Solutions for humanity on how to conserve insects

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Review

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ABSTRACT

The fate of humans and insects intertwine, especially through the medium of plants. Global environmental change, including land transformation and contamination, is causing concerning insect diversity loss, articulated in the companion review *Scientists' warning to humanity on insect extinctions*. Yet, despite a sound philosophical

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Habitat management
Climate change
Species extinction

foundation, recognized ethical values, and scientific evidence, globally we are performing poorly at instigating effective insect conservation. As insects are a major component of the tapestry of life, insect conservation would do well to integrate better with overall biodiversity conservation and climate change mitigation. This also involves popularizing insects, especially through use of iconic species, through more media coverage, and more inclusive education. Insect conservationists need to liaise better with decision makers, stakeholders, and land managers, especially at the conceptually familiar scale of the landscape. Enough evidence is now available, and synthesized here, which illustrates that multiple strategies work at local levels towards saving insects. We now need to expand these locally-crafted strategies globally. Tangible actions include ensuring maintenance of biotic complexity, especially through improving temporal and spatial heterogeneity, functional connectivity, and metapopulation dynamics, while maintaining unique habitats, across landscape mosaics, as well as instigating better communication. Key is to have more expansive sustainable agriculture and forestry, improved regulation and prevention of environmental risks, and greater recognition of protected areas alongside agro-ecology in novel landscapes. Future-proofing insect diversity is now critical, with the benefits far reaching, including continued provision of valuable ecosystem services and the conservation of a rich and impressive component of Earth's biodiversity.

1. Introduction

1.1. Aim of this review

British butterfly and beetle populations were noted as ‘fast disappearing’ in the 1870's, the result of ‘land enclosure’, ‘ruthlessly turning furze to turnips and potatoes’, ‘being ill at ease in changed and changing surroundings’ and being ‘heartlessly swept away in the present era of stream and telegraphy’ (Swinton, 1880). Since then, insect decline has accelerated, with indications of some alarming drops in abundance, biomass, populations, and species, with associated disruption of species interactions and services, but all yet to be fully quantified (Montgomery et al., 2020). Known extent of declines is summarized in the companion review *Scientists' warning to humanity on insect extinctions* (Cardoso et al., 2020). Addressing this serious global issue requires effective evidence-based strategies. Much work has already been done in various parts of the world. The extensive evidence is gathered and synthesized here, in words and graphics, to identify the most important ways forward for conserving insects globally. This is done by the many authors here, who represent various sub-disciplines of insect conservation, drawing upon their knowledge in the field, and then distilling the evidence into essentially simple formulae. References for what has worked in practice are considerable, and are given in seven sets of open access Supplementary material for the sections pertaining to specific systems, as well as in the section on approaches to insect assessment.

1.2. Developing appreciation for insects

Firstly, the value of insects to humanity needs better communication. Valuation is the foundation for what we do in practice, as it sets standards and directions. One approach is to address personal and collective well-being (eudaimonia), with conservation strategies likely to be more effective when we focus on these relational values (Chan et al., 2016). This is because they hinge on relationships and responsibilities for a shared destiny. This means that our valuing insects is ethical and essential (Samways, 2017; Basset and Lamarre, 2019), and valuing insects goes beyond pure economic terms. However, this does not mean shutting our eyes to the fact that some insect species are of medical significance, and some are costly invasive alien organisms (Bradshaw et al., 2016), while others have great practical value as natural enemies of forestry and agricultural insect pests (Hajek et al., 2016). Though there are noble opportunities, we must recognize that many humans view insects as ‘invisible and boring at best, and as ugly, small, mean, indestructible, overfecund disease vectors at worst’ (Nash, 2004), so we seek to find nonhuman charisma to provide us with essential new opportunities for moving forward on the entwined destiny of insects and humans (Lorimer, 2007), while recognizing that anthropomorphism plays a major role in biasing our views of wildlife conservation in general (Manfredo et al., 2020). Insect icons and flagship species will help us greatly in the task of improving insect conservation globally (Barua et al., 2012).

Although economics are clearly important, not least for funding of research strategy development, it is essential that we maintain the mutual value of well-being beyond today's perspectives, for long-term promotion of mutual well-being for future generations of both people and insects. This approach includes valuing insects for their own worth (i.e. having intrinsic value), but if we wish to galvanize action through communicating the hard value of conserving insects to civil society, then we must also engage instrumental value (Justus et al., 2009). Instrumental value is the language of policy makers and environmentally responsible large corporate landholders who offer great opportunities for insect conservation across novel landscapes.

To implement insect conservation based on value, we first require insect conservation psychology, which aims to understand and promote human care for insects, leading to insects serving us well, while also promoting human and insect well-being (Simaika and Samways, 2018). The issue is that the human brain is not well equipped to assimilate and act upon perceived unseen and abstract themes such as insect conservation, which are nebulous and seemingly not relevant to everyday life. Yet, given that insects have played an important role in human culture for millennia (Kritsky and Smith, 2018), an effective strategy would be to convey the message that appreciation and conservation of insects is now essential for our future survival. Insect conservation psychology is enabling us to develop a culture of improved personal and collective responsibility towards promoting insect conservation as a necessary step for our survival.

Valuing nature and realizing the importance of interactions translates into a focus on ecosystems and landscapes for insect conservation success (Samways, 2007; Ellis et al., 2012). Notwithstanding the great value of insect icons and flagship species for thematic insect conservation, most insects are neither iconic nor even particularly visible (Morris, 1987; Leandro et al., 2017). This makes the task of insect conservation difficult to justify in the eyes of civil society, and policy makers who represent them. By focusing on tangible and easily visualized landscapes, we aim to conserve them to ensure future survival of both insects and us. Careful and strategic conservation of landscapes conserves a whole range of species and their interactions (Samways, 2015), as shown for example in the case of pollinator networks (Kaiser-Bunbury et al., 2017), and more importantly for a whole suite of interaction networks (Pocock et al., 2012). Furthermore, by taking this precautionary landscape approach, insect conservationists have leverage relating more to healthy and historically functioning landscapes than to the conservation of insects as items, which are often considered as small, arbitrary, and unworthy ‘things’ that have little to do with human everyday life. The landscape and its biodiversity is literally the larger picture, and individual insects the pixels in that picture. Together, the diverse landscape along with its insects and other

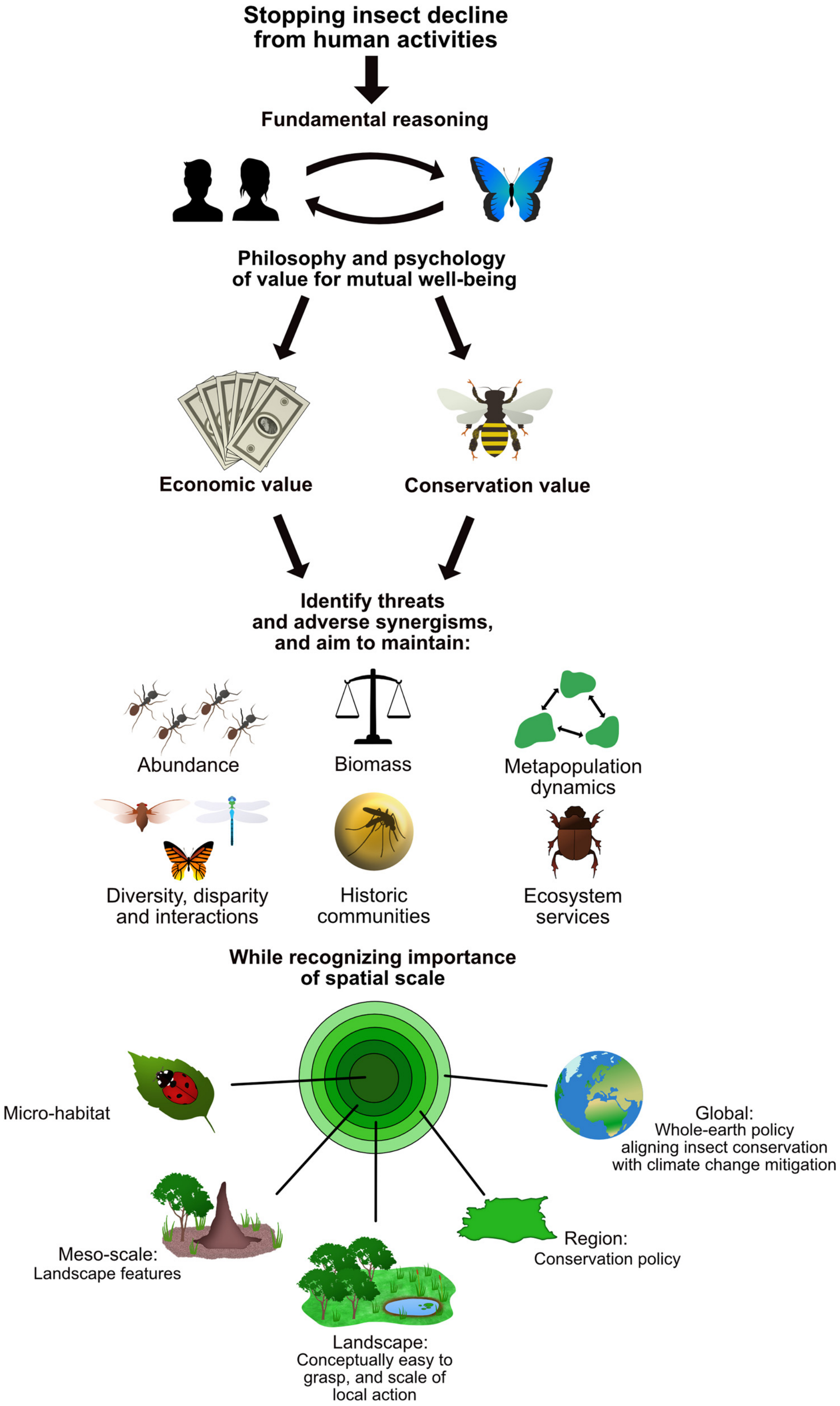


Fig. 1. Stopping insect decline rests on a foundation of appreciating that human and insect survival depends on mutual well-being, while being clear on the difference between financial value in terms of service provision and conservation value in terms of irreplaceable compositional and functional ecological integrity (Kleijn et al., 2015; Senapathi et al., 2015). We then need to understand the threats facing insects, and aim to maintain their various components and aspects. To do this, we require an acute appreciation of spatial scale, most easily communicated through conservation of the landscape.

biodiversity make up the scene that we appreciate, leading to the realization that the complete picture is something on which our existence and well-being depends (McClure et al., 2019). The public at large is beginning to recognize this through the essentially non-consumptive and well-being value of insect tourism and recreation (Lemelin, 2013). Furthermore, we seek general principles that have global significance, while also embracing the need for specific local action and incorporating the intrinsic value of insects.

