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Insect conservation in boreal and temperate forests

Rudi C. Swart[1], Tim R. New[2], D. Johan Kotze[3], Michael J. Samways[4]

[1]Department of Conservation Management, Faculty of Science, George Campus, Nelson Mandela University, Madiba Drive, George 6530, South Africa

[2]Department of Environment and Genetics, La Trobe University, Victoria 3086, Australia

[3]Faculty of Biological and Environmental Sciences, Ecosystems and Environment Research Programme, University of Helsinki, Helsinki, Finland

[4]Department of Conservation Ecology and Entomology, Stellenbosch University, Matieland 7652, South Africa

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Abstract

Earth's high latitude and temperate forest regions harbour significant insect diversity, and have massive ecological and economic values, both as carbon sinks and sources of timber. Northern boreal forest and temperate forests, both in the northern and southern hemisphere, are floristically distinct, but suffer parallel pressures from climate change, exploitation for timber, and invasions by alien species, processes that threaten forest integrity and the wellbeing of many endemic insects in these far separated parts of the world. A few species have become serious pests of production forestry, but most are poorly documented, and their patterns of endemism, local diversity, and distributions are unclear. Harmonising forest insect conservation with anthropogenic pressures is critical for sustaining the numerous interactions in which insects participate. Some of these interactions are immensely intricate. The disappearance of a single tree species in a natural forest can lead to accompanied insect species extinctions. Many of these interactions, especially in southern hemisphere forests, are undescribed. Here, we synthesize current challenges and opportunities for insect conservation in boreal and temperate forests.

Keywords: boreal forest, global change, insect conservation, temperate forest

Boreal forests

Boreal forests, the world's northernmost forests, cover more than 1300 million ha (Högberg et al. 2021) across large parts of Alaska, northern Canada, Fennoscandia, and Russia. As the world's largest terrestrial biome, boreal forests represent a third of all global forested areas, much remote wilderness, but with large areas under forestry management. About half of boreal forests are unmanaged, mainly due to inaccessibility of many regions. However, in some, such as the boreal forests of Fennoscandia, timber extraction has proliferated (Högberg et al. 2021). Boreal forests not only provide much timber but are also a massive carbon sink – especially in their soils (Crowther et al. 2019) – influencing regional and global climates. Boreal forest trees have a combined carbon stock of over 42 000 million metric tons (Högberg et al. 2021) (ca. 49% of global forest carbon storage: Dixon 1994) reflecting the slow growth rates of boreal trees and the ability of their roots to store carbon in dense, organic soils. The functional wellbeing of such a vast and influential biome is vital to wider global ecological and climatic integrity.

Themes in insect research and patterns

Boreal forests, despite their harsh environment, have high insect diversity, the role of which is only beginning to be understood (Hanski 2008). Nearly a quarter of forest-dwelling insect species in Fennoscandian boreal forests are saproxylic and depend on dead wood habitats (Siitonen 2001). Decomposition of dead wood by saproxylic taxa is vital to retain soil fertility and an intact carbon cycle. Sustaining these processes depends on insects. In healthy forests, decomposition of leaf litter and other organic debris by bacteria, fungi, and insects are important nutrient releasers, unlocking nutrients trapped in the litter and are key to tree growth. For instance, the white-spotted sawyer beetle, *Monochamus scutellatus scutellatus*, is pyrophilous, actively feeding on burned logs after fire. This beetle's frass increases microbial respiration rates in the soil, and significantly alters nitrogen availability (Cobb et al. 2010).

