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REVIEW PAPER

Insects from the southwest Australia biodiversity hotspot: a barometer of diversity and threat status of nine host-dependent families across three orders

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Abstract
The mass loss of insects is gaining momentum in the twenty-first century, compared with the previous 100 years. The loss is coinciding with accelerating threats, including megafires, flooding, temperature extremes, urbanisation, and habitat loss. In global diversity hotspots, where endemism is high, and native vegetation highly impacted, many insect species would likely be both endemic and threatened. However, insect diversity, endemicity and threat status are largely unknown in these regions. Here we assess the biodiversity and status of host-dependent insects in the southwest Australian (SWWA) hotspot. We selected nine insect families across three orders; Tingidae, Achilidae, Derbidae, Dictyopharidae, Triozidae (Hemiptera), Micropterigidae, Heliozidae (Lepidoptera), Boopidae, and Philopteridae (Psocodea). These families had 632+ species, of which 255 (~40%) were described. One species was formally listed as threatened, but a further 245 species potentially require conservation management. Threatening processes include coextinction (through loss or reduction in host populations), climate change, altered fire regimes, habitat loss, and fragmentation of host populations. Taxonomic and resourcing bias has inhibited attempts to describe the diversity and biogeography of the region, precluding comprehensive conservation assessments for the majority of insect families.

Implications for insect conservation Given the scale and intensity of threats faced by a hyperdiverse insect fauna in the southwest Australia biodiversity hotspot, a systematic approach to manage habitats at a landscape scale is most likely to succeed in conserving species in the short-term. Longer term solutions require addressing these knowledge gaps, thus increasing our understanding of the diversity and conservation needs of insect families in southwest Australia.

Keywords Threat status · Coextinction · Insecta · Threatening processes · IUCN Red List · Threatened species lists

Introduction

Mass loss of invertebrates has received increasing attention culminating with the term "insect apocalypse" (Bidau 2018; Goulson 2019; Sánchez-Bayo and Wyckhuys 2019; Cardoso et al. 2020). Empirical evidence suggests losses of 9% of general insect abundance each decade (van Klink et al. 2020), while 40% of all insect species may be threatened (Forister et al. 2019; Sánchez-Bayo and Wyckhuys 2019). The data behind these statistics originate from the Northern Hemisphere; for example, the rapid decline of British and Dutch Lepidoptera (Conrad et al. 2006; van Langevelde et al. 2018) and up to 82% loss in flying insect biomass across Germany in 27 years (Hallmann et al. 2017). While these studies are generally focused on restricted sets of insects in the Northern Hemisphere, there has been little empirical study and evidence of general decline in the Southern Hemisphere, particularly within Southern Hemisphere temperate zones (New and Samways 2014; Braby 2019). One exception is perhaps New Zealand where concern for the dwindling insect fauna has been long standing—dating back to the 1900s—given the threats of fires, introduced predators, habitat alteration and clearing (Watts et al. 2012). The New Zealand Stenopelmatidae fauna, also called wētā or King crickets provides evidence of this long decline, primarily after the introduction of rodents (Gibbs 1998a). The discovery of new

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wētā species over the past 25 years (Gibbs 1998b; Trewick 2021), however, emphasizes that even in better studied Southern Hemisphere systems, much remains undocumented (Gibbs 1998b). For the majority of other regions, the conservation status of the insect fauna is poorly known and often restricted to prominent individual species (Taylor et al. 2018; New 2022). For example, in Australia Green et al. (2021) detailed the significant decline of the once abundant bogong moth (*Agrotis infusa* (Boisduval)), while declines in the large green carpenter bee (*Xylocopa aerata* (Smith)) were outlined by Hogendoorn et al. (2021). In both species the decline was primarily caused by loss of appropriate habitat. The Southern Hemisphere insect fauna has received recent attention with the lack of adequate data to include in 'global' reviews of insect decline becoming apparent (Braby et al. 2021). However, most assessed insects are popular and well-known groups such as butterflies, bees and very large beetles (e.g., Geyle et al. 2021; Sánchez-Bayo and Wyckhuys 2021; Lewinsohn et al. 2022). This is because population data is generally only available in relation to these groups.

Myers et al. (2000), and subsequently Mittermeier et al. (2005), advocated that global conservation efforts should focus on regions with elevated levels of plant and mammal endemism, coupled with high rates of habitat loss, terming these regions global biodiversity hotspots. It is intuitive that these hotspots would also experience higher insect species loss than other areas, if plant and mammal endemism are indicative of insect diversity (i.e. Fonseca 2009; Kaneryd et al. 2012). Although plant and mammal endemism is not always indicative of invertebrate endemism and diversity particularly at smaller spatial scales (e.g., Moir et al. 2009; Rix et al. 2015), there is building evidence that insects exhibit higher diversity and endemism in the temperate Southern Hemisphere biodiversity hotspots than outside these regions, with most of this evidence from South Africa (e.g., Wright and Samways 1998; Procheş and Cowling 2006; Bazelet et al. 2016). Indeed, Fonseca (2009) estimated that in the hotspots between 213,830 and 547,500 herbivorous insect species are at risk of coextinction solely because of the high plant diversity that supports them.

There has been little empirical evidence of modern insect decline and the need for conservation within biodiversity hotspots in the Southern Hemisphere, aside from rare examples of extinctions such as a New Caledonian diving beetle (World Conservation Monitoring Centre 1996), an Australian mealybug (Moir 2021), a Seychelles cockroach (Gerlach 2012), and three specialised bird lice in New Zealand (Buckley et al. 2012). A large part of the problem are the Linnean and Wallacean shortfalls (sensu Cardoso et al. 2011) where the species present are largely undescribed, and their exact distributions are undocumented. This makes assessing their endemicity, applicable threats, and conservation status incredibly difficult. New (2022) provides a detailed discussion of these issues and points out that there is a "formidable ignorance of the insects of these southern zones….".

Southwest Australia (hereafter SWWA) is ranked the 16th biodiversity hotspot globally, primarily due to its high floristic diversity and endemism (Myers et al. 2000); 49% of the 8379 plant species are endemic (Gioia and Hopper 2017). Approximately 7.8% of SWWA flora have some conservation listing by the State Government, while ~ 19.5% are data deficient (Gosper et al. 2022). Such high plant endemism suggests significant in situ diversification (Cook et al. 2015), which is likely reflected in other taxa, including insects. However, empirical studies of the endemism of entire groups or conservation status of insect communities in SWWA are scarce. The likelihood of immediate threat is high, with recent evidence of insect extinction occurring both locally (Phillips et al. 2015; Moir et al. 2016) and globally (Moir 2021), and guestimates of 2347–5897 species extinctions already having occurred for plant-dwelling insects alone in this region (Fonseca 2009). In this study, we explore the likely conservation status of some less auspicious insect taxa in the SWWA biodiversity hotspot.

Materials and methods

Review

While developing this study, we found that there were too few surveys or taxonomic works specific to this area for the majority of insect families to estimate species diversity (e.g., parasitic Hymenoptera: A. Austin pers. comm. 2022) or the proportions of undescribed fauna (e.g., Tettigoniidae, Blattidae: D. Rentz pers. comm. 2022; Buprestidae: S. Barker pers. comm. 2022; Carabidae: N. Guthrie pers. comm 2022). We therefore selected nine families of parasitic, herbivorous or niche-specific insects to assess in detail. These families, representing three little-known insect orders in the SWWA, were selected because of the authors personal experience and knowledge of their taxonomic and geographic coverage: Tingidae, Achilidae, Derbidae, Triozidae, Dictyopharidae (Hemiptera: MLM); Heliozidae, Micropterigidae (Lepidoptera: DAY). The parasitic families of Boopidae and Philopteridae (Psocodea: MLM) were selected as representatives of parasitic lifestyles because there were adequate published records of their occurrence on hosts and their taxonomy in the SWWA for them to be assessed.

We compiled lists of described and undescribed species present in the SWWA in the selected families, excluding introduced species. We noted whether each species was present, or could be inferred as present, in the Stirling Range National Park, a large conservation area located near the junction of four of the nine bioregions of the SWWA biodiversity hotspot (Fig. 1a). The Stirling Range National Park was considered a subset, allowing us to assess conservation status in more detail. Recording undescribed species allowed us to indicate the level of 'hidden' diversity not often recorded by faunal inventories or on conservation lists because high percentages of undescribed species are common within insect groups of SWWA. Our knowledge of these some of these families in the southwest is derived from decades of fieldwork and experience with collections from across Australia. We produced accumulation curves of published species descriptions, to visualise the descriptions of taxa over time, for those families with more than two described species.

A map of the biodiversity intactness index for the SWWA (Newbold et al. 2016) was generated in the UN Biodiversity Lab (2022) portal. The biodiversity intactness index is the "average proportion of natural biodiversity remaining in local ecosystems" (Newbold et al. 2016) and was modelled from the megadata of the Projecting Responses of Ecological Diversity in Changing Terrestrial Systems (PREDICTS) project (Hudson et al. 2017). It encompasses datasets from most life-forms including plants, vertebrates and invertebrates.

Results

Forty-one insect species from the SWWA have been assessed for conservation either by State, Federal or International bodies (Table 1). This includes six species deemed too 'data deficient' for assessment. Of these, only the plantlouse *Trioza barrettae* Taylor & Moir represents a species from within the nine families that we outline here.