We start here by identifying various key factors for insect survival, with the landscape level key in this process, while also recognizing the importance of smaller (meso-scale and microhabitat) and larger (regional and global) spatial scales (Fig. 1). This approach does not overlook species-specific strategies, such as conservation of red-listed species or addressing issues of insect species overexploitation, nor species-specific interactions, such as vertebrate or plant host and a particular insect interactor, especially where there is risk of co-extinction should the host disappear.

2. Forests

2.1. Tropical forest insects

The complex architecture of primary tropical forests (including epiphytes) provides insects with a continuous warm and moist environment, rich in species from many taxonomic groups. In turn, many species mean many ecological interactions, some of which are highly specialized, both in the canopy and on the ground and involving fragile soils. Maintenance of tropical forest insect diversity, particularly in high-endemism areas, unquestionably requires conservation of large areas of intact primary forest, currently rapidly declining. All such areas should be formally protected, with clear ecosystem and species preservation goals, while also recognizing the historic tenure by indigenous peoples. However, it is looking as if not all biodiversity and processes are going to be preserved within solely within tropical protected areas. So, it is encouraging that even extensive remnant forest patches with no conservation status have insect conservation value, with tracts of primary forest being essential as source habitats for regenerating forests. In addition, remaining high-quality fragments need to be functionally well connected, and special attention also being given to the edges of forests, either as buffer areas or as areas of conservation importance in their own right.

Areas that are now degraded need to be recovered so as to regenerate. Areas left to regenerate on their own take many years to develop into secondary forest, with recolonization by insects varying according to their specific traits. However, these secondary forests may not recover to the primary state owing to changing environmental conditions, such as presence of alien species and increased nitrogen deposition. Recovery entails more than just the trees, but also the epiphytes, a natural understorey, dead wood, and leaf litter, leading also to a healthy soil. Furthermore, restoration should aim at a natural age structure, including veteran trees that are important for many saproxylic insects. Hence, regeneration strategies should be given priority, and the findings put into practice to enable and accelerate the regeneration process.

While certain plantations can provide some benefit (e.g. decomposition webs), their insect assemblages are very different from primary forest. Closeness to primary forest enables insect species to colonize plantations, though plantations and reforestation requires the natural diversity of native trees and the right proportion of shade and sunflecks. Careful, selective logging can provide some benefit, unlike extensive logging, even if their utility is necessarily limited (Fig. 2).

The evidence for tropical forest insect conservation is provided as references in Supplementary material 1.

2.2. Temperate and other non-tropical forest insects

Temperate and other non-tropical forests, while not as complex as primary tropical forests, nevertheless have high structural diversity, possess many microhabitats, and create sheltered microclimates allowing many species to co-exist under optimal conditions. Of concern is that most north-temperate forests are already much reduced in size, or are highly modified, with very little primary forest remaining, with protected areas needed for what is left.

Given the small size of remaining primary temperate forest, old and veteran trees within varied landscape often are the last remnants and refuges for many insect species. They provide microhabitat diversity important for many specialist insect species, such as those associated with dead wood. Conservation interventions also involve retention and protection of individual trees, while bearing in mind that they might be carrying an extinction debt, but can be valuable source habitats.

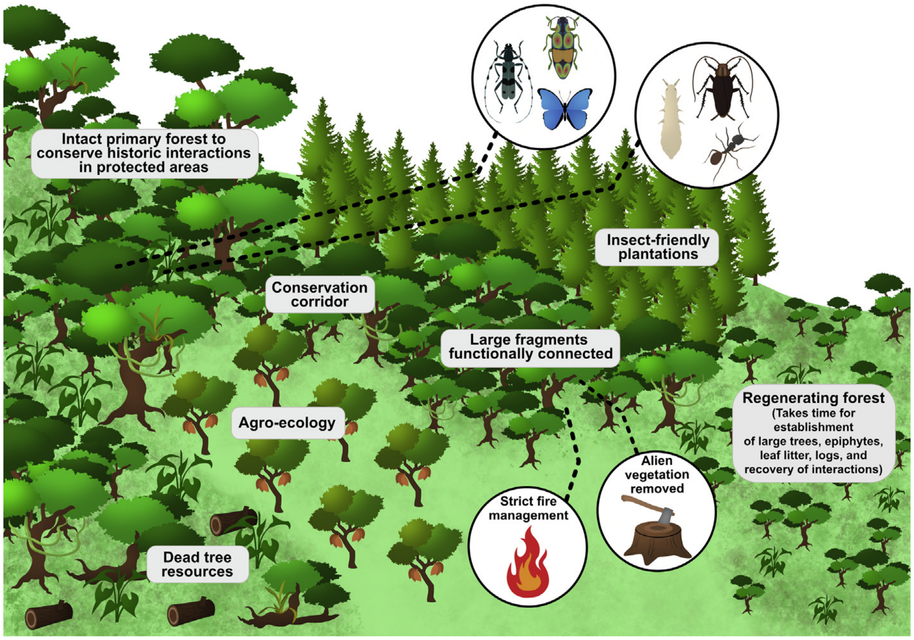


Fig. 2. Essential components for tropical forest insect conservation.

Provision of ‘colonization credit’ in the form of regenerating forests on abandoned farmland has been highly beneficial for threatened and rare forest insect species in Europe. However, a return to the historic state can take decades, even centuries. This process involves aiming for quality forest heterogeneity, while recognizing different insect species' traits. Instigation of functional connectivity through management for similar seral stages is also important. Natural forest gaps, restoration of natural forest margins, and maintenance of the forest understorey is an essential part of this process, as long as the processes are managed against true historic reference conditions and not as simply perceived by humans.

Temperate forests are often so heavily modified that they depend on human management to prepare the way for passive restoration and the re-appearance of at least semi-natural cycles. Appropriate forest-fire cycles, for example, can retain the historic grassland/forest mosaic. In turn, small clear cuts that mimic natural tree fall or local large mammal activity (such as that of beaver, deer, wild boar or wombat) and even beetle and moth damage, can benefit both forest and grassland insect species across the subsequent grassland/forest mosaic. Traditional grazing with livestock also encourages forest openings.

Sustainable forest management can also be improved for insect conservation. Log stacking procedures are now improved to avoid being ecological traps for saproxylic species. Additionally, pollarded snags, stumps, and fallen branches are retained for insect colonization. Even wooden boxes that act as artificial tree cavities have benefitted certain rare saproxylic species. In turn, there should be introduction of a more sensitive approach to plantations, especially use of indigenous trees of local provenance, which can benefit insects (Fig. 3).

The evidence for temperate forest insect conservation is provided as references in Supplementary material 2.

3. Grasslands and other low-growth systems across the world

Native grasslands and other low-growth primary habitat, such as deserts, savanna, sclerophyllous vegetation, heathlands, and moist meadows, have experienced human impact for many millennia, especially around the Mediterranean sea. All remaining fragments with historic heterogeneity and function are of great value. Large fragments of many tens of hectares and above are particularly valuable as they enable, at least to some extent, large insect populations, and serve as source habitats. These often support the last remnants of rare insect species. Certain insect species benefit from having natural forest adjacent to grassland or similar habitats to provide all the necessary resources associated with their adaptation to a historic landscape mosaic.

As with forests, it is also necessary to maintain functional connectivity, through instigation of large-scale conservation corridors, similar seral stages, and high-quality stepping-stone habitats to improve metapopulation dynamics. Even high-quality well-managed roadsides can provide great benefit for many insects. Powerline servitudes can do the same, and they are often the only remaining high quality grasslands in areas otherwise subject to agricultural intensification. Military training areas, roughs of golf courses, wind turbine sites, airports, and railway embankments also provide refuge for many insect species.

In the absence of long lost native megaherbivores, a moderate level of livestock grazing is often the best way to create habitat heterogeneity, and it can be fine-tuned through rotational or well-timed livestock grazing regimes, as well as rough grazing, which can also help with alien plant control. The same applies to mowing as a grazing surrogate, although the right machinery and approaches are necessary. However, where indigenous grazers are present, they create more effective heterogeneity and increased insect diversity than does domestic livestock, at least in Africa. Similarly, fire regimes of natural intervals can create habitat heterogeneity, but there must be appropriate integration with grazing to optimize opportunities for high insect diversity. Sometimes this may include rewilding through re-introduction of lost native megaherbivores. Sensitive management of hydromorphic grasslands is essential, and periodic flooding may be necessary to improve habitat quality, which is particularly important in extensive wetlands such as the South American Pantanal. Sometimes, even deliberate but careful disturbance such as light ploughing can improve the sward.

As grasslands are particularly vulnerable to excessive fertilizer and atmospheric nitrogen, their input must be reduced. However, while removal of excessive nitrogen in nature reserves can be achieved by intensive mowing or grazing, these activities can be detrimental to many insects. Harmful pesticides must be avoided in the conservation area in general, as even pesticide drift and sub-lethal does can pose a major threat. Similarly, use of pesticides such as ivermectin, used for parasite control in domestic livestock but harmful to dung beetles, should also be curtailed (Fig. 4).

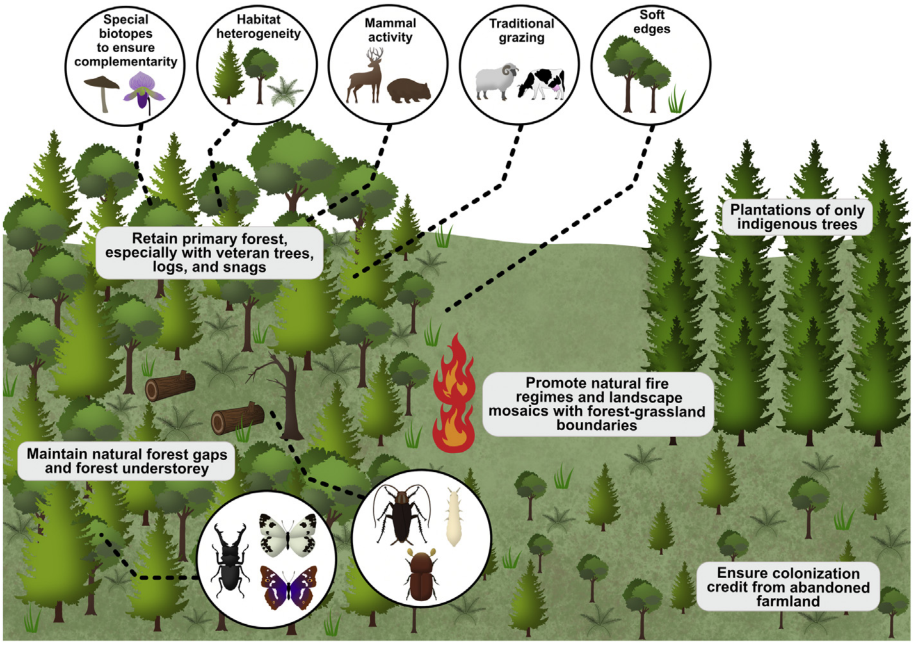


Fig. 3. Essential components for temperate forest insect conservation.