Woody debris can be up to 10 times less in managed forests compared to unmanaged forests (Siitonen 2001) due to removal during forestry operations, markedly lessening this critical resource for about 3000 species of saproxylic insects in Finland alone (Hanski 2008). Dead wood is an exceptionally important habitat feature for many insects and other taxa in boreal forests, with studies showing an increase in abundance and richness of saproxylic insects with increasing amounts of dead wood (Sandström et al. 2019), including in fruiting bodies of wood-decaying macrofungi, which can be considered hotspots of boreal forest insect diversity (Komonen 2003). The effect of removal of woody biomass from large areas of the landscape on the rest of the soil food web, and the functioning of the boreal ecosystem as a carbon sink, is likely to be severe, but may not always be evident as the extinction debt takes time to be paid (Hanski and Ovaskainen 2002).

Increasing severity and frequency of droughts are often linked with insect outbreaks, causing large areas of dieback, reducing timber production and threatening ecological integrity. Insect responses to long-term climatic changes are evident among major pest species. Thus, the spruce beetle (*Dendroctonus rufipennis*) is sustained by extremely cold conditions typical of boreal regions. Laboratory trials confirmed that warmer temperatures favour spruce beetle larval success, whereas drier and warmer weather can decrease tree defences (Berg et al. 2006). Past spruce beetle outbreaks have caused large-scale tree mortality, with about 1 million ha of forest area lost in Alaska following years of record warm temperatures. Higher autumn and winter temperatures preceded spruce beetle outbreak years, compared to non-outbreak years (Hart et al. 2014). The period of ca. 75 years between spruce beetle outbreaks at specific sites could be ascribed to the large mortality of spruce trees during the outbreak, and subsequent long-term recovery of spruce as a dominant canopy species. Increases in the incidence and longevity of warmer temperature events could see a great drop in spruce abundance, impacting the larger ecosystem as well as the timber industry. Similarly, due to climate change, the European spruce bark beetle (*Ips typographus*) is expected to swarm earlier in the spring and have additional generations per year in Fennoscandia (Jönsson et al. 2009), with potentially devastating consequences ecologically and for the forestry industry. Such wide-ranging pests demand suppression measures that may have non-target impacts on other forest insects.

In the Arctic and Subarctic, climate warming is increasingly affecting species' distribution patterns. An increase in the growing season of 2.6 days/decade between 1984 and 2014 for these zones will lead to significant shifts in insect ranges, due to changes in phenology and an earlier onset of insect activity (Klimaszewski et al. 2021). Additionally, with the boreal treeline advancing toward higher latitudes, a major change to habitat availability will affect Arctic biodiversity, with warmer winter spells already implicated in declines of beetle abundance and diversity between 1970 and 2010 (Harris et al. 2019).

The Arctic zone, characterized by a short growing season and a largely treeless landscape, hosts a unique biome, the tundra, with a permanently frozen soil layer (permafrost) in large areas. Rapidly increased warming of these high latitude regions may lead to up to 40% of near-surface permafrost being lost. This will increase plant productivity at increasing latitudes (Berner et al. 2020), but also increase the ability of soil microbes to decompose old organic material, releasing historically stored carbon to the atmosphere (Heijmans et al. 2022). As the boreal treeline shifts northwards, many invertebrate species confined to the tundra are at risk of becoming locally extirpated.

More herbivore outbreaks and droughts are predicted should temperatures increase by only 2 °C. Biodiversity and ecosystem services are at risk of being reduced and perhaps lost, together with large regional carbon sinks. Significant changes in midsummer vapour pressure in Alaskan boreal forests could lead to a 'tipping point' transforming a productive boreal forest landscape to one of early succession angiosperms, and have tundra replaced by boreal forests (Trugman et al. 2018). Likewise, land-use change and droughts greatly increase the risk of megafires (Stephens et al. 2014). Such changes will also induce changes in insect communities, for example many keystone ant species disrupting interactions between potential herbivorous pests and their natural enemies (Trigos-Peral et al. 2021). Those changes, difficult to predict, may threaten numerous taxa. Importantly, only a few insect species cause outbreaks, with most species far less conspicuous. Insects play disproportionately important roles in forest functioning and are central components of food webs throughout strata from soil and litter layers to emergent tree crowns. Understanding changes in insect diversity, distribution and behaviour is of critical importance. Loss of vital ecosystem services inevitably threatens forest integrity. This means that it is important that managers and conservationists must recognise the central role of insects in maintaining forest integrity.