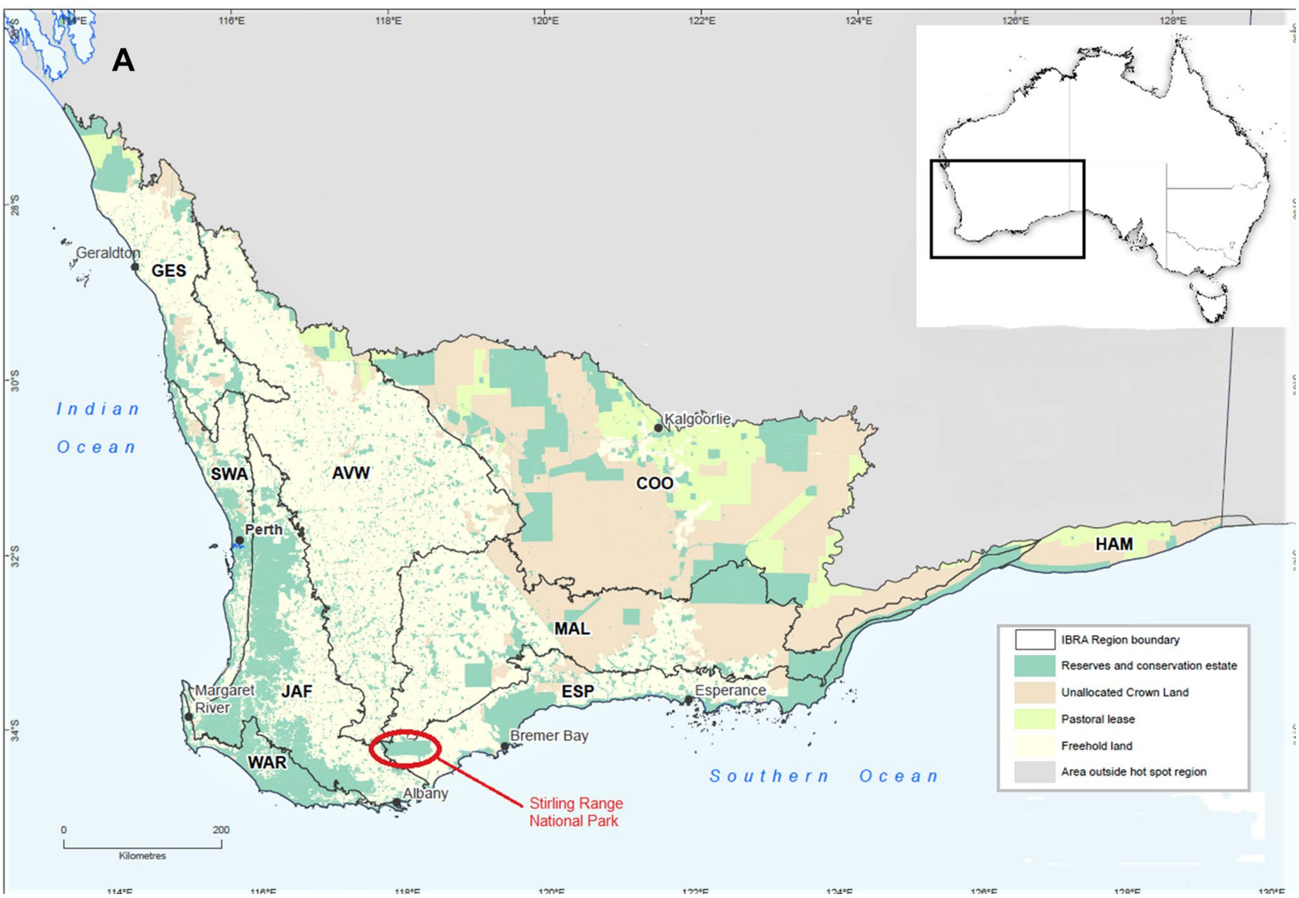

Fig. 1 The southwest Australia biodiversity hotspot region. Map **A** features the Stirling Range National Park circled in red and inset shows map of Australia with the southwest section selected. Regions follow IBRA (2020) bioregion classification of *HAM* Hampton; *ESP* Esperance sandplains; *MAL* Mallee; *COO* Coolgardie; *AVW* Avon Wheatbelt; *JAF* Jarrah Forest; *WAR* Warren; *SWA* Swan Coastal Plain; *GES* Geraldton Sandplains. Map **B** indicates the intactness of biodiversity in the region (or the average proportion of natural biodiversity remaining with 1 = wholly intact and 0 = no longer intact) using Newbold et al. (2016) and generated using UN Biodiversity Lab (2022). (Color figure online)

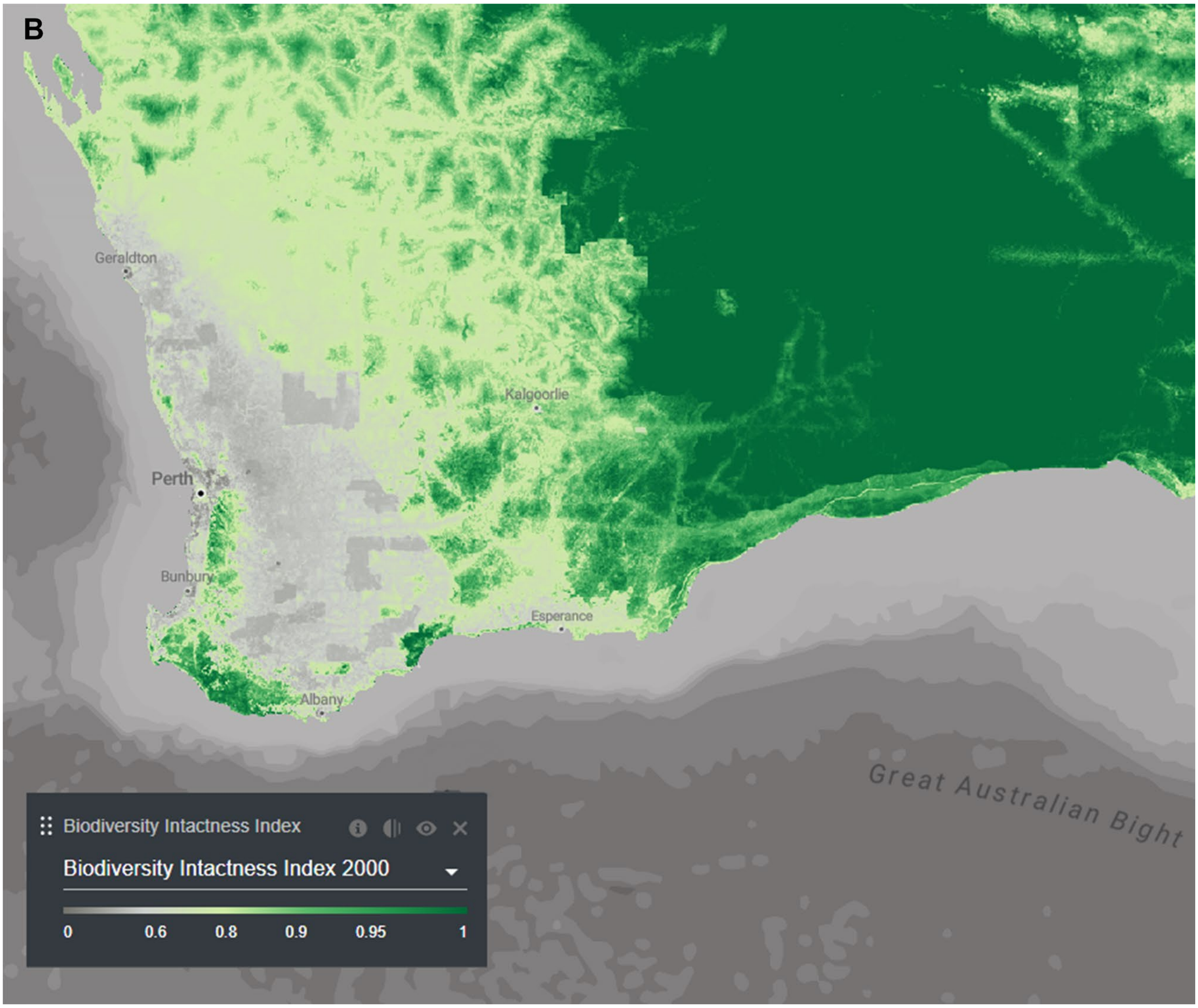

Fig. 1 (continued)

Planthoppers: Achilidae, Derbidae and Dictyopharidae (Hemiptera: Fulgoroidea)

The planthopper families Derbidae, Achilidae and Dictyopharidae from SWWA are poorly known, with only one or two formally described species per family (Table 2). All families are herbivorous, but Derbidae and Achilidae are mycophagous in the nymphal stages. Derbidae are exceedingly depauperate in SWWA, represented by three species (Table 2). This is unsurprising as Derbidae typically display higher diversity in the tropics (Bourgoin 2017). Two species, *Cedusa venosa* Fowler and an undescribed *Cedusa*, are very common particularly in the mesic regions of the Esperance sandplains, Jarrah Forest, Warren and Swan Coastal Plain bioregions (Fig. 1), but a second undescribed species of *Cedusa* has only been found in a small nature reserve north of Albany. Although protected within a conservation estate, this species is threatened by changes in the habitat caused by fire or plant disease.

Achilidae are common across the SWWA, but all known species are restricted within the region to date. The majority of the 32+ species are small and dull coloured; just four species are greater than 8 mm in length. *Bunduica rubrovenosa* Jacobi is the only described species, it represents a monotypic genus endemic to the southwest, *B. rubrovenosa* is common under Karri (*Eucalyptus diversicolor F.Muell.*) tree bark, it’s preferred host plant. There is a very large diversity of small black, brown, white and tan species in the tribe Plectoderini which are mostly widespread within one or more IBRA regions in SWWA. Likely threatened species in the Stirling Range National Park encompass an undescribed species of the tribe Trophlepsini, and two

Table 1 Insect species present within southwest Australia that are conservation listed at the level of State (WA: Western Australia), Federal (under the *Environmental Protection and Biodiversity Conservation Act, 1999* EPBC), or International (International Union for Conservation of Nature Red List IUCN)

