Australian Journal of Entomology (2007) **46**, 177–187

Australian biodiversity: threats for the present, opportunities for the future

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Abstract Australia's insect fauna comprises a very large component of its biodiversity, and one that remains a largely unknown and untapped resource. Estimates of global and Australian insect species richness are reviewed, and Australia's insect biodiversity is placed in its biogeographical context of Mesozoic, Gondwanan connectivity and Tertiary isolation. Some unique, relict faunal elements derived from Australia's long periods of isolation are highlighted. Examples of the dramatic insect evolutionary radiations are profiled that are the consequence of successful adaptation to new biomes made available by the environmental transformations in Australia in the latter half of the Tertiary. Then conservation of Australian forests and the major processes threatening Australian biodiversity are discussed: invasive species, habitat conversion and climate change. The four components necessary to build sustainability in Australia or throughout the world are discussed: description and understanding, direct action for conservation, promoting sustainable use in balance with conservation, and providing education and information to maintain the overall effort.

Key words Australian insect, biodiversity, conservation, sustainability.

FOREWORD

This paper is adapted from the speech notes that the senior author prepared for his opening plenary address on Monday 16 August 2004 at the 22nd International Congress of Entomology (ICE) in Brisbane. For many Australian entomologists, that plenary speech signified Australia's importance to world biodiversity, and encouraged our efforts to manage that biodiversity in the face of current and future challenges. We have adapted the speech as a written document to capture its ideas for those not in the ICE audience.

The speech was dedicated by the Congress to the memory of a great entomologist, Dr Ebbe Schmidt Nielsen, who was Secretary to the Council for Congresses of Entomology until his untimely death at the age of 50 in March 2001. Ebbe, a Dane who spent the last two decades of his life in Canberra, was a citizen of the world, and his life and scientific contributions have been addressed in a number of authoritative biographies (Edwards 2003; Scoble 2003; Whitten 2003). In particular, he was largely responsible for the formation of the Global Biodiversity Information Facility (GBIF), an initiative of Organisation for Economic Cooperation and Development (OECD) countries, at its headquarters in Copenhagen (Edwards 2004). – David Yeates

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INSECTS

The incredible richness and diversity of the insect world has astonished people ever since they began to appreciate its seemingly limitless variety (Grimaldi & Engel 2005). As the investigation of this diversity has continued, and our store of knowledge increased, more comprehensive sampling methods have led us to understand that patterns of insect diversity are even more complex and more interesting than we thought in the past. Many papers have been published on the topic since the classical paper by Terry Erwin (1982), which estimated the number of species of insects at 30 million or more, based on sampling the tropical forest canopy. These very large estimates stimulated experimental and theoretical investigations by many scientists, and have greatly increased our knowledge of how to approach the problem, if not as strongly of its ultimate solution.

One of the most thoughtful recent, comprehensive attempts to calibrate the diversity was offered by Lord May of Oxford at a symposium in 1997 (May 2000). He concluded that there were approximately 720 000 named, distinct species of insects and 855 000 species of arthropods overall described at that time, considering that Hammond (1992, 1995) had not discounted sufficiently for synonymy in reaching his earlier estimate of 950 000 species. For the overall total number of insect species, described and undescribed, May balanced earlier estimates based on rates of discovery of new species, extrapolations from sampling, and statistical analysis to arrive at an

doi:10.1111/j.1440-6055.2007.00601.x

estimate of 4 million species rather than the 8 million estimated earlier by Hammond (1995), or the 2 million estimated by Nielsen and Mound (2000). How has this estimate stood up to various methods of analysis?

Probably the most startling recent demonstration of how little we know of the diversity of insects has been the detection of a new order, Mantophasmatodea, with both living and fossil members, just a few years ago (Klass *et al*. 2002). Earlier confused with Orthoptera in museum collections, the description of this distinct order has now led to the discovery of three genera including several species in Tanzania, South Africa and Namibia; a number of additional species probably await discovery (Zompro *et al*. 2002, 2003). Whether the order will eventually be found to be restricted to Africa remains to be seen, but it is fascinating to have brought to light the first new order of insects since the early 19th century. However, it is likely that we already have classified at least a few representatives of the great majority of orders and families of insects that will ultimately be recognised, but have not sorted out their appropriate status in the taxonomic hierarchy yet.

Another approach is to estimate degree of host plant specificity in various ways and in different parts of the world. Thus, Novotny *et al*. (2002), basing their calculations on the low plant host specificity they encountered in New Guinea samples, found their results consistent with earlier estimates of 4.8 million (Odegard 2000) and 6.6 million (Basset *et al*. 1996) total insect species globally, and with the 5 million species in various papers by taxonomists that they reviewed.

One result that demonstrates our uncertainty over the estimates is the proportion of species represented by single individuals in insect surveys. For example, after sampling over 80 000 individuals, Novotny and Bassett (2000) found that 26% of tropical insect herbivorous species sampled were represented by singletons. Extrapolating these considerations to insects could mean that there are substantially more than 5–6 million species in existence, but we simply cannot verify the basis for such an argument yet. This certainly is an argument for much more intensive sampling than is normally considered reasonable, and of course by specialised methods related to the habits and life histories of the groups concerned.

The various approaches summarised here are consistent with a total number of insect species in the 5–6 million range, with perhaps another 650 000 to 1 million or more species of other arthropods. It appears that May's estimates may have been about 25% too low. Much more needs to be understood about the distribution and abundance of insects and other arthropods, especially in tropical forests, before we can provide improved estimates of their diversity (e.g. Miller *et al*. 2002), but the overall estimate just mentioned is consistent with what we know now.

