Trends in Ecology & Evolution

CellPress

Science & Society

Conserving forest insect biodiversity requires the protection of key habitat features

J. Ryan Shipley, [1,*] Martin M. Gossner, [1,2] Andreas Rigling, [1,2] and Frank Krumm, [1]

Loss of insect biodiversity is widespread, and in forests habitat loss is one of the major drivers responsible. Integrative forest management must consider the preservation and promotion of key habitat features that provide essential microhabitats and resources to conserve biodiversity alongside ecosystem functions and services.

Biodiversity in decline

Global biodiversity is under threat, and insects are no exception, experiencing declines in diversity and abundance due to human-induced factors such as land-use and climate change [1]. The decline of insects is concerning as they play crucial roles in ecosystems as pollinators, predators, and facilitators of nutrient cycling. The diminishing numbers of insects can have far-reaching consequences, disrupting interaction networks and food webs, and thereby reducing ecosystem functions and compromising vital services [2]. Simultaneously, there has been a significant loss of structural diversity in forests over the past century, driven by human activities and resource demands from a growing population. As society recognizes the multifaceted benefits of forests, there is a growing demand for managed forests to balance timber production with the preservation of biodiversity and other **ecosystem functions** (see Glossary) and **services** [3]. Species-rich unmanaged forests tend to be complex heterogeneous mosaics of varying structure, age, and composition that promote a high diversity of insect species by providing essential microhabitats and resources throughout their complex life cycles [4]. By contrast, management practices to maximize yield often result in an overall homogenization of forests, reducing variation within stands to increase uniformity in structure and composition. **Small-habitat features** (such as caves, rock piles, **temporary water bodies**, small streams) and **tree-related microhabitats** often associated with **ancient trees** and/or **veteran trees** are essential components of forest biodiversity [5,6]. Here, we highlight the significance of promoting such features in **integrated forest management** and their relationship to ecosystem functions and services, using as examples two key hotspots of forest insect biodiversity: temporary water bodies and tree-related microhabitats associated with ancient and/or veteran trees.

Significance to ecosystem services and biodiversity

Herein we focus on three important mechanisms through which temporary water bodies and ancient and/or veteran trees contribute to biodiversity and ecosystem services by (i) creating a diversity of microhabitats, (ii) promoting **food web modularity** that moves energy and nutrients across ecosystem borders, and (iii) providing connectivity between discontinuous habitat patches.

Temporary water bodies, or shallow (typically <1 m deep) seasonally inundated wetlands are crucial for many insect species as they undergo a part of their life cycle in water. The ecosystem services provided are linked to habitat complexity [7], where they supply emergent vegetation, algae, sediment, rocks, and mud as essential substrates for laying eggs in addition to energetic and nutritional resources for juvenile development and

Glossary

Ancient tree: a tree that has lived for a significant amount of time, often several centuries or more, and is considered a remnant of the past forest ecosystem. Ancient trees play an important role in forest ecology by providing habitat, contributing to soil stability, and serving as a source of seed dispersal, which can help maintain the diversity of forest ecosystems and support their resilience to disturbances.

Ecosystem function: the range of processes and interactions that support the integrity or maintenance of forest ecosystems, including the cycling of nutrients, energy and nutrient flow, decomposition, primary production, and biodiversity.

Ecosystem services: the benefits that humans derive from natural ecosystems, including the provision of food, water, air purification, soil formation, climate regulation, and recreational opportunities.

Food web modularity: or compartmentalization refers to the tendency of species in a community to form distinct groups that interact more strongly with each other than with other species groups.

Integrated forest management: the management of forests to meet multiple societal demands (wood production, water and soil protection, recreation, and biodiversity conservation) in a smaller limited spatial extent, from the individual tree specimen to the local landscape rather than maximizing individual objectives at a larger regional scale.

Small-habitat features: refers to relatively small-scale elements within a landscape or ecosystem that provide important ecological benefits and significantly contribute to the overall biodiversity of an area. These features can include various physical components such as patches of unique vegetation, hedgerows, ponds, rock outcrops, fallen logs, tree-related microhabitats, or small water bodies. These elements, though small in size, can serve as crucial habitats, nesting sites, shelter, and food sources for a diverse range of plant and animal species. They play a significant role in supporting biodiversity by providing connectivity between larger habitats, promoting species movement, and enhancing overall ecological resilience.