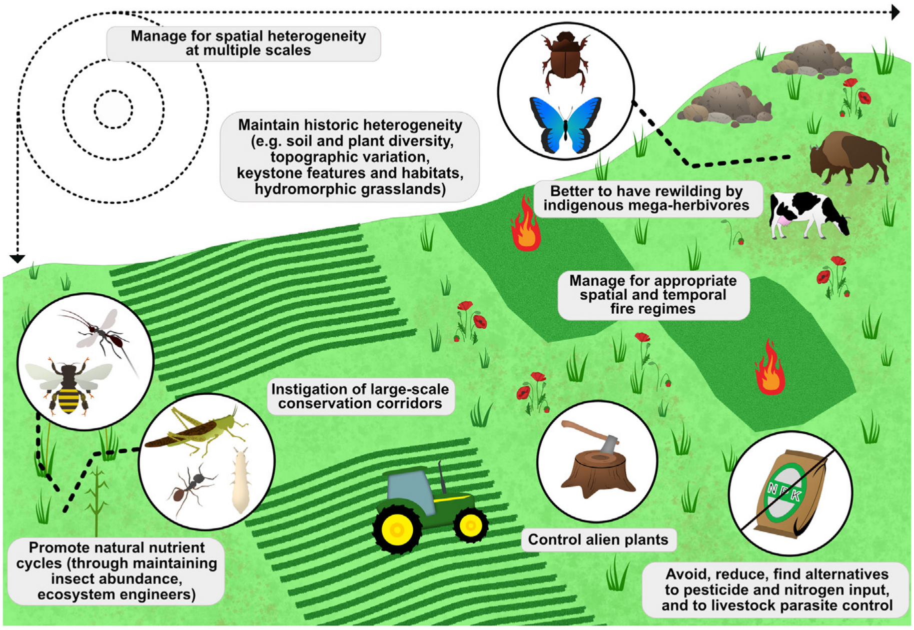


Fig. 4. Essential components for grassland insect conservation.

The evidence for grassland insect conservation is provided as references in Supplementary material 3.

4. Freshwater systems

Freshwaters, while covering < 1% of the Earth's surface, support 6% of all known insect species, and are strongly related to topography, biogeochemistry, flow regime, hydro-period, and vegetation both within the water and on the banks. Wetland loss and pollution from agro-chemicals in particular is a major issue for biodiversity in general. Protected areas play a major role, but aquatic insects are usually not considered in their proclamation, leaving out many aquatic insect species. As with terrestrial insects, extensive tracts of intact forest are essential for many aquatic insects, including those of tank bromeliads rich in aquatic insect species, and pitcher plants that support certain rare mosquitos. In turn, biosphere reserves are playing a valuable role in maintaining aquatic insects.

Catchment-wide conservation of freshwater systems is an important management objective. At the local level, conservation of headwater streams is particularly important, as are high-elevation ponds for endemic insects. Maintenance of historic river dynamics is essential, including historic seasonality and physiochemical water conditions. Also important are location-specific factors such as consideration of river network connectivity, sensitive land use, topographic heterogeneity, and biotic interactions, as well as promotion of macrophyte and riparian/bank vegetation quality and diversity for adult aquatic insects as well as protecting the areas of open water. Channelization should be avoided as it greatly reduces insect diversity and causes local

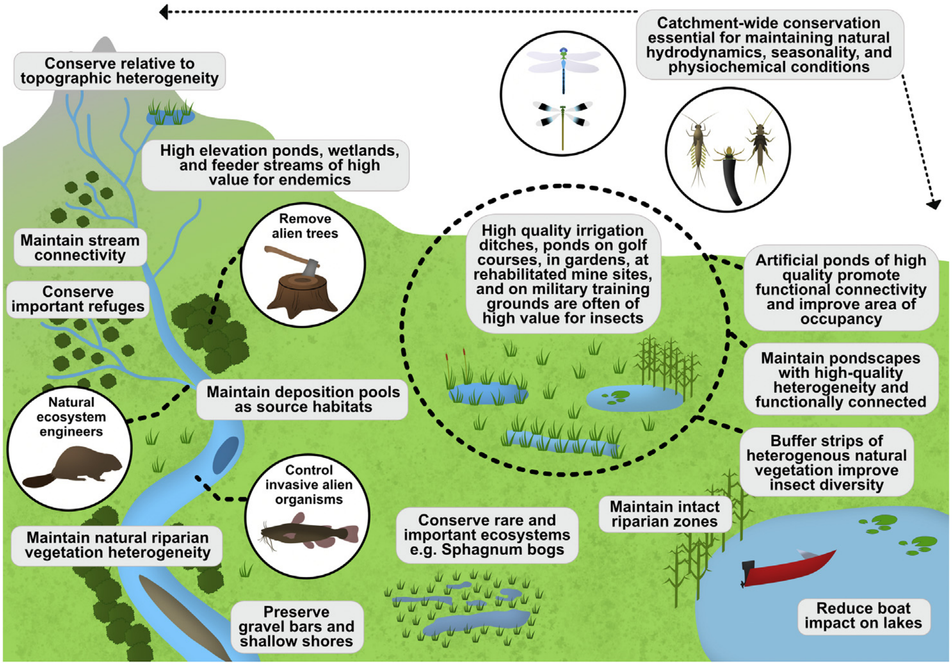


Fig. 5. Essential components for freshwater insect conservation.

hydrological drought. On the positive side, artificial, shallow and well-vegetated shorelines should be created, while also maintaining substrata that are rich in organic matter, both of which increase insect diversity. Historic vertebrate engineers, especially beavers, should be recovered. Although alien trees sometimes can be a substitute for loss of indigenous trees, in general alien trees must be removed, leading to considerable insect habitat improvement. Maintenance of floodplains and ensuring gravel bars are intact has become crucial for many terrestrial as well as aquatic insects, as is maintaining or restoring intact hydrology, and careful management of saline systems.

Connectivity is important for freshwater systems as it is for other systems, most importantly for many ponds making up a pondscape network. Pondscapes should be of high quality, with high pond heterogeneity, connectivity and size variation, as well as high functional connectivity among each other and to deposition pools of streams and rivers. It is important to maintain natural dynamics of freshwater systems in general for improved vegetation and insect heterogeneity. However, as some aquatic insect species are adapted to short hydroperiods, it is necessary to retain a variety of both permanent and ephemeral ponds and deposition pools of streams as part of pondscape heterogeneity. In turn, for some aquatic insects, permanent ponds and pools can be source habitats from which to colonize ephemeral ponds. Buffer strips instigated around ponds mitigate the effects of agriculture. In turn, well-designed artificial ponds can provide valuable supplementary habitat, as can high-quality irrigation ditches for marshland insects, and storm water ponds for aquatic insects.

Increased natural vegetation heterogeneity benefits both agricultural and urban ponds, with city ponds having the added benefit of increasing insect conservation awareness. In turn, there is great opportunity for improving artificial ponds, and doing so greatly improves pond functional connectivity across the landscape (i.e. improves the pondscape). Certain human-designed landscapes provide a great opportunity for aquatic insect conservation, including garden ponds, roughs of golf courses, and military training areas.

There are also some special cases significant for aquatic insect conservation. These include reducing ship and boat wave impact, introducing biological control of invasive water plants, preservation of river-lake ecotones, rehabilitation of mining pools, retention of well-managed *Sphagnum* bogs, removal of alien predators such as fish, erection of physical diversion structures to deflect certain threatened flying adults, and in some special habitats reducing tourist impact through use of designated paths and duckboards (Fig. 5).

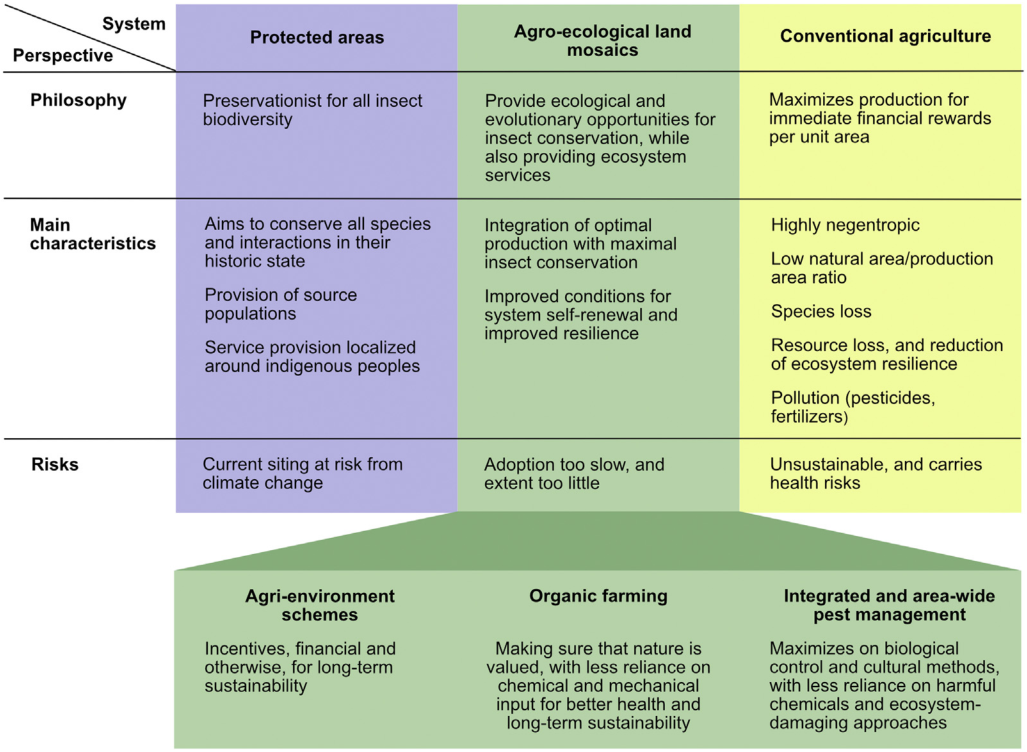
The evidence for freshwater insect conservation is provided as references in Supplementary material 4.