Management as a form of forest disturbance and retention forestry

Natural disturbance-based management, incorporating especially fire but also insect outbreaks and windfall, are gaining traction in boreal forests (De Grandpré et al. 2018). The premise is that forests have developed over time with disturbance, building up an inherent resilience. Forest management should work within the limits of such natural disturbance regimes. Sound knowledge of the parameters of natural disturbance is essential for this approach toward management. In managed boreal forests, disturbances through management practices (i.e., clear felling, active forest renewal) have largely taken over from natural disturbances (i.e., fire, passive forest renewal). The net result is large areas devoid of old trees or dead wood, and a landscape dominated by even-aged stands.

Retention forestry is the process where some trees, logs and snags are left post-harvesting to more closely mimic natural mosaic disturbances. Indeed, natural disturbances (fire, windfall, outbreaks) would typically leave legacies of pre-disturbance forests and are therefore inherently different from the conventional forestry practice of blanket clear-felling (Heikkala et al. 2014). Retention forestry allows for a greater diversity of saproxylic insects and increases available soil nutrients for a new generation of trees, while also facilitating insect conservation spanning numerous other feeding guilds (i.e., nectarivores, predators, parasitoids (Gustafsson et al. 2020)). Retention trees can aid conservation of many rare and red-listed beetles, which would otherwise be lost from the landscape when applying conventional clear-felling. Uneven-aged forest stands can increase beetle diversity at the landscape level, compared to even-aged stands (Joelsson et al. 2018) by sustaining greater environmental heterogeneity. More diverse forest stands of mixed tree species could also mitigate negative growth effects of future climate change, as in eastern Canada (Chavardes et al. 2021). A review of mixed versus pure boreal forest stands showed the former to have higher biodiversity, soil health, and number of uses (Huuskonen et al. 2021).

Retention forestry maintains higher levels of biodiversity than clear-felling, to the benefit of early successional forests. Increased biodiversity linked to remnant large trees and coarse woody debris can increase the ecological services provided, as well as long term ecological integrity. Increased substrate diversity also widens possible microclimatic niches through increased structural and compositional diversity at the stand level, while increasing connectivity across the landscape for tree-associated biodiversity, including insects (Koskela et al. 2006). This approach can assist survival of populations of key biodiversity within harvested landscapes, providing post-harvest stepping-stone habitats, following a successional model closely mimicking natural disturbance and recovery (Heikkala et al. 2014). This can be achieved by retaining scattered, individual large trees during clear felling, and through aggregated retention, whereby trees are left in clusters (Koskela et al. 2006). The many forms of retention forestry thus include individual living trees left standing, retention patches of trees of various sizes and/or high stumps (cut at heights 3-5 m). Each approach can provide benefits but also negative outcomes.

Arguably, the best approach is to retain larger patches (at least half a hectare but preferably larger (Gustafsson et al. 2020)), ranging from sunny to shaded microclimates (e.g., north and south-facing, as these will host differing insect and other saproxylic taxa) that afford connectance of key biodiversity across the clear-felled landscape. Approaches such as the addition of dead wood and/or prescribed burning could benefit certain saproxylic species (Koivula and Vanha-Majamaa 2020). In the case of dead wood, it is advised that dead wood of at least each species present in the system be left or added to the logged landscape. Unlogged buffer zones along streams and rivers can also contribute to regional biodiversity conservation, by acting as reservoirs for rare and red-listed species that are absent from logged buffer zones. Like retention forestry, wider stream buffers and more trees promote conservation of increased biodiversity. However, even small buffers and individual trees may confer benefit over clear-felling (Gustafsson et al. 2020).

