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Introduction

Invertebrates comprise about 80 per cent of the world's biodiversity, yet they rarely attract the same level of conservation attention as the more 'charismatic' vertebrates, such as mammals and birds (Cardoso et al. 2011a, 2011b). They are rarely incorporated into standard wildlife inventory and monitoring programs, let alone used to inform conservation management. Butterflies, however, are an exception. They are popular with the general public, respond rapidly to environmental change and are widely recognised as a key flagship group for insect conservation (Pollard and Yates 1993; New 1997; McGeoch 1998, 2007; Braby and Williams 2016). These are the reasons we have chosen them as our focal group.

However, it may come as a surprise to many readers that there are currently no national long-term recording schemes to determine the geographic range size or to evaluate broad changes in the spatial distribution and relative abundance of butterflies in Australia. This contrasts markedly with other developed countries, where butterfly inventory and/or monitoring schemes—such as 'Butterflies for the New Millennium' in Great Britain and Ireland (Asher et al. 2001), the 'Mapping European Butterflies' and related monitoring programs (van Swaay et al. 2008; Kudrna et al. 2011) and other collaborative initiatives such as the 'Tropical Andean Butterfly Diversity Project' in South America (Willmott et al. 2011; Merckx et al. 2013)—have been running for many years or even decades. The vast size of the Australian continent and the comparatively low interest in insects have undoubtedly been impediments to mapping and monitoring the distribution and abundance of butterflies nationally.

There have been only three previous attempts in Australia to systematically catalogue the distribution of butterflies in the form of an atlas. The first atlas was produced more than 30 years ago when a set of maps for all species in Victoria was published by the Entomological Society of Victoria based on a pioneering study (ENTRECS: insect distribution data collection and recording scheme) using a grid cell resolution of 10º longitude x 10º latitude (Crosby 1986). These maps were updated and released 10 years later in CD format by Gullan et al. (1996). More recently, Field (2013) revised the distribution maps of Victorian butterflies, presenting the records as individual data points and distinguishing the records from before and after 1970. The second atlas was the popular book on Tasmanian butterflies by Virtue and McQuillan (1994), which included distribution maps for all 39 species presented as plots of actual records on a 10 km x 10 km grid based on a database maintained by the Tasmanian Parks and Wildlife Service. This work built on the substantial field inventory and base maps prepared earlier by Couchman and Couchman (1977). The species distribution maps presented in the books by Field (2013)

and Virtue and McQuillan (1994), however, were limited by the exceedingly small map sizes and the relatively small spatial scale of the areas covered (Victoria and Tasmania together comprise only 3.9 per cent of the land area of Australia). The third major study was a useful set of maps for all Australian butterfly species compiled by Dunn and Dunn (1991). However, that report and the dataset on which it is based are now out of date and not widely accessible to the general public.

Diurnal moths have received substantially less attention in Australia; however, some progress has recently been made to systematically document the geographical distributions of sun-moths (Castniidae) in Western Australia (Williams et al. 2016). That work shows that the few known species from the northern Kimberley are vastly undersampled and highlights the need for further field surveys.

Sixteen years ago, Sands and New (2002: 29) called for an atlas of the butterflies of Australia, stating: 'We regard the establishment of a National Data Base for Australian Butterflies as a key tool for conservation planning'. Despite this vision and critical objective, little progress has been made in this direction. The online *Atlas of Living Australia* (2017) seeks to address this gap, but contains a relatively small amount of data based primarily on collections in most state museums; however, there is currently no process in place to verify or moderate the accuracy of these records, and therefore the error rate in data quality (whether it be taxonomic, spatial, temporal or observer related) is fairly high.

We thus attempt to fill some of these deficiencies by producing a dedicated atlas of butterflies and diurnal moths of northern Australia—a stepping stone towards a national atlas. Our focus is on the western portion of the Australian Monsoon Tropics (AMT)—that is, the region west of the Gulf of Carpentaria (i.e. Kimberley, Top End, Northern Deserts and western Gulf Country). Although we deal with only a small subset of the continent, the region is still a vast and remote area representing about 1,212,200 sq km (15.8 per cent of Australia). This coverage is substantially larger than the combined areas of Victoria and Tasmania for which point data maps of butterflies have previously been produced (Virtue and McQuillan 1994; Field 2013). Until now, this region was arguably the most poorly known area of the continent for butterflies in terms of basic knowledge, such as taxonomy, distribution and biology. Moreover, it is hoped that this work will stimulate similar studies elsewhere in Australia and ultimately lead to the development of a national recording and monitoring scheme.

In this book, we have attempted to break new ground. Our study is unique in several respects: not only does it produce a set of maps for a remote and poorly known area of Australia, but also the distributional point data of each species are integrated and compared with the spatial distribution of their larval food plants. The geographic range of each species is then estimated using Geographical Information System (GIS) software. Using a novel approach, the geographic range is inferred using a set of explicit criteria that integrate the spatial records of each butterfly and diurnal moth with those of their larval food plants (based on online data in *Australia's Virtual Herbarium* and the *Atlas of Living Australia*). In addition, the book includes images of living butterflies, graphs of seasonal changes in relative abundance and phenology charts of the immature stages for each species—information that has been lacking in previous Australian butterfly atlases.

There is currently increasing pressure for the exploitation of northern Australia's natural resources, particularly expansion of the pastoral, agricultural/horticultural and mining industries, which will inevitably result in substantial habitat loss, fragmentation and degradation and loss of biodiversity (Garnett et al. 2010). In addition, there are a multitude of other threats to the region's biodiversity, including invasive species (e.g. weeds, feral animals, tramp ants), inappropriate fire regimes, intensification of pastoralism (impacts of cattle grazing) (Garnett et al. 2010) and, of course, climate change, particularly increased atmospheric carbon dioxide concentrations and its effect on vegetational change (Parr et al. 2014). Hence, there is an urgent

need to identify the region's biological assets, to inform policy and management agencies in their decision-making processes and to set priorities for biodiversity conservation.

While a broad-scale inventory of the terrestrial vertebrates of northern Australia has been undertaken in relation to the extent of their representativeness in the conservation reserve system (Woinarski 1992), there has been little synthesis of the region's invertebrates. Such baseline data on the composition, distribution and abundance of this key component of biodiversity are critical because they allow us to identify areas of high conservation value, as well as determine the extent and direction of change in future. This atlas aims to collate and disseminate baseline information for one key group of invertebrates: the butterflies and diurnal moths of the insect order Lepidoptera.