Order	Scientific name	Common name	WA status (ranking)	EPBC status (ranking)	IUCN ranking
Coleoptera	*Tesserodon pilicrepus*	Flightless Kalbarri Scarab	–	–	DD
Coleoptera	*Trichosternus relictus*	Margaret River Pterostichid Ground Beetle	P3	–	–
Diptera	*Austroconops mcmillani*	McMillan's biting Midge	P2	–	–
Hemiptera	*Acizzia mccarthyi*	McCarthy's Plant-louse	VU		EN
Hemiptera	*Acizzia veski*	Vesk's Plant-louse	VU	–	CR
Hemiptera	*Budginmaya eulae*	Eula's Planthopper	P1	–	–
Hemiptera	*Pseudococcus markharveyi*	Banksia montana mealybug	CR	CR	CR
Hemiptera	*Trioza barrettae*	Banksia brownii plant-louse	EN	EN	CR
Hymenoptera	*Glossurocolletes bilobatus*	Short-tongued bee	P2	–	–
Hymenoptera	*Hesperocolletes douglasi*	Douglas's broad-headed bee	CR	CR	–
Hymenoptera	*Hylaeus globuliferus*	Woolybush bee	P3	–	–
Hymenoptera	*Leioproctus contrarius*	Short-tongued bee	P3	–	–
Hymenoptera	*Leioproctus douglasiellus*	Short-tongued bee	EN	CR	–
Hymenoptera	*Neopasiphae simplicior*	Short-tongued bee	EN	CR	–
Lepidoptera	*Agrotis infusa*	Bogong Moth	–	–	EN
Lepidoptera	*Jalmenus aridus*	Inland hairstreak, desert blue butterfly	P1	–	–
Lepidoptera	*Ogyris subterrestris petrina*	Arid bronze azure butterfly	CR	CR	–
Lepidoptera	*Synemon gratiosa*	Graceful sunmoth	P4	–	–
Odonata	*Archaeosynthemis spiniger*	Spiny Tigertail	–	–	VU
Odonata	*Archiargiolestes parvulus*	Midget Flatwing	–	–	NT
Odonata	*Archiargiolestes pusillissimus*	Tiny Flatwing	–	–	NT
Odonata	*Armagomphus armiger*	Armourtail	–	–	VU
Odonata	*Hesperocordulia berthoudi*	Orange Streamcruiser	–	–	NT
Odonata	*Lathrocordulia metallica*	Western Swiftwing	–	–	VU
Odonata	*Petalura hesperia*	Western Petaltail	–	–	DD
Orthoptera	*Austrosaga spinifer*	Spiny Katydid	P2	–	VU
Orthoptera	*Hemisaga irregularis*	Odd sluggish Katydid	–	–	VU
Orthoptera	*Hemisaga lucifer*	Devil's Slide Katydid	P2	–	VU
Orthoptera	*Hemisaga vepreculae*	Thorny bush Katydid	P2	–	VU
Orthoptera	*Kawanaphila pachomai*	Grey vernal Katydid	P1	–	–
Orthoptera	*Pachysaga munggai*	Odd Pachysaga	P3	–	VU
Orthoptera	*Pachysaga strobila*	Vasse Pachysaga	P1	–	CR
Orthoptera	*Phasmodes jeeba*	Springtime corroboree stick Katydid	P3	–	VU
Orthoptera	*Psacadonotus seriatus*	Fan-winged Katydid	P1	–	VU
Orthoptera	*Throscodectes xederoides*	Mogumber Throsco	P3	–	EN
Orthoptera	*Throscodectes xiphos*	Northern Throsco	P1	–	EN
Orthoptera	*Windbalea viride*	Green west wind Katydid	P1	–	VU
Phasmida	*Arphax brunneus*	Brown Arphax Stick-insect	–	–	DD
Phasmida	*Arphax michaelseni*	Michaelsen's Arphax Stick-insect	–	–	DD
Phasmida	*Denhama eutrachelia*	WA Thin Stick-insect	–	–	DD
Phasmida	*Tropidoderus michaelseni*	Michaelsen's Stick-insect	–	–	DD

CR critically endangered; *EN* endangered; *VU* vulnerable; *P1, P2, P3 or P4 (WA rankings only)* priority taxa for conservation action; *DD* data deficient; – not listed

undescribed Plectoderini species. Of the total fauna in the southwest, seven species are likely to be threatened as they are known from single individuals or restricted habitats. For example, an undescribed genus and species of Plectoderini (Fig. 2d) is restricted to several mountain peaks of the Stirling Range National Park. Given the bushfires in this habitat

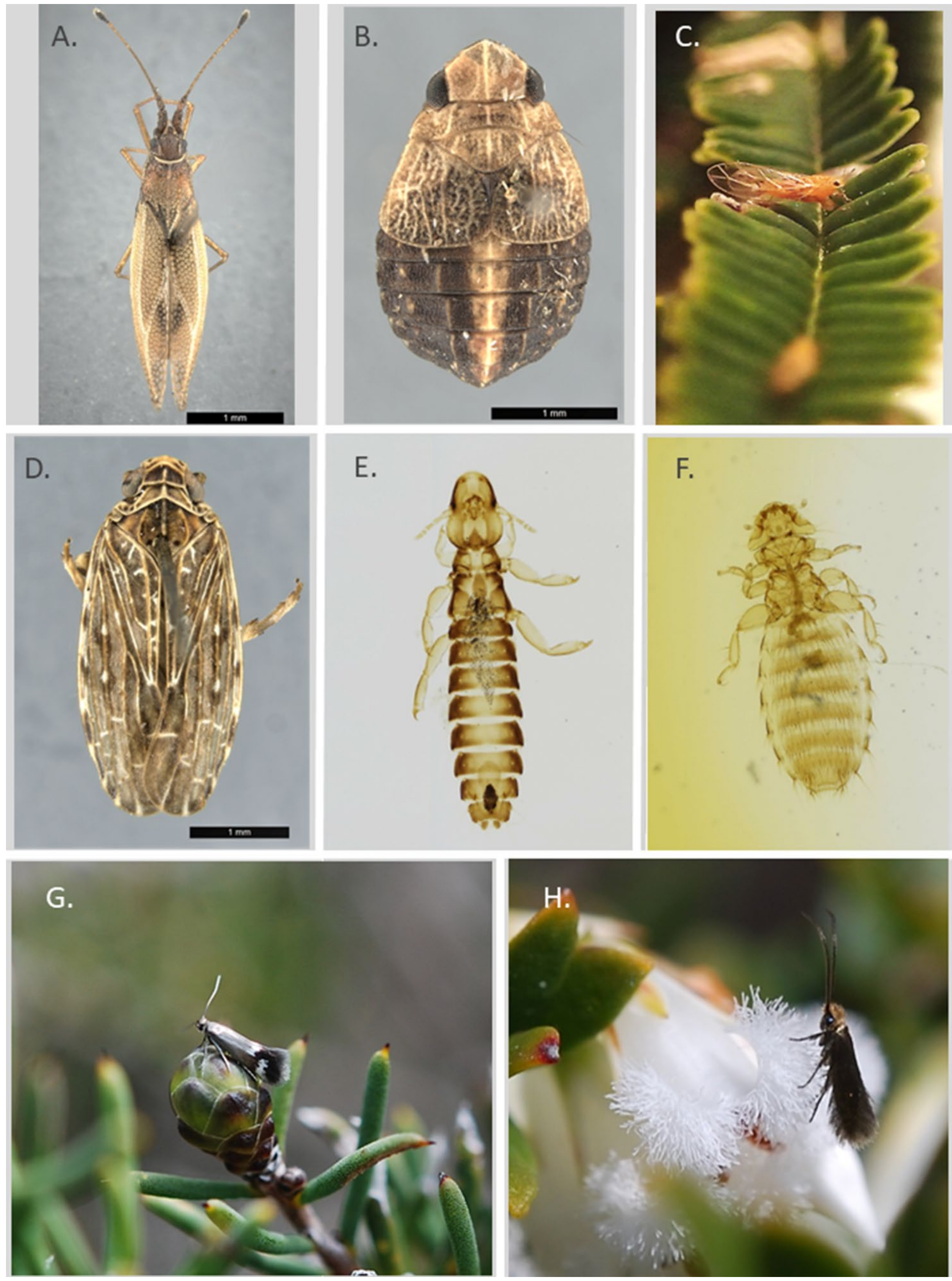

Fig. 2 Images of selected families. **a** *Swaustraltingis isobellae* (Hemiptera: Heteroptera: Tingidae). **b** An undescribed genus and species of Orgeriinae (Hemiptera: Auchenorrhyncha: Dictyopharidae) from the endangered Eastern Stirling Range Montane Heath and Thicket ecological community in the Stirling Range National Park. **c** *Trioza barrettae* (Hemiptera: Sternorrhyncha: Triozidae). **d** An undescribed genus and species of Plectoderiini (Hemiptera: Auchenorrhyncha: Achilidae) from the Stirling Range National Park. **e** *Neopsittaconirmus borgiolii* (Phthiraptera: Philopteridae), a louse restricted to large cockatoos such as the red-tail black and Baudins. **f** Paratype of *Paraheterodoxus calcaratus* (Phthiraptera: Boopidae), a louse restricted to woylies. **g** A species of *Heliozela sensu lato* (Lepidoptera: Heliozelidae) breeds on *Melaleuca* buds near Bluff Knoll, Stirling Range National Park and has a total known range of a couple of square kilometres, and **h** an undescribed genus and species of Micropterigidae (Lepidoptera) known from three extremely restricted sites in the Stirling Range National Park, all of which experienced intense fire in 2018–2019

between 2019 and 2020 which extinguished other species (e.g., *Pseudococcus markharveyi* Gullan: Moir 2021), this achilid may be extinct.

The Dictyopharidae contain a hidden diversity, with only two of the estimated > 23 species being described. The majority of undescribed taxa are well camouflaged, small, reduced winged and dull-coloured species (Fig. 2b). The first species described from SWWA, *Hasta hastata* Kirkaldy is relatively large, green and fully winged. It is also found in eastern Australia, but this needs revising as the SWWA population may represent a cryptic species, with no published taxonomy on western individuals available. The remaining species are predominantly brachypterous ground-dwelling taxa, and could be overlooked in pitfall traps or other ground sampling techniques by ecologists believing them to be nymphs or mistaking them for debris. The diversity that has been uncovered thus far indicates that there is a much larger number of species remaining undiscovered. Most dictyopharid species are potentially threatened as they are dispersal inhibited, ground-dwelling and restricted to specific habitats. Using the Stirling Range National Park as an example, there are six known undescribed species from the park and all would be threatened, primarily by fire and drying habitats (Table 2). One species in particular (Fig. 2b) is restricted to the Federally listed critically endangered ecological community of the Eastern Stirling Range Montane

Heath and Thicket. Given the recent bushfires experienced in this habitat, as discussed above, the dictyopharid may now be extinct.

Lace bugs: Tingidae (Hemiptera: Miroidea)

Tingidae are small herbivorous insects which spend the majority of their lifecycle on their host plants and tend to be relatively host, or host genus, specific. Unlike the other families discussed so far, a number of taxonomists have been actively working on the Australian fauna over the past 25 years and, for many of the 36 species that are described from the SWWA, their ecology (especially host preferences), and distribution are better known than for many other insect groups. Despite this, less than half the known SWWA fauna are described (Fig. 3), with 50 undescribed species recognised in collections from the region (Table 2).