Woodland key habitats

In addition to retention forestry, woodland key habitats (WKHs) are another approach toward conservation without sacrificing large areas to production. This approach contrasts with the traditional conservation approach of large areas of forests reserved for conservation only. It focuses within the production landscape itself – areas of natural vegetation, distinct from the composition and structure of surrounding, managed forests. These areas are typically small, in Finland about 0.6 ha on average. They can provide significant increases in functional biodiversity at the landscape scale. Using WKHs, managers can effectively promote the protection of key biodiversity which would otherwise become regionally extinct (Hanski 2008). Larger areas are better for biodiversity conservation efforts and landscape sustainability, but even smaller WKHs may increase metapopulation connectivity. In fragmented boreal landscapes, such as WKHs in production landscapes, forest patches can still retain a high richness of forest ground beetles (Niemelä et al. 2007). This highlights the role of even fragmented forests in contributing to regional biodiversity and the importance of their ongoing conservation.

Ecologically sensitive management must, however, consider the possibility of extinction debt – the future extinction of a species due to past and/or current activities. Boreal forests had lower extinction rates of beetle species the shorter they were exposed to industrial forestry practices (Hanski and Ovaskainen 2002). Indeed, many beetle species could eventually disappear from the landscape without the presence of old-growth forest refugia (Niemelä et al. 2007). To prevent this, forest management should, where possible, mimic natural disturbance when harvesting timber, maintain natural vegetation, structural and compositional variation at the landscape level, and maintain especially old-growth forests across the forestry landscape (Hanski and Ovaskainen 2002; Niemelä et al. 2007, see also the EMEND project: https://emend.ualberta.ca/). Forests left undisturbed for long periods through sustainable forestry practices or due to topography and inaccessibility, will also eventually become important carbon sinks and conservation areas for rare insect taxa (Högberg et al. 2021).

Northern temperate forests – veteran trees and rehabilitation efforts

To the south of boreal forests, northern temperate forests dominate large areas, notably in Europe, eastern North America and eastern Asia, notwithstanding the coastal sequoia forests along North America's northwest coast. Whereas boreal forests are characterized by conifer spruces (*Picea*), firs (*Abies*), pines (*Pinus*) and larches (*Larix*), temperate forests harbour a richer diversity of deciduous or evergreen, broad-leaved species. A relatively large, ca. 500 km wide ecotone bridges boreal and northern temperate forests, where many tree species are shared between the two otherwise distinct biomes.

Some northern temperate tree species, for example the giant sequoia (*Sequoiadendron giganteum*), are extremely long-lived (up to 3200 years old) and can be classified as veteran trees. Three measures define a veteran tree: diameter, age and microhabitat availability; of which diameter has been most often used (Horák 2017). However, tree age and microhabitat availability are important drivers of tree-associated biodiversity with veteran trees acting as hotspots within the landscape (Horák 2017; Wetherbee et al. 2021).

Apart from being part of our cultural heritage, veteran trees have unique conservation value, notably for associated insects. The number of microhabitats associated with veteran trees are relatively high, for example through hosting extensive areas of epiphytes, mosses and lichen, with numerous cavities for fungal growth, water capturing and dead bark accumulation. Also, veteran trees typically have various levels of exposed wood, and extensive root systems, living and dead (Siitonen and Ranius 2015). In Sweden, for example, of oak trees that were less than 100 years old, only 1% had cavities (Ranius et al. 2009). This increases to over 50% for oak trees 200-300 years old, whereas trees over 400 years all had cavities (Ranius et al. 2009). In Europe alone, hundreds of insect species are associated with tree cavities, with the most important taxa being beetles, flies, wasps and ants (Stokland et al. 2012). Veteran trees have significantly higher taxonomic and functional beetle diversity than young trees, as shown for oak trees in Norway (Wetherbee et al. 2021). This shows the importance of not only adequate tree species conservation efforts, but also to target conservation efforts towards including veteran trees as contributors of unique conservation value and associated biodiversity.