Australian Monsoon Tropics

The AMT biome is a distinct geographical region defined by a combination of climate, vegetation types and the kinds of animals and plants adapted to it (Bowman et al. 2010). The AMT covers a vast area (more than 1.5 million sq km, or 20 per cent of Australia) that includes the Kimberley of northern Western Australia, the 'Top End' of the Northern Territory, the 'Gulf Country' adjacent to the Gulf of Carpentaria and Cape York Peninsula of northern Queensland. The AMT is defined by areas that receive more than 85 per cent of their rainfall between November and April (Bowman et al. 2010); thus, the southern boundary of the region equates to approximately 20–21°S latitude and the northern boundary to the coastline. A characteristic feature of the AMT is the strong latitudinal rainfall gradient, with parts adjacent to the northern coastline having average annual rainfall exceeding 1,500 mm, but with much of the inland region experiencing averages of only 300–600 mm.

The AMT is of international significance because of its large and relatively intact natural landscapes, high biodiversity and strong Indigenous culture (Woinarski et al. 2007a; Bowman et al. 2010; Garnett et al. 2010; Moritz et al. 2013) that spans 65,000 years (Clarkson et al. 2017). The geological landscape is mostly old, eroded and infertile with few marked topographic features. The climate is harsh, with extreme seasonality driven by monsoon rainfall, destructive cyclonic events and an intense dry period during which little or no rain falls. Disturbance by fire is an integral part of the ecosystem (Russell-Smith and Yates 2007; Andersen et al. 2012; Parr et al. 2014), particularly during the dry season. The biome supports a range of habitats and vegetation types not found in the temperate areas of southern Australia. Moreover, the AMT supports the largest single expanse of tropical savannah woodland in good ecological condition in the world, and contains more than 25 per cent of the world's remaining savannahs (Woinarski et al. 2007a). The high integrity of the tropical savannahs of the AMT is related to the comparatively low human population density, low density of livestock (cattle and sheep, excluding feral herbivores) and the small proportion of land cleared for agriculture and mining. Unlike the temperate woodlands of southern Australia—which have largely been cleared, fragmented or heavily degraded—the tropical woodlands of northern Australia are intact and remain in a relatively unmodified condition (Woinarski et al. 2007a).

Another striking feature of the AMT is the disjunct blocks of ancient Proterozoic sandstone, which are embedded within the extensive savannah lowland plains (Woinarski et al. 2005, 2007a; Bowman et al. 2010). These sandstone blocks form substantial plateaus associated with steep cliffs and escarpments in the northern Kimberley and Top End (especially in western Arnhem Land) and to some extent in the western Gulf Country and on Cape York Peninsula, and support high levels of species richness and narrow-range endemism with many relict species (Press et al. 1995; Crisp et al. 2001; Woinarski et al. 2006), which contrast markedly with the savannahs in which species typically have very wide distributions.

Two major biogeographic barriers that divide the AMT into three main subregions are the Carpentarian Gap in the east and the Joseph Bonaparte Gulf in the west (Bowman et al. 2010; Eldridge et al. 2012; Catullo et al. 2014; Edwards et al. 2017). The Carpentarian Gap or Carpentaria Basin (at the base of the Gulf of Carpentaria) comprises an extensive area of flat and seasonally dry alluvial plains, tidal estuaries and deltas, and, together with the Gulf of Carpentaria, it separates Cape York Peninsula from the Top End. The Joseph Bonaparte Gulf may actually form two barriers that separate the Top End from the Kimberley, according to recent investigations on the distribution of frogs (Catullo et al. 2014) and vascular plants (Edwards et al. 2017). Eldridge et al. (2012) referred to this broad area as the Ord Arid Intrusion–Victoria River Drainage Barrier. The Ord Arid Intrusion (or Ord region) is a region of lowland country immediately west of the Ord River Basin and Cambridge Gulf, whereas the Victoria River Drainage Barrier (also known as the Daly River Plains) comprises a large tract of lowland country formed by the Victoria River and the headwaters of the Roper River, devoid of any permanent streams (Edwards et al. 2017). The effect of these barriers is reflected in the distinctive elements of the flora and fauna associated with each major subregion.

The biodiversity of the AMT is exceptionally rich (McKay 2017), but only recently have scientific studies revealed the true extent of endemism and the historical assembly (evolutionary origins and adaptive radiation) of its biota. Recent systematic and molecular phylogenetic studies of invertebrates (land snails) (Cameron et al. 2005; Köhler 2010; Criscione et al. 2012; Criscione and Köhler 2013; Köhler and Criscione 2013) and vertebrates (for a review, see Moritz et al. 2013) in the Kimberley and Top End suggest a vastly underdescribed fauna with high levels of narrow-range endemism and a deep evolutionary legacy. The emerging picture is one in which the AMT has substantially higher biodiversity value than previously realised, with multiple 'hotspots' of endemism in the Kimberley and Top End (Crisp et al. 2001; Rosauer et al. 2009; Moritz et al. 2013; Pepper and Keogh 2014; Rosauer et al. 2016; Oliver et al. 2017). These hotspots are areas that support high concentrations of taxa with restricted geographic ranges and typically coincide with evolutionary refugia, usually associated with high topographic variability enabling mesic species to persist and evolve during past climatic extremes.

A review of the biogeography of butterflies in the AMT in terms of patterns of species richness, endemism and historical area relationships (Braby 2008a) indicated that the AMT supports a rich fauna, comprising 265 species (62 per cent of the Australian fauna), but endemism is low, with only 15 endemic species (6 per cent). Most of the endemic species (13, or 87 per cent) are associated with savannah, eucalypt woodland and heathy woodland habitats, while most of the non-endemic range-restricted species (38 of 46 species for which the breeding habitat was known) are restricted to various rainforest habitats. Cape York Peninsula was identified as an area of exceptional biodiversity. However, while the biodiversity of the butterfly fauna of Cape York Peninsula has been relatively well explored and documented (Kikkawa et al. 1981), the Kimberley and Top End remain a biological frontier in which the taxonomy and distribution of species are substantially less well known. Hence, one of the goals of this work is to fill knowledge gaps concerning the composition and distribution of butterflies in this western part of the AMT.