Using the case study of the Stirling Range National Park as an indicator of the SWWA, 20 species have been recorded here, of which five are described (20%). No species appear restricted to the Stirling Ranges. If the percentage of undescribed tingid species is consistent across the broader region, there could be approximately 180 species in SWWA.

Of the seven tingid species that are potentially threatened in SWWA, four are rare Ceratocaderini species represented by few specimens and likely restricted to relictual habitats on mountain peaks or in tall wet forests (i.e. *Coolacader valentine* Moir, *Ceratocader bridgettae* Moir & Lis, *Ceratocader coatsi* Moir & Lis and *Ceractocader fulvus* Lis; Moir 2022). One species, *Celantia nitidula* Stål has not been recollected since the types were described in 1873. The remaining two taxa are *Swaustraltingis* species; an undescribed species found in the far southwest and *Swaustraltingis isobellae* Moir & Guilbert (Fig. 2a) which is restricted to the relictual peatland plant *Empodisma gracillimum* (F.Muell.) (Moir and Guilbert 2012). This plant forms the basis for a nominated (2017, 2019, and currently under consideration) Federal threatened ecological community. The nomination emphasized the threats of fire, climate change and development of acid sulphate soils (Threatened Species Scientific Committee 2019) and the lacebug is likely cothreatened by these pressures (i.e. Moir and Brennan 2020).

Plantlice: Triozidae (Hemiptera: Psylloidea)

Triozidae are a family of the hyperdiverse Australian plantlice or lerp insect fauna (Psylloidea). In the SWWA, the majority of triozid taxonomic work has occurred in the last 12 years (Fig. 3), with 17 species recognised formally and at least 25 species present in the region in total (Table 2:

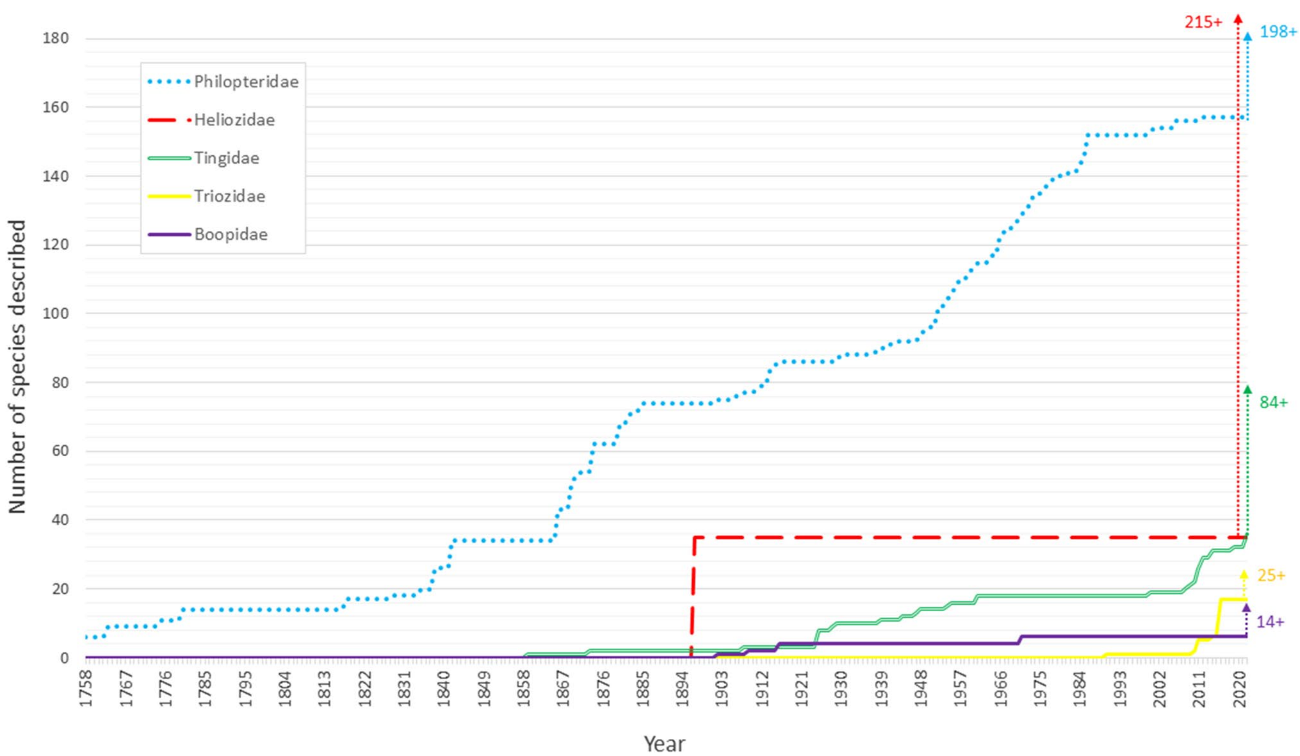

Fig. 3 Accumulation curves of descriptions of insects from selected groups: Philopteridae (blue dots); Tingidae (green solid line), Triozidae (light yellow solid line); Boopidae (dark purple solid line); and Heliozidae (red dashes). Dotted arrows and associated numbers indicate the estimated diversity in southwest Australia. Excluded are the Achilidae, Derbidae, Dictyopharidae, Micropterigidae where only 1 or 2 species have been described. (Color figure online)

Table 2 The number of species within each of the selected host dependent insect families present in the southwest, including undescribed species, and whether they are thought to be threatened

Order Suborder	Family	Insect species in southwest							
		Total	Described	% undescribed	Threatened (estimate)	Total in SRNP	Threatened in SRNP	% of SRNP threatened	Listed threatened species
Hemiptera Heteroptera	Tingidae	84+	36	57.1%+	5+	20	3	15%	0
Hemiptera Auchenorrhyncha	Achilidae	32+	1	97%+	7+	17	3	17.6%	0
Hemiptera Auchenorrhyncha	Derbidae	3	1	66.7%	1	2	0	0%	0
Hemiptera Auchenorrhyncha	Dictyopharidae	23+	2	92%+	6+	6	6	100%	0
Hemiptera Sternorrhyncha	Triozidae	25+	17	32%+	1+	11	1	9%	1
Lepidoptera	Heliozidae	250	35	86%	177	45	36	80%	0
Lepidoptera	Micropterigidae	3	0	100%	3	1	1	100%	0
Phthiraptera	Philopteridae	198+	157	20.7%+	42+	103*+	10*?	9.7%	0
Phthiraptera	Boopidae	14+	6	42%+	4+	5*+	3*?	60%	0

Taxa were considered threatened if their host plant was a listed threatened species, they are themselves restricted to a specific habitat or where they are known from a limited area and are scarce as extensive collecting has resulted in very few specimens. Also presented is the number of species inferred as present in the Stirling Range National Park (SRNP), the percentage of these estimated to be threatened and the total number of species officially recognised on threatened species lists (State, Federal or IUCN Red List)

*Based on presence of host species in SRNP

?Too under-assessed to give reasonable estimate

+The number is at least that provided

Martoni et al. in review). Triozidae tend to be relatively host-specific, particularly in regards to host genera. In SWWA the host species are predominantly *Allocasuarina, Casuarina*, and *Eremophila* (Taylor et al. 2010, 2011, 2016) which are widespread, and the triozids are expected to be correspondingly distributed. Being winged, with strong host locating characteristics (e.g., Kristoffersen et al. 2008; Farnier et al. 2015), they appear to have few barriers to movement and locating hosts (Hodkinson 1974), thus most species may not currently require conservation management. Diversity could, however, be significantly under-estimated here particularly in drier, under-surveyed habitats. For example, intensive collecting at Credo station in the semi-arid Coolgardie region (Fig. 1), resulted in the discovery of 11 new species of triozid (Taylor et al. 2016), demonstrating the need for further targeted surveys.

In SWWA one triozid species has highlighted the importance of both (1) assessing fauna dependent on threatened host species, and (2) of not discounting faunal groups which don't typically display short-range endemism traits. *Trioza barrettae* (Fig. 2c) is the only species from any family included within this study that is conservation listed (Table 1) because of its reliance on the critically endangered plant *Banksia brownii* R.Br. (Taylor and Moir 2014). Molecular evidence demonstrates that *T. barrettae* populations are tightly aligned with populations of *B. brownii*, with some *T. barrettae* populations likely having gone extinct prior to host plant expiration (Moir et al. 2016). Further targeted surveys are expected to reveal more cothreatened species in SWWA.

Lice on birds: Philopteridae (Psocodea: Phthiraptera: Ischnocera)

Philopteridae are chewing lice that specialise predominantly on birds, and there are at least 198 species present in SWWA including many undescribed species (Table 2; Fig. 2e: Stranger and Palma 1998). However, taxonomic work on them has been steadily increasing over the past 270 years (Fig. 3) with many of the bird hosts present in SWWA also migratory to other regions of the world, thus explaining the depth of work on their louse fauna. Stranger and Palma (1998) suggested that the true diversity of Philopteridae in Australia was double the described number known in 1998. In the intervening 24+ years since this observation, there have only been four new species of Philopteridae described from birds with ranges extending to SWWA. This suggests that there remain many species to be documented and described, with perhaps as many as 300 bird lice species in SWWA. While the first mechanism for this diversity is the level of endemism of the bird species present in SWWA (Cracraft 1986), while another mechanism is that widespread bird species may be geographically partitioned and host different communities of lice in SWWAfrom elsewhere. For example, the Common bronze wing pigeon (*Phaps chalcoptera* (Latham)) is parasitized by *Columbicola angustus* Rudow in Western Australia but *Columbicola tasmaniensis* (Tenderio) in eastern Australia (Adams et al. 2005). A species of *Philopterus* louse on the widespread Australian Magpie (*Gymnorhina tibicen* (Latham)) provides further evidence of this pattern as it demonstrates distinct molecular divergence in southwestern and eastern Australian populations (Toon and McHugh 2008) possibly indicating the beginning of speciation.

Pigeon and dove hosts (Columbidae) offer examples of how Australian bird lice differs from the rest of the world in coevolution and undescribed diversity. Unlike in other regions, wing lice have displayed coevolution with their Columbidae hosts in Australia, promoting host-specificity (Sweet et al. 2017), particularly in geographically isolated regions such as SWWA. Within these Columbidae lice species, many are undescribed. For example, *Columbicola* is a highly speciose louse genus specific to pigeons and doves, with 77 described species globally (Adams et al. 2005). Adams et al. (2005) points out, however, that there is a paucity of records for half the world's pigeons and doves, with eight genera of Columbidae concentrated around Australia, New Guinea and south Pacific island nations from which we have no records of *Columbicola* at all. Thus, it is likely that there is a vast diversity of undiscovered bird lice in the southwest. Our results here confirm this lack of recorded lice, as we have eight native species of Columbidae recorded within SWWA and 13 lice documented from only half of these host birds (Crested pigeon, Brush bronzewing, Common bronzewing and Spinifex pigeon).