Unfortunately, many of the world's veteran trees have been lost. This is especially true for northern temperate forests, with a long history of clearing. Since 1850, *Sequoia* forests have decreased from ca. 8900 km^2 to 457 km^2 at present. The losses of tree-associated biodiversity are perhaps unquantifiable. This is even more concerning given the fact that a third of the world's tree species is currently at risk of extinction (Rivers et al. 2022). With extensive loss of temperate forests in Europe and Asia, often many centuries ago, there has been much focus on preserving any remaining ancient forests and even remnant patches of woodland. Great efforts have been made to restore temperate forests, with an emphasis on ensuring that forest heterogeneity, both in terms of tree species and spatial light regimes, are maintained using physical intervention management. This has often been associated with rewilding with large herbivorous mammals such as deer and bison, as well as reintroduction of the beaver. However, temperate forest restoration and insect recovery take many decades. One challenge is that some insects such as the Greater Capricorn beetle *Cerambyx cerdo*, which hollows out galleries suitable for many other insect species, requires mature native oak (*Quercus robur*) trees with intermediate aged trees not sufficient (Oleksa and Klejdysz, 2017).

Southern hemisphere forests

Temperate forests in the southern hemisphere are less widespread than northern forests, due to a fragmented, much smaller, and widely separated land area, but are perhaps even more diverse biologically. Each region harbours numerous localized endemic insects, some comprising diverse radiations intricately linked with endemic forest flora. They occur across all major lands towards the south, except Antarctica, so characterise parts of southern South America, Africa, New Zealand, and Australia, each with endemic insect fauna. Many of these forests share a palaeohistory through being on remnants of the former supercontinent Gondwana, with correspondingly ancient, and endemic, insect lineages. For example, the 58 mm-long dragonfly, *Neopetalia punctata,* is the only member of the family Neopetaliidae and confined to forest streams and seeps at the southern tip of South America. Its conservation status, as with many southern forest insects, is listed as 'Data Deficient'. Indeed, compared to northern forests, most southern hemisphere forests have received less research attention, largely reflecting a shorter history of intensive exploitation, although their biological significance and peculiarities have long been recognised.

Despite less documentation, southern temperate forests are no less susceptible to global change and other disturbances. In *Nothofagus* forests of southern Chile, for example, the native moth *Ormiscodes amphimone* caused defoliation across an area totalling 164 000 ha between 2000 and 2015 (Estay et al. 2019), but it is unclear whether this phenomenon is a natural, cyclic process. Here, increases in monthly maximum temperatures have already been recorded. Perhaps unsurprisingly, outbreaks of *O. amphimone* have increased in frequency and severity since 2000 (Gutiérrez et al. 2020). In general, *Nothofagus* forests in South America and Australia have depauperate insect faunas, compared with New Zealand (McQuillan 1993), where endemic margarodid bugs (sooty beech scales, *Ultracoelostoma* spp.) are functionally important in forest nutrient dynamics. However, each region supports endemic insects - South American *Nothofagus*, for example, supports primitive heterobathmiid moths, and endemic Geometridae occur in all areas. There is little overlap between insects of *Nothofagus* and co-occurring flora – Australia's vast psyllid diversity, for example, is almost all associated with acacias or eucalypts, and scarcely with *Nothofagus*. Regardless, *Nothofagus* forest insects can be highly sensitive to disturbance – forest fires greatly diminish insect diversity more than 15 years post fire, with richness and abundance showing prolonged declines in severely burned Chilean *Araucaria-Nothofagus* forests (Tello et al. 2020). This is partially ascribed to the low fire tolerance of *Nothofagus* trees, which sees a sharp decrease in *Nothofagus*-associated insect fauna for decades post fire.