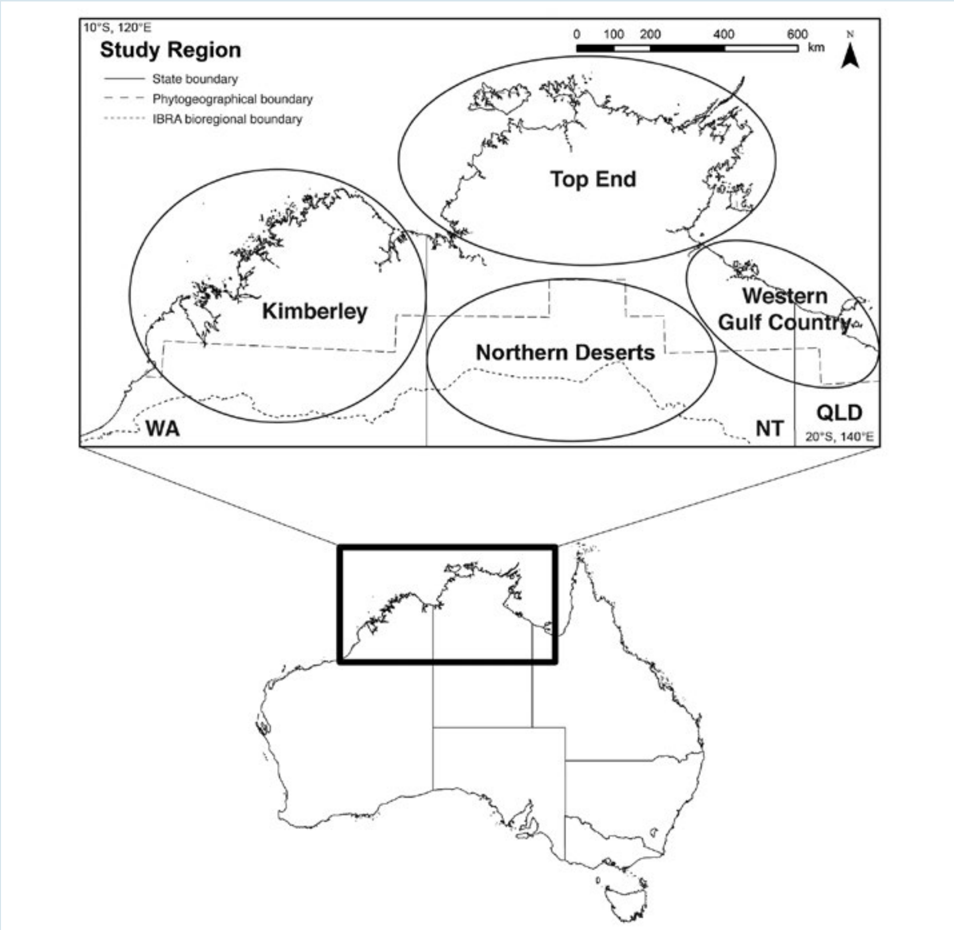
Butterflies are also deeply interwoven in Aboriginal culture and are recognised by the traditional owners of northern Australia. For example, in the Top End, butterflies (and moths) are known to the Burarra people in central coastal Arnhem Land around Maningrida as *burnpa*, to the Yolngu people of eastern Arnhem Land as *bonba*, to the Mangarrayi and Yangman peoples of the Roper River district as *bardbarda*, to the Dalabon people of southern Arnhem Land as *merlemerleh*, to the Bilinarra, Gurindji and Malngin peoples of the Victoria River District as *marlimarli* and to the Warray people of Adelaide River as *mirli-mirli*. The Warray people even have a specific name,

langga-langga, for the Common Crow, *Euploea corinna* (White et al. 2009)—a species known for its habit of forming spectacular aggregations of adult butterflies in sheltered gorges during the dry season. Traditional language names have been used as the scientific names for several taxa described from the Top End—for example, *Protographium leosthenes* ***geimbia*** (Tindale 1927), *Suniana lascivia* ***larrakia*** (Couchman 1951), *Synemon* ***wulwulam*** (Angel 1951) and *Candalides geminus* ***gagadju*** (Braby 2017). The application of such names for butterflies is unparalleled elsewhere in Australia, reflecting the rich traditional culture that still exists in the AMT.

Study region

For the purposes of this work, the boundaries of the study region are similar to those adopted by Woinarski (1992): the western boundary was set to 120°E, the eastern boundary to 140°E, the northern boundary to 10°S (i.e. the northern coast including continental islands) and the southern boundary to 20°S. Within the study region, we recognise four subregions: the Kimberley, Top End, Northern Deserts and the western Gulf Country (Map 1). The four subregions have been delineated more for convenience for describing broad distribution patterns of butterflies and diurnal moths, and do not necessarily represent natural bioregions (c.f. Ebach 2012; Ebach et al. 2015), although the Kimberley Plateau, Top End and Northern Deserts are now generally recognised as distinct bioregions (Bowman et al. 2010; Eldridge et al. 2012; Catullo et al. 2014; González-Orozco et al. 2014; Edwards et al. 2017). In this work, the Kimberley includes almost all of the area of Western Australia north of the Great Sandy and Tanami deserts; the Top End includes areas in the Northern Territory north of approximately 15.5°S latitude; the Northern Deserts comprise the semi-arid and arid zones receiving less than 700 mm mean annual rainfall; whereas the western Gulf Country extends approximately from Limmen Bight in the Northern Territory to Burketown in Queensland and inland to the Barkly Tableland. The definition of the 'Top End' is somewhat arbitrary—for example, some authors treat the whole area in the Northern Territory and western Queensland north of about 19°S latitude as the Top End (Eldridge et al. 2012); others limit it to the Northern Territory north of 18°S latitude (Russell-Smith and Bowman 1992; Woinarski et al. 2007a); while yet others have adopted a more stringent approach and just include the area in the Northern Territory north of approximately 15°S latitude, bounded by the mouth of the Victoria River in Joseph Bonaparte Gulf in the south-west and the mouth of the Roper River in Limmen Bight in the south-east (Rosauer et al. 2016).