Given the lack of geographic knowledge of even the described Philopteridae fauna, we estimated that the number of threatened louse species in SWWA is approximately 42 species as a function of the host's threat status (following Buckley et al. 2012; Moir and Brennan 2020). The majority (24 species) were on migratory birds. There were approximately 231 bird species in SWWA when Europeans first arrived (Rix et al. 2015), while host records here are from 155 bird species. Physically larger birds feature foremost in the SWWA host-louse records (e.g., Fig. 2e), with smaller birds like wrens (Maluridae), fan-tails (Rhipiduridae), pardolates (Pardalotidae), honeyeaters (Meliphagidae), robins (Petroicidae), thornbills and gerygones (Acanthizidae) absent from them. It is also worth noting that no lice have been documented on most of the endemic threatened birds of the region such as the bristlebird, noisy scrub bird or western ground parrot.

Lice on native mammals: Boopidae (Psocodea: Phthiraptera: Amblycera)

Very little taxonomic work has been conducted over the decades on lice of Australia's native mammals, and there remains much to be done (Spratt and Beveridge 2019), so we readily admit that we do not know of their undescribed diversity. However, it is worth highlighting the Boopidae. This family of louse, with the exception of one species [*Heterodoxus spiniger* (Enderlein)], are restricted to Australasian marsupials, with a high degree of endemism and host specificity (Kéler 1971; Beveridge and Spratt 2003). There are currently six described species present in SWWA (Table 2), with five of these on conservation dependent or threatened hosts. The most threatened louse is likely *Paraheterodoxus calcaratus* Kéler (Fig. 2f), as its host is the critically endangered Woylie (*Bettongia penicillata ogilbyi*) and, although it is also found outside of SWWA on the Brush-tailed bettong (*Bettongia penicillata penicillata*) in eastern Australia, this host is equally threatened as it has already gone extinct in most other states of Australia.

There are four highly threatened marsupial species in SWWA with no known lice species (Numbat, Gilbert's potoroo, Western ringtail possum, Dibbler). Endangered Numbats purportedly have no lice (see Cooper 2011), and no records exist for the endangered Dibbler or critically endangered Gilbert's potoroo (e.g., Vaughan 2008) and Western ringtail possum. It seems improbable that these taxa never hosted lice given the diversity of ectoparasites that have been discovered on better studied taxa (see Beveridge and Spratt 2003; Northover et al. 2018). This suggests some louse species either remain undetected or have already been lost to extinction. In support of the former, Dunlop (2015) recorded an unknown boopid species of louse on Boodies (*Bettongia lesueur*), a vulnerable (EBPC) marsupial, being translocated from Barrow Island. Unfortunately, any lice that have managed to survive on threatened mammal hosts to date will require targeted conservation action to continue to exist as conservation actions suitable for the host species are not always suitable for the parasites (Moir et al. 2012). For example, MacLeod et al. (2010) reported 40% of chewing lice failed to establish in New Zealand after host translocations. What Dunlop's (2015) study demonstrates is that more lice remain undiscovered, even on threatened host marsupials. Further surveys of the native parasites of these hosts are urgently required before we lose them, either through indirectly causing their extinction through management of the host, or directly through the host population becoming too small and fragmented to sustain the louse population (see Moir et al. 2012).

Micro-moths: Heliozidae and Micropterigidae (Lepidoptera)

The Heliozelidae (Fig. 2g) and Micropterigidae (Fig. 2h) represent contrasting families, but which highlight the lack of knowledge of the 'micro-moth' fauna of SWWA. Intensive collecting over the past 10 years has revealed hidden diversity and endemism in both families. The Heliozelidae represent the potential breadth of speciation of understudied taxa, while the relatively recent discovery of three species of Micropterigidae demonstrate the taxonomic distinctness of the southwest taxa.

The SWWA Heliozelidae fauna consist of 35 described species (Meyrick 1897; Nielsen et al. 1996) and an estimated 215 undescribed species (Table 2), making it a hotspot of heliozelid diversity. Globally, there are only 137 described species. The majority of these undescribed species have been discovered through a 9-year Australian Heliozelidae project (2011–2020), including around 30 months of dedicated fieldwork by D.A.Y. in SWWA. New species discoveries occurred frequently towards the end of the project, suggesting that a significant number of species remain undetected. For example, collection efforts around Cape Arid, while restricted in time and area, produced impressive new species diversity, indicating that this region may be particularly speciose with numerous undetected species present.

The SWWA heliozelids are predominantly host-specific as larvae, and there appears a constancy between the higher heliozelid taxonomic divisions and their larval host-plant families, with clear groups of 'Ericaceae feeders', 'Rutaceae feeders', etc. Short-range endemism and niche-specificity is also prevalent in the heliozelids, so, although species may be abundant locally, one stochastic event may threaten an entire species. For example, during the 2019/2020 Stirling Range bushfires several locally abundant species had 90–100% of their total known range burnt and are now likely to be Critically Endangered, if not already extinct (Fig. 2g). For these reasons, we estimate that at least 35 species (80%) in the Stirling Range National Park are threatened (Table 2). A similar percentage of the total SWWA heliozelid fauna are also estimated to be threatened (82%—Table 2).

The SWWA Micropterigidae fauna are less diverse. Three species are currently known (Table 2), but all appear highly niche specific. All of the world micropterigid fauna fall into two broad groups; liverwort larval-feeders, or decaying vegetation larval-feeders. Species from SWWA represent these two biological groupings. The first species, representing a new genus, is found in a narrow strip from Denmark (Warren region) to Dwellingup (Jarrah forest region—Fig. 1). Despite this extended occurrence, we consider it threatened, as the total area of occupancy is small in terms of potential habitat. Despite extensive surveys, it is known from only six sites indicating a high degree of site specificity and, therefore, of vulnerability. Furthermore, distantly related species often form cryptic species groupings, and it is possible that the northern and southern populations of this species may not be conspecific. The other two species belonging to a second, distinct undescribed genus, are highly restricted, and we consider both threatened. One species is known from two small sites 90 km apart; one site is restricted to a road drain, the other site is approximately the area of a tennis court. The second species (Fig. 2h) occupies approximately 150 m^2 of montane heathland across three peaks in the Stirling Range National Park. The entire range was burnt during the 2019/2020 bushfires, so this undescribed moth is now likely Critically Endangered or Extinct.

The SWWA Micropterigidae discovery in 2012 was both a new familial and subordinal record for Western Australia. Micropterigidae is considered a 'basal' family of Lepidoptera, with their ecology suggesting that they are niche-specific and require long-stable humid landscapes, so they would be slower to respond to disturbances such as fire. The importance of these taxa to science and SWWA, as well as their taxonomic distinctiveness, highlights the urgency for conservation action given their potential threat status and extinction.

Discussion

Our review of nine host-dependent insect families from three orders in the SWWA biodiversity hotspot highlighted several commonalities. Firstly, we know very little about arguably the most imperiled insect species, those dependent on threatened hosts. Secondly, insects are poorly represented on threatened species lists; only 0.040% (1 of the 246) of species that we considered at risk were present on any conservation schedule. Thirdly, it takes dedicated, prolonged surveys to reveal the true diversity of any insect family in SWWA, often with specialized collecting techniques and prior knowledge of the familial taxonomy. It is unsurprising, therefore, that most insect families have received minimal ecological or taxonomic attention.

Threatening processes

For the majority of insect taxa assessed here, loss of access to the host organism (be it plant, bird or mammal) will cause coextinction as defined by Moir et al. (2010). This is a significant direct threat to the insect's survival. Threatening processes rarely occur in isolation. Coextinction is often a secondary process, triggered by a separate threatening process impacting the host. Insects are especially prone to these cascading extinctions (Kehoe et al. 2021), particularly in species-diverse systems where many specialist species may occur (Kaneryd et al. 2012). Within SWWA, numerous plant species are experiencing dwindling populations through the major threatening processes of disease, fragmentation, invasive weeds, altered fire regimes, grazing, altered hydro-ecology and climate change (Monks et al. 2019). SWWA is predicted to be one of six hotspot regions globally where plant species extinction from climate change will be especially profound, with some models suggesting over 2000 species could be extinguished if atmospheric CO_2 doubles (Malcolm et al. 2006). In our representative subset site, the Stirling Range National Park, insects dependent on certain dieback-prone plant species or restricted to mesic sites (e.g., montane habitats) were likely pushed to extinction by the large wildfires that occurred between 2018 and 2020. Our results suggest that 49 insect species, primarily within Achilidae, Tingidae, Dictyopharidae, and Heliozidae, could be extinct in the park after the wildfires, and one Triozidae species may have lost populations of conservation value.

Parasitic lice in southwest Australia would similarly experience coextinction flowing from the extinction and dwindling numbers of vertebrate hosts. The main threatening processes impacting on the hosts are habitat alteration and clearing, predation by introduced carnivores (cats, foxes, rats) and changes in fire regime, which have been occurring over the past 200+ years (Burbidge et al. 2009; Szabo et al. 2012; Garnett and Baker 2021). The impact of these threatening processes towards the host animals are exemplified within the southwest in the sharp decline of Gilbert's potoroo *Potorous gilbertii* considered the most threatened marsupial globally (Courtenay and Friend 2004), and the Western ground parrot *Pezoporus flaviventris*, one of the world's rarest bird species (Burbidge et al. 2016). As previously noted, no lice have been recovered from these fauna, and it is likely that the lice have already been lost to extinction when the host reached populations became too low to sustain the dependents (Moir et al. 2010; 2012). Of further note, threatened vertebrates native to SWWA are being translocated to predator-free islands or fenced areas as insurance populations. Experience elsewhere has shown that dependent parasites may not survive in translocated host populations as host populations may feature too few individuals for the insect (e.g., wing louse *Rallicola* (*Huiacola*) *extinctus* on translocated little spotted kiwi in New Zealand: Buckley et al. 2012; and examples in Moir et al. 2012).