5. Agricultural landscapes

5.1. Agro-ecology

Instigating agro-ecological approaches improves the production landscape away from that of conventional agriculture towards protected areas. This shift is based on a different philosophical base, and when translated into action, has certain main characteristics, but the shift also carries some risks (Fig. 6). The land sharing-land sparing spectrum is an agro-ecological approach where production and conservation are integrated, ranging from virtual total mixing of production plants and natural vegetation (sharing), through to spatial separation of production and conservation areas (sparing), according to spatial scale. At the land-sharing end of the spectrum, indigenous trees, for example, can provide shade for high quality cacao and coffee, while also providing much insect habitat. Further along the spectrum, naturally-growing flowering plants provide resources for pollinators and natural control agents of aphids at orchard margins. At the land-sparing end of the spectrum, large-scale networks of conservation corridors can act as conservation set-asides among plantation forestry for a wide range of insect species and functional groups. All parts of the spectrum aim for optimal production while maintaining as much natural biodiversity and intact ecosystem processes as possible.

High yields and effective biodiversity conservation become integrated when traditional cultural practices, relating to local crop



System / Perspective	Protected areas	Agro-ecological land mosaics	Conventional agriculture
Philosophy	Preservationist for all insect biodiversity	Provide ecological and evolutionary opportunities for insect conservation, while also providing ecosystem services	Maximizes production for immediate financial rewards per unit area
Main characteristics	Aims to conserve all species and interactions in their historic state Provision of source populations Service provision localized around indigenous peoples	Integration of optimal production with maximal insect conservation Improved conditions for system self-renewal and improved resilience	Highly negentropic Low natural area/production area ratio Species loss Resource loss, and reduction of ecosystem resilience Pollution (pesticides, fertilizers)
Risks	Current siting at risk from climate change	Adoption too slow, and extent too little	Unsustainable, and carries health risks

Agri-environment schemes	**Organic farming**	**Integrated and area-wide pest management**
Incentives, financial and otherwise, for long-term sustainability	Making sure that nature is valued, with less reliance on chemical and mechanical input for better health and long-term sustainability	Maximizes on biological control and cultural methods, with less reliance on harmful chemicals and ecosystem-damaging approaches

Fig. 6. Comparison of protected areas, agro-ecological land mosaics, and conventional agriculture against three perspectives: philosophy, main characteristics, and inherent risks that they face in this age of environmental change.

production systems, are applied. These historical integrated systems provide both ecological and evolutionary opportunities, and long-term sustainability through safeguarding the intrinsic capacity of ecosystems for self-renewal.

Insect species richness, assemblage composition, and particularly abundance, are significant in agro-ecology. Pollination of various field crops requires fluctuating pollinator abundance to drive ecosystem service delivery, with abundance of a few common species being more important than species richness and composition. Similarly, for pest control services, a few species of predators or parasitoids are usually the mainstay for controlling specific pest species. Spatial scale relative to functional activity is a further important consideration, with species composition of rare parasitoids of gall insects affected more by landscape-scale effects than by patch-level effects compared to the common species. In short, to increase the services of both rare and common insects, there must be opportunities at both the local scale (adjacent to the crop) and across the wider landscape.

Furthermore, interacting species may experience their surrounding landscape at different spatial scales. In turn, insect interactions may change when certain interacting organisms respond differently to the surrounding landscape, as when low- and high-dispersal insects interact and compete. In short, novel landscapes should function as do local natural ecosystems, with the full complement of species for long-term survival. When agro-ecological diversity is near-natural, key ecosystem processes and services, such as pollination, decomposition, and biological control, are sustained.

5.2. *Agri-environment schemes (AES)*

AES are sets-aside non-production areas to benefit local biodiversity, first developed in Europe but later expanded elsewhere. They involve, for example, maintaining field borders and hedgerows which maintain higher species diversity than production areas. AES may for example benefit flower-visiting insects and herbivorous species, with agro-ecological practices tailored to promote different taxonomic and functional groups, usually though increasing the proportion of land area assigned to conservation relative to production areas, while also identifying areas of high natural value. General management of set-aside areas is also important, with many herbivorous and parasitic insects benefiting from more sensitive hedgerow management, pesticide-free improvement of field borders, establishment of conservation headlands (margins with reduced pesticide input), plant-rich roadsides, and buffer areas around ponds, all of which support insects to survive climate change. Roadside verges can be particularly valuable, as field-facing margins are subject to the adverse impacts of in-field agro-chemicals.

AES strongly benefits insects in *absolute* terms at medium levels of landscape modification, whereas at low levels the local species pool is much reduced and leaving a dearth of insects, while at the other extreme of complex landscapes, there are already high levels of insect diversity, meaning that supplementary action is not essential.

In cereal field conservation headlands, bumble bee nesting habitat and pollen and nectar resources are supplied through seed-sown flowers, based on a good knowledge of wild bee ecological requirements, and resulting in their improved species richness and abundance. Such sown flowers also have a beneficial effect on aphid natural control agents, with native flowers providing maximum benefits to insect diversity. In turn, minimally managed hay meadows greatly improve insect diversity, as does leaving margins around livestock farms. Field margins with no or minimal cutting, and no input from inorganic fertilizers, enriches the insect fauna.

AES can supplement the wider countryside, where flowering plant diversity supports many solitary bee species. In turn, moth abundance is highest in semi-natural chalk grassland, and lowest in arable field centres. AES close (< 1 km) to large grassland patches (> 10 ha) benefit various insects. As there are many different options for good management, many different types of crops at many different locations, each system is improved according to its particular features and context.

5.3. *Organic farming*

The aim of organic farming is to move away from the negentropic, artificial substance, and disturbance characteristics of conventional agriculture to, in essence, working with nature for a healthy and resilient landscape mosaic. Doing this mean also appreciating the traits of the natural organisms involved. Overall, organic farming has a positive effect on insect diversity compared to conventional farming, with a general increase of 30% in species richness, though benefits are greatest in the long-transformed European landscapes, especially when there is a near historical local pool of insect species. However, spatial scale is also important, with most improvement coming from the spatial level of fields (10.5% improvement), followed by farms (4.6%) and then the region (3.1%). However, this is not the case for all types of cultivation. Highly productive cereal fields make gains in insect diversity but see a reduction in yield. This illustrates that insect conservation is more effective in low-productivity systems and on non-agricultural land. When groups of organic farms are functionally well-connected and operate together, both yield and insect diversity is improved. Organically managed fields with their high insect diversity can act as source habitats for conventionally managed fields, providing countryside-wide benefit to insect diversity from organic farming.

Insect pollinator diversity benefits from high landscape heterogeneity with high but appropriate floral diversity within pollinators' foraging ranges, especially for rare pollinator species. This heterogeneity benefits both natural plants and pollination services. Organic and diversified fields with high-quality habitats generate wild bee species richness that mitigates adverse effects of monocultures, especially for small fields (< 2 ha). In turn, naturally small prairie wetlands provide high-quality habitat for many native pollinators, while also benefiting canola production.

High wild bee diversity and abundance comes with increased natural landscape diversity. In turn, landscape diversification, which includes semi-natural areas, then provides a buffer against climate change, improved further when organic farming replaces conventional farming. Greatest absolute increase in pollinator services occurs in the simplest and most disturbed farming systems, especially from generalist bees. However, extra measures encourage rarer bees, especially through restoration of natural habitat, for example, by sowing ‘pollen and nectar flower mix’ seeds. Placement of flowers must also be cognisant of bee foraging ranges, and when done, adds much value to semi-natural habitats.

Conservation enhancement using wildflower strips in association with production fields, and a variety of bee-friendly plant species, improves diversity and abundance of pollinator assemblages, with great benefit to certain arable crops. Besides attracting local pollinators, these strips also boost pollinators across the whole agricultural landscape, and improved even further by using various seed mixtures. Using strips to penetrate crop fields as inter-crops, can also enhance crop production. Furthermore, vegetation between the crop rows can benefit local insect diversity and improve ecosystem service delivery and soil health by 20%. However, identifying which are the important and beneficial pollinator guilds is crucial.

Increasing landscape heterogeneity also considers crop field size, with insect species diversity increasing at crop field edges as overall landscape complexity increases. As there is a decrease in field interiors, smaller crop fields have higher diversity than large ones. Furthermore, additional remnant patches of natural habitat also increases local insect diversity, by acting as refuges among disturbed landscape elements, and of benefit to, for example, specialist butterflies. Refuges and high-quality corridors are critical for specialized taxa such as parasitoids, which then spill over into crop fields. In turn, hedgerows provide shelter, and when combined with raised banks, provide nectar resources and food plants, so enhancing local diversity. Additional woody habitats adjacent to grassland patches in farmland areas also improve insect diversity through availability of complementary resources.

Roadsides rich in indigenous flowers and grasses are source habitats which greatly benefit local bee diversity, while high abundance of flowering plants and structurally complex vegetation benefit lepidopterans. In turn, refuges and dispersal corridors are good for ground beetles, and seed resources for seed harvester ants. Occasional mowing of roadsides improves conditions for flower-visiting insects. However, advantages of roadsides must be offset against the risk of vehicle strikes.

5.4. Integrated pest management

Many pesticides pose risks for human health and maintenance of biodiversity, while pests can also become genetically resistant, rendering pesticides ineffective. Of concern is widespread use of insecticidal neonicotinoid seed dressing which severely affects bee behaviour, and even terrestrial and aquatic food webs. Other insecticides reduce abundance of various bees. Yet with improved application, there is a 42% reduction in insecticide use in France while not affecting yield.

In response to the harmful effects of pesticides, integrated pest management has been implemented, an ecologically sensitive approach using cultural methods (such as inter-cropping) to enhance levels of biological control to guarantee pest control while enhancing insect diversity. Reduced pesticide application in a 3–6 m margin on the outer edge of arable crop fields (conservation headland) increases butterfly species richness and abundance in the immediate area, while reducing pesticide use also mitigates the effect of climate change, through arthropod assemblages becoming more resilient. Cultural methods include reducing field size and increasing density of grassy field margins to increase parasitism of aphid pests, while engaging agro-ecological approaches improves functional evenness among natural control agents, such as coccinellids and parasitoids, conferring better system resilience.

Using trees to provide shade improves the activity of predaceous ants on cacao pests, with 30–40% shade-tree cover being optimal. European hedgerows provide functional connectivity across farmland, improving both natural enemy and pollinator activity, while mature hedgerows benefit slow-dispersing predatory ground beetles, especially when there is also high spatial and temporal heterogeneity across the agricultural landscape.