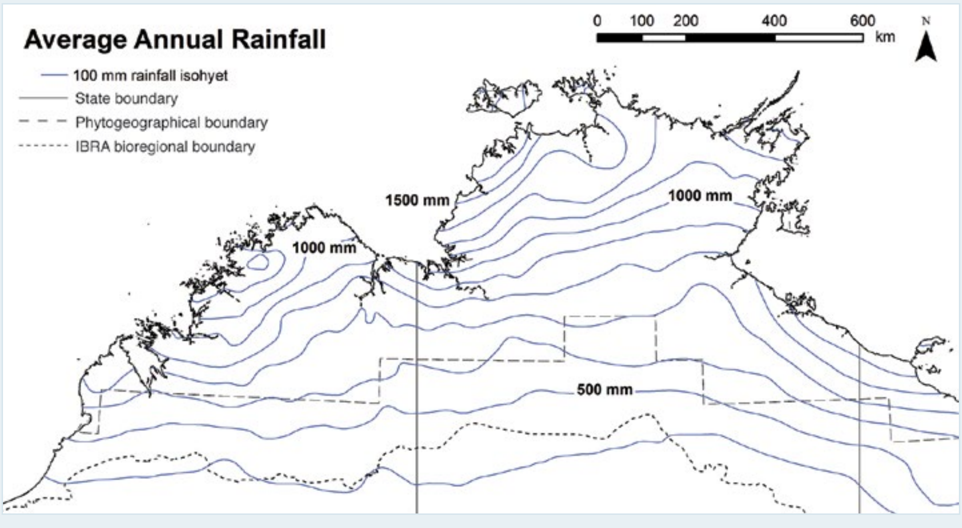
Two useful biogeographical regionalisations within Australia have been recognised that have relevance to the AMT and hence our study region (Map 1). One is the widely used Interim Biogeographic Regionalisation for Australia (IBRA), in which 89 geographical areas are recognised, representing a landscape approach to classifying the land surface for protecting biological diversity (Thackway and Cresswell 1995). A boundary commonly used to delineate northern Australia is that adopted by the Tropical Savannas Cooperative Research Centre (CRC), which was based on the IBRA classification; the CRC's southern boundary essentially follows the northern boundary of the Great Sandy Desert, Tanami Desert and Davenport Murchison Ranges bioregions. The second is a set of five phytogeographical regions for Australia recently developed by González-Orozco et al. (2014) and Ebach et al. (2015) based on species turnover in plant distributions (i.e. the rate of change in species composition between sites) that is also correlated with climatic variables (rainfall and temperature seasonality). For northern Australia, two phytogeographical regions are recognised: the Northern and Northern Desert bioregions. The phytogeographical boundary between these two bioregions is shown in Map 1, together with the IBRA bioregional boundary adopted by the CRC. We have included these biogeographical boundaries in our maps because they provide a useful comparison with the delineation of the AMT based on rainfall patterns and with the geographical distributions of our faunal group of interest, butterflies and diurnal moths.



Map 1 Location of the study region in northern Australia

Four component subregions are shown: the Kimberley, Top End, Northern Deserts and western Gulf Country. Two biogeographical boundaries are shown: the phytogeographical boundary that separates the Northern and Northern Desert bioregions (González-Orozco et al. 2014; Ebach et al. 2015), and the IBRA bioregional boundary (Thackway and Cresswell 1995) adopted by the Tropical Savannas CRC.

Source: Prepared by the authors.



Map 2 Map of the study region showing spatial variation in average annual precipitation

Both the phytogeographical and bioregional boundaries coincide closely with average rainfall, which shows a pronounced latitudinal gradient. Note: the 1,100 mm mean rainfall isohyet is not shown.

Source: Prepared by the authors.

Climate

The climate in the AMT is one of extremes: it is highly seasonal or 'monsoonal', in which there are pronounced wet and dry seasons driven largely by seasonal fluctuations in rainfall (Bowman 2002; Bowman et al. 2010). The warmer months are characterised by high temperatures and high humidity, a pronounced wet period and north-westerly trade winds, typically from November to March or April (the wet season), while the cooler months are characterised by a long drought period and south-easterly trade winds, usually from May to October (the dry season). During the wet season, high moisture and torrential rainfall are associated with equatorial monsoon troughs and severe tropical storms, including cyclones, whereas the dry season is dominated by a subtropical high-pressure system and dry air. The Australian summer monsoon is a component of the large-scale Asian–Australian monsoon system, which appears to be of great antiquity, its origins dating back to the Late Eocene–Early Oligocene (for review, see Bowman et al. 2010). The onset and duration of the wet season, and the amount of rainfall and intraseasonal breaks between the monsoon troughs, are highly variable from year to year (Garnett and Williamson 2010; Drosdowsky and Wheeler 2014).

There is a strong latitudinal gradient in annual rainfall, which is a distinctive feature of the AMT (Map 2). The highest rainfall zones in the study region occur in the north-western corner of the Top End (> 1,600 mm mean annual rainfall), Gove Peninsula (> 1,400 mm) and the coastal areas of the north-western Kimberley (> 1,200 mm), with progressively lower rainfall in the inland areas. The highest mean annual rainfall occurs on the Tiwi Islands (> 2,000 mm) and the lowest in the Tanami and Great Sandy deserts (< 400 mm). For the purposes of this atlas, we divide the study region into three climatic zones according to rainfall pattern based on Gaffney (1971): the wetter tropics, with 700–2,200 mm mean annual rainfall; the semi-arid zone, with a mean annual rainfall of 350–700 mm; and the drier arid zone, with a mean annual rainfall of less than 350 mm (Map 5).

The seasonality in rainfall is a major driver of the ecology of the region, with species showing a range of adaptive responses to the alternating annual cycle of rainfall and flood, followed by drought and fire (Bowman 2002; Woinarski et al. 2007a; Garnett et al. 2010). Many animals, for instance, undertake local dispersal or seasonal migration at various spatial scales in response to changes in the availability of resources (Woinarski et al. 2005). The pronounced latitudinal rainfall gradients in the Kimberley and Top End also have a major influence in determining the vegetation type and habitats (see below) and hence the geographic distribution of animals, including butterflies and diurnal moths. Studies of vertebrates (Woinarski 1992; Woinarski et al. 1999) and vascular plants (Bowman 1996) have revealed substantial changes in species richness and composition, with high spatial turnover associated with this latitudinal rainfall gradient from the northern coast to the dry interior of arid Australia. In contrast, there is remarkably little longitudinal variation in species composition across the lowland savannah plains that extend across the region from west to east, with many species having extensive geographic ranges (Woinarski 1992; Woinarski et al. 2005).

