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Review

Protected areas and the future of insect conservation

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Anthropogenic pressures are driving insect declines across the world. Although protected areas (PAs) play a prominent role in safeguarding many vertebrate species from human-induced threats, insects are not widely considered when designing PA systems or building strategies for PA management. We review the effectiveness of PAs for insect conservation and find substantial taxonomic and geographic gaps in knowledge. Most research focuses on the representation of species, and few studies assess threats to insects or the role that effective PA management can play in insect conservation. We propose a four-step research agenda to help ensure that insects are central in efforts to expand the global PA network under the Post-2020 Global Biodiversity Framework.

Highlights

Insects dominate the biosphere and play a central role in ecosystem processes, but they are rapidly declining across the world.

Protected areas (PAs) are designed to insulate biodiversity from human-induced threats, but they have been mainly designated for vertebrates and plants. Most research on insects in PAs focuses on the representation of species, and few studies assess threats to insects or the role that effective PA management can play.

We propose a four-step research agenda to help ensure that insects are central in efforts to expand the global PA network under the Post-2020 Global Biodiversity Framework.

Insects in the Anthropocene

Insects comprise >80% of all animal species [1] but are frequently overlooked in conservation assessments and environmental management activities [2,3]. Recent studies from North America and Europe have documented dramatic declines in insect diversity and abundance [4–7] driven by factors including agricultural intensification, climate change, habitat loss and fragmentation, pollution, invasive species, and insecticide use [6,8–11]. Given the importance of insects in many ecosystems, halting and reversing these trends is among the most important tasks of conservation globally [3,6,9,12,13]. However, the extent of the global insect collapse is still relatively poorly understood [14,15], and insects comprise only 8% of species assessed against International Union for Conservation of Nature (IUCN) Red List criteria [16].

If the extinction rate of insects is similar to that of birds, at least 44 000 species have disappeared since 1500, but only 70 insect extinctions are documented [17]. Although this might be an erroneous comparison owing to ecological differences between birds and insects, the scale of the insect extinction crisis is surely profound. Comprehensive regional Red List assessments for particular insect groups suggest that the outlook is bleak. For example, 11% of European saproxylic beetles are listed as threatened, 13% are Near Threatened, and 28% are Data Deficient [18]; in Bangladesh 62% of butterflies are threatened, and a further 11% are Data Deficient [3].

Insects dominate the biosphere where they play a central role in ecosystem processes and functioning [1,15,19]. Most notably, insects pollinate flowers, their herbivory influences the physiology and population dynamics of plants, they are a major food source for higher trophic levels, and they transfer more energy from plants to animals than any other plant-eating taxa [1,20,21]. Some 80% of wild plants rely on insects for pollination, and 60% of birds use insects as a food source [14,15,22,23]. Nevertheless, despite their manifest importance, insects remain neglected in the conservation literature [3,24], and strategies for their protection and management are poorly developed in comparison to those for vertebrates [1,24–26].

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As anthropogenic impact accelerates across the planet [15,27], about 60% of terrestrial Earth is under moderate to intense human pressure [28], and the current rate of species extinctions exceeds the natural background rate by 1000-fold [29,30]. Following Goal 3 of the current Post-2020 Global Biodiversity Framework draft, area-based conservation measures and ecosystem-based approaches ('nature-based solutions') are seen as crucial to halt the collapse of biodiversity [31]. **PAs** (see Glossary) and other conserved areas are, and will continue to be, a significant global tool to conserve threatened and endemic species [32]. In recent decades, thousands of new PAs have been established to harbor plants and animals [33]. However, what is the role of PAs in conserving insects?