Farmers co-operating over pest control produce a more co-ordinated and extensive approach, area-wide pest management, resulting in more efficient pest control as well as better insect diversity conservation. Natural control agents respond positively to landscape complexity at various spatial scales, sometimes alongside good pollinator conservation. Yet, specialist natural control agents respond most strongly at the small field or farm scale, leading to improved natural pest control. Furthermore, for natural agents of aphids in apple orchards, natural vegetation provides better service than planted wildflower strips. Overall, as natural control agents and pollinators respond similarly to landscape complexity, there are opportunities for managing agro-ecosystems to benefit both, especially as pest control is 46% less effective in simpler, more homogeneous agricultural landscapes. In sum, maintaining and/or restoring natural habitats is an essential first step for enhancing natural agent activity.

The evidence for insect conservation in agricultural landscapes is provided as references in Supplementary material 5.

6. Conservation of insects in urban and suburban areas

Cities and towns are characterized by high human density and greatly changed ecosystems through replacement of green landscapes (greenspaces) with hard surfaces (hardscape). Greenspaces vary greatly in their insect conservation value according to size, functional connectivity, heterogeneity, and vegetation type, structure and volume. They also vary according to their history, with some having undergone great change and isolation, and others in a more natural state and well-connected.

While greenspaces are no substitute for wild areas, they can be richer in insect species than surrounding semi-rural areas in Europe. Their insect conservation value increases when greenspace proportion is high compared to hardscape, and when herbaceous and shrubbery vegetation is high compared to lawn. Forest insect species are usually at greater risk than grassland species in urban environments, emphasizing the importance of having clumps of large indigenous trees wherever possible. However, there can be a trade-off among insect groups, such as butterflies vs. hoverflies, depending on how green spaces are managed, and sometimes even small patches of greenspace have value for certain insects. Nevertheless, the larger the patch the better, especially when indigenous plants with much structural variation and diversity are included. Furthermore, grass left to grow tall benefits certain insects, with little impact on aesthetics.

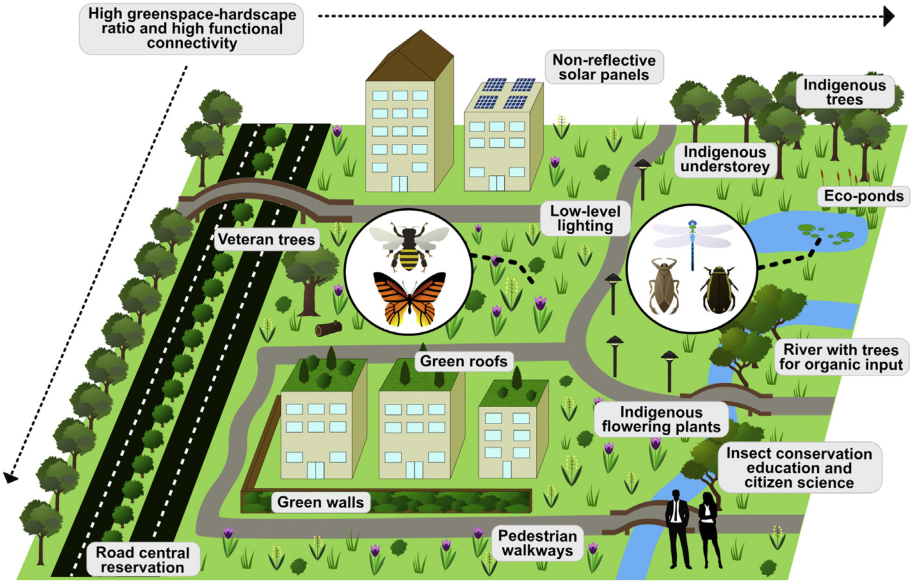


Fig. 7. Essential components for urban insect conservation.

Many herbivorous urban insects benefit from alien plants, though natural enemies must also be present, otherwise pest outbreaks can occur. Parasitoid activity is enhanced by planting forbs, and through use of classical biological control. Indeed, greenspaces, as well as allotments, can provide valuable ecosystem services such as pollination and predation. However, for conservation of rare insect species, indigenous is preferred over alien vegetation. Hived honeybees should not be encouraged as they can be a risk to human well-being, and can reduce other pollinator activity.

Public parks have high value for human and insect well-being, and can be reserves for rare species. This is especially so when they are rich in critical resources, and managed for high heterogeneity, including forest patches and much undergrowth, and have low insecticide input. Sensitively managed power line clearings can also be rich in insect species through provision of additional habitat.

Railway lines penetrate urban areas as vegetated linear corridors, and when managed well, can be of high conservation value. Railway embankments, along with abandoned land, roadsides, and urban brownfield sites can mimic semi-natural habitats, and in the UK, can support 35% of the rare and threatened ground beetles. Urban botanical gardens are also important refuges for many insects, as are urban churchyards and sacred groves, but shiny slate gravestones are ecological traps for some flying aquatic insects. Many ponds making up an urban pondscape improve metapopulation dynamics of aquatic insects, and remnant mires in less-dense cities can be high in insect diversity. They also provide urban blue space for improved human health and well-being, while bearing in mind that some insects, such as mosquitoes, can be unpleasant and even disease transmitters.

Old walls with crevices are often rich in plant species for insect herbivores, and surfaces for sunning insects. Modern walls can be ‘greened’ with vegetation to benefit insects, as well as to soften the wall to the human eye, although possibly at risk from insect pest attack. Green roofs can benefit insects greatly, particularly when indigenous plants are used and plant communities undergo succession.

Tackling the impact of artificial lighting is particularly challenging. Replacing metal halide lights with less harmful sodium lights and light-emitting diodes is one option, as is use of low-to-the-ground lighting along paths. Combining energy-saving measures with insect conservation by turning off lights (partially or wholly) late night to early morning, as well as linking with ‘dark sky parks and reserves’ are other options. The only practical way forward however, is to combine insect conservation with human security and safety (Fig. 7).

The evidence for insect conservation in urban environments is provided as references in Supplementary material 6.

7. Ecological assessment in insect conservation

7.1. Large-scale assessment of the state of ecosystems and species

Global conservation initiatives aim is to have 17% of global terrestrial areas conserved and that are ecologically representative, and well managed. However, such an aim is certainly too low to protect all insect species. Improvements in functional connectivity between protected areas enables range expansion in response to climate change, with some UK insects thriving in protected areas recently colonized in response to climate warming. Protected area networks must also represent both threatened species and ecosystems for their improved viability. They must also include special sites for irreplaceable biota, while also considering local human indigenous cultures. Protected areas can be extended outside proclaimed borders using large-scale ecological networks of interconnected conservation corridors, which is highly effective for insect conservation in South Africa. Biosphere reserves are also playing a valuable role in conserving insects, as are the 36 global biodiversity hotspots with their exceptional concentrations of endemic species.

The IUCN Red List of Threatened Species assesses species for their global conservation status. Red-listing is an ongoing process, with newly assessed insect species constantly added to the list. However, the conservation status of most insects is unknown. Red List assessments are the starting point for conservation, and contribute to raising the profile of the threats facing insects, while emphasizing the dire need for action.

There are also other global insect assessments, such as the Global Butterfly Index which uses standardized methods of transect counts (alongside fruit baiting where appropriate) to assess global trends. Citizen scientists are involved in the data gathering, leading to an estimate of how this insect group is changing with time across the globe.

Beyond presence of insect species at particular locations is the importance of knowing insect abundance levels and their change over time. A global database, BioTIME, is dedicated to this, with currently about 9 million species abundance records from over 44,400 species, enabling identification of specific drivers, such as landscape fragmentation, pollution, and climate change, as well proposing conservation actions such as transitioning from conventional agriculture to agroecology, introduction of sustainable forestry, and restoration of ecosystems.

The IUCN Green List of Species is a practical tool for species with high conservation dependence yet high potential for conservation success and long-term persistence. The Lord Howe Island stick insect *Dryococelus australis* is a case study for the Green List, a protocol now being extended to other species.

The Conservation Evidence platform (https://www.conservationevidence.com/) aims to support decision making for maintenance and restoration of biodiversity by summarizing effectiveness of conservation actions. Currently, the platform contains > 5000 studies that report conservation actions' outcomes, with about 10% of these focused on invertebrates, and used for conservation planning.

7.2. Inventorying insects

Rapid Assessment Programmes have discovered many new insect species, especially in biodiversity-rich areas of the world. Such protocols involve rapid field surveys in any one area by experts often assisted by citizen scientists, followed by rapidly produced reports as a baseline for conservation action. These programmes also have considerable educational value through providing opportunities for taxonomic specialists and the training of citizen scientists. Statistical tools already exist that allow optimizing and standardizing sampling protocols, and have led to a rapid increase of knowledge at local to global scales. However, modelling suggests total insect diversity in any one local area can be much higher than is seen by actual sampling, emphasizing that knowing the full extent of insect diversity, even in one tiny area, can only be achieved by exhaustive sampling using many methods and over a considerable time period.

Inventories are essential for documenting insect diversity, with scientifically named species being essential for activities such as legislation and determining levels of endemism, as well as a base for biodiversity informatics, ecology, and ultimately, for assessment and conservation. However, insect conservationists often have to work with referenced morphospecies for assessments in taxonomically poorly known parts of the world, especially where there is lack of taxonomic expertise. Inventorying at a site is more efficient by engaging informed and trained paraecologists and parataxonomists drawn from the local pool of citizen scientists, especially in species-rich areas of the world, so speeding up sampling.

There is an increasing use of metabarcoding and eDNA to rapidly assess species richness and abundance. However, this method does not usually allow recovery information such as species identity and traits, particularly in regions without reference barcode libraries. In turn, museum collections of insect specimens serve as biodiversity libraries towards determination of long-term population trends through space and time. Museum collections also maintain a record of taxa already extinct and undescribed diversity.

7.3. Mapping insect distributions

Mapping is the plotting and visual representation of items, such as individuals, populations, species, habitat types, ecosystems, or biomes, across geographical space. It is also used to show the locations of particular interactions, such as herbivorous insects feeding on particular tree types. Mapping individuals is valuable for assessing where a species occurs across a designated area, and used for species predictive distribution modelling, which aids discovery of new species in an area. The models use a combination of geographical range size, location, and trophic variables to enable focused searches in unexplored areas distributed in small areas (i.e. particular biotopes or ecosystems), and on insects living on single or a few host plants.

Mapping is also used in habitat suitability modelling of favourability of conditions for long-term survival of specified insects, including those that are red-listed and vulnerable to climate change. It also helps refine where further species might be discovered, or threatened species reintroduced, with satellite remote sensing helping to refine these approaches.