Habitats

The study region supports a variety of habitats or vegetation types used by butterflies and diurnal moths, including savannah woodland, rainforest, heathland, mangrove, saltmarsh and floodplain wetlands (Brock 2001; Woinarski et al. 2007a; McKay 2017) (Plates 1 and 2).

The overwhelmingly predominant habitat in the landscape is tropical savannah woodland, also known globally as 'tropical grassy biomes' (Parr et al. 2014). This habitat is distinguished by the ubiquitous presence of C_4 grasses in the understorey, shade-intolerant plant species, an overstorey dominated by eucalypts (*Eucalyptus* and *Corymbia*) (Plates 1a–c) and the prevalence of fire and herbivory. Tropical savannah woodlands in northern Australia occur extensively on the lowland plains comprising deep, well-drained sandy or lateritic soils.

In the higher rainfall areas, the savannahs comprise eucalypt woodland or eucalypt open forest with a tall grassy understorey (Plate 1a) and, depending on the frequency of fire and soil type, a woody shrub layer. In the lower rainfall areas, the savannahs typically comprise eucalypt open woodland (Plate 1b), tropical grassland or, in some areas, *Acacia* low open woodland (Plate 1d) or *Acacia* tall open shrubland. On the sandstone country that dominates much of the Kimberley and parts of the Top End, such as the Arnhem Land Plateau, tropical heathland, low shrubland and eucalypt heathy woodland (Plate 1c) persist on the dissected plateaus and steep breakaways with nutrient-poor, acidic soils that hold little moisture through the dry season (Russell-Smith et al. 2002). On wetter sites—such as seasonal swamps and the edges of permanent billabongs and creeks—various types of paperbark (*Melaleuca*) habitats prevail (Platess 2g–h), including paperbark open forest, paperbark woodland and paperbark swampland. Paperbark forests are the wetland analogue to the drier eucalypt forests and persist in wetter places at the expense of rainforest where the level of disturbance by fire and/or flood is high (Franklin et al. 2007b).

Where the landscape is protected from fire, forests with a closed canopy, buttressed roots and lianes may occur. These habitats are variously termed rainforest or 'monsoon forest' because of their adaptation to the pronounced dry season; they vary in stature and in the dominance of evergreen or deciduous species (Plates 2a, 2b and 2d). Monsoon forests typically occur as a mosaic of relatively small fragmented patches (< 5 ha), with an estimated 16,500 patches occurring in the study region, embedded in the vast savannah landscape (Russell-Smith 1991; Russell-Smith et al. 1992; Russell-Smith and Bowman 1992). The largest and most diverse patches of monsoon forest occur in the higher rainfall areas of the north-western Kimberley (Kenneally et al. 1991; McKenzie et al. 1991), northern coastal areas of the Top End and in western Arnhem Land, where they may exceed 100 ha in extent (Russell-Smith et al. 1992). Although in total they comprise a relatively small area of the study region (2,750 sq km or 0.4 per cent), they nevertheless support a disproportionately high number of plant species (13 per cent of the Northern Territory total) (Woinarski et al. 2005). They also support a rich diversity of butterflies (Hutchinson 1973, 1978; Bailey and Richards 1975; Kikkawa and Monteith 1980; Naumann et al. 1991) and diurnal moths, many of which do not occur in other habitats, while others use them as refuges for aggregation during the long dry season (Monteith 1982). The wetter monsoon forests comprise evergreen monsoon vine forest (Plate 2a) or riparian (gallery) forest and occur where water is available throughout the dry season, such as along perennial rivers, below springs associated with underground aquifers or in deep rocky sandstone gorges and escarpments. The drier monsoon forests frequently occur as semi-deciduous monsoon vine thicket (Plates 2b and 2d) on coastal laterite, coastal sand dunes, inland rocky outcrops composed of limestone, granite and basalt, and sandstone escarpment talus slopes where access to water is limited or unavailable during the dry season. These dry monsoon forests include both evergreen and deciduous tree species, hence the term 'semi-deciduous' monsoon vine thicket.

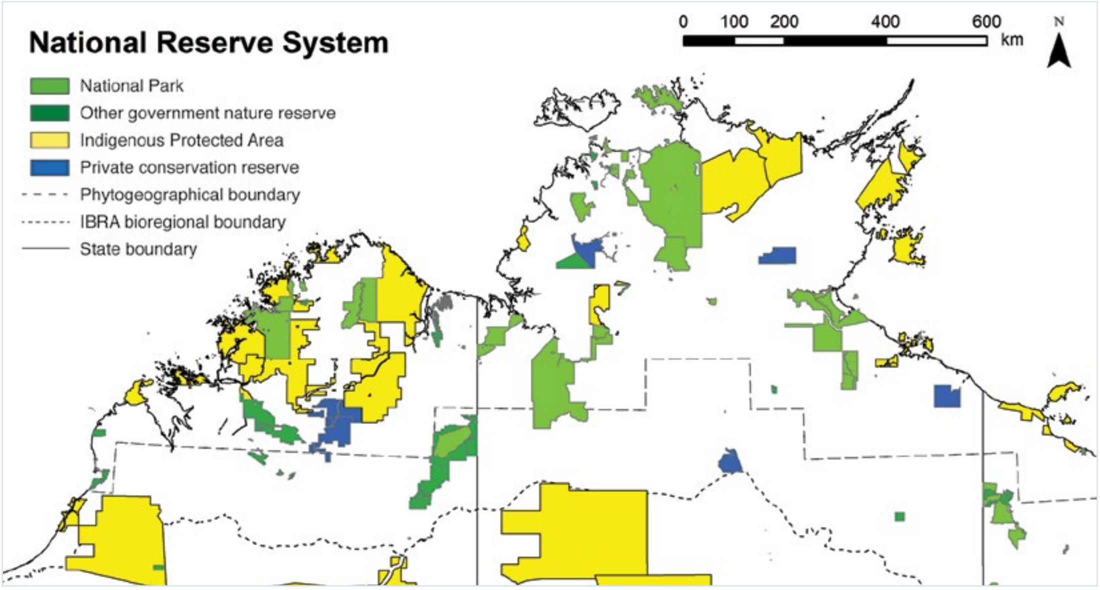
In the higher rainfall areas of the savannah landscape, both eucalypt and paperbark woodland/swampland may develop rainforest elements in the understorey if fire is excluded for a considerable period (Plate 2f). These habitats are important for butterflies and diurnal moths, particularly in riparian areas where mixed riparian monsoon forest (Plate 2c) or mixed riparian woodland develops, because of the high floristic diversity, longer growing season of the larval food plants and cooler, moist microclimatic conditions. Another important habitat for butterflies is rainforest edge (Plate 2e), which comprises the ecotone between monsoon forest and eucalypt woodland.