HISTORY AND BIOGEOGRAPHY OF AUSTRALIA: AN OVERVIEW

During the early history of insects, about 400 million years ago (Grimaldi & Engel 2005), Australia was part of Gondwana, a large southern land mass that included South America, Africa, India and Antarctica, with direct migration between these lands impeded only by climatic differences (Veevers 2001). About 80 million years ago, however, in Upper Cretaceous time, the land mass that includes New Zealand and New Caledonia separated from Australia-Antarctica, which were then directly connected with South America as well. The eastern highlands of Australia date from this time period (Nott 2005). Subsequently, Australia separated from Antarctica and began its history as a distinct continent (reviewed in Hill *et al*. 1999). Prior to these events, and to the subsequent opening of Drake's Passage between South America and Antarctica 41 million years ago (Scher & Martin 2006), migration between the lands of the Southern Hemisphere was direct, and the possibilities afforded by such direct migration explain many of the biotic similarities between the southern continents that have persisted to the present. For example, plants such as many gymnosperms, and angiosperms such as Proteaceae, Myrtaceae, and the genus *Nothofagus* link South America and Australia, as do many insect groups (e.g. Sequeira & Farrell 2001), some directly associated with these plants. Linkages between Australia and Africa are often more ancient, or may reflect long-distance dispersal, as may those between any of the southern lands (De Queiroz 2005); the winds are much more powerful over the southern oceans than they are in the Northern Hemisphere.

During the past 15 million years, the climate of Australia, like that of the rest of the world, rapidly diversified and the forests became more open. The moist forests that had dominated the continent earlier became increasingly restricted to the more temperate regions and more abundant precipitation that persisted in the mountains along the eastern side of the continent and in Tasmania, reaching New Guinea progressively and partly over land during the ice ages of the Pleistocene (Hill 1994; White 1994). Forests with similar assemblages of plants and animals also persisted, but following long periods of separation, in New Zealand and southern South America, as well as locally in Antarctica into the Miocene Period or perhaps ever more recently. In this context, New Caledonia, which occupies warmer climates and has been isolated for some 80 million years, is a particularly striking 'museum' of the same kinds of archaic organisms that occur in the forests of Queensland and New Guinea. Over the past 2–3 million years, the trend towards more open vegetation accelerated and desert vegetation spread to occupy most of the continent (Fujioka *et al*. 2005). By the Pleistocene, aridification of the continent has become so extreme that during the glacial maxima much of central Australia was covered in active, moving dunefields (Williams 1984). On the east coast and highlands, the sudden and dramatic transition between Australian rainforest and sclerophyll forests is one of the most distinctive ecotones on the planet. Finally, following the arrival of Aboriginal people, perhaps about 60 000 years ago, and European settlers from the late 18th century onward, these changes have been accelerated, first by fire and later by agriculture, with drastic effects on the native ecosystems (Bowman 2000; Miller *et al*. 2005).

During the Quaternary Era, Australia was connected with New Guinea, Tasmania and other offshore islands, making direct migration over land possible between them. The appearance of human beings in the late Pleistocene, perhaps a bit less than 60 000 years ago, led to the massive alteration of an Australian environment that had undergone including the extensive spread of arid climates, beginning millions of years earlier. The extinction of many large mammals and other vertebrates was almost certainly a result of humans hunting them (Kershaw *et al*. 2000; Miller *et al*. 2005). Once accomplished, it further altered the composition and functioning of the communities in which these animals had occurred.

AUSTRALIAN INSECTS AND OTHER ARTHROPODS

Given Australia's remarkable history, it should not be a surprise that its plants and animals are so unusual and highly endemic. The most recent estimate of terrestrial arthropod diversity for Australia has been presented by Yeates *et al*. (2003). After a thorough review and consultation with taxonomic experts, they estimated the total number of valid, described species of insects in Australia as 58 491, including 22 901 Coleoptera, 10 586 Lepidoptera, 8013 Hymenoptera and 6432 Diptera. The total number of described and undescribed Australian terrestrial arthropods was estimated to be about 253 000, with 205 000 of them insects (Yeates *et al*. 2003). With about 600 species of terrestrial arthropods being described from Australia per year, it would take approximately another 240 years to complete the job of describing the diversity of Australian arthropods! Against the background of rapid habitat alteration and destruction that we shall review, and given the economic importance of the organisms involved, such a slow rate of discovery and description is clearly unacceptable. Regardless of the ultimate numbers, it is reasonable to assume that no more than one in four of the species of insects in Australia has been described scientifically – and the actual proportion is probably lower than that. Taking the estimates of May (2000) that arthropods may constitute about 70% of the total species of terrestrial eukaryotic organisms, and a conservative estimate of more than 300 000 species of arthropods for the continent (see also Majer *et al*. 2002), then the total eukaryotic biota of Australia could amount to about 450 000 species, approximating 5% of the world total, well under a quarter of which is known scientifically. Thus, perhaps 20–25% of Australia's biota, at best, has been described.