Mapping at large spatial scales, continental and global, aims to portray distribution, levels of endemism, and threats to insects, but must be based on a sound and reliable database. This continental-scale approach also identifies priority areas for insect conservation, and level of coincidence with biodiversity hotspots. Undertaking mapping at these large-scales for freshwater insects is especially important, as protected areas are biased towards terrestrial systems, and currently declining at an alarming rate.

Recording dates can be used to determine how a species' geographical range has changed, especially relative to various impacts, including climate change, with some species being much more tolerant than others to climatic change. The differences relate to species-specific traits, partly honed by intensive natural environmental filtering in the past, predisposing certain species for surviving anthropogenic climate change.

Citizen science recording schemes, such as observation.org or iNaturalist provide easy-to-use applications for mobile devices to record exact data in the field, easily converted to create global maps on open platforms, as long as a reliable validation scheme is in place to avoid misidentifications.

A cautionary note is that a map of a species' distribution really only indicates where a species (and assuming its identification is correct) was observed, i.e. maps contain observer bias, and always more observations are required to gain a more comprehensive picture of a species' actual distribution. Furthermore, a map at one time does not mean that this is the fixed geographical distribution of a species, especially as many insect species move across the landscape, and even region, especially with changing weather and climatic conditions.

7.4. Monitoring insects

While inventorying is about uncovering local species richness and its spatial change, monitoring is largely about uncovering differences over time. Monitoring is the continuous reassessment of a population, assemblage, community, ecosystem, landscape, region, or the world, over time, and undertaken at regular intervals to re-assess the state of a system in terms of improvement or deterioration.

For insects, timing of monitoring is crucial, especially for rare and/or cryptic species that might not be easily detectable. Timing includes right time of day, on the right life stage, at the right time of year. Monitoring must reflect the changes anticipated, and there should be complementarity between the subject taxa or functional groups to gain insight into how drivers of change are affecting insect/biodiversity over time. For effective comparisons, different sites are monitored in the same way, and at the same spatial scale. While standardized insect monitoring is science-based, citizen scientists, including school learners, are playing an increasingly important role. Flagship insect species or species groups engage society and illustrate environmental change, such as large saturniid moths for monitoring climate change in tropical forests, and dung beetles for tropical forest vegetation change.

Freshwater monitoring is well-established, and besides measuring physiochemical components directly, certain surrogate taxa and functional groups are used, with a strong focus on traits of component species. Species richness, composition, diversity, and abundance of significant insect groups, such as mayflies, stoneflies, caddisflies, and dragonflies (all featuring strongly in unperturbed river systems) and chironomid flies (featuring strongly in perturbed systems), are often used to determine the state of the system.

Environmental DNA (eDNA) is the sampling of genetic material shed from living organisms, and obtained directly from environmental samples. The method combines bulk field samples containing DNA with high-throughput, and while often used alongside traditional morphological methods, can be more effective than traditional specimen sampling. eDNA can also determine the historic state from biological material laid down many years ago, and provides a baseline against which to monitor modern samples, with due caution given to careful sampling.

As monitoring cannot be done on everything, all of the time, appropriate surrogates are first selected for conservation action and management at a practical spatial scale.

7.5. Surrogacy in insect conservation

Ecological surrogates provide information on ecological systems, such as insect species composition, to indicate the relative naturalness of a range of sites. In contrast, management surrogates indicate effectiveness of management, such as using selected components of insect species composition to measure the success or not of a restoration project against an equivalent historically intact site.

Insects can be surrogates for other insects, and may be a single iconic insect species (e.g. a threatened birdwing butterfly), a set of insect species (butterflies representing grasshoppers), or a functional insect group representing other functional groups (e.g. herbivore diversity representing parasitoids). Rare or threatened insect species can sometimes represent a range of other insect species, usually because of similar habitat requirements, and at times, subtle differences.

Another approach is to use higher insect taxonomic groups as surrogates, but this carries inherent risks, as there are usually a variety of species within a particular taxon that have different traits and respond in different ways to ecosystem condition or change. At large spatial scales, issues of strong species replacement, differing environmental variables, and deep history come into play, affecting the value of interchangeability of surrogates. Though there may be similar responses to adverse drivers or to recovery, when those drivers are removed, responses can vary among ecosystems. This means that effective use of surrogates requires a deep understanding of inherent patterns of species turnover.

Other taxa can be surrogates for insects, though using vertebrates to represent insects is hampered by their respective home and distributional range sizes and species turnover rates often being very different. Yet threatened bird and mammal species on islands are an effective surrogate for endemic insects, and birds associated with Californian oak woodlands can represent butterflies across an urban gradient. A significant exception is the close relationship between parasitic insects on their vertebrate host, and together facing co-extinction. Overall, the conclusion is that when undertaking general biodiversity assessments insects must be included. Also, while surrogacy can be effective under natural conditions, it can break down with increasing disturbance, yet at other times can be of value, for example in patchy agricultural mosaics.

Plants can represent insects, with host plants being a good surrogate for insects. However, plant-insect surrogacy varies according to spatial scale. Nevertheless, enhancing plant diversity can benefit insects, but many host plant specific insect species require additional resources, such as breeding habitats or a favourable microclimate. Aquatic plants can be congruent with certain aquatic insects, and indicative of good wetland condition.

Satellite remote sensing can assess plant community structure and degradation. It is of value for insect conservation, with thermal imaging improving searches for threatened insect microhabitats. Remotely piloted aircraft (drones) can produce high-resolution aerial pictures of insect microhabitats required for the various life stages, and provide details for habitat suitability models, including secondary habitats in transformed areas. Satellite data can also explore important abiotic and biotic surrogates for insects, such as geology, topography, slope, microtopography, rockiness, bare ground cover, microclimate, vegetation heterogeneity, glacial refugia, and many more, especially for rare and specialized insects. However, satellite imagery requires supplementation with first the testing and then the use of surrogates on the ground. Most conclusions to date emphasize the importance of maintaining high levels of abiotic and biotic spatial heterogeneity from fine to coarse scales.

7.6. Insect indicators

Indicators in insect conservation illustrate the state of insect diversity, impact of environmental change on insect habitats, communities or ecosystems where they live, and biotic or abiotic state of the environment. They help determine stress levels in the system, or recovery from stress following interventions, using an evaluation framework built on goals, effective indicators, and identified reference values such as visual and recreational, or agro-ecological, or restored to near-natural ecological integrity.

Both terrestrial and freshwater insects are often good indicators, reacting rapidly as populations, owing to their short lifespan, and being small, mostly live in a small area, and so are a point source of indication. Insects also readily move to different extents according to their different traits, or die out locally. They are speciose and abundant in any one area, and show differential assemblage responses to change or stress. Many insect indicators are available, but we must choose them carefully for effectiveness in telling us what we want to know, and discard those that are not responsive. Threatened insect species, in general, are an effective indicator group for over 80% of other insect species.

Identifying arthropod indicators of ecosystem services in agricultural landscapes can reduce costs. Identifying certain taxon/functional sets means less dependence on highly trained scientific personnel, as far fewer species are required.

Various sets of effective invertebrate indicators have been shortlisted. These include 1) springtails and isopod crustaceans, along with mites and earthworms for soils, 2) springtails, ants, ground beetles, ground-dwelling spiders and snails for leaf litter, 3) ants, chrysomelid leaf beetles, heteropteran bugs, moth larvae, and web-making spiders for foliage, 4) grasshoppers, butterflies and hoverflies for open habitats, 5) dung beetles for primary and secondary forest, as well as forest disturbance effects and grazing impacts, and 6) dragonflies, water beetles, and chironomid flies, as well as the EPT set (Ephemeroptera (mayflies), Plecoptera (stoneflies) and Trichoptera (caddisflies)) for freshwater condition. These sets are not the only candidates, but are a good starting point. For undertaking functional indication (interaction networks involving pollinators, parasitoids, seed dispersers, soil makers, decomposition webs etc.), selecting species interaction networks with high, rather than low, connectance is particularly effective.

High congruency can improve selection of indicator taxon sets, in that one set begets conservation of the other, such as grasshoppers and butterflies for indicating habitat quality in African grasslands, with an emphasis on species composition, with its higher currency than species richness. However, while there may be high congruence, one taxon set may be more sensitive than another, which in turn is also dependent on sampling methods used, and use of an adequate number of sites to account for species turnover. Sampling must be strategic, as it may not be practical or even feasible to collect the last species present to make

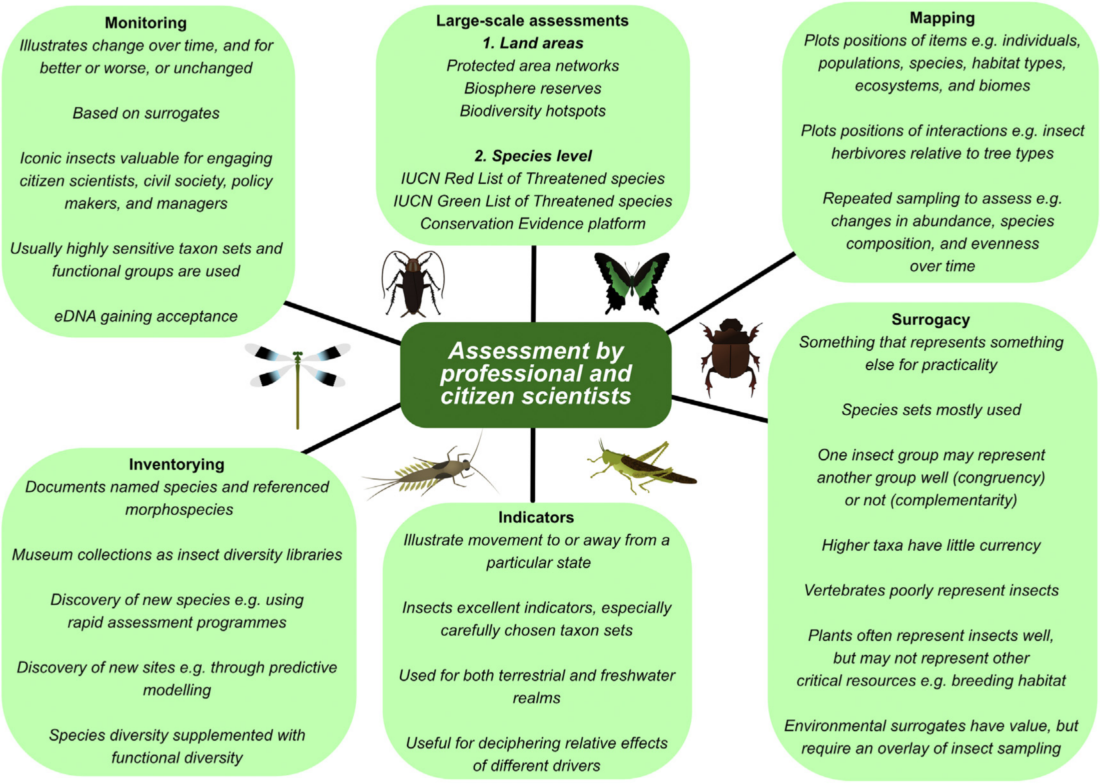


Fig. 8. Essential components of ecological assessment for insect conservation.

an assessment.