In other southern hemisphere forest systems, insect outbreaks (mostly of Hemiptera, Coleoptera, or Lepidoptera) can become severe and extensive. However, in both South Africa and Australia increasing severity and frequency of fires are threatening long term forest integrity and many of their inhabitants. The southern Afrotemperate forests do not burn naturally, although they occur as fragments in a fire-prone landscape, dominated by shrubby, sclerophyllous fynbos vegetation. In the southern Cape region, large areas of indigenous fynbos have been converted to plantation forestry, largely comprised of stands of exotic *Pinus* species. These plantations are often planted right up to indigenous forest edges, displacing the natural fynbos-forest ecotone (Swart et al. 2018; Giddey et al. 2021). When southern Afrotemperate forests are bordered by pine plantations, there is increasing variability in the distances that fires penetrate natural forests, with smaller forest patches at higher risk of being lost (Giddey et al. 2021). Two of the most severe fires recorded for this region (in 2017/18), followed a record dry period. Pine plantations and invaded fynbos (largely by Australian acacias) provide more biomass of fuel wood compared to uninvaded fynbos, further exacerbating the effects of fire on forest edges and fragments across the landscape (Kraaij et al. 2018). When natural fynbos-forest ecotones are replaced by pine stands or clear-felled areas, severe edge effects impact ground-dwelling arthropods up to 50 m into natural forests, further fragmenting a forest system already consisting of numerous isolated forest patches (Swart et al. 2018). Alien invasive species encroaching along borders, coupled with increased incidence of fires, are serious risks to future insect conservation efforts in southern Afrotemperate forests. For example, the geographically isolated butterfly, *Charaxes xiphares occidentalis*, shows severe negative responses to alien invasive plants – further habitat degradation and forest isolation could be detrimental to its long-term survival (Crous et al. 2015).

Moreover, a recent (2018) outbreak of the invasive alien polyphagous shot hole borer (*Euwallacea fornicatus*) in the southern Cape has shown to impact a great variety of indigenous forest tree species, including the edge specialist and important forest successional tree genus *Virgilia*, posing another significant threat to forest edges and smaller forest fragments (Van Rooyen et al. 2021). Moreover, *Virgilia* spp. are the larval host plants of the endemic silver-spotted ghost moth, *Leto venus*, forming an important mutualism for forest succession: adult females lay eggs in the soil among the roots of mature trees, and the emerging larvae bore upwards through the tree before emerging as adults (Geertsema 1964). Oftentimes, the stem becomes hollowed out – when these pioneer trees succumb due to strong winds, later successional forest species are able to proliferate in the opened-up canopy. The polyphagous shot hole borer poses a direct threat to this vital process of forest succession in the southern Cape.

The southern Cape region is currently at great risk from global change: a warming climate, a changing fire cycle, an increasing dominance of alien vegetation, and a novel and major outbreak of an invasive, tree-killing bark beetle. Researchers and managers in this largest indigenous forest complex in southern Africa have adopted a policy termed 'exit areas' in line with these landscape level challenges faced. Exit areas are those previously earmarked for timber production through plantation stands of largely *Pinus* species, now set aside to be rehabilitated back to natural vegetation. Conservation corridors of natural vegetation, linking isolated forests and maintaining the integrity of fynbos-forest ecotones, could greatly contribute to insect conservation of forest species in the southern Cape region (Samways and Pryke 2016). This collaborative effort between South African National Parks, commercial forestry companies and national government, is planned to merge production forestry and conservation interests into a sustainable landscape. Like the southern Cape, *Pinus radiata* plantations are widespread also in southern Australia, as the major local source of softwood. Many plantations are on land cleared of native forests, and within which native insect diversity is highly impoverished.

The rich and endemic insect fauna of south temperate forests

Temperate forests of the southern hemisphere have a diverse insect fauna, rich in many localized endemics. As with many other forests across the world, insects in these regions are currently exposed to multiple stressors, especially landscape fragmentation, habitat loss, invasion by invasive alien plant species, and increasing fire risk. While many of the insect groups are poorly known, we can begin to understand the effect of stressors and are able to put effective management practices in place based on what we have learned from charismatic groups.