As to the degree of endemism of Australian biota, strong images are provided by eucalypts and kangaroos, the platypus and echidna, and the eucalypts and acacias that are so symbolic of the nation. Quantitatively, and although estimates have varied, it is likely that about 90% of its native arthropods and plants are endemic to Australia, which is a level of endemism as high as that recorded for any part of the world, including small, remote islands. In addition, many of these endemics represent remarkable relicts of the early evolutionary pathways of their particular groups and phylogenetic lineages that diversified in Gondwana and subsequently in the temperate to warm-temperate forests that covered almost all of the continent prior to the Miocene. Others, and this would represent the great majority of species of Australian insects, have radiated as the continent has changed to largely arid deserts, desert scrub, Mediterranean vegetation and open woodlands that dominate the contemporary scene almost everywhere.

Considering a few other groups of terrestrial arthropods, Yeates *et al*. (2003) listed Greenslade's estimates of 322 distinct, validly described species of Collembola in Australia, but a probable actual total of 2000–3000 species – perhaps as few as one in 10 species have yet been described. For spiders, there are approximately 2400 valid, described Australian species, but 80% of the fauna may still await description (NI Platnick pers. comm. 2004), so that the actual total could amount to as many as 12 000 species, in agreement with the estimate in Yeates *et al*. (2003). The World Spider Catalogue (Platnick 2005) lists just over 38 500 validly published and distinct species of spiders from throughout the world, but twice that many may actually exist for a world total of perhaps 80 000 species (NI Platnick pers. comm. 2004). As for many groups of invertebrates, the Australian fauna remains one of the most poorly known anywhere.

For mites, Halliday *et al*. (2000) estimated that 2700 distinct species had been validly published for Australia by that time, and gave what they considered a conservative estimate of more than 20 000 species for the continent. Globally, they considered that there were likely to be more than 500 000 species of mites, with about 48 200 validly described at present.

One of the most striking features of the Australian biota that we have mentioned is the presence of many groups relict from the Tertiary. These mostly occur in the moist forests of eastern and south-eastern Australia and Tasmania (along with New Zealand and New Caledonia), with the greatest concentration in the rainforests of northern Queensland (Yeates & Monteith 2007). The forests in which they occur are the surviving examples of those that covered almost all of Australia and adjacent Gondwana in the past. They are therefore not only a rich treasure for Australia, but an important part of our common global heritage. As such, they should be cherished and preserved for the study and enjoyment of future generations, a topic to which we shall return below.

The Australian cicadas are a group that includes both relictual species and demonstrates evolutionary radiation that has developed as the continent's ecosystems have become more arid and diverse. For example, the cicada *Tettigarcta crinita*, which has a number of archaic features and is restricted to certain areas of the moist, dense *Nothofagus cunninghamii* forests of Tasmania (Claridge *et al*. 1999), has been shown on both morphological and molecular grounds to be the sister group of all other cicadas (Cryan 2005). It closely resembles fossil cicadas that were widespread in the Northern Hemisphere in Mesozoic and Early Tertiary times (Carver *et al*. 1991), and is apparently the only survivor of an ancient phylogenetic line. On the other hand, all but four of the 224 described species of cicadas in Australia are endemic, as well as 28 of the 39 genera in which they are placed, and there may

