allowing protective measures to be continuously adjusted to changing environmental conditions, is a promising tool for the long-term protection of forests. Ecosystem diversification, promotion of antagonist species and selection of climate adapted tree species will increase the resistance against pests and diseases and the resilience of forests against future climate change. The success of these measures requires continuous evaluation against the backdrop of new environmental conditions. Curative measures, such as treatments of woodpiles, sanitary harvesting or the use of plant protection products, will only become effective in limiting forest damages and in preventing stand loss once forest resilience is reestablished.

& Hahn, 2025, this issue), like oak (Langer et al., 2025a, this issue), sycamore maple (Burgdorf et al., 2025, this issue), or Douglas fir (Langer et al., 2025b, this issue). As climate change progresses and global trade continues to increase, insects and disease dynamics are likely to change further, along with novel introductions of alien pests and pathogens into new habitats. This will make the situation of forest protection even more complex and challenging.

Shaping sustainable forest adaptation strategies with preventive measures is a difficult task because of uncertainties in future climatic conditions. Curative measures are currently a crucial tool for preserving forest cover and maintaining ecosystem functions that are necessary for adaptive forest conversion. Curative measures still include the use of PPPs, which are controversially debated in politics and society. Risks imposed by the use of PPPs to ecosystems integrity cannot easily be attributed to the active ingredients of the chemical products. The studies by Bräsicke et al. (2025b, this issue) and Günther et al. (2025, this issue) have addressed these important questions and were able to provide results that increase transparency of strategic decision making in forest protection (Möller et al., 2025, this issue). Increasing the use of PPPs may sometimes be advantageous from an economic perspective (Maaß & Kehlenbeck, 2025, this issue), however, there is a decreasing societal and political acceptance in Germany (Möller et al., 2025; Otto & Bandau, 2025, this issue). Because occurrences of novel or unexpectedly severe biotic disturbances are on the rise, there is little time for developing and testing new and alternative curative measures, like the use of antagonist species, but also not for creating societal and political acceptance that is needed to keep conflict potential at bay (Hartmann et al., 2025, this issue).

The recent trend of increasing risks for forests and hence the increasing reliance on curative measures to maintain forest cover must be overturned, and forest protection agencies must be provided with alternative strategies approaches for preventing damages. Maybe the most promising option, a suitable compromise between effectiveness on the one hand, societal acceptance, and environmental suitability on the other, is to strengthen the development of forward-looking methodologies that can increase future forest resistance and resilience by the means of adaptive forest management (AFM, see Fig., Bolte et al., 2009). For example, AFM aims to introduce provenances of native tree species that are better adapted to the new climate into regions with substantial forest decline, or to accelerate the movement of currently non-native species that would likely migrate into these regions, but at a much slower rate (Spathelf et al., 2018). AFM can improve forest resilience to changing climate by increasing functional and structural diversity in forests (Mina et al., 2022), thereby creating a sensible balance between stand density and forest microclimate (Muys & Messier, 2023). An essential prerequisite for this approach is a recurrent evaluation of the adaptation process, informed by advanced modelling of forest dynamics that includes monitoring of forest vitality indicators as well as impact of insect pests and diseases (Fischer et al., 2025, this issue). To reduce the necessity of reliance on PPP in the future, sophisticated biotechnical solutions like RNA interference (RNAi) may become part of the future forest protection toolbox (Joga et al., 2021). Furthermore, biological control via priming or viral hyperparasites that can reduce virulence in fungal pathogens of trees may become an important avenue to pursue (Lutz et al., 2024), as is the use of predators (invertebrate and vertebrate), parasitoids and pathogens of damaging forest insects (Fischbein & Corley, 2022).

This special issue comprises several articles that address important forest protection issues from practical and theoretical viewpoints, and it can provide useful information for people working as practitioners or researchers. Yet, many challenges remain in forest protection. Below, we define some of these challenges and divide them in three categories:

Detection, monitoring and forecasting of insect and disease dynamics

a) Data availability on forest damage: there is currently no coordinated assessment of forest damages and its integration in an **openly accessible international forest damage database**. Such information can inform forest practitioners of new biotic threats in neighboring regions and help forest scientists establishing causal relationships between climate and site conditions and insect/disease occurrences.

b) Forecasting of forest damages from insects and diseases: recent forest damages across Europe could not have been predicted using current models, which simulate either forest dynamics (vegetation models) or spread and/or population development of insects and diseases, but not their interactions. Yet, the interplay of stress in forest trees with climate-induced changes in pest dynamics determines outbreak and damage level, calling for **process-based modelling of interacting insect/disease dynamics in forests**.

c) Bridging the scales of observational data with remote sensing: developing forest damage-mitigation strategies requires knowledge about the spatial distribution of damage occurrence. Much observational data on forest damage is at a very fine scale and with diffuse spatial coverage. There are large forested areas that are not routinely surveyed or are only reported on a voluntary basis. In order to obtain comprehensive and near real-time information on forest damage for entire countries, it is essential to **combine empirical forest damage data with remote sensing data**, using multi-sensor approaches in the future.

Biology, ecology and control of insects and pathogens

a) Biology and ecology: native insect pests and pathogens are increasingly often reaching damaging levels, calling for reliable risk assessment and development of management strategies. A better understanding of the impact of climate change on life cycles of established harmful organisms, shifts in their geographic distribution or their host spectra is needed. The **impact of abiotic stresses on host tree species and the interplay with endophytic/endemic organisms and insect pests** requires more research.

b) Control: PPPs remain an important tool in forest protection, in particular during large-scale outbreaks driven by climatic extremes. A **broader spectrum of active substances with high selectivity and low persistence is needed** to achieve targeted and effective control of pests and pathogens while minimizing impacts on non-target organisms and the environment. Innovative approaches that use natural mechanisms of attraction and repellence (e.g., semiochemicals) or interfere with development of organisms (e.g., RNAi) may fulfil such requirements.

Increasing forest resistance and resilience under ongoing climate change

a) Diversification of forest resistance: Structurally diverse forest stands may buffer against variations in temperature and moisture during climate extremes and thus reduce predisposition to biotic vulnerability. A diverse array of tree species protects against herbivores and pathogens via lower host density and 'associational resistance', i.e. non-host trees interfering with herbivore foraging, and for masking the presence of host trees. **Diversification efforts should also consider tree defense capacities under changing environmental conditions**, but the mechanisms driving climate impacts on defenses are still poorly understood.

b) Forest soil resilience: Functioning and resilience of forest ecosystems are intricately linked to soil health and biodiversity, nutrient cycling, carbon storage and water retention and reduced soil health increases forest vulnerability to pest and pathogens. **Forest management strategies must embrace the complexity of belowground biodiversity**, including multiple functional groups of soil microbes and fauna. Knowledge about the impacts of aboveground vegetation management on soil biodiversity is sparse, and more research on the linkages between forest management practices and soil health is badly needed.

We thank all authors of this special issue for their contributions and believe that future research can be guided by their findings. Most of the authors are practicing scientists and are exposed not only to academic challenges but also to the difficulties in solving forest protection issues in the field. We underscore our admiration for their dedicated devotion to the protection of our forests. To most people, the struggle against the ever-increasing threats from abiotic and biotic stressors in times of rapid climate change may be too challenging; for these brave heroes the battle has just begun!

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