A drying climate is a direct threat to some ground-dwelling groups that we assessed (i.e. Tingidae, Dictyopharidae and Micropterigidae as larvae) as many species are niche-dependent and rely on humid conditions or habitats for survival. These mesic areas can act as refugia when a landscape is burnt. For example, in the Nanga Swamp area at Dwellingup, near the centre of the 2014 Dwellingup/Pinjarra/Waroona fires, one of the Micropterigidae moths we considered threatened was abundant when surveyed in 2019. But under current climate change scenarios (Bureau of Meteorology 2020), these mesic areas, along with most of SWWA, will experience less rainfall and warmer conditions (Head et al. 2014), and will be more prone to fire (Harvey and Enright 2022). Fragmentation of habitat exacerbates the threat further because potential immigrant insects cannot reach isolated host populations after a stochastic event, such as a fire, extinguishes the host-dependent insect population (e.g., Moir et al. 2016).

Given the threat faced by the flora and fauna of the region, exemplified by the probable loss of the mealybug insect *Pseudococcus markharveyi* in large bushfires during the past 5 years (Moir 2021), surveys of the insect fauna of the region are urgent. It is highly likely that we have been steadily losing co-dependent insects in the southwest over the past 200 years with the documented extinctions of nine species of bird and mammal, plus 14 plant species (Government of Western Australia 2022). More undocumented extinctions of potential insect hosts are highly likely, particularly of the plants (Coates 2019) and fungi. Although SWWA boasts astounding biotic endemicity and diversity, particularly of flora (e.g., Hopper and Gioia 2004; Wege et al. 2015; Gioia and Hopper 2017), it is important to remember that it is the threats to this diversity, primarily the loss of a large proportion of the native vegetation, that has catapulted SWWA into an unenviable global biodiversity hotspot position as classified by Myers et al. (2000). In fact, the 'biodiversity intactness' of the SWWA (Fig. 1b) is estimated to be one of the worst for such hotspots in the world (Table S3 of Newbold et al. 2016).

Future prospects

The basis for species conservation assessment is knowing the species' taxonomy, distribution and the threatening processes impacting its populations (e.g., IUCN 2017). There has been a clear bias within Western Australia towards funding projects on the biogeography and taxonomy of vertebrates, and vascular plants (in the last 40 years), over invertebrates. Funding for plants is understandable in SWWA given the sheer diversity of the biota (> 9000 species). With an estimated 1470 SWWA vascular plant taxon currently undescribed (Wege et al. 2015), much work remains. Rix et al. (2015) highlight, however, despite insects being the most diverse component of the SWWA terrestrial fauna, knowledge of their biogeography and evolution remains the most depauperate. Recent studies have indicated that insect rarity in SWWA is even threatening the survival of plant species through lack of specialized pollinators (Phillips et al. 2015; D.A. Young unpublished data). Most global extinctions likely occur in insects, underscoring the importance of gathering this knowledge (Dunn 2005). The estimated phytophagous insect diversity in SWWA alone is several magnitudes that of plants [14,203–27,555 species of monophagous insects (Fonseca 2009) versus 8379–9000+ plant species (Wege et al. 2015; Gioia and Hopper 2017)]. Yet, the relative number of positions available to describe this diversity through the State Government herbarium (terrestrial plants only: 7 staff—DBCA 2022) and museum (all insect orders: 1 scientist—Western Australian Museum 2022), when excluding purely technical roles and adjunct positions, is heavily skewed. Although a crude measure, the basic number of government 'taxonomic' positions clearly emphasizes the disparity of resources invested in the two groups, and the implausibility of rectifying the dearth of knowledge on insect diversity and ranges in the near future.

The fallout of taxonomic bias and lack of specialist taxonomists across insect families has a multitude of consequences. Fundamentally organisms may not be recognized as important and discarded from samples (e.g., brachypterous Dictyopharidae, Micropterigidae), alternatively the collecting technique, habitat or time of year may not be ideal in which to find the target taxa (e.g., Heliozelidae, Achilidae). Taxonomic uncertainties inhibit assessments of diversity, biogeography, drivers of population declines and conservation status, which ultimately preclude clear strategies to mitigate threats and develop proactive conservation management plans. Management plans should incorporate as many species as possible using conservation priorization analyses (e.g., Tallis et al. 2021), thereby capturing the actual cost of actions for the majority of fauna present (i.e. McCarthy et al. 2008). Such an approach teases out differences between species: a 'one size fits all approach' to management of insects cannot be adopted. Fire, for example, is beneficial to some of the phytophagous insects we assessed (e.g., Derbidae, Heliozelidae, Triozidae) with habitats burnt 4–10 years previously often yielding higher abundances of taxa we defined as 'threatened'. The key is creating a patch mosaic of different fire ages through controlled burning from which insects can recolonise from unburnt refuges (e.g., Moir et al. 2016 for evidence of this for Triozidae), and mitigates the threat of very large wildfires—an approach which has been happening in SWWA for decades (reviewed by Burrows and McCaw 2013; Bradshaw et al. 2018). Comprehensive conservation assessment in diverse regions such as SWWA is impossible without a reasonable baseline taxonomic resolution of the biota present.

Within insects as a whole, taxonomic bias of which groups receive conservation and management resources is prevalent; even within the continent with the longest history in entomology, Europe, this is apparent. Here, butterflies, dragonflies and grasshoppers receive most of the attention (Leandro et al 2017). This bias has also occurred in Australia (New 2022), and, to a much lesser extent in SWWA with the majority of listed insects falling into these groups (Table 1). Thus, targeted taxonomic and biogeographical work is required on profoundly under-represented taxa such as (but not limited to) flies (Diptera), micro-wasps (Hymenoptera) and weevils (Curculionidae). Several foundational underpinnings of such a targeted approach have been established. Bush blitz (https://bushblitz.org.au/) is a program of concentrated fieldwork trips by specialized taxonomists in under-surveyed areas across Australia, resulting in > 1700 new species described across all biota. Within SWWA another format proved fruitful; a collaborative project between a non-government organization, state museum and government land management agency resulted in regional targeted surveys of short-range invertebrate groups (predominantly millipedes, spiders, snails, scorpions and harvestmen) (Framenau et al. 2008). Approximately 14 weeks of surveys over 9 months targeted refugial habitat that models predicted would support range-restricted species (Gilfillan 2002). The invertebrates collected resulted in contributions towards a proliferation of taxonomic (e.g., Moir and Harvey 2008; Fletcher and Moir 2009; Crews and Harvey 2011; Edward and Harvey 2010; Moir and Guilbert 2012; Moir and Lis 2012; Waldock 2013; Harvey et al. 2015; Rix et al. 2017) and biogeographical work (Moir et al. 2009; Cooper et al. 2011). Importantly, this project also resulted in the State conservation listing of at least 21 species.

What are the options for immediate insect conservation management in SWWA given the current state of knowledge for most insect orders? With the acceleration of threats and disturbance to native habitats such as urbanization, agricultural impacts, invasive species, climate change and altered fire regimes; landscape scale habitat conservation approaches, coupled with threat mitigation, are most likely to be successful at retaining the majority of insect species in the short term. This is not a novel perspective, with a call for such an approach toward insect conservation being made across Australia (e.g., Taylor et al. 2018; New 2022), but is perhaps more essential in SWWA given the proportion of native vegetation remaining and the suspected diversity within these remnants (Fig. 1).

Conclusion

Our knowledge and the published accounts of host-dependent families in SWWA is largely derived from decades of fieldwork and experience with collections from around Australia, providing insight into the true diversity and threat status of these insects. This indicates the level of survey work and taxonomic expertise required for every insect family if we are to begin to comprehend their conservation needs. The complex ecological services provided by the insect fauna of the SWWA suggest that localised extinction of any of these taxa may have unpredictable and significant effects across the broader ecological communities of the region. Pollination relationships are a case in point, where local paucity or extinction of obligate pollination taxa might initially be noticed in the endemic flora declining or disappearing (e.g., Phillips et al. 2015). We concede that, for many host-dependent insects, the paucity of knowledge precludes any estimation of likely diversity. Furthermore, their threat status cannot even be estimated based on host status, because often their hosts, when discovered, are poorly known, such as the hyperparasitic wasps which utilize other invertebrates as hosts. When these other taxa are examined in detail within the context of the SWWA hotspot, high species richness or taxonomic distinctiveness is to be expected, just as we have outlined in the Tingidae, Achilidae, Derbidae, Dictyopharidae, Triozidae, Micropterigidae, Heliozidae, Boopidae, and Philopteridae.

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Declarations

Conflict of interest Neither author has any conflicts of interest to declare.

References

Adams RJ, Price RD, Clayton DH (2005) Taxonomic revision of Old World members of the feather louse genus *Columbicola* (Phthiraptera: Ischnocera), including descriptions of eight new species. J Nat Hist 39:3545–3618

Bazelet CS, Thompson AC, Naskrecki P (2016) Testing the efficacy of global biodiversity hotspots for insect conservation: the case of South African katydids. PLoS ONE 11:e0160630

Beveridge I, Spratt DM (2003) Parasites of carnivorous marsupials. In: Jones M, Archer M, Dickman C (eds) Predators with pouches: the biology of carnivorous marsupials. CSIRO Publishing, Clayton, pp 383–396

Bidau CJ (2018) Doomsday for insects? The alarming decline of insect populations around the world. Entomol Ornithol Herpetol 7:e130. https://doi.org/10.4172/2161-0983.1000e130

Bourgoin T (2017) FLOW (Fulgoromorpha lists on the web): a world knowledge base dedicated to Fulgoromorpha. https://hemiptera-databases.org/flow/. Accessed 19 June 2022

Braby M (2019) Are insects and other invertebrates in decline in Australia? Austral Entomol 58:471–477

Braby MF, Yeates DK, Taylor GS (2021) Population declines and the conservation of insects and other terrestrial invertebrates in Australia. Austral Entomol 60:3–8

Bradshaw SD, Dixon KW, Lambers H, Cross AT, Bailey J, Hopper SD (2018) Understanding the long-term impact of prescribed burning in Mediterranean-climate biodiversity hotspots, with a focus on south-western Australia. Int J Wildland Fire 27:643–657

Buckley TR, Palma RL, Johns PM, Gleeson DM, Heath ACG, Hitchmough RA, Stringer IAN (2012) The conservation status of small or less well known groups of New Zealand terrestrial invertebrates. N Z Entomol 35:137–143