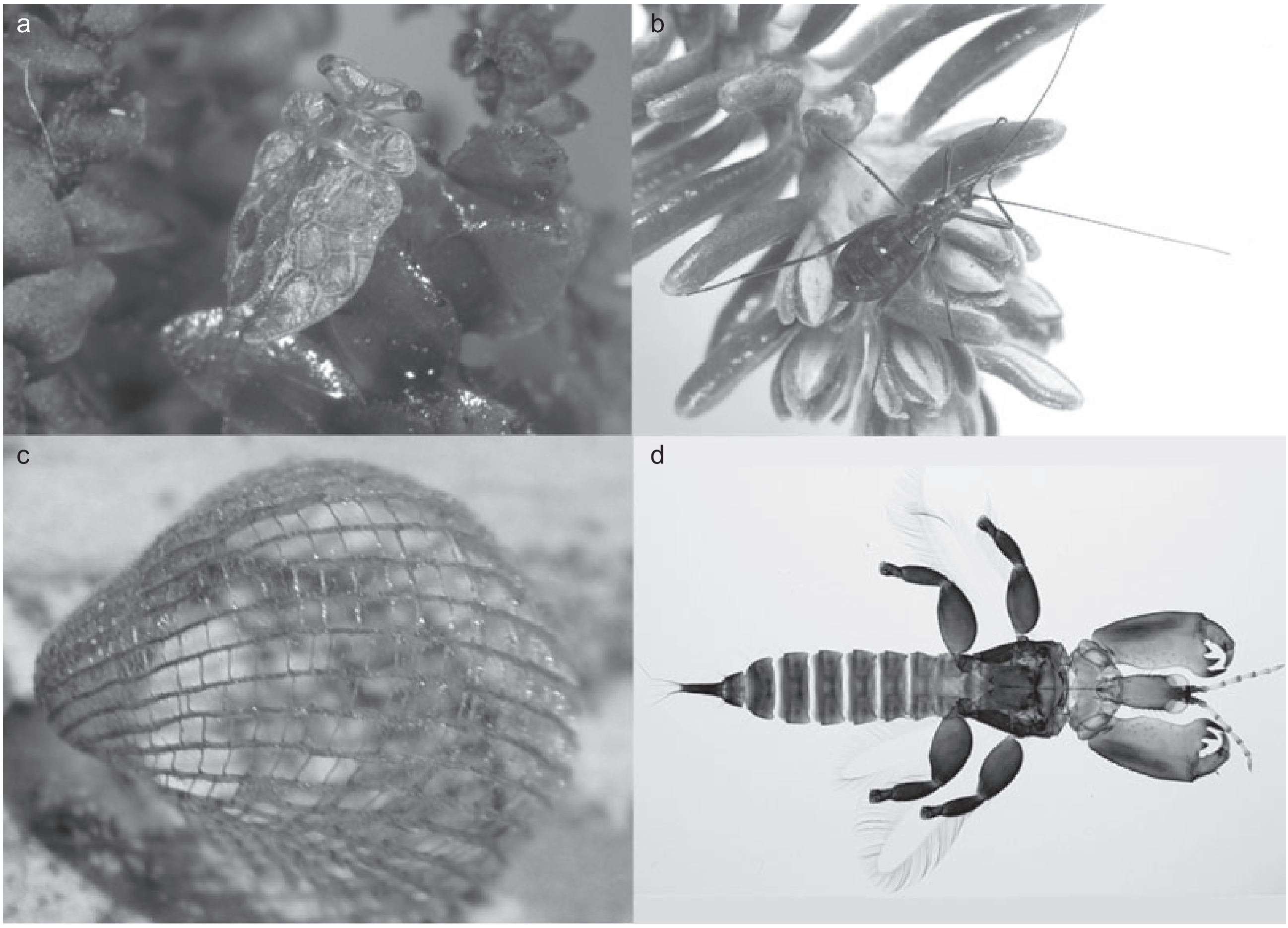

Fig. 1. (a) The moss bug *Hackeriella veitchi* (Hemiptera Peloridiidae) in Lamington National Park, Queensland (Jeff Wright, Queensland Museum). (b) A female of the wingless scorpionfly genus *Apteropanorpa* (Apteropanorpidae) from Mt Wellington, Tasmania (Chris Palmer, NT NPWLS). (c) The lerp insect *Cardiaspina* sp. (Hemiptera: Psyllidae) on *Eucalyptus* (Laurence Mound, CSIRO Entomology). (d) *Carcinothrips* sp., the crab thrips, a domicile creator on Australian *Acacia* (Laurence Mound, CSIRO Entomology).

be as many as 700 species here (Moulds 1990; C Simon and M Moulds pers. comm. 2004).

Among the relict groups of insects that have a circumantarctic distribution and were almost certainly distributed across Gondwana across more or less continuous land, peloriid bugs (Peloridiidae), which live in saturated moss at the base of *Nothofagus* trees, provide a well-known example (Fig. 1a). The peloriids are now known from Australia, New Zealand, Lord Howe Island, New Caledonia and southern South America. They are phylogenetically isolated relicts, forming a distinct lineage of Hemiptera (the Coleorrhyncha), which is intermediate between the planthoppers, scale insects and the true bugs, Heteroptera (Ouvrard *et al*. 2000).

Another relict and very interesting group are the Southern Hemisphere wingless snow scorpionflies (Mecoptera – Apteropanorpidae), with two described species and a number of undescribed species restricted to Tasmania (Palmer & Yeates 2005; Fig. 1b). Although occupying similar ecological niche, the Northern Hemisphere snow scorpionflies, Boreidae, are unrelated to the Apteropanorpidae (Whiting 2002).

Turning now to the extensive evolutionary radiation of species that is characteristic of some Australian groups of insects, it should not be surprising that some of the most impressive are those that have co-evolved with the huge genera *Eucalyptus*, perhaps better regarded as a group of related genera, with some 700 Australian species, and Acacia, with approximately 1000 Australian species. The dry-fruited Myrtaceae related to *Eucalyptus* are almost entirely restricted to Australia, although now cultivated for timber and pulp throughout the warmer parts of the world. Similarly, the Australian species of Acacia, most of which form leaf-like phyllodes, form a group that is endemic except for a few species, one of them the familiar *Acacia koa* of Hawaii. No records of *Acacia* are known from Australia before the Miocene, and few of other legumes; *Eucalyptus* too has radiated since that time, with both genera evolving into the drier forests and other habitats that became clearly differentiated over the past 15 million years, while the temperate moist forests withdrew to their current areas (Ladiges *et al*. 2003; Crisp *et al*. 2004; Bowman & Yeates 2006).

Perhaps the most remarkable of these radiations is that of the endemic oecophorine moths (Oecophoridae, subfamily Oecophorinae). This subfamily includes 1850 valid named Australian species in 263 genera, some 45% of these genera named by Common (1994, 1997, 2000) in his great monographic series; overall, however, it is estimated that there may be about 5500 species in Australia, amounting to about a quarter of the total Lepidoptera fauna of the continent! In contrast, there are about 100 species of the subfamily in Europe, and 35 species in the Nearctic. The larvae of these moths feed largely on the leaves of *Eucalyptus* and related genera of the plant family Myrtaceae, most of them on dead leaves that have fallen to the forest floor. They are among very few insects that feed on these leaves, which are low in nutritional value and rich in phenolic compounds. Feeding on the fallen leaves in great abundance, oecophorine moths maintain a relatively clean forest floor under Australian *Eucalyptus* woodland, and have contributed greatly to the formation of the soils in these habitats. There are typically hundreds of oecophorine larvae per square metre in the leaf litter under eucalypt forest, with one to two dozen species, each with a narrowly defined niche, typically present (Van Dugteren 1999, I Common pers. comm. 2004). In other parts of the world, where *Eucalyptus* is grown on a very large scale in plantations and the moths are absent, the dead, phenolic-rich leaves accumulate as a thick layer that strongly inhibits other plants and animals in their vicinity.