Other habitats that are used by a few ecologically specialised butterflies include mangrove, saltmarsh, floodplain wetland and open sandstone pavement (Plates 1e–h). Mangrove and saltmarsh occur along the coastline and adjacent areas and are subject to

Plate 1 Examples of breeding habitats used by butterflies and diurnal moths in the study region

(a) savannah woodland, in higher rainfall areas; (b) savannah woodland, in lower rainfall areas; (c) eucalypt heathy woodland on sandstone breakaway; (d) *Acacia* low open woodland; (e) open sandstone pavement; (f) floodplain wetland; (g) mangrove; (h) saltmarsh.

Plate 2 Examples of breeding habitats used by butterflies and diurnal moths in the study region
(a) wet monsoon forest (evergreen monsoon vine forest); (b) dry monsoon forest (semi-deciduous monsoon vine thicket) on coastal laterite; (c) mixed riparian monsoon forest; (d) dry monsoon forest (semi-deciduous monsoon vine thicket) on limestone; (e) rainforest edge (ecotone between monsoon forest and savannah woodland); (f) paperbark tall open forest with rainforest elements in the understorey; (g) paperbark swampland; (h) paperbark woodland.



Map 3 Map of the study region showing the extent and land tenure of the National Reserve System

Source: Prepared by the authors.

periodic tidal inundation; saltmarsh typically occurs as extensive flats along the landward edge of mangroves. Floodplain wetlands are ephemeral or seasonal habitats reliant on major river systems flooding during the wet season; during the late dry season, the heavy clay soils crack and dry out. Open sandstone pavements support 'resurrection' grasses (*Micraira* spp.), the only plant genus that has adapted and radiated to any extent on this very specialised and harsh habitat.

National Reserve System

The National Reserve System (NRS) in northern Australia, according to the *Collaborative Australian Protected Area Database* (2014), consists of three major categories of land tenure: government, Indigenous and private (Map 3). Government land includes world heritage areas, national parks and other nature reserves managed by the Commonwealth, state or Northern Territory governments. Indigenous Protected Areas (IPAs) are Aboriginal-owned land managed by traditional owners through dedicated ranger groups on country. Private conservation reserves include areas that have been purchased for conservation purposes by non-governmental organisations (NGOs), such as the Australian Wildlife Conservancy, Bush Heritage Australia and the Nature Conservancy. In the study region, IPAs cover 154,575 sq km (61 per cent), government national parks and nature reserves 86,062 sq km (34 per cent) and NGO reserves represent 12,765 sq km (5 per cent) of the NRS. Collectively, these different reserve types in northern Australia, which constitute 253,402 sq km (21 per cent of the study region), aim to protect and manage unique landscapes and their biological diversity by forming a network of protected areas that is comprehensive, adequate and representative, with the added value that IPAs also protect and maintain cultural values and customary practices (Woinarski et al. 2007a; Garnett et al. 2010; Moritz et al. 2013).

Some of the more significant national parks in the study region include Prince Regent River, Drysdale River and Purnululu national parks in Western Australia; Keep River, Judbarra/Gregory, Litchfield, Kakadu, Garig Gunak Barlu (on Cobourg Peninsula) and Limmen national parks in the Northern Territory; and Boodjamulla (Lawn Hill) National Park in Queensland. Both Purnululu and Kakadu national parks have been afforded World

Heritage status. Significant IPAs include Karajarri, Bardi-Jawi, Wilinggin, Uunguu, Dambimangari and Balanggarra in the Kimberley; Northern Tanami in the Northern Deserts; Wardaman, Warddeken, Djelk, Laynhapuy, Dhimurru and Anindilyakwa (on Groote Eylandt) in the Top End; and Yanyuwa (Barni-Wardimantha Awara), Thuwathu/Bujimulla (on Mornington Island) and Nijinda Durlga in the western Gulf Country. Examples of private conservation reserves are Mornington Wildlife Sanctuary in Western Australia and Fish River Station, Wongalara Sanctuary and Pungalina-Seven Emu Wildlife Sanctuary in the Northern Territory.

The land tenure outside the NRS consists predominantly of pastoral land (both freehold and leasehold) used for cattle production (c. 70 per cent of the total area) and private Indigenous lands, with smaller areas devoted to agriculture/horticulture and mining (Woinarski et al. 2007a; Garnett et al. 2010). Mining may also occur under permit in conservation reserves, on Indigenous lands (for example, Melville Island) and on pastoral leases. However, while protected areas are crucial for biodiversity conservation, management of the non-protected areas (i.e. the larger 'matrix' surrounding conservation reserves) is also necessary to ensure connectivity and continuity of ecological and evolutionary processes within the landscape (Woinarski 1992; Garnett et al. 2010; Moritz et al. 2013). In other words, pastoral lands and Indigenous lands that are not part of the NRS also have critical roles to play in biodiversity conservation.

Early history of butterfly studies

The sparse population density of the study region and its remoteness from the major population centres of Australia, which are primarily concentrated in the south-east of the continent, has meant that not until recent times have there been regular and substantial field collecting and research activity. Prior to 1970, recording of the butterfly and diurnal moth fauna was spasmodic, undertaken largely by naturalists and entomologists visiting the Kimberley or Top End for brief periods and usually concentrated around the major ports such as Darwin, Wyndham and Derby, although some did make arduous explorations to areas that would have been extremely challenging at the time, and are still frontier places today! A brief account of some of these pioneers and their published studies is provided here.