Burbidge AA, McKenzie NL, Brennan KEC, Woinarski JCZ, Dickman CR, Baynes A, Gordon G, Menkhorst PW, Robinson AC (2009) Conservation status and biogeography of Australia's terrestrial mammals. Aust J Zool 56:411–422

Burbidge A, Comer S, Lees C, Page M, Stanley F (2016) Creating a future for the western ground parrot: workshop report. Department of Parks and Wildlife, Perth

Bureau of Meteorology (2020) State of the climate 2020. Commonwealth Scientific and Industrial Research Organisation (CSIRO), Canberra

Burrows N, McCaw L (2013) Prescribed burning in southwestern Australian forests. Front Ecol Environ 11:e25–e34. https://doi.org/10.1890/120356

Cardoso P, Erwin TL, Borges PAV, New TR (2011) The seven impediments in invertebrate conservation and how to overcome them. Biol Conserv 144:2647–2655

Cardoso P et al (2020) Scientists' warning to humanity on insect extinctions. Biol Conserv 242:108426

Coates DJ (2019) Undocumented plant extinctions are a big problem in Australia—here's why they go unnoticed. The Conversation. https://theconversation.com/undocumented-plant-extinctions-are-a-big-problem-in-australia-heres-why-they-go-unnoticed-118607. Accessed 20 July 2022

Conrad KF, Warren M, Fox R, Parsons M, Woiwod IP (2006) Rapid declines of common, widespread British moths provide evidence of an insect biodiversity crisis. Biol Conserv 132:279–291

Cook LG, Hardy NB, Crisp MD (2015) Three explanations for biodiversity hotspots: small range size, geographical overlap and time for species accumulation. An Australian case study. New Phytol 207:390–400

Cooper CE (2011) *Myrmecobius fasciatus* (Dasyuromorphia: Myrmecobiidae). Mamm Spec 43:129–140

Cooper SJB, Harvey MS, Saint KM, Main BY (2011) Deep phylogeographic structuring of populations of the trapdoor spider *Moggridgea tingle* (Migidae) from southwestern Australia: evidence for long-term refugia within refugia. Mol Ecol 20:3219–3236

Courtenay J, Friend T (2004) Gilbert's Potoroo (*Potorous gilbertii*) recovery plan. Wildlife Management Program No. 32. Department of Conservation and Land Management, Perth

Cracraft J (1986) Origin and evolution of continental biotas: speciation and historical congruence within the Australian avifauna. Evolution 40:977–996

Crews SC, Harvey MS (2011) The spider family Selenopidae (Arachnida, Araneae) in Australasia and the Oriental Region. Zookeys 99:1–104

DBCA (2022) Staff profiles—Herbarium. https://science.dpaw.wa.gov.au/people/?find=systematics%20curation. Accessed 24 July 2022

Dunlop J (2015) The ecology and host–parasite dynamics of a fauna translocation in Australia. PhD Thesis, Murdoch University, Perth

Dunn RR (2005) Modern insect extinctions, the neglected majority. Conserv Biol 19:1030–1036
Edward K, Harvey MS (2010) A review of the Australian millipede genus *Atelomastix* (Diplopoda: Spirostreptida: Iulomorphidae). Zootaxa 2371:1–63
Farnier K, Dyer AG, Taylor GS, Peters RA, Steinbauer MJ (2015) Visual acuity trade-offs and microhabitat-driven adaptation of searching behaviour in psyllids (Hemiptera: Psylloidea: Aphalaridae). J Exp Biol 218(10):1564–1571
Fletcher MJ, Moir ML (2009) *Budginmaya eulae gen. et sp. nov.*, a myrmecophilous planthopper (Hemiptera: Fulgoromorpha: Flatidae) from Western Australia. Aust J Entomol 48:36–39
Fonseca CR (2009) The silent mass extinction of insect herbivores in biodiversity hotspots. Conserv Biol 23:1507–1515
Forister ML, Pelton EM, Black SH (2019) Declines in insect abundance and diversity: we know enough to act now. Conserv Sci Pract 1:e80. https://doi.org/10.1111/csp2.80
Framenau VW, Moir ML, Harvey MS (2008) Terrestrial invertebrates of the south coast NRM region of Western Australia: short-range endemics in Gondwanan relictual habitats. Western Australian Museum, Perth, p 184
Garnett ST, Baker GB (2021) The action plan for Australian birds 2020, 1st edn. CSIRO Publishing, Melbourne
Gerlach J (2012) *Margatteoidea amoena*. The IUCN Red List of Threatened Species. p. e.T199495A2594210. https://doi.org/10.2305/IUCN.UK.2012.RLTS.T199495A2594210.en. Accessed 31 July 2022
Geyle HM, Braby MF, Andren M, Beaver EP, Bell P, Byrne C, Castles M, Douglas F, Glatz RV, Haywood B, Hendry P, Kitching RL, Lambkin TA, Meyer CE, Moore MD, Moss JT, Nally S, New TR, Palmer CM, Petrie E, Potter-Craven J, Richards K, Sanderson C, Stolarski A, Taylor GS, Williams MR, Woinarski JCZ, Garnett ST (2021) Butterflies on the brink: identifying the Australian butterflies (Lepidoptera) most at risk of extinction. Austral Entomol 60:98–110
Gibbs GW (1998b) Why are some weta (Orthoptera: Stenopelmatidae) vulnerable yet others are common? J Insect Conserv 2:161–166
Gibbs G (1998a) Raukumara tusked weta: discovery, ecology and management implications. Conservation advisory science notes 218. Department of Conservation, Wellington
Gilfillan S (2002) South coast invertebrate refugia project. Department of Conservation and Land Management, Perth
Gioia P, Hopper SD (2017) A new phytogeographic map for the Southwest Australian Floristic Region after an exceptional decade of collection and discovery. Bot J Linn Soc 184:1–15
Gosper CR, Percy-Bower JM, Byrne M, Llorens TM, Yates CJ (2022) Distribution, biogeography and characteristics of the threatened and data-deficient flora in the southwest Australian floristic region. Diversity 14:493
Goulson D (2019) The insect apocalypse, and why it matters. Curr Biol 29(19):R967–R971
Government of Western Australia (2022) Threatened species and communities. Available at https://www.dpaw.wa.gov.au/plants-and-animals/threatened-species-and-communities. Accessed 1 July 2022
Green K, Caley P, Baker M, Dreyer D, Wallace J, Warrant E (2021) Australian Bogong moths *Agrotis infusa* (Lepidoptera: Noctuidae), 1951–2020: decline and crash. Austral Entomol 60:66–81
Hallmann CA, Sorg M, Jongejans E, Siepel H, Hofland N et al (2017) More than 75% decline over 27 years in total flying insect biomass in protected areas. PLoS ONE 12(10):e0185809
Harvey BJ, Enright NJ (2022) Climate change and altered fire regimes: impacts on plant populations, species, and ecosystems in both hemispheres. Plant Ecol 223:699–709
Harvey MS, Main BY, Rix MG, Cooper SJB (2015) Refugia within refugia: in situ speciation and conservation of threatened *Bertmainius* (Araneae: Migidae), a new genus of relictual trapdoor spiders endemic to the mesic zone of south-western Australia. Invertebr Syst 29:511–553
Head L, Adams M, McGregor H, Toole S (2014) Climate change and Australia. Faculty of Social Sciences - Papers. University of Wollongong, p 621. https://ro.uow.edu.au/sspapers/621
Hodkinson I (1974) The biology of the Psylloidea (Homoptera): a review. Bull Entomol Res 64:325–338
Hogendoorn K, Glatz RV, Leijs R (2021) Conservation management of the green carpenter bee *Xylocopa aerata* (Hymenoptera: Apidae) through provision of artificial nesting substrate. Austral Entomol 60:82–88
Hopper SD, Gioia P (2004) The southwest Australian floristic region: evolution and conservation of a global hot spot of biodiversity. Annu Rev Ecol Evol S 35:623–650
Hudson LN, Newbold T, Contu S, Hill SL et al (2017) The database of the PREDICTS (Projecting Responses of Ecological Diversity In Changing Terrestrial Systems) project. Ecol Evol 7:145–188
IBRA (2020) Interim Biogeographic Regionalisation for Australia (subregions—states and territories) v. 7 (IBRA). Department of Agriculture, Water and the Environment, Canberra
IUCN Standards and Petitions Subcommittee (2017) Guidelines for using the IUCN red list categories and criteria. Version 13. Available at https://www.iucnredlist.org/resources/redlistguidelines
Kaneryd L, Borrvall C, Berg S, Curtsdotter A, Eklöf A, Hauzy C, Jonsson T, Münger P, Setzer M, Säterberg T, Ebenman B (2012) Species-rich ecosystems are vulnerable to cascading extinctions in an increasingly variable world. Ecol Evol 2:858–874
Kehoe R, Frago E, Sanders D (2021) Cascading extinctions as a hidden driver of insect decline. Ecol Entomol 46:743–756
Kristoffersen L, Larsson MC, Anderbrant O (2008) Functional characteristics of a tiny but specialized olfactory system: olfactory receptor neurons of carrot psyllids (Homoptera: Triozidae). Chem Senses 33:759–769
Leandro C, Jay-Robert P, Vergnes A (2017) Bias and perspectives in insect conservation: a European scale analysis. Biol Conserv 215:213–224
Lewinsohn TM, Agostini K, Lucci FAV, Melo AS (2022) Insect decline in Brazil: an appraisal of current evidence. Biol Lett. https://doi.org/10.1098/rsbl.2022.0219
MacLeod CJ, Paterson AM, Tompkins DM, Duncan RP (2010) Parasites lost–do invaders miss the boat or drown on arrival? Ecol Lett 13:516–527
Malcolm JR, Liu C, Neilson RP, Hansen L, Hannah L (2006) Global warming and extinctions of endemic species from biodiversity hotspots. Conserv Biol 20:538–548
Martoni F, Bartlett J, Moir ML, Steinbauer MS, Taylor GS. (in review) Psylloidea of Australia
McCarthy MA, Thompson CJ, Garnett ST (2008) Optimal investment in conservation of species. J Appl Ecol 45:1428–1435
Meyrick E (1897) Descriptions of Australian Microlepidoptera. XVII. Elachistidae. Proc Linn Soc NSW 22:297–435
Mittermeier RA, Gil PR, Hoffman M, Pilgrim J, Brooks T, Mittermeier CG et al (2005) Hotspots revisited: earth's biologically richest and most endangered terrestrial ecoregions. Conservation International, Washington, DC
Moir ML (2021) Coextinction of *Pseudococcus markharveyi* (Hemiptera: Pseudococcidae): a case study in the modern insect extinction. Austral Entomol 60:89–97
Moir ML (2022) Revision of the tribe Ceratocaderini (Hemiptera: Tingidae). Austral Entomol 61:277–301
Moir ML, Brennan KEC (2020) Incorporating coextinction in threat assessments and policy will rapidly improve the accuracy of threatened species lists. Biol Conserv 249:108715