One of the most intriguing Australian co-evolutionary explosions is that of the Psyllidae (Hemiptera), the plant lice or lerp insects (Hollis 2004; Fig. 1c). This group has undergone parallel radiations on eucalypts and on *Acacia*. Their radiation on eucalypts is of the subfamily Spondyliaspidinae, and consists of several hundred species of lerp-forming psyllids. The immature insects cover themselves with beautiful and highly varied structures called lerps, which are scales or tests formed largely of excreted honeydew that have a high carbohydrate content. The parallel radiation of the subfamily Acizziinae on *Acacia* is the more extensive morphologically, involving especially the genus *Accizzia*. The existence of these two evolutionary lines presents a wonderful opportunity for comparative studies of the independent course taken on each of the major host groups.

Another extraordinary evolutionary radiation that has been well documented recently is that of the *Acacia* thrips (Fig. 1d), monographed recently (Crespi *et al*. 2004). A close examination of this group has revealed the presence of at least 250 species strictly associated with the 1000 species of Acacia in Australia; fewer than 10% of these thrips species had been recognised when the study just reported began. These Acacia thrips fall into four ecological suites: gall-inducers, those that glue phyllodes together; parasites of these two groups; and opportunists. Overall, the pattern of evolutionary radiation in these thrips offers a model system for understanding the co-evolution of insects with plants in general, as well as illustrating a fine and newly elucidated model of evolution in Australia (Austin *et al*. 2004).

A recently discovered evolutionary radiation of stygobiont diving beetles (Dytiscidae) and other invertebrates in isolated calcrete aquifers in the Yilgarn Craton of arid Australia highlights the recent aridification of the continent. Most individual calcrete aquifers contain an assemblage of diving beetle species of distantly related lineages and/or a single pair of sister species that significantly differ in size and morphology. Evolutionary transitions from surface to subterranean life took place in a relatively small time frame between 9 and 4 million years ago, coinciding with an aridity maximum in the Early Pliocene. This is a remarkable example of an escape from aridification on the landscape surface (Cooper *et al*. 2002; Leys *et al*. 2003).

A final example is that of the fegussoninid gall flies (Diptera: Fergussoninidae). These flies form galls on myrtaceous plants, with the galling induced by an inquiline nematode. There seems to be a high degree of host specificity here, and the three-way relationship between the flies, nematodes and plants is a fascinating one about which we have much to learn. Obviously, there has been extensive coradiation between the flies, the nematodes and the eucalypts (Davies & Giblin-Davis 2004; Scheffer *et al*. 2004).

THE AUSTRALIAN ENVIRONMENT

Australia, with a surface area of more than 7.5 million square kilometres, is somewhat smaller than the USA or Europe. Its landscape has been transformed significantly by human activities over the past 50 000 years or so, with the extensive use of fire by Aboriginal people playing a major role in establishing its contemporary appearance. Over this period of time, many closed forests were converted to open savannas. Along the eastern side of Australia, open grassy areas in moist forest are being actively invaded by rainforest plants; there seems no doubt that the grasslands were maintained over earlier centuries by deliberate burning. In addition, the widespread harvesting of native plants and hunting of animals would also have changed the character of the vegetation profoundly as Aboriginals shaped it to support their lifestyle. These activities certainly caused the extinction of many large vertebrates, and the loss of those species in turn would greatly have affected the communities of which they were once a part (Flannery 1997; Miller *et al*. 2005).

Australia has been changed much more profoundly in the years since European settlement began in 1788. As the *State of the Environment 2001* report puts it, 'The agriculture, mining, and urban settlements that form the basis of the successful economy and multicultural society that constitutes Australia today have come at a cost some which has yet to be repaid' (Australian State of the Environment Committee 2001, p. 3). Significantly, although about a third of the land in Europe and 20% of that in the USA are arable, only about 7% of Australia is classified in this way. Australia's population, currently just over 20 million people, is highly concentrated in cities, where about 91% of all Australians live. A highly dispersed rural population produces Australia's wool, meat and crops. In connection with this production, some 61% of Australia is affected by grazing.

The quality of life and the levels of consumption and waste production in Australia are similar to those in the USA and Europe, while the ecological footprint of each Australian is among the highest in the world – comparable to that in the USA and roughly 50% higher than those characteristic of European nations (*Economist* 2004). This very high level of consumption is sustained in Australia in an environment that is one of the most fragile anywhere in the world. Further growth of the human population therefore is environmentally feasible only when the resources that support people are used sustainably.

The antiquity and isolation of Australia, its ancient and often infertile soils, and its overall aridity, have given its environment a unique fragility that has not responded well to methods of cultivation and grazing developed in other better-watered and more fertile parts of the world. Early settlers in Australia emphasised its similarity to lands that they had left behind, often to their great disadvantage. Arguably, Australia's unique set of environmental features combine to make sustainability an even more elusive target here than in most other parts of the world. The continent's movement in isolation over some 50 million years from temperate southern latitudes into broadly arid climatic zones has given rise to a partly archaic and highly endemic biota. Australia's most difficult problem will be maintaining its profitable extractive industries while developing sustainability on a continental scale. Although the arid interior remains sparsely populated, and people are concentrated mainly in the major cities near the coast, the settlement of virtually all of the arable land during the 19th century without regard to the peculiar properties of the Australian environment led rapidly to many of the environmental problems faced today (Kirkpatrick 1994; Young 2000).

