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The invasion and potential impact of the Asian House Gecko (*Hemidactylus frenatus*) in Australia

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Abstract *Hemidactylus frenatus* is an Asian gecko that has spread pantropically to become one the world's most widespread reptiles. It has been established in Australia for approximately 50 years, but the last two decades have seen massive range expansion across settled areas of northern and eastern Australia; and this spread continues at pace. Disturbingly, *H. frenatus* is increasingly being detected in natural habitats in Australia, in some cases at high densities. Despite rampant spread, there has been little concern regarding the potential impact of this species on native geckos or natural systems more broadly. This is surprising given that Australia is a centre of gecko origin and diversity, and that *H. frenatus* has had well documented detrimental impacts on geckos in other parts of its introduced range. Here I review the biology and global distribution of *H. frenatus*, plot its spread in Australia over the five decades since establishment, and review the research on invasive populations of this species overseas and in Australia to assess potential impacts. I argue that Australia should be more concerned about *H. Frenatus* because: (i) it is spreading rapidly across northern, eastern and central Australia; (ii) it can invade natural habitats; (iii) it is a very strong competitor and may out-compete Australian geckos in some situations; and (iv) it carries novel parasites that may impact native reptile species. *Hemidactylus frenatus* is here to stay and represents a potential threat to Australia's diversity and ecology. A key question is the degree to which it will invade natural habitats and what its impacts will be in these. Research is required to assess the current and potential impacts of *H. frenatus* in Australia so as to determine how these can be managed and the level of investment warranted.

Key words: competition, invasive species, parasite, range expansion, reptile.

INTRODUCTION

Species continue to be introduced, deliberately or accidentally, to areas outside their natural range, where they may establish, spread and significantly impact ecology and diversity (Williamson 1996; Mack *et al.* 2000). As seen for other long-isolated islands and landmasses (e.g. Hawaii, New Zealand), the Australian fauna and flora has been severely impacted by introduced species (Case & Bolger 1991; Caughley & Gunn 1996; Fritts & Rodda 1998; Low 1999; Towns *et al.* 2001; Phillips & Shine 2004). However, to date, reptile introductions have been of relatively limited impact. Globally, at least 185 species of reptiles have become naturalized (introduced and established) outside their native range (Lever 2006). Only four of these involve introductions into Australia – the Red-eared Slider (*Trachemys scripta*), the Flowerpot Snake (*Ramphotyphlops braminus*), the Asian House Gecko (*Hemidactylus frenatus*) and probably the Mourning Gecko (*Lepidodactylus lugubris*). This is a relatively small number compared with mammals and birds (approx. 25 introductions each), but not amphibians (one species, the Cane Toad) (Low 1999); and these reptile introductions have generally remained localized.

The exception is the Asian House Gecko *H. frenatus*, which is currently spreading rapidly across Australia. Despite the speed and extent of this spread, and widely documented impacts of this species on gecko fauna in other parts of its introduced range (reviewed herein), very little concern has been shown for its potential impact in Australia. This is particularly surprising given that Australia is a centre of gecko origin and diversity. Four of the seven families of Gekkota are present in Australia (Gamble *et al.* 2008) and much of Australia's gecko diversity represents diversification of ancient lineages of Gondwanan origin (Bauer 1990; Oliver & Sanders 2009). Australia has over 115 described gecko species from 27 genera (Wilson & Swan 2008) and species diversity in some groups remains well underestimated (e.g. Oliver *et al.* 2009). Therefore, a rapidly invading gecko of known consequence should have raised serious concern in Australia, but it has not.

Here I explore whether Australia should be so relaxed about the invasion of *H. frenatus*. I review the research on *H. frenatus* internationally and in Australia, and outline the likely extent of invasion, the primary threats posed and what should be done to assess and

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manage this threat. I start by reviewing the biology of *H. frenatus*, because this is fundamental to understanding the spread and impact of an invasive species.

NATURAL HISTORY, ECOLOGY AND PHYSIOLOGY OF *HEMIDACTYLUS FRENATUS*

General ecology

Hemidactylus frenatus Duméril & Bibron 1836 is a small- to medium-sized (up to approx. 60 mm snout–vent length) arboreal gecko (Cogger 2000; Greer 2006). It is nocturnal, seeking refuge in crevices and other sheltered sites during the day. The fingers and toes of *H. frenatus* have claws as well as pads with setae, which enable activity on a variety of surfaces (Greer 1989; Zani 2000). For animals that forage under the relatively cooler conditions of the night, many geckos have remarkably broad physiological tolerances (Greer 1989). *Hemidactylus frenatus* conforms to this generality, selecting relatively warm conditions in the lab and displaying critical thermal minima and maxima similar to that of a diurnal lizard (Huey *et al.* 1989). Peak activity varies across studies, from just after sunset to midnight, but is generally high throughout the night (Greer 2006). Activity is influenced by air and substrate temperatures, to which body temperature is closely matched (Marcellini 1971, 1976; Cogger *et al.* 1983). *Hemidactylus frenatus* has been recorded active at body temperatures between 19 and 34°C (Marcellini 1976, 1977; Cogger *et al.* 1983; Greer 1989; Savage 2002).