Assessments of PA performance focus almost exclusively on coverage of vertebrate distributions, vegetation communities, or ecosystems, perhaps because these aspects of biodiversity are most readily mapped [33]. There has been little assessment of how well PAs conserve insects. Worryingly, insect declines have been documented within some PAs, including those in the UK, Germany, The Netherlands, Sweden, Costa Rica, and Puerto Rico [15,34]. For example, flying insect biomass has declined more than 75% in some PAs in Germany [35]. Although the trends for insect decline are often weaker in protected than unprotected areas [5], it is unknown whether systemic declines inside PAs are occurring globally [36], and whether PAs are being adequately managed for insect conservation. Given the crucial role of insects in ecosystem processes, managing them within PAs could be vital to ensure the ecological functioning and resilience of PAs themselves [37].

Here we (i) review the effectiveness of PAs for insect conservation; (ii) explore the geographic, taxonomic, and thematic scope of studies of insects in PAs; (iii) compile a list of threats to insects in PAs; and (iv) outline a research and policy agenda to promote insect conservation within PAs.

Protected areas and insect conservation

There are relatively few studies exploring insect representation in PAs, especially when compared to the literature on other taxa [33,38,39]. However, those that do paint a bleak picture, revealing, for example, that three in four insect species are inadequately represented within PAs globally [40], 25% of endemic Orthoptera are absent from Natura 2000 sites in Greece [41], 40% of insects are unprotected by biosphere reserves in Costa Rica, USA, and Mexico [42], and PAs in Bangladesh cover <2% of the geographic range of its butterflies [3].

By contrast, some studies have reported relatively high levels of coverage of insect distributions by PA networks. For example, the distributions of 76% of rare and threatened Odonata overlap PAs in the Mediterranean [43], and >80% of freshwater insects in Spain occur within PAs [44]. Compared to unprotected areas, butterfly species richness in Germany was highest inside PAs, and consistently declined with increasing distance from PAs [34]. Butterflies and some other invertebrates undergoing climate-driven range expansion disproportionately colonize PAs in the UK [45].

Although insects have sometimes featured prominently in the designation of PAs [46], such examples are rare in the published literature. Dragonflies have a cultural significance in Japan, and about 24 PAs are being established specifically to conserve them. The Okegaya-numa conservation area contains some of the rarest dragonflies in the world, including bekko tombo (*Libellula Angelina*). In Great Britain, several PAs have been established for insects, principally to promote interest in Odonata and Lepidoptera [46,47]. Elevating the profile of insects through PA designation could help to raise public awareness about the plight of insects.

Despite these examples of PAs playing an effective role in insect conservation, of the 44 studies comparing insect richness or abundance inside and outside PAs, only four reported higher species richness within PAs. Conversely, eight studies found higher species richness or abundance outside PAs. Although comparing species richness inside and outside PAs provides little direct information about the effectiveness of PAs in conserving insects, the poor results suggest that placement of existing PAs has not considered the present distribution of insects. Enhancing the inclusion of hotspots of insect species richness and abundance within PAs seems to be a high priority [33,48], and PAs might also enhance insect protection by, for example, better representing areas of topographic and hydrological complexity, facilitating migrations, and serving as corridors to connect suitable habitats.

The designation of PAs generally reduces broadscale threats to ecosystems, such as habitat clearance [49], implying that insects threatened by these threats will also benefit. For example, larger, more connected, and well-managed PAs could reduce species sensitivity to climate change and could also facilitate faster recovery from perturbations [50,51]. However, where other types of threats harm insects, such as a decline in a specific host plant or the presence of a non-native parasite or predator, then specific interventions beyond PA designation alone will be needed [8,36,52]. We found little evidence of widespread PA management with insects in mind (Figure 1C).