FORESTS AND THEIR CONSERVATION

By the time the ancestors of the Aboriginal people reached Australia, apparently about 50 000 years ago, only about 50% of the continent was forested – the result of a progressive shrinking of the forested area over the past tens of millions of years. This original small area of forest has subsequently been reduced to only an estimated 60% of its original extent, and the loss of the remainder has had severe impacts on the plants and animals that occur there (Australian Native Vegetation Assessment 2001). The most diverse and biologically rich of these forests are the rainforests of eastern Australia, occupying only about 0.5% of the continent before Europeans arrived. It is here that the remnants of the original gondwanan forest that once nearly covered the continent have survived. The total area of remaining rainforests in eastern Australia, however, is smaller than that of the Sydney metropolitan area. Amounting to about 3 million hectares, they clearly represent a precious part of our common heritage worthy of preservation for the benefit of all.

The greatest percentage of rainforest loss has been in New South Wales (54%), followed by Queensland (35%). In absolute terms, however, Queensland has lost far more rainforest than any other state: more than 1 million hectares. The heaviest toll has been in the south-east, north-east, central coast and the subcoastal southern portions, each a core rainforest refugium with a major centre of endemism (Webb & Tracey 1995).

The north-eastern Wet Tropics of Queensland retains the world's greatest concentration of archaic plant families, including Winteraceae, Himantandraceae, Eupomatiaceae, Austrobaileyaceae, Monimiaceae, ancient Proteaceae and *Idiospermum*, most either confined to this area or much more poorly represented elsewhere. The area contains 30% of Australia's frogs, 62% of butterflies, 73 endemic species of vertebrates (Moritz 2005) and hundreds of endemic flightless insects (Yeates & Monteith 2007). Although the rainforests of north-east Queensland were listed as a World Heritage Site in 1988, they still have not completely been transferred to National Park status, and weeds, feral pigs, invasive ants and *Phytophthora* are exacting a growing toll on them. Important centres of endemism also exist in south-eastern Queensland, where they face continuing private development also, and in subcoastal southern Queensland, where the largest rainforest floristic region in the state, two-thirds cleared, contains impressive numbers of plants with archaic features, often in forest fragments highly subject to fire.

The second class of drier vine forest includes microphyll vine thickets occurring in areas that receive 500–800 mm of rainfall annually. Over 80% of these thickets have been cleared in the last few decades (Keto *et al*. 2004). Such vine thickets have their greatest development in the Brigalow Belt bioregion of Queensland. In these thickets, fragmentation, clearing, grazing, weed invasion and unnatural fire regimes threaten the viability of the remaining fragments. Of the whole Brigalow Belt, however, 93% (14 million hectares) have been acutely modified over the last few decades. For Australia generally, temperate and subtropical woodlands have been greatly impacted by clearing for agriculture: these 'subhumid' woodlands covered around 57 million hectares and have now been reduced to 23 million hectares. Of this remaining area, 10 million hectares occur in the Queensland Brigalow Belt.

Although they are small, amounting to about 700 000 hectares, Tasmania's forests consist of relict communities most similar to those in south temperate South America and New Zealand, and are essentially composed of endemic conifers (Enright & Hill 1995), *Nothofagus* and many other striking austral relicts. The rate of destruction of these forests, largely for woodchips, has caused the continuing loss of about 40 000 hectares per year since 1997. Native forest woodchip exports from Australia represent one-third of the world market, and two-thirds of Australia's exports come from Tasmania.

One of the daunting aspects of biodiversity conservation in forest fragments is that species survive poorly in small patches. The relationship was outlined in the development of the field of island biogeography by EO Wilson and Robert MacArthur in the 1960s. For island and mainland areas, the relationship between species number and biodiversity is a logarithmic one: a 10-fold decrease in the area of the habitat reduces the number of species that the smaller area can maintain to half of the number that could be sustained in the original one. For that reason, some of the species in remnant forest are what Dan Janzen has aptly termed 'the living dead': species on the way to extinction. This relationship has recently been illustrated vividly for the local extinction of species in the remnant forests of Singapore (Brook *et al*. 2003), for Amazonian forests logged on an experimental basis (Ferraz *et al*. 2003), and rainforest patches in Australia (Grimbacher *et al*. 2006). The effect of such reductions in forest size and extent is, in general, exacerbated by climate change, the accelerated invasion of alien species into smaller patches of vegetation, and other human influences, such as local hunting and gathering, on them.

OTHER ENVIRONMENTAL PROBLEMS

The destruction of grasslands throughout Australia is related to the fact that extensive and more intensive agriculture occupy about 60% of the continent's land surface. In most of the natural areas that are grazed, the environment has deteriorated badly, and the grazing is clearly unsustainable. Droughts have regularly increased the extent of the damage, and rabbits, introduced into Victoria in 1859, blackberries and thistles have spread with them. Feral cats have wreaked havoc with populations of native vertebrates. Over 200 million rabbits now exist in Australia, and feral cattle, horses, donkeys, camels, buffalo, pigs, mice, foxes and goats have joined them in large numbers regionally. Agricultural soils have, in widespread areas, become saline and alkaline. Native grasslands, especially in the eastern part of the continent, have largely been replaced by artificial pastures, and the diversity of their animals and plants, already greatly reduced almost everywhere by decades of grazing, continues to decline (Kirkpatrick 1994, pp. 41–43). In addition, Australia has more than 1700 species of introduced weeds – more than any other country in the world except the USA. Many of these alien species have become environmental weeds of great significance. One of the most harmful organisms introduced into Australia has been the cinnamon fungus (*Phytophthora cinnamomi*), probably introduced in soil associated with cultivated plants. Unfortunately, this fungus, which belongs to the same genus as the organisms causing sudden oak death in California and spreading in the USA currently, is killing the plants over wide sections of the Australian bush and threatens to do a great deal of additional damage over the years to come.