Aquatic insects are effective for indicating adverse effects of pesticides in freshwater, with a negative relationship between species presence/abundance and insecticide presence. They also indicate freshwater recovery following mitigation, such as ecosystem service levels. In turn, singing insects, especially bush crickets, are indicators of ecological integrity of a particular ecosystem against reference sites, and used at a large-scale through engagement of citizen scientists. Insects also detect pollution events in terrestrial environments, while springtails indicate changes in soil and leaf litter, and quality of pasture and grazing land. Insect indicators of biodiversity and environmental change generally perform better when the taxon sets are chosen specifically to address a conservation objective. These sets are measured and assessed at appropriate spatial and temporal scales that are similarly matched to the objective.

Air pollution may cover wide areas, while climate change is everywhere. However, there are some more spatially explicit ramifications of climate change, such as high winds, floods, drought, and increased fire frequency, all of which can be measured using insects. Certain impacts are often the same across all spatial scales, with any specific insecticide (chemical resistance aside) having the same effect on insects in all parts of the world. In contrast, effects of invasive alien plants vary from one area to another.

Impacts can also be adversely synergistic, and insects used to disentangle their effects. For example, shortened fire intervals encourage invasive plants, and insects are used to determine the effect of each together or separately. Excessive livestock grazing can further aggravate the situation, while pesticide drift or pollution adding more pressure, with these added effects also able to be investigated using insect indicators.

Additionally, there may even be subtle effects, not originally detected, such as changes in predator-prey relationships, deterioration of the seed bank, compaction of the soil, or reduced essential nutrient cycling, to name just a few (Fig. 8).

The evidence for assessing insects for conservation is provided as references in Supplementary material 7.

8. Emergent themes for insect recovery

8.1. *The importance of 'space' - at multiple scales*

As pointed out by Díaz et al. (2019), the challenges posed by biodiversity loss, climate change and human well-being are deeply interconnected, and need to be urgently addressed in an integrative manner from local to global levels. Insects are intrinsic to this challenge. However, opportunities for stopping insect population loss, leading ultimately to species loss, vary greatly across the world. Insect conservation progress is far more likely among human communities where valuing nature and caring for it are high, and where caring for nature means respecting ourselves, i.e. where there is a sound philosophical base, often developed from a historical cultural heritage (Fig. 9, centre), as shown by Ulicsni et al. (2016) in Central Europe.

Opportunities also arise according to the relationship between humans and landscape. For example, areas of high human population density provide less opportunity for set-aside land for insect conservation than those with a low density. In short, insects require 'space'. Interestingly, from the evidence gathered here (Supplementary material 1–7), relevant 'space' for insects ranges from the microscale of a local habitat, through to the continental, as in the case of the migrating Monarch butterfly (*Danaus plexippus*). Yet this 'space' must be of a certain quality, and where there is functional connectivity for foraging, mating and resting, according to essential resource requirements, intrinsic traits, and metapopulation dynamics for maintaining genetic integrity, both for today and for a changing world. This 'space' must also be free of adverse drivers, ranging from pollution to alien invasive organisms.

Where there is space, the challenge is then how to design and manage the set-aside areas, based on how we value insects and share the land with the indigenous insect inhabitants. Expansive and intensive mechanized agriculture, for example, provides less opportunity than areas where agro-ecology is practiced, such as polycropping, maintenance of nurse trees, rotational grazing, and low-input or no application of pesticides (e.g. Perfecto and Vandermeer, 2008).

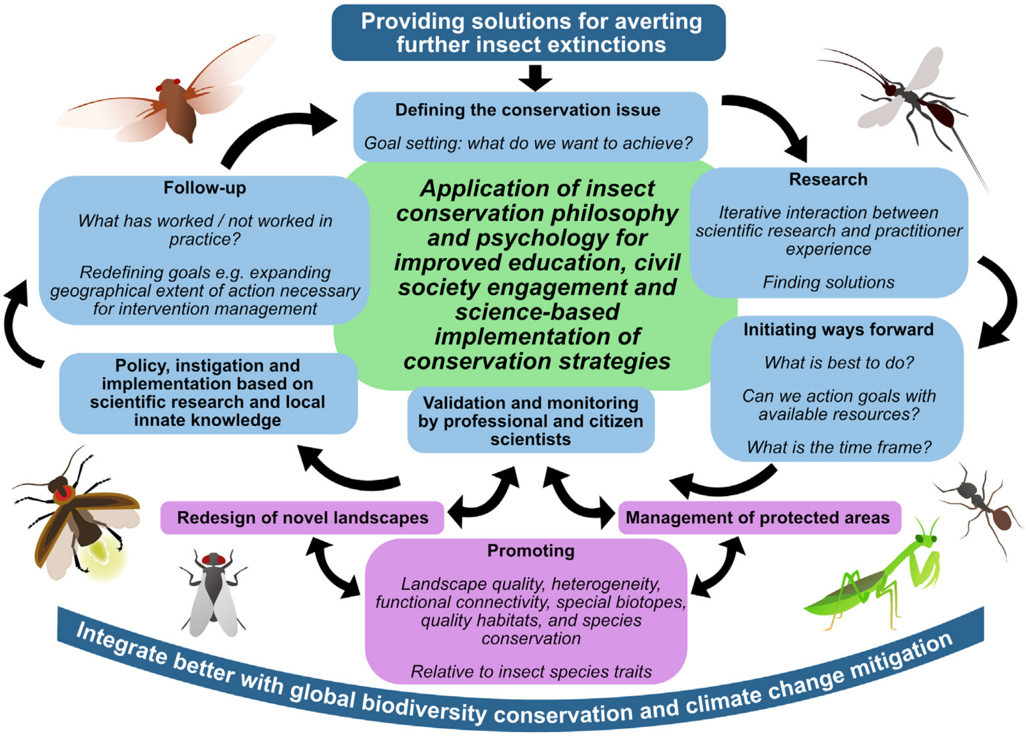


Fig. 9. Addressing the grand challenges for insect conservation.

By having adequate physical and functional quality 'space' means that insects can maintain effective populations (i.e. leaving the maximum number of healthy progeny). The baseline is the historic state of large areas of land without human adverse transformation. This is not the absence of humans, but rather the living in harmony with each other in a resilient natural landscape. This is not a romantic ideal, but a goal to respect and attain, as in the case of the Amazon rainforest (Fig. 9, top). These high-quality, expansive areas also recognize the dynamics of nature, with its fluctuating spatial and temporal interaction networks, and its response to and recovery from occasional natural events, from fire and flood, to volcanic eruptions. Given the chance, many insect populations can be resilient to changes and events, with the issue now letting them continue to have that opportunity. We require research to elucidate whether that is the case (Fig. 9, top right), and a logistical plan (Fig. 9, middle right), with some clear pointers already emerging in the various ecosystems (Supplementary material 1–6).

Emergent themes are arising across all ecosystem types, especially the critical importance of maintaining quality nature-based heterogeneity. This also means ensuring rare biotopes are present in addition to the more extensive ones with their often considerable nested heterogeneity embedded within them. Whatever the physical size of the focal area, it is essential that metapopulation dynamics, resource-seeking behaviour, and enemy-free space, and reduced adverse are present to bolster source populations. These are consistent requirements whether in forest, grassland and other open ecosystems, water, air, underground, and even in cities. In terms of conservation, this means having high-quality source and reception sites for insect individuals to move, establish, and reproduce.

An important feature of maintaining insect populations is that we need to assess how successful we have been with implementation of strategies (validation), using strategically selected and effective surrogates and indicators, and then whether other interventions are required as a result of strategic monitoring (Fig. 9, lower middle).

Protected areas are essential source areas for insects, especially rare specialists, and these protected areas may or may not require some intervention management to achieve this objective. (Fig. 9, bottom). Interestingly, some protected areas are becoming reception areas into which insects have moved in response to global warming. In turn we then must redesign novel landscapes from conventional to agro-ecological landscapes (Fig. 9, lower left). For both novel landscapes and protected areas, all the while the challenge is to promote landscape quality, heterogeneity, functional connectivity, and maintenance of special biotopes, habitats, and certain selected insect species of special concern (Fig. 9, bottom).

8.2. The grand challenges

From a survey of nearly 13,000 scientific papers in recent years, Godet and Devictor (2018) have clearly shown that the current conservation debate should focus on what is working or not, and why, rather than proposing new directions for the discipline of conservation science. We support that view, starting with recognizing insects' need for quality 'space', with its inherent physiochemical and biotic complexity, temporal and spatial heterogeneity, functional connectivity, and opportunities for maintaining genetic diversity. Furthermore, there is now sufficient evidence to recognize these globally applicable principles, which then require honing according to local conditions of culture, awareness, and human activities, as well as a willingness to change the world of insects and humans for the better. Moving forward however, requires a sound philosophical foundation of shared value for both insect and human well-being. Embracing value then leads to scientific investigation towards effective practical insect conservation, notwithstanding the perspectives and knowledge of the local human inhabitants. But there are two major challenges, one physical and the other social, that now need addressing, and fast.

Firstly, while many insects have the potential to adapt to climate change, either by moving or by genetic adaptation, they are thwarted by global fragmentation of landscapes. While some edge species do very well in these changed conditions, for most species, fragmentation flies in the face of functional connectivity. In turn, this is aggravated by climate change, the effects of which are particularly concerning with regards to core value of protected areas as retainers of source populations. As these areas are fixed in position, they can no longer be guaranteed to be home to source populations of rare and threatened specialist insect species in the future. This means that it behoves agroecology in rural areas and greenspace development in cities to soften the landscape for improved functional connectivity. This approach is multifarious, ranging from physical structures, such as veteran trees, green roofs, and roadside and riparian corridors, through to control of adverse chemicals, whether pollutants, fertilizers or pesticides, which are, in effect, chemical-based barriers to insect movement across wider landscapes.