Temporary water body: aquatic ecosystems that experience cycles of inundation and drying, typically because of seasonal precipitation patterns. They provide important habitats for a diverse range of organisms and play many ecological functions for surrounding landscapes by providing breeding habitat, water storage, filtering pollutants, and supporting the movement of nutrients and organic matter.

Tree-related microhabitats: fine-scale, specialized habitats that increase in diversity and density as trees experience injuries and age. Recent efforts have created a standardized typology grouping them into a hierarchical structure, with seven main forms (cavities, tree injuries and exposed wood, crown deadwood, excrescences, fungal fruiting bodies, epiphytic structure, and exudates) that can be further classified into 15 groups and 47 specific types.

Veteran trees: trees that have often survived previous disturbance events and possess unique structural features – such as hollows, cracks, and dead wood – that provide microhabitat features for a wide range of species.

growth. Different feeding functional groups inhabiting freshwater microhabitats then sequester resources from algae and periphyton (grazers), plants (herbivores), and detritus (shredders, filterers, collectors, etc.) that move energy and nutrients through complex food webs (Figure 1). Increasing food web complexity in terms of functional groups, trait diversity, and interaction strength within food web members generally increases their resistance and resilience to disturbance. Due to their large shoreline-to-area ratio, the impact of temporary water boundaries on the surrounding landscape extends far beyond their physical borders, and insect dispersal subsidizes the movement of energy and nutrients from aquatic to terrestrial ecosystems [8]. Temporary water bodies also play an important role in the movement and reproduction, acting as stepping-stones within terrestrial habitats by providing breeding and foraging grounds for insects, as well as an essential source of surface water for terrestrial organisms during dry periods [9]. The loss of temporary water bodies is detrimental to local biodiversity because their cyclical nature and relative isolation often creates conditions encouraging diverse endemic communities.

Trees are exposed to manifold biotic and abiotic impacts throughout their lifespan that leave behind broken branches, cavities, and other injuries. These processes create a wide range of tree-related microhabitats (Figure 1) that provide habitats and nutrients for a diversity of specialized forest insects. The diversity and density of tree-related microhabitats increase with tree age [10], underscoring the importance of conserving these features where they exist and promoting them when they are absent. The presence of dead wood also promotes forest biodiversity, as many insect species rely on this resource for at least one stage of their reproductive cycle, or at least benefit from it [11]. Decaying trees provide energy for food webs based upon cellulose and saproxylic fungi, where different functional groups capture energy and nutrients from decaying wood (xylovores) and fungi (fungivores) and then move it across the landscape as adults disperse (Figure 1). During dispersal, patches of ancient and/or veteran trees, as well as dead wood stores, create breeding habitat that maintains connectivity between often distant insect populations. These microhabitats are crucial for many species, with nearly 30% of European temperate hardwood forest insect biodiversity strictly associated with dead wood provided by the tree-related microhabitats typically found in ancient and/or veteran trees [12].

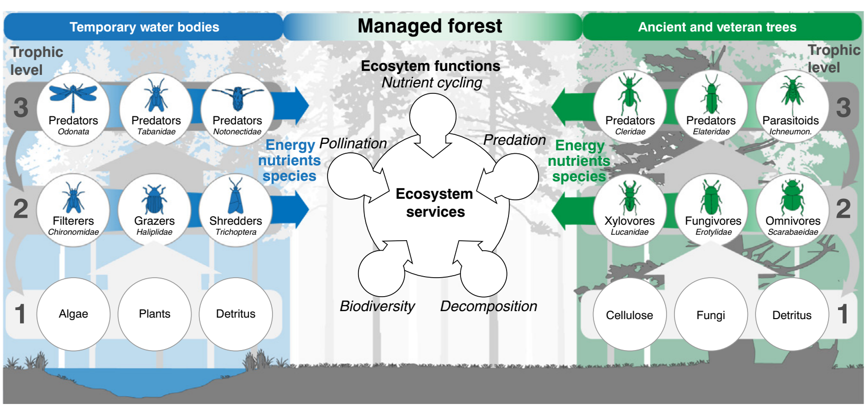
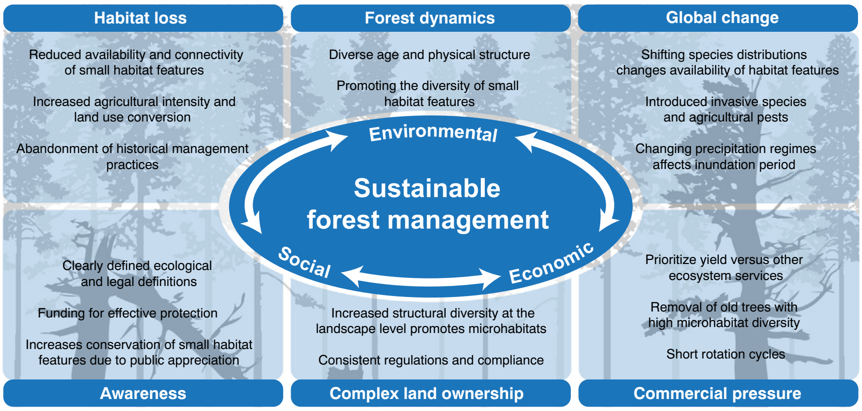