Studies of insects in protected areas

We searched for studies of insects in PAs, and located 1590 studies from 127 countries (detailed methods are given in the supplemental information online). There was a clear geographic bias,

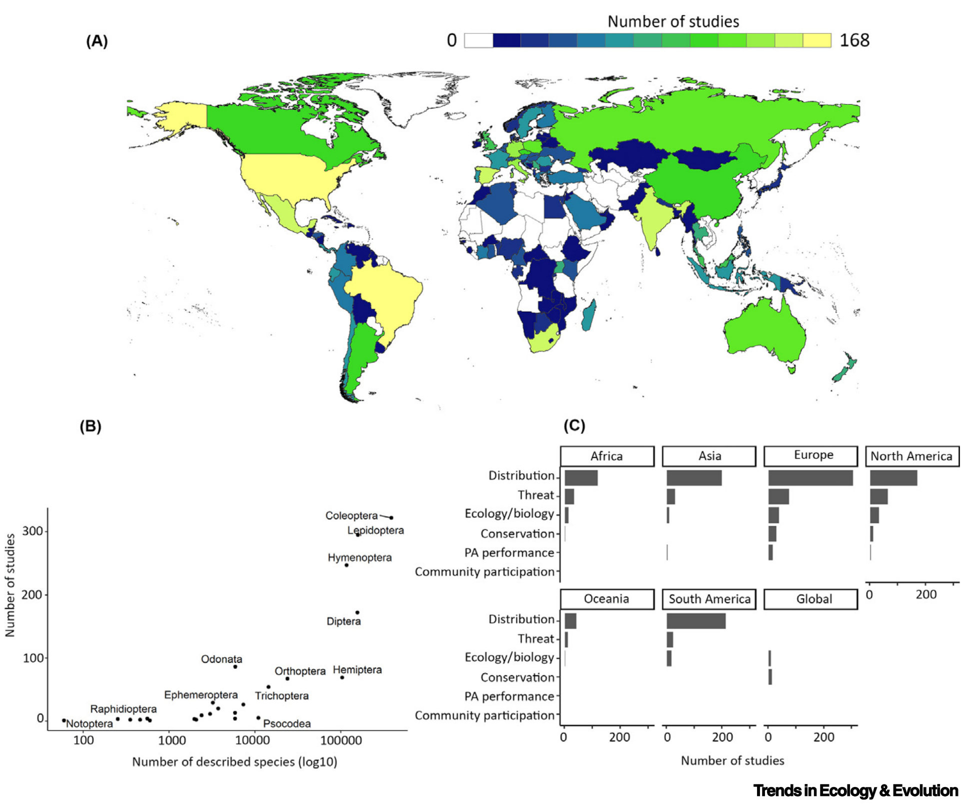

Figure 1. The (A) geographic, (B) taxonomic, and (C) thematic distribution of 659 studies of insects in protected areas (PAs) retrieved in a systematic literature search. Methods are presented in the supplemental information online.

Glossary

Protected areas: a clearly defined geographical space, that is recognized, dedicated, and managed through legal or other effective means, to achieve the long term conservation of nature [101].

and 18 countries had >20 studies and 38 countries only one study, and no studies were found for 70 countries (Figure 1A). Although there were few studies from the Afrotropics, there was better representation from tropical South-East Asia. South America, except for Brazil, was also poorly represented. These studies spanned 24 of the 29 insect orders (Figure 1B). Eleven orders were considered by <10 studies, there was only one study each on Notoptera and Mecoptera, and five orders were not the subject of any study.

Most studies (67%) investigated the distributions of species, most commonly documenting, or assessing the presence of a species in a PA. By contrast, 9% of studies focused on threats, 5% on conservation strategies, and only 3% on the efficacy of the PA for insect conservation (Figure 1C and see Table S2 in the supplemental information online for definitions of study types). These numbers suggest that studies on insects in PAs remain focused on collecting information on the distribution of species, and relatively little is known about threats to insects that might arise in PAs, and how these contrast with those in adjacent unprotected areas.