Many of the most aggressive plants and animals have been deliberately introduced, and a number of the most noxious weeds are still listed in nursery catalogues. It is evident that Australia must control further introductions strictly while continuing to attempt to contain and reverse the enormous damage already being caused by the established aliens. As Kirkpatrick (1994, p. 87) points out, some of the plants in cultivation are literally 'time bombs' that may spread explosively in the future. Thus, the cultivated flora should be considered carefully and managed soundly to protect Australia from additional environmental problems in the future.

Perhaps the most important problem of all affecting the survival of Australia's unique plants and animals is global warming (Williams *et al*. 2003; Williams & Hilbert 2006). Limited areas that have been set aside for the preservation of particular sets of species may be vulnerable to these changes, as their original habitats may change drastically and thus become unsuitable for the organisms that originally occurred there. Although the elevated levels of CO_2 may in part mitigate the impacts of climate change by reducing water stress, such environmental changes as the increasing encroachment of shrubs into arid and semiarid rangelands, the further incursion of mangroves into freshwater wetlands, increasing frequency of coral bleaching, and the elimination of alpine and subalpine vegetation as the timberline rises in the mountains – these will all become evident (Hughes 2003). And all of them are taking place in a landscape in which the habitats have been fragmented, invaded by alien species, and otherwise disturbed, all of these factors increasing the impact of global warming greatly.

Tropical Queensland, with many extremely local species, is apt to be affected more than most other parts of Australia (Krockenberger *et al*. 2004). Clearing vegetation is one of the activities most dangerous to biodiversity in the face of climate change. In addition, considering regional environments, private and public, together, in relation to their effectiveness for preserving species as the climate warms is of even greater importance in the 21st century than earlier. Alien invasive species may expand their ranges and damage biodiversity over expanded ranges as the climate shifts.

The projected global increases in temperature are, as far as we know, unprecedented for the past 10 000 years. CSIRO estimates indicate a rise in average annual temperatures for Australia of 0.4–2.0°C by 2030, relative to 1990, and 1.0–6.0°C by 2070. With as little as a 1°C rise in temperature, the bioclimates of some species are projected to disappear entirely, while the ranges of other may be greatly reduced or fragmented (Hughes 2003). It is being widely recognised that mountainous regions should be given priority as conservation areas because of the possibility of migration upward as the climate changes. In Australia, however, the relatively flat topography that is widespread makes the implementation of such a strategy impossible in many areas.

Thomas *et al*. (2004) extrapolated from regional studies including the Wet Tropics and estimated that 15–37% of the tropical forest species they analysed could be on the way to extinction by 2050, depending on the magnitude of the climate change that has occurred by that time. If these projections are valid worldwide, that would suggest the possible loss of 1.5 to about 4 million species, the great majority of them unknown, within the next 50 years or so – on the basis of climate change alone.

As natural communities are devastated by human actions like those just described, not only the extinction of individual species but also the progressive limitation provision of ecosystem services become serious problems. It is obvious that watershed protection can be disrupted, the fertility of fragile soils destroyed, wetlands rich in biodiversity, and climatic patterns disrupted. In addition, crop pollination may be curtailed to the point at which productivity declines (Allen-Wardell *et al*. 1998), and the often surprisingly balanced assemblages of insects, birds and other animals that provide natural integrated pest management in agricultural landscapes may be distorted and lose their ability to function well. In this connection, it has been estimated that an average of 1000 species of arthropods occur in each hectare of irrigated rice paddies in South-East Asia. The nested ecological cycles that are characteristic of such systems lead to the maintenance of pest populations at stable, low levels in these fields and thus clearly to increased productivity of the rice (Whitten & Settle 1998).

RECOMMENDATIONS

Biodiversity defines the way that Australia looks and the way that it functions. Therefore, the wise and sustainable use of Australia's unique set of organisms will increasingly determine major aspects of its existence in the future. Many believe that the 21st century is destined to become the age of biology, a time when we build sustainability for our children and grandchildren on the principles that we have learned during the half-century of the double helix. If this is to be Australia's future, what more valuable asset could exist than a set of some 450 000 species of eukaryotic organisms, no more than a quarter of them yet discovered? Only when we know what Australia's species are, and where they occur, can we manage them sustainably. Some 90% of these organisms are found nowhere else, and they are exquisitely adapted to the fragile soils and unique, mostly harsh and unpredictable, conditions of this remarkable land.

Biodiversity is intrinsically valuable, the properties of individual organisms and the services they provide in communities supporting our lives (Losey & Vaughan 2006), and it also has spiritual values that far transcend the practical and inform every aspect of our lives. As a matter of simple morality, many would argue that we have no right to destroy so many of what are as far as we know our only living companions in the Universe in such an ignorant and passive way, thus committing the one crime for which our descendants are least likely to forgive us. In the words of American ecologist Kai Lee, who wrote, 'Against this background it is possible to see that sustainable development is not a goal, not a condition likely to be attained on earth, as we know it. Rather, it is more like freedom or justice, a direction in which we must strive, along which we search for a life good enough to warrant our comforts' (Lee 1993, p. 200).