We focus here on a familiar group, dragonflies (Odonata), and their relationship with southern Afromontane forests along the coastline at the southern tip of Africa. In this region there is a range of mountains, the Cape Fold Mountains, that has a long geological history without glacial sheets, and much precipitation as rain and condensation. There are many streams and small rivers of great eco-evolutionary significance as they release water throughout the dry summer, providing a perennial habitat that supports many localized endemics specifically adapted to local habitats, yet susceptible to novel stressors. Forest specialist dragonfly taxa such as *Ecchlorolestes nylephtha*, *Chlorolestes umbratus*, *Allocnemis leucosticta*, *Pseudagrion hageni hageni*, and *Syncordulia venator*, are all characteristic of healthy forested stream habitat, and being endemic to southern Afromontane forest, are used to monitor streams and their riparian zones (Samways and Deacon 2022). A handbook, based on dragonfly assemblage response helps with practical implementation of effective conservation measures (Samways and Simaika 2016). Conserving high-scoring species leads to forest protection while also umbrellas for other important freshwater taxa such as Ephemeroptera, Plecoptera, and Trichoptera (Kietzka et al. 2019).

Figure 1: The localized deep Afromontane forest specialist *Chlorolestes umbratus* (left). The untransformed natural forest habitat of the species (right).

In late 2019 and early 2020, Australia experienced some of the most severe fires on record and, as with the megafires of the southern Cape, followed a record dry year of ca. 2 ºC warmer than historic records (Abram et al. 2021). Over 23% of temperate forests in southeast Australia burned, with over 10 million ha affected of which about 7 million ha were temperate forest and woodland (Abram et al. 2021; Saunders et al. 2021). In southeast Australia, temperate forests are largely comprised of broad-leaved and evergreen species of highly flammable *Eucalyptus* and related Myrtaceae trees that host high numbers of endemic insect herbivores and their associates, many of them poorly known and apparently both local and rare. During these megafires, an estimated 0.31 - 1.03 Pg (petagram, or billion metric tonnes) of carbon were released from *Eucalyptus* forests to the atmosphere (Bowman et al. 2020). The extent of loss of invertebrates from these immense fires is unknown, although with major implications of losses to this diverse but incompletely described fauna. A total of 787 invertebrate species (including two species of dung beetle and four species of drosophilid fly: Hyman et al. 2020) have most of their known distribution ranges (>50%) within the 2019/2020 fire-affected area (Marsh et al. 2022). Of these, 41 species are listed as nationally threatened. The absolute numbers of individuals lost are unquantifiable and population effects are predictably severe. Also, as most of the Australian invertebrate fauna are undescribed, the number of species affected is predictably much higher than reported and could include many short-range endemic species (Marsh et al. 2022).

Losses of natural temperate forest have contributed to increase plantations of *Pinus* and of native *Eucalyptus*, the latter including species planted far beyond their localised native Australian range, so essentially also being 'aliens'. Both monocultures can induce pest problems, including outbreaks of native insects. Alien species impacts are demonstrated by *Vespula* wasps in New Zealand's *Nothofagus* forests and, more recently, southern forests of Chile. Suppression of the wasps is a continuing endeavour (Lester and Beggs 2019). Since 2017, invasive *Vespula* wasps in southern South America have increasingly moved into natural habitats, ranging from evergreen, deciduous and mixed forests, feeding on many native insect species (Rendoll-Cárcamo et al. 2022). Notably, *V. vulgaris* can shift its foraging behaviour depending on forest type, with its invasion success ascribed to this adaptive behaviour. Some prey items include native crane fly (Tipulidae) and hover fly (Syrphidae) species in evergreen forests, and lepidopterans in mixed forests, possibly important native pollinators. Predation on beetles, geometrid larvae, spiders, and a local dragonfly (*Rhionaeschna variegata*) by *V. vulgaris* is reason for concern, as it has been acknowledged that eradication is, at present, non-viable if not impossible (Rendoll-Cárcamo et al. 2022).