Threats to insects within protected areas

Threats to insects have been shown to permeate PA boundaries. Flying insect biomass declined <75% in some PAs in Germany, and 61 of the 62 studied PAs were adjacent to agricultural fields [35]. Habitat loss and fragmentation due to agriculture, development, and urbanization threaten insects in PAs [53], and climatic variability such as drought appears to be driving the decline of tropical insects, a threat that PAs cannot abate [54]. The exploitation of aquifers for cities and agriculture is a major threat to insects in arid lands, where rivers and other waters are being overexploited at alarming rates, and in extreme cases are drying up altogether [15,53]. In Australia, major bushfires in 2019–2020 reduced the distributions of native bee species so severely that 29 species might be eligible for listing as globally threatened (endangered and vulnerable) [55].

Insects face 12 major types of threat inside PAs (Table 1 and Figure 2), of which natural system modifications (a range of activities that alter or deteriorate habitats, mostly due to anthropogenic activities such as habitat fragmentation and loss), development, and climate change have been the most widely discussed (Figure 2A). Threats to insects in PAs were identified in 94 countries, and natural system modifications were reported in 39 countries and were the most extensively studied threat in PAs in all the continents (Figure 2A). Eleven threats were identified as potentially affecting Hymenoptera, and nine as potentially affecting Lepidoptera. By contrast, only one threat has been studied for Hemiptera, Neuroptera, Notoptera, and Trichoptera (Figure 2B). Of course, there is unlikely to be a close correspondence between the rate at which threats are identified in the literature and their true prevalence or impact.

Insects are apparently facing similar threats to many other taxa – habitat loss and degradation through deforestation, climate change, resource exploitation, invasive species, pollution, and environmental contamination – even within PAs (Table 1 and Figure 2). There are, however, some threats that appear to disproportionately affect insects, most notably light pollution and agricultural intensification both inside and outside PAs [15,56,57]. Inside PAs, natural system modifications are the most widely studied threat, consistent with the pressure this threat exerts globally on insect diversity and abundance [15]. For example, the critically endangered Epirus dancing grasshopper (*Chorthippus lacustris*) occurs within Natura 2000 sites but has strongly declined, possibly because of the construction of houses and land conversion even within PAs [41]. The last German subpopulation of the steppe bush-cricket (*Montana montana*), which is listed as endangered in the EU, became extinct within a nature reserve owing to inappropriate management [41]. In Australia, breeding sites of Illidge's ant-blue butterfly (*Acrodipsas illidgei*)

Table 1. Threats insects are facing inside PAs, with illustrative examples

Threat	Example	Refs
Agriculture and aquaculture	High-density beekeeping depressed the occurrence (–55%) and nectar foraging success (–50%) of local wild bees in PAs in Côte Bleue, France	[60]
Biological resource use	The annual rate of forest degradation in the Monarch Butterfly Biosphere Reserve in Mexico from 1971 to 1984 was 1.70%, rising to 2.41% over the next 15 years	[61]
Climate change and extreme weather	By 2080, Brazilian Atlantic Forests are predicted to become climatically unsuitable, decreasing the distributions of species inside PAs. Around 4% of species in the Brazilian Atlantic Forest might become extinct, of which some are endemic	[62]
Energy production and mining	The milkweed (*Asclepias* sp.) habitat in the Monarch Butterfly Biosphere Reserve in Mexico has been lost due to increasing demand for biofuels	[63]
Geological events	The PAs where the hoverfly (*Aneriophora aureorufa*) occurs are threatened by active vulcanism in Puyehue National Park, Chile	[64]
Human inclusions and disturbance	Dung beetles declined in richness and abundance owing to human disturbance in Los Tuxtlas Biosphere Reserve, Mexico	[65]
Invasion, disease, and problematic species	In some PAs in Israel, honey bee introduction has resulted in a decreased frequency of floral visitation by native bees	[66]
Natural system modifications	Intensification of PA management has heavily reduced the diversity of saproxylic insects in Europe	[67]
Pollution	Lakes in Keibul Lamjao National Park in India contain high levels of heavy metals that reduce freshwater insect diversity	[68]
Residential and commercial developments	Insect mortality significantly increased during the peak hiking period in some PAs in southern Poland	[69]
Transportation and service corridors	In some Romanian PAs, weevils were killed in high numbers by cars in the spring. Some of the road-killed species were first recorded from this region, and others are rare in Romania	[70]

are threatened by coastal development inside PAs [58,59]. Insect biomass has declined by >75% in German PAs, paralleled by a loss of 20% in species richness and 80% in total abundance over 25 years [35]. The literature suggests that many threats will not be abated by a strategy that simply focuses on the acquisition of land, and that wider management techniques must be applied to overcome these threats, both inside and outside formal PAs [49].