Figure 1. Temporary water bodies and ancient and veteran trees play a crucial role in fostering biodiversity and facilitating energy flows within forest ecosystems. These habitats function as diversity hotspots, offering unique energy sources to support different food webs that move through trophic levels (numbered 1, 2, and 3). For example, temporary water bodies provide habitat for algal and vascular plant growth, which serves as an energy source for aquatic organisms, whereas veteran trees provide cellulose for decomposers such as fungi and saproxylic insects. These differences in energy sources lead to specialization among species and result in complex, modular food webs with diverse traits within these microhabitats. However, the role of these microhabitats extends beyond their local food webs, as species originating from these habitats also serve as dispersers of energy and nutrients across the forest landscape. Upon reaching adulthood, many species emerge from the microhabitat and disperse, carrying with them energy and nutrients acquired through their development. The movement of energy, nutrients, and species enhances ecosystem services through increased pollinator, predator, and decomposer diversity, which increase the connectivity and resilience of the managed forest food web. Note: organisms shown are illustrative, and not an exhaustive representation of all groups and functional roles within these habitat features.

Challenges to management and conservation

The conservation of temporary bodies and the tree-related microhabitats provided by ancient and/or veteran trees face several key challenges within a sustainable management framework to meet social, environmental, and economic needs (Figure 2). Perhaps foremost, the identification and classification of temporary water bodies and ancient tree microhabitats is challenging due to their dynamic and heterogeneous nature, making it difficult to establish clear conservation criteria [7,13]. For example, the duration, frequency, and size of temporary water bodies can vary greatly throughout a single year, creating challenges to accurately delineate the physical extent of a temporary water habitat



Trends in Ecology & Evolution

Figure 2. Major threats and challenges for forest management practices that promote biodiversity. Successful integrated forest management that conserves habitats such as temporary water bodies and ancient or veteran trees requires a cross-sectorial approach to find compromise amongst differing interest groups. Each of these six factors present specific challenges that vary at different spatial and temporal scales that need to be considered for sustainable forest management aiming to promote forest biodiversity (based on [7]).

for conservation [7]. Similarly, as trees grow and age, the number and diversity of tree-related microhabitats increases, but this varies considerably between habitats even within tree species. As many species are dependent on the tree-related microhabitats and not tree age, experts have developed a hierarchical typology for the classification of the diversity of tree-related microhabitats to facilitate cross ecosystem comparisons and to quantitatively inventory and measure their contributions to biodiversity [14].

Without clear definitions of what delineates these smaller habitat features, it is even more challenging to create public awareness, enact legislation, and enforce protection [15]. Furthermore, regulatory frameworks tend to focus on larger habitats, and protections for individual habitat features such as temporary water bodies and ancient and/or veteran trees are inconsistent and tend to lack rigor. In some cases, legal protection may be focused on specific species, rather than the conservation of habitats that underlie biodiversity. This lack of attention to smaller habitat features like temporary water bodies and ancient and/or veteran trees can lead to the neglect of their cumulative, landscape-scale impacts on biodiversity and ecosystem services.

Complex land ownership can present both challenges and opportunities for the preservation of small-habitat features and thus integrated forest management [4]. While having more shareholders can increase the time and effort to reach a consensus on achieving individual goals, it can also promote a greater diversity of management plans on local spatial scales. Complex land ownership creates the opportunity for the creation of a more heterogeneous forest at the landscape level. As a result, these forests tend to have a greater structural diversity, which in turn can promote and support a higher density of small-habitat features such as ancient and/or veteran trees. This is achieved by creating management plans at the local level to meet societal demands of forests, as opposed to only addressing single shareholder objectives such as timber production at larger regional scales [4].