Over about two centuries of European settlement, much of Australia's temperate forest estate has been cleared, with much remaining temperate eastern forest now formally included in a global biodiversity hotspot. Economic and political pressures for timber extraction from native forests continue (New 2018), together with measures to curtail the impacts of severe wildfires such as the above on human life and the wider environment. The latter includes extensive advocacy for 'fuel reduction burning'; control burning of forests to reduce ground fuel loads as insurance against intensity of future wildfires, likely to increase as climate changes. Both practices are concerns for insect conservation: direct loss of habitats, increased fragmentation, facilitation of alien weed, and other invasions confound direct destruction of insect life. Many litter-dwelling taxa, for example, are susceptible to direct burning from unnatural fire regimes. Australia's most diverse moth family, Oecophoridae, includes several hundred species whose larvae feed on dead eucalypt foliage on forest floors and collectively are major contributors to decomposition webs. Recommendations for mosaic, or 'micromosaic' imposed burns, rather than the large areas attractive to managers are based on needs to conserve heterogeneity and refuges for insects on the forest floor (New 2014).

Protection of southern forests is difficult, but necessary. The endemic *Fitzroya* forests of central/southern Chile and Argentina include the oldest dense forest stands in the world (Urrutia-Jalabert et al. 2015), vital carbon sinks, and were formerly exploited heavily for timber. The monotypic tree, *Fitzroya cupressoides*, is now officially protected and listed as 'threatened', and stands in several National Parks are apparently secure, together with their insect inhabitants. Future insect conservation, still based in a very incompletely documented fauna, but one clearly of immense and intricate variety, necessitates protection of key forest areas selected to span their considerable botanical variety, reduction of further fragmentation and losses from sensitive areas, control of threats and perceived impacts as far as possible, and increased knowledge of the unique insect biodiversity these forests support. These measures are inevitably general, with the variety of forest structures, environments, vulnerabilities, and landscape contexts largely precluding detailed proforma management plans beyond specific contexts. Numerous – and more popular – vertebrates are threatened by forest changes, and conjoint conservation efforts demand consideration.

Conclusion

Boreal and temperate forests are the highest latitudinal forests on the globe, and central to the global carbon cycle. As well as direct loss to satisfy demands for wood products they are threatened by increased droughts and fires linked to climate change that can markedly change forest structure. Southern eucalypt forests, in particular, are 'old': as ancient climax systems, once lost they cannot be replaced for, perhaps, 500 years or more. Substantial remnants of southern and northern temperate forests, and many areas of remote boreal forest remain intact, as natural laboratories from which understanding of forest functions can flow in the absence of logging. It is possible to significantly conserve biodiversity at the landscape level, while retaining timber production. Managed boreal forests can therefore not only maintain their important role in the global timber trade and carbon cycle but also conserve rare and red-listed insect species, for example those of dead and decaying wood. Defining these elsewhere is 'a work in progress', with much of the southern hemisphere insect fauna unknown in any detail, and their resource needs still obscure across a considerable botanical variety of forests. Many are known from singletons or single localities and assessed as 'Data Deficient' is currently the only option. However, global change is already affecting ecological integrity of southern temperate forests in southern Chile (increases in insect outbreaks, invasive species), southern Africa (increases in fire severity and frequency, alien invasive vegetation and invasive pests) and southeast Australia (increases in fire severity and frequency). Effects on insects, including numerous endemic taxa, are predictably severe. Countering the more tangible threats arising from human activities and continuing timber needs and ensuring security of forest biodiversity – including the unique natural heritage of insect life – must become an increased priority across the entire spectrum of forests included here.

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