There appear to be at least four components necessary to build sustainability in Australia or throughout the world: description and understanding; direct action for conservation; promoting sustainable use in balance with conservation; and providing education and information to maintain the overall effort. All of these components should proceed in parallel, conservation actions for example being based on the best information available at the time and then modified as more is learned. Thus, although we cannot possibly afford to wait for a complete description of Australia's biota and the interactions between the component species as a basis for moving towards conservation or sound sustainable development, the more we know the better choices we shall be able to make. Landscape-level considerations of sustainability or sustainable use are worthwhile, but they cannot be fully successful unless they are underpinned with knowledge of the biodiversity that allows the communities to function as they do.

The urgency of the situation in Australia stems from the same factors that make it unsustainable almost everywhere in the world: habitat destruction, often with no clear view of what will follow after the resources of the area have been stripped away; the exhaustion of renewable and non-renewable water supplies; the alienation of land used for crops or grazing; the invasion by alien plants and animals; and, above all, climate change. In Australia, however, this unique and fragile land, all of these factors seem to have come together to produce one of the most challenging situations encountered anywhere, one in which the adjustment of natural communities to habitat destruction, natural and human-induced drought, and an especially aggressive set of invasive species, has made the major ecosystems unstable (e.g. Beattie *et al*. 1992).

Specific steps that might be taken include accelerating the inventory of Australia's biota with the provision of additional funds. As reviewed above, it would take at least 240 years to survey the continent's arthropods at current rates. The exploration of the structure of ecosystems and the ways in which individual species interact in them must also be stressed to achieve sustainability.

To be able to obtain a reasonably comprehensive survey of Australia's biota in a reasonable length of time would require not only an expansion of the basic budgets that are now available, but also the implementation of training programs, perhaps along the lines of the Partnerships for Enhancing Expertise in Taxonomy (PEET) program of the National Science Foundation in the USA (Rodman & Cody 2003), to provide the taxonomists necessary to complete the inventory. In addition, more positions would need to be provided in museums and universities so that trained systematists could contribute over their lifetimes to the increase of knowledge about their particular group of organisms. The current Australian Biological Resources Study (ABRS) budget would need to be dramatically increased to advance these goals effectively and during a more reasonable period than can now be anticipated. It is, however, clear that increases in research grants alone will not increase the rate of description of Australia's biota adequately; more trained professions with stable employment will also be required. Funds devoted to such purposes would be a strong investment in the future of Australia. In the rapidly changing Australian and world environment, the opportunities to accomplish these objectives in the future will never be as good as they are now.

At a global level, the production of a comprehensive list of arthropod species, including significant synonyms, is being pursued by Species 2000 and the Integrated Taxonomic Information System (ITIS) and coordinated by the Global Biodiversity Information Facility (GBIF). The highly developed Australian databases on biodiversity will clearly be able to provide relevant input to GBIF in a way that can scarcely be matched elsewhere. The relevant ABRS databases can be referenced through the following website: (http://www.deh.gov.au/biodiversity/abrs/online-resources/abif/).

With such a 'backbone' list, images of types and other specimens and information of critical importance can be made available online for easy retrieval. It is often not easy to recognise insect species from the literature alone, but the kinds of images that can be made available now, together with interactive keys (e.g. Hamilton *et al*. 2006), move a very long ways towards the solution of this problem. Making the core literature of systematic biology online would likewise go a long way to expediting taxonomic work everywhere. An electronic encyclopaedia of species that integrates digital information is the goal of the Atlas of Living Australia, a program recently funded by the National Collaborative Research Infrastructure Strategy initiative of the Federal Government.

With an estimated 450 000 species of eukaryotic organisms in Australia, only a quarter of them recognised scientifically, the complex interactions of the tropical rainforest and the Great Barrier Reef, Australia's biodiversity presents fields of discovery for generations to come. The knowledge gained while studying Australia's biodiversity has resulted from the attention of successive Australian governments that have been both wise and farsighted, providing a model for the rest of the world and enriching the nation at the same time.

ACKNOWLEDGEMENTS

We thank the following people for information and advice: J Adis, Max-Planck-Institute; AD Austin, University of Adelaide; AJ Beattie, Macquarie University; R Beeton, The University of Queensland; JA Coddington, National Museum of Natural History; M Colreavy, Australian Biological Resources Study; R Cowling, University of Port Elizabeth; T Flannery, South Australian Museum; TJ Hawkeswood, Richmond NSW, Australia; M Horak, CSIRO Entomology; A Keto, Australian Rainforest Conservation Society; D Mabberley, University of Washington; R Makinson, Centre for Plant Biodiversity Research, Canberra; Lord May of Oxford, University of Oxford; G Midgley, South African National Biodiversity Institute; SI Miller, Smithsonian Institution; M Moulds, Australian Museum; L Mound, CSIRO Entomology; T New, La Trobe University; P Parker, Australian Landscape Trust; S Pimm, Duke University; NI Platnick, American Museum of Natural History; C Simon, University of Connecticut; Q Wheeler, Arizona State University; M Whitten, Maleny, Australia; S Williams, James Cook University; O Zompro, Max-Planck-Institute.

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