Prospects for insect conservation in protected areas

For many species, PAs have become a last refuge from proliferating human-induced threats [71], but it remains unclear whether the major changes effected by PA designation, such as a slowing of habitat clearance or a reduction in overharvesting of vertebrates, deliver comprehensive threat abatement for insects. Even if inadequately resourced for threat management, PAs can still substantially lower threat intensity. For example, an Australian study [49] concluded that designating PAs without implementing specific management would attenuate one or more threats for 76% of threatened species and all identified threats for 3% of species [49]. This is because the designation of PAs in Australia generally at least halts major habitat destruction. However, in the presence of explicit threat-management approaches, the same set of PAs would remove one or more threats for 100% of species and all identified threats to 48% of species, highlighting the enormous increase in PA effectiveness when they are managed [49,72]. Further research on PA management that best abates threats to insects now seems to be urgent, as is creating conservation approaches that span both PA designation and broader landscape management beyond PA boundaries.

There are key differences in the management responses that are likely to benefit insects compared to other taxa, but only a fraction of existing PAs are explicitly managed for insect diversity.

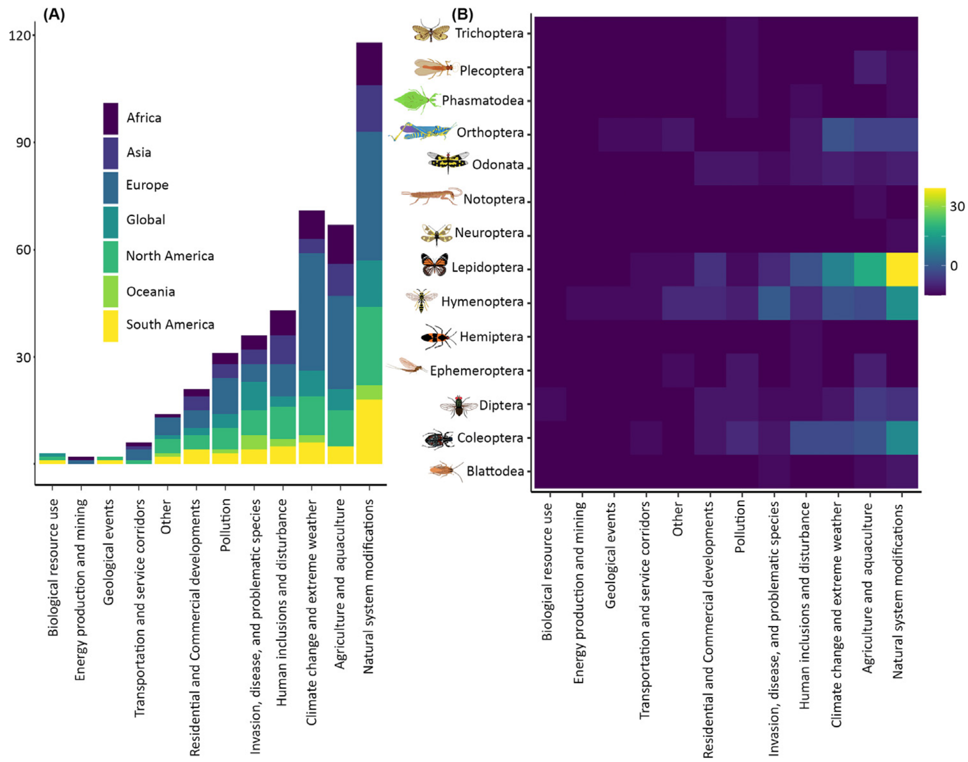

Figure 2. The number of published studies mentioning threats to insects within protected areas (PAs). (A) Prevalence of threats by continent. (B) Prevalence of threats among insect orders. Threats were categorized threats using the Threats Classification Scheme of the International Union for Conservation of Nature (IUCN) [16].