Moir ML, Guilbert E (2012) *Swaustraltingis isobellae*, a new genus and new species of Australian lacebug (Insecta: Heteroptera: Tingidae), with a redescription of *Cysteochila cracentis* Drake, 1954 and notes on the lacebug fauna of south-west Australia. Aust J Entomol 51:258–265

Moir ML, Harvey MS (2008) Discovery of the pill millipede genus *Epicyliosoma* (Diplopoda: Sphaerotheriida: Sphaerotheriidae) in Western Australia, with the description of a new species. Rec West Aust Mus 24:113–119

Moir ML, Lis B (2012) New species of *Ceratocader* (Hemiptera: Tingidae) from Western Australia. Rec West Aust Mus 27:148–155

Moir ML, Brennan KEC, Harvey MS (2009) Diversity, endemism and species turnover of millipedes within the southwest Australia global biodiversity hotspot. J Biogeogr 36:1958–1971

Moir ML, Vesk PA, Brennan KEC, Keith DA, Hughes L, McCarthy MA (2010) Current constraints and future directions in estimating coextinction. Conserv Biol 24:682–690

Moir ML, Vesk PA, Brennan KEC, Poulin R, McCarthy MA, Keith DA, Hughes L, Coates D (2012) Considering extinction of dependent species during translocation, ex situ conservation and assisted migration of threatened hosts. Conserv Biol 26:199–207

Moir ML, Coates DJ, Kensington WJ, Barrett S, Taylor GS (2016) Concordance in evolutionary history of threatened plant and insect populations warrant unified conservation management approaches. Biol Conserv 198:135–144

Monks L, Barrett S, Beecham B, Byrne M, Chant A, Coates D, Cochrane JA, Crawford A, Dillon R, Yates CJ (2019) Recovery of threatened plant species and their habitats in the biodiversity hotspot of the southwest Australian floristic region. Plant Divers 41:59–74

Myers N, Mittermeier RA, Mittermeier CG, Fonseca GAB, Kent J (2000) Biodiversity hotspots for conservation priorities. Nature 403:853–858

New TR (2022) Insect diversity, declines and conservation in Australia. Springer, Cham, p 236

New TR, Samways MJ (2014) Insect conservation in the southern temperate zones: an overview. Austral Entomol 53:26–31

Newbold T, Hudson LN, Arnell AP, Contu S, De Palma A, Ferrier S, Hill SLL, Hoskins AJ, Lysenko I, Phillips HRP, Burton VJ, Chng CWT, Emerson S, Gao D, Pask-Hale G, Hutton J, Jung M, Sanchez-Ortiz K, Simmons BI, Whitmee S, Zhang H, Scharlemann JPW, Purvis A (2016) Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. Science 353:288–291. https://doi.org/10.1126/science.aaf2201

Nielsen ES, Edwards ED, Rangsi TV (1996) Checklist of Lepidoptera of Australia. CSIRO Publishing, Melbourne

Northover AS, Elliot AD, Keatley S, Lim Z, Botero A, Ash A, Lymbery AJ, Wayne AF, Godfrey SS, Thompson RCA (2018) Debilitating disease in a polyparasitised woylie (*Bettongia penicillata*): a diagnostic investigation. Int J Parasitol Parasites Wildl 7:274–279

Phillips RD, Peakall R, Retter BA, Montgomery K, Menz MHM, Davis BJ, Hayes C, Brown GR, Swarts ND, Dixon KW (2015) Pollinator rarity as a threat to a plant with a specialized pollination system. Bot J Linn Soc 179:511–525

Procheş Ş, Cowling RM (2006) Insect diversity in Cape fynbos and neighbouring South African vegetation. Glob Ecol Biogeogr 15:445–451

Rix MG, Edwards DL, Byrne M, Harvey MS, Joseph L, Roberts JD (2015) Biogeography and speciation of terrestrial fauna in the south-western Australian biodiversity hotspot. Biol Rev 90:762–793

Rix MG, Bain K, Main BY, Robert J, Raven RJ, Austin AD, Cooper SJB, Harvey MS (2017) Systematics of the spiny trapdoor spiders of the genus *Cataxia* (Mygalomorphae: Idiopidae) from south-western Australia: documenting a threatened fauna in a sky-island landscape. J Arachnol 45:395–423

Sánchez-Bayo F, Wyckhuys KAG (2019) Worldwide decline of the entomofauna: a review of its drivers. Biol Conserv 232:8–27

Sánchez-Bayo F, Wyckhuys KAG (2021) Further evidence for a global decline of the entomofauna. Austral Entomol 60:9–26

Spratt DM, Beveridge I (2019) Wildlife parasitology in Australia: past, present and future. Aust J Zool 66:286–305

Stranger RH, Palma RL (1998) Lice (Insecta: Phthiraptera) from some Australian birds. Rec West Aust Mus 19:169–186

Sweet AD, Chesser RT, Johnson KP (2017) Comparative cophylogenetics of Australian phabine pigeons and doves (Aves: Columbidae) and their feather lice (Insecta: Phthiraptera). Int J Parasitol 47:347–356

Szabo JK, Butchart SHM, Possingham HP, Garnett ST (2012) Adapting global biodiversity indicators to the national scale: a Red List Index for Australian birds. Biol Conserv 148:61–68

Tallis H, Fargione J, Game E, McDonald R, Baumgarten L, Bhagabati N, Cortez R, Griscom B, Higgins J, Kennedy CM, Kiesecker J, Kroeger T, Leberer T, McGowan J, Mandle L, Masuda YJ, Morrison SA, Palmer S, Shirer R, Shyamsundar P, Wolff NH, Possingham HP (2021) Prioritizing actions: spatial action maps for conservation. Ann N Y Acad Sci 1505:118–141

Taylor GS, Moir ML (2014) Further evidence of the coextinction threat for jumping plant-lice: three new *Acizzia* (Psyllidae) and *Trioza* (Triozidae) from Western Australia. Insect Syst Evol 45:283–302

Taylor GS, Austin AD, Jennings JT, Purcell MF, Wheeler GS (2010) *Casuarinicola*, a new genus of jumping plant lice (Hemiptera: Triozidae) from *Casuarina* (Casuarinaceae). Zootaxa 2601:1–27

Taylor GS, Jennings JT, Purcell MF, Austin AD (2011) A new genus and ten new species of jumping plant lice (Hemiptera: Triozidae) from *Allocasuarina* (Casuarinaceae) in Australia. Zootaxa 3009:1–45

Taylor GS, Fagan-Jeffries EP, Austin AD (2016) A new genus and twenty new species of Australian jumping plant-lice (Psylloidea: Triozidae) from *Eremophila* and *Myoporum* (Scrophulariaceae: Myoporeae). Zootaxa 4073:1–84

Taylor GS, Braby MF, Moir ML, Harvey MS, Sands DPA, New TR, Kitching RL, McQuillan PB, Hogendoorn K, Glatz RV, Andren M, Cook JM, Henry SC, Valenzuela I, Weinstein P (2018) Strategic national approach for improving the conservation management of insects and allied invertebrates in Australia. Austral Entomol 57:124–149

Threatened Species Scientific Committee (2019) Developing the Proposed Priority Assessment List (PPAL) for the assessment period commencing 1 October 2019. https://www.awe.gov.au/sites/default/files/documents/191005.pdf. Accessed 19 June 2022

Toon A, Hughes J (2008) Are lice good proxies for host history? A comparative analysis of the Australian magpie, *Gymnorhina tibicen*, and two species of feather louse. Heredity 101:127–135

Trewick SA (2021) A new species of large *Hemiandrus* ground wētā (Orthoptera: Anostostomatidae) from North Island, New Zealand. Zootaxa 12:4942

UN Biodiversity Lab (2022) http://unbiodiversitylab.org/, https://doi.org/10.34892/95q9-mp91. Accessed 15 Aug 2022

van Klink R, Bowler DE, Gongalsky KB, Swengel AB, Gentile A, Chase JM (2020) Meta-analysis reveals declines in terrestrial but increases in freshwater insect abundances. Science 368:417–420

van Langevelde F, Braamburg-Annegarn M, Huigens ME et al (2018) Declines in moth populations stress the need for conserving dark nights. Glob Change Biol 24:925–932

Vaughan R (2008) The health and disease status of Australia's most critically endangered mammal the Gilbert's Potoroo (*Potorous gilbertii*). PhD Thesis, Murdoch University, Perth von Kéler S (1971) A revision of the Australasian Boopiidae (Insecta: Phthiraptera). Austral J Zool Suppl 6:1–126

Waldock JM (2013) A review of the peacock spiders of the *Maratus mungaich* species-group (Araneae: Salticidae), with descriptions of four new species. Rec West Aust Mus 28:66–81

Watts C, Stringer I, Gibbs G (2012) Insect conservation in New Zealand: an historical perspective. In: New T (ed) Insect conservation: past, present and prospects. Springer, Dordrecht

Western Australian Museum (2022) Terrestrial zoology curator and contacts. https://museum.wa.gov.au/research/departments/terrestrial-zoology/terrestrial-zoology-curator-and-contacts. Accessed 24 July 2022

World Conservation Monitoring Centre (1996) *Rhantus novacaledoniae*. The IUCN Red List of Threatened Species. p. e.T19460A8894644. https://doi.org/10.2305/IUCN.UK.1996.RLTS.T19460A8894644.en. Accessed 31 July 2022

Wege JA, Thiele KR, Shepherd KA et al (2015) Strategic taxonomy in a biodiverse landscape: a novel approach to maximizing conservation outcomes for rare and poorly known flora. Biodivers Conserv 24:17–32

Wright MG, Samways MJ (1998) Insect species richness tracking plant species richness in a diverse flora: gall-insects in the Cape Floristic Region, South Africa. Oecologia 115:427–433