It is not certain when the first specimens were collected from the study region. The subspecies *Euploea darchia darchia*, which is endemic to the Kimberley and Top End, was described by W. S. Macleay in 1826 (under the name *Danais darchia*) based on material collected during Captain P. P. King's voyages (Macleay 1826; Edwards et al. 2001), and may represent the first scientific collection of butterflies from the region. King made four voyages between 1817 and 1822 during which he explored and meticulously charted the northern coast of Australia. He was accompanied by the botanist A. Cunningham, who also collected insects on these voyages, but it is not clear where the specimens were collected, other than somewhere along the Northern Territory coast (Oberprieler et al. 2016). Unfortunately, the type material of *E. darchia* is lost and presumably destroyed (Waterhouse 1937b), and the exact locality for the type is unlikely to be established, as is the case for all type specimens of other insects described by Macleay (Oberprieler et al. 2016).

King was also the first European to visit Cobourg Peninsula and, in 1818, he mapped (and named) the inlet of Port Essington. A remote British military colony was subsequently established at Port Essington between 1838 and 1849, which at that time was the only European settlement in northern Australia. The colony allowed many early Victorian-era natural history collectors to visit the area, the most notable of whom was John Gilbert, in 1840 and 1841 (Fisher and Calaby 2009). Although Gilbert collected mainly birds and mammals, he also collected insects, which were sent back to England for taxonomic appraisal (Fisher and Calaby 2009). The insects almost certainly included samples of butterflies and moths, but this material has not yet been

studied. However, the type of *Idalima leonora* was collected from Port Essington (Walker 1854); this fine diurnal moth species was described (as *Agarista leonora*) by Edward Doubleday in England in 1846 based on material (two specimens) in the John Gould collection. Doubleday subsequently described *Euploea sylvester pelor* in 1847, although it is not certain exactly where the type came from other than somewhere in 'north-western Australia' (Edwards et al. 2001). A few years earlier, *Papilio fuscus canopus* was described by J. O. Westwood, in 1842 (as *Papilio canopus*), based on type material from nearby Melville Island (Edwards et al. 2001). A small British military outpost was established on Melville Island between 1824 and 1829 (Fisher and Calaby 2009), and this may have been the time when the first specimens of *P. fuscus canopus* were collected.

In 1887, W. W. Froggatt—who a few years earlier was appointed the natural history collector for the Macleay Museum at the University of Sydney—was sent to the western Kimberley (Derby, Lennard River, Fitzroy River, 'Barrier Ranges') for almost a year to collect insects and other natural history objects (Froggatt 1934). Most of Froggatt's material is housed in the Macleay Museum and has not been examined, although a specimen of the rare and currently undescribed *Hecatesia* sp. 'Amata' on permanent loan in the Australian National Insect Collection (ANIC) has been examined.

In 1908–09, F. P. Dodd and his second son, W. D. Dodd, spent 10 months stationed at Darwin (Anonymous 1909; Dodd 1935a; Monteith 1991), where they made a substantial collection of butterflies and other insects. They were based at the old railway workshops and locomotive depot (now subsumed by the suburb of Parap) and collected extensively within a radius of a few kilometres and from the nearby East Point (Braby and Nielsen 2011). Most notable among the many discoveries made by the Dodds was *Ogyris iphis doddi*, which was formally described by G. A. Waterhouse and G. Lyell in 1914 (Waterhouse and Lyell 1914; see also Dodd 1935a; Braby 2015a). Waterhouse (1932) also later described several hesperiids based on Dodd material from 'Port Darwin'. W. D. Dodd subsequently visited the Kimberley (Broome, Derby, Fitzroy River, Grant Range) and the Top End (Melville and Bathurst islands, Darwin, Pine Creek, western Arnhem Land) during an epic (18-month) solo field expedition in 1912–13 funded by the South Australian Museum (Monteith 1991). The butterfly and other natural history specimens collected on that field trip are currently registered in the South Australian Museum (SAM). Many years later, Dodd (1935b, 1935c, 1935d) recounted his experiences in the Kimberley and the Top End and referred to several butterflies—namely, *Ogyris amaryllis*, *Papilio fuscus*, *Liphyra brassolis* and *Candalides margarita*.

During 1921–22, N. B. Tindale, an anthropologist and entomologist at the South Australian Museum, undertook extensive field studies on Groote Eylandt and its adjacent islands and the Roper River area, in the Northern Territory, and published several key papers from this work (Tindale 1922, 1923, 1927), including the description of *Nesolycaena urumelia* (as *Adaluma urumelia*). Tindale subsequently visited Mornington Island, Queensland, in 1963 (Fisher 1992). T. G. Campbell visited the Northern Territory from 1929 to 1933; he mainly collected butterflies at Brocks Creek, but also on Melville Island and Wyndham, in Western Australia. Much of his material was new and subsequently described by Waterhouse (1933, 1938). J. O. Campbell visited Darwin in 1945 and published an account of the butterflies he recorded (Campbell 1947). F. M. Angel and F. E. Parsons made an expedition to the Northern Territory in 1948; they travelled along the Stuart Highway from Adelaide, in South Australia, and made thorough collections around the major towns between Elliott and Darwin, details of which they subsequently published (Angel 1951; Couchman 1951). Of particular interest were the discovery and description of two new taxa: *Synemon wulwulam* and *Suniana lascivia larrakia* (as *Suniana larrakia*).

Warham (1957) and Koch (1957) made early compilations of the butterfly fauna of the Kimberley. Koch subsequently published a list of species from Koolan Island in Yampi Sound, Western Australia (Koch and van Ingen 1969; Koch 1975), which was later updated by McKenzie et al. (1995). J. C. Le Souëf visited the Top End in 1969 and again in 1971 (Le Souëf 1971); he mainly collected between Darwin and Mataranka, and between Timber Creek in the Northern Territory and Wyndham in Western Australia. Of particular note was the discovery of *Deudorix smilis*, which was recorded for the first time from Australia and described as a distinct subspecies, *Deudorix smilis dalyensis* (as *Virachola smilis dalyensis*) (Le Souëf and Tindale 1970; see also Braby 2016c).