For example, the strategy of reducing hunting pressure is a major benefit of PAs for many mammals in sub-Saharan Africa [73,74]. By contrast, direct exploitation of insects is rare (with some exceptions, e.g., harvesting of larvae of the moth *Gonimbrasia belina*). Instead, insects are often dependent on specific host plants, and even apparently minor changes in plant community composition can make large areas uninhabitable for some insect species [25,52]. Likewise, the aggressive burn cycles recommended by restoration ecologists for grassland are often too short for many insects [75]. Ecosystem changes that negatively impact on insects can readily occur when management is focused on other priorities, for example maintaining open grassland areas in an African game reserve to allow visitors to view game, or removing grazing from a newly designated PA. However, examples are emerging of successful insect conservation both inside and outside PAs, and we synthesize these into a set of approaches that could be applied more broadly (Figure 3).

Step 1. Integrate insects into management plans

A first priority is to integrate insect conservation into the management plans for existing PAs (Figure 3). Individual insect species are often host-specific and require access to one or more particular plant species to complete their life cycle [76,77]. Increasing the availability of floral resources and host plants can be among the most efficient ways to promote insect diversity in PAs [78,79]. The presence of many insects also depends on the availability of waterbodies, vegetation mosaics, and high-quality habitats; PA management plans could focus on increasing the presence and diversity of such resources when planning for insect conservation [78]. For example, ~56% of all forest beetles are associated with both standing and fallen dead wood

Figure 3. Four actions to enhance the future of insect conservation. Abbreviation: PA, protected area.

in Central Europe; hence, providing or not removing dead wood can support more diverse communities of beetles and other insect groups, as well as many ground-dwelling vertebrates [80].

Conflict between the management of insects and other groups in PAs occasionally arises. For example, several invasive plant species (e.g., *Lantana* spp.) support many adult insects with generalist feeding habits [81]. Insect richness can be positively associated with the presence of invasive plants such as Himalayan balsam (*Impatiens glandulifera*) and Japanese aralia (*Fatsia japonica*) [82]. Conservation management plans that involve the elimination of invasive plants might therefore consider how best to replace the removed floral resources used by insects [79]. Restoration of floral resources can have positive impacts on plant–pollinator interaction networks and reverse ecosystem degradation caused by invasion [82–84]. Likewise, considering the impacts on insects of common PA management practices such as controlled burning, controlling illegal activities by enforcing laws and strengthening policies, maintaining and safeguarding high-quality habitats, controlling disease spread, sustainable land-use, safeguarding native species plant diversity, and regular assessments of habitats can be effective in helping to conserve insects inside PAs [25,79,82,84,85]. However, it is important to note that different management interventions might be needed for different taxa and across different stages of their life cycles.

Step 2. Strategically designate new PAs for insects

Careful planning can ensure that new PAs better represent insects (Figure 3), especially those most likely to benefit from PA designation as opposed to broader landscape-level management interventions [49] (Figure 3). For example, PA planning could focus on insect species that are at risk from threats readily abated by PA designation, such as habitat clearance, rather than on species threatened by issues that require broader management, such as climate change mitigation. Of particular importance for insects is to ensure that any metapopulation structure is accounted for in the spatial configuration of the PA system [42].