Concluding remarks and future directions

By creating more heterogeneous landscapes with a greater diversity of structure, age, and composition, we can promote small-habitat features important to forest insect biodiversity using integrated forest management principles. Planning should include the conservation of remaining temporary water bodies while minimizing nutrient and sediment runoff [7], and the promotion of temporary water bodies where appropriate topographic and edaphic conditions exist. In addition, practice should promote mixed stands with species that tend to develop tree-related microhabitats at an earlier age [4]. The impact of interventions on tree-related microhabitats should be assessed, and candidate trees that are likely to support a diversity of tree-related microhabitats in young forest stands should be identified, selected, and preserved [14]. Without a better understanding of the relationship between forest age structure, small-habitat features, and species requirements throughout the forest life cycle, we risk ineffective management practices that fail to meet societal demands.

The widespread loss of biodiversity and the accelerated decline of insects are a warning sign for our future, highlighting the need for effective conservation strategies. While there are some guidelines in place for the preservation of temporary water bodies and microhabitats associated with ancient and/or veteran trees, it is uncertain whether these guidelines are sufficient to meet current biodiversity conservation goals. As the human population grows, placing increasing demands on our forests to fulfill a multitude of roles, it is crucial that we take steps to ensure the long-term existence of these critical habitats and the diversity of species that rely on them. By preserving and promoting small but important habitat features, we can contribute to the resilience and long-term survival of our forest ecosystems in the face of a rapidly changing world.

Declaration of interests

No interests are declared.

[1]Swiss Federal Institute for Forest, Snow, and Landscape Research WSL, 8903 Birmensdorf, Switzerland
[2]Institute of Terrestrial Ecosystems ITES, ETH Zürich, 8092 Zürich, Switzerland

*Correspondence:
ryan.shipley@wsl.ch (J.R. Shipley).

https://doi.org/10.1016/j.tree.2023.05.015

© 2023 Elsevier Ltd. All rights reserved.

References

1. Outhwaite, C.L. *et al.* (2022) Agriculture and climate change are reshaping insect biodiversity worldwide. *Nature* 605, 97–102
2. Soliveres, S. *et al.* (2016) Biodiversity at multiple trophic levels is needed for ecosystem multifunctionality. *Nature* 536, 456–459
3. Felipe-Lucia, M.R. *et al.* (2018) Multiple forest attributes underpin the supply of multiple ecosystem services. *Nat. Commun.* 9, 4839
4. Krumm, F. *et al.* (2021) *How to balance forestry and biodiversity conservation? A view across Europe*, European Forest Institute and Swiss Federal Research Institute WSL
5. Hunter, M.L., Jr *et al.* (2017) Conserving small natural features with large ecological roles: a synthetic overview. *Biol. Conserv.* 211, 88–95
6. Piovesan, G. *et al.* (2022) Ancient trees: irreplaceable conservation resource for ecosystem restoration. *Trends Ecol. Evol.* 37, 1025–1028
7. Meerhoff, M. and de los Ángeles González-Sagrario, M. (2022) Habitat complexity in shallow lakes and ponds: importance, threats, and potential for restoration. *Hydrobiologia* 849, 3737–3760
8. Twining, C.W. *et al.* (2021) The evolutionary ecology of fatty-acid variation: implications for consumer adaptation and diversification. *Ecol. Lett.* 24, 1709–1731
9. Kirsch, J.J. *et al.* (2021) The use of water-filled tree holes by vertebrates in temperate forests. *Wildlife Biol.* 2021, 1–4
10. Courbaud, B. *et al.* (2017) Modelling the probability of microhabitat formation on trees using cross-sectional data. *Methods Ecol. Evol.* 8, 1347–1359
11. Graf, M. *et al.* (2022) Coverage based diversity estimates of facultative saproxylic species highlight the importance of deadwood for biodiversity. *For. Ecol. Manag.* 517, 120275
12. Ulyshen, M.D., ed (2018) *Saproxylic Insects: Diversity, Ecology and Conservation*, Springer
13. Lindenmayer, D.B. and Laurance, W.F. (2016) The unique challenges of conserving large old trees. *Trends Ecol. Evol.* 31, 416–418
14. Larrieu, L. *et al.* (2018) Tree related microhabitats in temperate and Mediterranean European forests: a hierarchical typology for inventory standardization. *Ecol. Indic.* 84, 194–207
15. Calhoun, A.J. *et al.* (2017) Temporary wetlands: challenges and solutions to conserving a 'disappearing' ecosystem. *Biol. Conserv.* 211, 3–11