Other less well-known field workers operating during the early twentieth century were M. Lain and F. Omer-Cooper, both of whom collected in northern Arnhem Land (including King River and Maningrida) in 1915–16 and 1968, respectively (Peters 1969). L. D. Crawford collected many butterflies from Darwin in 1955, as did R. G. Byrnes, who also travelled widely in the north-western corner of the Top End and eastern Kimberley during 1969–70.

In the 1950s and 1960s, agricultural research stations were established at Kununurra in Western Australia and Humpty Doo and Katherine in the Northern Territory. This led to the appointment of permanent entomologists in these towns and, although their focus was mainly on insect pest species, butterflies were reared and collected, especially skippers (Hesperiidae) associated with rice. The study by Koch (1957), for example, was based primarily on material in the Kimberley Research Station and Ord River Station (near Kununurra) made by C. F. H. Jenkins in 1944, R. G. Lukins in 1953 and L. E. Koch in 1957, among others.

Between 1970 and 1980, the level of field exploration of northern Australia and resulting scientific publications on the butterflies of the region increased dramatically, particularly from remote areas that previously had been poorly surveyed, such as the western and northern Kimberley and western Arnhem Land (e.g. Common 1973, 1981; Hutchinson 1973, 1978; Bailey and Richards 1975; Hall 1976, 1981; Common and Upton 1977; Edwards 1977, 1980, 1987; Dunn 1980; Kikkawa and Monteith 1980; Monteith 1982). From the 1980s to the present there has been a more or less permanent presence of local naturalists, amateur lepidopterists and professional entomologists, mainly based in Darwin, with an interest in butterflies.

Aims and purpose

This book has several aims. The main purpose is to compile a comprehensive inventory and atlas of the butterflies and diurnal moths of the western section of the AMT. In particular, we aimed to answer the following questions:

1. How many species occur in the region (i.e. what is the overall species richness)?
2. What kinds of species occur in the region (i.e. what is the composition)?
3. What proportion of and which taxa are restricted to the region (i.e. what is the level of endemism)?
4. What is their geographical/breeding range (i.e. what is their spatial distribution)?
5. What are their ecological requirements according to larval food plant specificity and habitat preferences?
6. What is the breeding status of those species (i.e. which taxa are resident, immigrant, visitor or vagrant)?
7. When are they most abundant as adults (i.e. what is their temporal distribution), do they breed continuously or seasonally and what strategies have they evolved to cope with the adversity of the dry season?
8. What is their conservation status (i.e. which taxa are under threat)?

The overall goal is to provide the scientific basis on which to ensure the future conservation of this diverse group of invertebrates. By answering such fundamental questions, analysis of distributional patterns can then be undertaken to provide a broader perspective of the historical biogeography and evolutionary history of the fauna as a whole (Bowman

et al. 2010), as well as to identify centres of endemism or biodiversity 'hotspots' that enable policymakers and managers to set priorities for conservation management (Braby and Williams 2016). Although not strictly part of this work, these later goals will be the subject of a forthcoming study.

Although our main focus is on butterflies, we have included a set of diurnal moths (31 species) for several reasons. First, diurnal moths are usually ignored by butterfly workers because they are moths, yet they show many characteristics similar to, and are often confused with, butterflies—for example, they are day-flying, colourful, often conspicuous, may feed on flowers and many have similar life histories in that most are phytophagous folivores. Second, moth workers frequently ignore diurnal moths because they are not active, or rarely active, at night. However, our selection and inclusion of diurnal moths are somewhat subjective. We have generally included only the more conspicuous species representing the families Sesiidae, Castniidae, Zygaenidae, Immidae, Geometridae, Uraniidae, Erebidae and Noctuidae (Agaristinae) and have not dealt with the smaller, less conspicuous groups (e.g. Heliozelidae, Glyphipterigidae, Heliodinidae, Brachodidae, Choreutidae). Also, with the exception of one species, we have not included members of the diurnal Arctiinae (family Erebidae) (e.g. *Amata*, *Asura*) because the taxonomy and species boundaries of these genera are in such a parlous state. And we have not included the Sphingidae, several of which are day-flying (e.g. *Cephonodes*) or crepuscular (e.g. *Macroglossum*), because of the great difficulty of identifying the species in flight. Even specimens of *Cephonodes* are difficult to identify and the genus in northern Australia comprises a complex of at least four species, which are currently under taxonomic revision (M. S. Moulds, unpublished data). Two species of Agaristinae appear to be strictly nocturnal (*Leucogonia cosmopis*, *Ipanica cornigera*) while several others are crepuscular (*Periopta ardescens*, *Radinocera* spp., *Mimeusemia* spp.); however, all of these are included for completeness given that the subfamily is such a dominant group in the fauna, with 19 taxa.

Using this book

This book is intended as a reference work for lepidopterists, butterfly naturalists, hobbyists and collectors, as well as professional natural resource managers, conservation biologists, entomologists, scientists and students interested in landscape ecology and tropical ecology. It should also provide an important resource for those people interested in butterflies who are visiting northern parts of Australia. Moreover, it will provide a baseline assessment of the biodiversity of butterflies and day-flying moths in the region, given that the AMT is undergoing substantial environmental change. Thus, it will undoubtedly be viewed as a valuable information resource for political debate on future land use.

Of interest to most readers will be the species accounts, which form the basis of this book. For each species, we have organised the information into eight topics: distribution, any excluded records, habitat, larval food plants, attendant ants (for lycaenid butterflies), seasonality, breeding status and conservation status. The distribution (and excluded data) section includes a map showing the point data, together with the spatial distribution of the relevant larval food plants, and a geographic range map based on those data points. The habitat and larval food plant (and attendant ants) sections provide a summary of the main ecological resources required for each species within their geographic distribution. The seasonality section includes phenology charts of the adult and immature stages and, where sufficient data are available, graphs showing seasonal changes in relative abundance—that is, their occurrence in time. The section on breeding status was derived by integrating information on distribution, habitat, larval food plants and seasonality. The section on conservation status was determined from an analysis of distribution and breeding status.

This text is taken from *Atlas of Butterflies and Diurnal Moths in the Monsoon Tropics of Northern Australia*, by M.F. Braby, D.C. Franklin, D.E. Bisa, M.R. Williams, A.A.E. Williams, C.L. Bishop and R.A.M. Coppen, published 2018 by ANU Press, The Australian National University, Canberra, Australia.