Step 3. Design wider insect conservation initiatives beyond the PA boundary

Preserving mountainous topography with its elevational and hydrological diversity, as well as conserving forest openings, buffer zones, and small green spaces, has been shown to be effective in conserving diverse insect groups [86,87]. In some cases, effective insect conservation can be achieved outside the formal PA network. For example, Chowdhury *et al.* [88] showed that the modest number of small urban green spaces in Dhaka, Bangladesh, contained about half of the country's butterfly species, of which 40% were nationally threatened. Managing such urban green spaces with insects in mind could contribute greatly to regional insect biodiversity [89].

Many studies have documented the negative impact of agricultural intensification on insects; however, small-scale traditional farming and organic farming can benefit insect diversity, suggesting a role for multi-use landscapes in insect conservation. For example, the presence of wild grazers increased the alpha- and beta-diversity of all insect taxa compared to domestic grazing in South African PAs [90]; species richness increased by 70% with the inclusion of traditional farming methods adjacent to PAs in Belize [91]. However, traditional small-scale farming is unlikely to provide food for ~8 billion people. Future studies should assess the impact of intensive agriculture on insect diversity and abundance on a global scale, focusing especially on how different pesticides (e.g., neonicotinoids) affect insects (including non-target species) and how conservation management is seeking to minimize their diffusion into wildlands [92–94]. Ideally, agriculture needs to make better use of urban and ex-urban landscapes in freeing up land for PAs [53,88].

Step 4. Invest in insect monitoring and research

The global conservation effort has so far been slow to incorporate insect taxa into PA designation and management, mostly owing to inadequate knowledge of their distribution [5,20,24,95]. Targeted field surveys, biodiversity assessments, and long-term systematic surveys could improve this situation (Figure 3). Although conducting such assessments on a global scale is highly ambitious, citizen science could greatly expand the scope of monitoring [96]. Citizen science platforms such as iNaturalist (https://www.inaturalist.org/) can widen the geographic and taxonomic coverage of biodiversity occurrence datasets and rapidly improve the delimitation of species distributions to inform PA prioritization analyses [19,95,97,98] (Figure 3). Similarly, IUCN Red List assessments at regular intervals can help to track successes and to guide the formulation of priority conservation actions. Identifying insects in the field is complex, labor-intensive, and inefficient, but advances in computer vision and deep learning are making progress in solving this challenge [99].

Concluding remarks

PAs may be the last refuge for many species globally [25]. However, most PAs have been established to protect landscapes, vascular plants, or large vertebrates [33]. To conserve insects inside

Outstanding questions

In what circumstances are PAs an effective conservation tool for insects, and what should conservationists do when they are not?

How do we increase the PA coverage efficiently to cover more of the geographic ranges of insects?

Where should new PAs and other site-based conservation strategies be immediately established to mitigate insect declines and meet the Post-2020 Global Biodiversity Framework?

Should PAs be managed differently to achieve effective insect conservation?

How can whole-of-landscape conservation interact with PA designation to safeguard insect populations?

PAs, we argue that four major steps need to be taken: (i) integrate insects into management plans for existing PAs, (ii) strategically designate new PAs for insects by including insect specific habitats that would benefit from management, (iii) design wider insect conservation initiatives beyond PAs by considering both threatened and widespread species, and (iv) invest in insect monitoring programs. Given the future that biodiversity faces, it is essential to raise public awareness of the need for insect conservation (see Outstanding questions). In addition, researchers working on area-based conservation efforts might need to extend their purview beyond the easily employed vertebrate datasets and examples. We hope that this review stimulates greater scrutiny and assessment of the value of PAs and other conserved areas for safeguarding insects, especially at a time when the international community is striving for bold conservation commitments [100]. We need detailed investigation of the role of other effective area-based conservation measures for insects outside formal PAs. There is an urgent need to plan more systematically for insect conservation to take advantage of the current wider momentum to conserve biodiversity. Given the push for an expansion of PA coverage to 30% of the terrestrial surface by 2030, we urge the explicit inclusion of insects into spatial planning analysis, and that PA managers explicitly consider insect conservation.

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Declaration of interests
No interests are declared.

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