The second major challenge is the current lack of sufficient collective political will and concerted effort, as with climate change mitigation (Fig. 9, bottom left). We are faced with a lack of societal understanding or appreciation of the importance of insect well-being for our well-being. This means that we must communicate the importance of insect conservation much better, especially using the tools of insect conservation psychology, which includes the important and inter-related components of education and citizen science. For example, dragonflies are used as flagships to illustrate the sustainable use of freshwater resources in environmental education in many parts of the world (Clausnitzer et al., 2017). In Austria, school learners are contributing to butterfly monitoring and conservation through selection of high-quality grassland sites for follow-up by professional scientists (Rüdisser et al., 2017).

In keeping with the ethos of Godet and Devictor (2018), all the above approaches must also go hand-in-hand with follow-up on what has worked and what has not, both scientifically and in the eyes of society. This means expanding effective conservation strategies from core areas out into further surrounding areas, all the while growing the physical areas of influence and action far more widely. This can aided by, for example, civil society engagement and education not just of the young but also of mature land stewards in a process of engagement between tutor and learner (Fig. 9, top left). But care is required that scientists do not assume a position of arrogance in 'having all the answers'. The real way forward is iterative engagement by scientists with civil society in a feedback loop where both parties learn and benefit from each other, and work together to produce practical outcomes. Extensive strategies for doing this are discussed in detail by Samways (2019).

Although we are not going to be able to conserve every insect population or even every species, civil society is now becoming aware of the precipitous decline in insects and its severe consequences for planetary survival. However, with possible exception of concern over the loss of bees and pollination services, civil society in general does not see 'the use' of insects, which is where insect icons, popular media, natural history clubs, education, and citizen scientist activities can all play a major role. This is especially important in urban and peri-urban environments, where there is overall the greatest disconnect with nature yet the greatest concentrations of people. In rural settings, there is also great opportunity for better education, especially of the young and impressionable, who often actually educate the parents in matters of 'our future' and 'small lives matter'.

As insects are braided into ecosystems, their plight is essentially integrated with more expansive movements such as global biodiversity conservation and climate change mitigation (Ripple et al., 2019), and in an alliance with them. However, there is still considerable inertia and insufficient political will, especially in the mining and manufacturing sectors. Yet in the agricultural sector, where there is much more appreciation of ecosystem processes, especially soil formation and biological control of pests, great progress is being made. Nevertheless, the transition to agro-ecology is still thinly spread, although increasing as certain farmers and farming organizations illustrate the benefits of preserving the land and then conveying the benefits to others. By conserving as many naturally-intact ecosystems as possible, alongside more extensive softening food- and fibre-producing landscapes, together we can get on course for leaving a sound legacy to future generations.

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Declaration of competing interest

All authors declare no conflict of interest.

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References

Barua, M., Gurdak, D.J., Ahmed, R.A., Tamuly, J., 2012. Selecting flagships for invertebrate conservation. Biodivers. Conserv. 21, 1457–1476. https://doi.org/10.1007/s10531-012-0257-7.

Basset, Y., Lamarre, G.P.A., 2019. Toward a world that values insects. Science 364 (6447), 1230–1231. https://doi.org/10.1126/science.aaw7071.

Bradshaw, C.J.A., Leroy, B., Bellard, C., Roiz, D., Albert, C., Fournier, A., et al., 2016. Massive yet grossly underestimated global costs of invasive insects. Nat. Commun., 12986. https://doi.org/10.1038/ncomms12986.

Cardoso, P., Barton, P.S., Birkhofer, K., Chichorro, F., Deacon, C., Fartmann, T., et al., 2020. Scientists’ warning to humanity on insect extinctions. Biol. Conserv (in press).

Chan, K.M.A., Balvanera, P., Benessaiah, K., Chapman, M., Díaz, S., Gómez-Baggethun, E., et al., 2016. Opinion: why protect nature? Rethinking values and the environment. PNAS 113, 1462–1465. https://doi.org/10.1073/pnas.1525002113.

Clausnitzer, V., Simaika, J.P., Samways, M.J., Daniel, B.A., 2017. Dragonflies as flagships for sustainable use of water resources in environmental education. Appl. Environ. Educ. Commun. 16, 196–209. https://doi.org/10.1080/1533015X.2017.1333050.

Díaz, S., Settele, J., Brondízio, E.S., Ngo, H.T., Agard, J., Arneth, A., et al., 2019. Pervasive human-driven decline of life on earth points to the need for transformative change. Science 366 (6471). https://doi.org/10.1126/science.aax3100. 13 Dec. 2019.

Ellis, S., Bourn, N.A.D., Bulman, C.R., 2012. Landscape-scale Conservation for Butterflies and Moths: Lessons From the UK. Butterfly Conservation, Wareham, Dorset.

Godet, L., Devictor, V., 2018. What conservation does. Trends Ecol. Evol. 33, 720–730. https://doi.org/10.1016/j.tree.2018.07.004.

Hajek, A.E., Hurley, B.P., Kenis, M., Garnas, J.R., Bush, S.J., Wingfield, M.J., et al., 2016. Exotic biological control agents: a solution or contribution to arthropod invasions? Biol. Invasions 18, 953–969. https://doi.org/10.1007/s10530-016-1075-8.

Justus, J., Colyvan, M., Regan, H., Maguire, L., 2009. Buying into conservation: intrinsic versus instrumental value. Trends Ecol. Evol. 24, 187–191. https://doi.org/10.1016/j.tree.2008.11.011.

Kaiser-Bunbury, C.N., Mougal, J., Whittington, A.E., Valentin, T., Gabriel, R., Olesen, J.M., Blüthgen, N., 2017. Ecosystem restoration strengthens pollination network resilience and function. Nature 542, 223–227. https://doi.org/10.1038/nature21071.

Kleijn, D., Winfree, R., Bartomeus, I., Carvalheiro, L.G., Henry, M., Isaacs, R., et al., 2015. Delivery of crop pollination services is an insufficient argument for wild pollinator conservation. Nat. Commun. 6, 7414. https://doi.org/10.1038/ncomms8414.

Kritsky, G., Smith, J.J., 2018. Insect biodiversity in culture and art. In: Foottit, R.G., Adler, P.H. (Eds.), Insect Biodiversity: Science and Society. 2. Wiley-Blackwell, Oxford, UK, pp. 869–898. https://doi.org/10.1002/9781118945582.ch29.

Leandro, C., Jay-Robert, P., Vergnes, A., 2017. Bias and perspectives in insect conservation: a European scale analysis. Biol. Conserv. 215, 213–224. https://doi.org/10.1016/j.biocon.2017.07.033.

Lemelin, R.H. (Ed.), 2013. The Management of Insects in Recreation and Tourism. Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/CBO9781139003339.

Lorimer, J., 2007. Nonhuman charisma. Environ. Plann. D: Soc. Space 25, 911–932. https://10.1068/d71j.

Manfredo, M.J., Urquiza-Haas, E.G., Don Carlos, A.W., Bruskotter, J.T., Dietsch, A.M., 2020. How anthropomorphism is changing the societal context of modern wildlife conservation. Biol. Conserv. https://doi.org/10.1016/j.biocon.2019.108297.

McClure, M., Machalaba, C., Zambrana-Torrelio, C., Feferholtz, Y., Lee, K.D., Daszak, P., et al., 2019. Incorporating health outcomes into land-use planning. EcoHealth. https://doi.org/10.1007/s10393-019-01439-x.

Montgomery, G.A., Dunn, R.R., Fox, R., Jongejans, E., Leather, S.R., Saunders, M.E., et al., 2020. Is the insect apocalypse upon us? How to find out. Biol. Conserv. https://doi.org/10.1016/j.biocon.2019.108327. (in press).

Morris, M.G., 1987. Changing attitudes to nature conservation: the entomological perspective. Biol. J. Linn. Soc. 32, 213–223 (doi:1111/j.1095-8312.1987.tb00428.x).

Nash, S., 2004. Desperately seeking charisma: improving the status of invertebrates. BioScience 54, 487–494. https://doi.org/10.1641/0006-3568(2004)054[0487:DSCITS]2.0.CO;2.

Perfecto, I., Vandermeer, J., 2008. Biodiversity conservation in tropical ecosystems: a new conservation pradigm. Ann. N. Y. Acad. Sci. 1134, 173–200. https://doi.org/10.1196/annals.1439.011.

Pocock, M.J.O., Evans, D.M., Memmott, J., 2012. The robustness and restoration of a network of ecological networks. Science 335, 973–977. https://doi.org/10.1126/science.1214915.

Ripple, W.J., Wolf, C., Newsome, T.M., Barnard, P., Moomaw, W.R., 2019. World scientists’ warning of a climate emergency. BioScience biz088. https://doi.org/10.1093/biosci/biz088.

Rudisser, J., Tasser, E., Walde, J., Huemer, P., Lechner, K., Ortner, A., Tappeiner, U., 2017. Simplified and still meaningful: assessing butterfly habitat quality in grasslands with data collected by pupils. J. Insect Conserv. 21, 677–688. https://doi.org/10.1007/s10841-017-0010-3.

Samways, M.J., 2007. Insect conservation: a synthetic management approach. Annu. Rev. Entomol. 52, 465–487. https://doi.org/10.1146/annurev.ento.52.110405.091317.

Samways, M.J., 2015. Future-proofing insect diversity. Curr. Opin. Insect Sci. 12, 71–78. https://doi.org/10.1016/j.cois.2015.09.008.

Samways, M.J., 2017. Reconciling ethical and scientific issues for insect conservation. In: Foottit, R.G., Adler, P.H. (Eds.), Insect Biodiversity: Science and Society, second ed. 1. Wiley-Blackwell, Oxford, UK, pp. 747–766. https://doi.org/10.1002/9781118945568.ch23.

Samways, M.J., 2019. Insect Conservation: A Global Synthesis. CABI, Wallingford, Oxon, UK (ISBN-13: 978 1 78924 168 6).

Senapathi, D., Biesmeijer, J.C., Breeze, T.D., Kleijn, D., Potts, S.G., Carvalheiro, L.G., 2015. Pollinator conservation — the difference between managing for pollination services and preserving pollinator diversity. Curr. Opin. Insect Sci. 12, 93–101. https://doi.org/10.1016/j.cois.2015.11.002.

Simaika, J.P., Samways, M.J., 2018. Insect conservation psychology. J. Insect Conserv. 22, 635–642. https://doi.org/10.1007/s10841-018-0047-y.

Swinton, A.H., 1880. Insect Variety: Its Propagation and Distribution. Cassell, Petter, Galpin & Co., London.

Ulicsni, V., Svanberg, I., Molnár, Z., 2016. Folk knowledge of invertebrates in Central Europe – folk taxonomy, nomenclature, medicinal and other uses, folklore, and nature conservation. J. Ethnobiol. Ethnomed. 12, 47. https://10.1186/s13002-016-0118-7.