Foraging ecology

Hemidactylus frenatus emerges from its diurnal refuge on dusk to forage on nearby surfaces, particularly those that are vertical (Petren & Case 1996, 1998). It is a generalist predator of insects, particularly Diptera, Lepidoptera, Blattodea and Coleoptera, and also spiders (Tyler 1961; Chou 1974; Cogger *et al.* 1983; Greer 1989; Bolger & Case 1992; Newberry & Jones 2007). Compared with most geckos, *H. frenatus* is a fast, active forager, pursuing prey rather than just waiting for it to come within striking distance (Case *et al.* 1994; Petren & Case 1996). It is also a very efficient forager (Case *et al.* 1994; Petren & Case 1996), displaying higher consumption rates than a native Australian gecko in experimental trials (Canyon & Hii 1997). Although generally seen foraging around lights, *H. frenatus* can also forage effectively under near-complete darkness (Canyon & Hii 1997).

Intraspecific and interspecific aggression

Both when foraging and sheltering, *H. frenatus* often occurs at very high densities compared with many other geckos, in part due to relatively low intraspecific aggression (Petren & Case 1998; Brown *et al.* 2002). It is nonetheless an aggressive species, with vocal interactions and fighting being conspicuous activities in high-density populations. Unlike all Australian gecko species, *H. frenatus* is very vocal, uttering several different call types – a rapid burst of short chirps ('churr' call) uttered at close range between males in highly aggressive encounters, a 'single chirp' call when attacked or handled, and series of chirps 'chuck, chuck, chuck . . .' ('multiple chirp' call) that functions in social interactions associated with spacing, aggression and mating behaviour (Marcellini 1974, 1977). Sexually mature individuals of both sexes call but males call and respond to calls much more than females, and the primary function of the multiple chirp call appears to be territoriality in males (Marcellini 1974, 1977). The multiple chirp call is the most frequently uttered, both night and day, and is a distinctive nocturnal sound wherever *H. frenatus* is present. *Hemidactylus frenatus* is also aggressive towards other gecko species, in some cases actively excluding them from food sources and retreat sites (Bolger & Case 1992; Petren *et al.* 1993; Brown *et al.* 2002; Cole *et al.* 2005; reviewed herein).

Breeding biology

Hemidactylus frenatus has year-round activity and breeding in tropical areas, but is seasonal in subtropical, temperate and higher altitude areas with cool winters (e.g. Brisbane) (Church 1962; Cogger *et al.* 1983; Ota 1994; Murphy-Walker & Haley 1996; Wilson 2006; Yamamoto & Ota 2006). Breeding is sexual, with mature males being externally distinguishable by a bulbous post-cloacal swelling associated with the copulatory organs. There is little sexual dimorphism in body size (Sabath 1981), but males are on average slightly larger than females (Church 1962; Savage 2002; Vences *et al.* 2004). Each clutch usually consists of two hard-shelled eggs that are laid in a crevice (Church 1962; Husband 1980; Cogger *et al.* 1983; Krysko *et al.* 2003); and eggs are sometimes adhered to surfaces and to each other (Greer 1989). Communal nesting has been recorded (Cogger *et al.* 1983; Cogger 2000; Krysko *et al.* 2003). Incubation time is 45–90 days, depending on temperature (Church 1962; Chou 1979; Husband 1980; Greer 1989; Krysko *et al.* 2003; Das 2006). Ota (1994) reported the minimum incubation temperature for hatching to be 19°C. Females can produce a clutch every 3–5 weeks, depending on temperature and

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female dietary intake (Murphy-Walker & Haley 1996; Krysko *et al.* 2003). Females can store sperm (Murphy-Walker & Haley 1996; Yamamoto & Ota 2006), with one female storing sufficient sperm to produce six clutches (totalling 10 eggs and including offspring of both sexes) over 1 year (Yamamoto & Ota 2006). *Hemidactylus frenatus* hatches at approximately 20 mm snout–vent length (Cogger *et al.* 1983) and reaches sexual maturity at 36–45 mm (Church 1962; Sabath 1981; Keim 2002; Savage 2002), which probably occurs within 1 year. Therefore, *H. frenatus* has very high potential reproductive output.

NATIVE RANGE AND INTERNATIONAL SPREAD

Hemidactylus is a large pantropical genus of approximately 80 species (Carranza & Arnold 2006). *Hemidactylus frenatus* is native to South and South-East Asia, including southern India, Sri Lanka, Bangladesh, Indo–China, Thailand, western Malaysia and Indonesia (Lever 2006). The exact limits of the native range are uncertain, particularly in South-East Asia and parts of the Indo–Pacific region such as eastern Indonesia, the Phillipines and New Guinea (Case *et al.* 1994; Das 2006; Lever 2006). A complication is the degree to which *H. frenatus* was inadvertently spread to Pacific islands by Polynesians and Melanesians approximately 4000 years ago (Dye & Steadman 1990; Case & Bolger 1991; Case *et al.* 1994). Furthermore, *H. frenatus* likely spread naturally to some remote Pacific islands as adults or eggs under bark of trees washed out to sea (Brown & Alcala 1957; Pianka & Vitt 2003). This uncertainty aside, of interest here is that *H. frenatus* is a tropical Asian species that has undergone massive, human-mediated range expansion in the last century; as supported by genetic studies (Carranza & Arnold 2006).

Range expansion since the 1950s is well-documented and has occurred primarily with increased shipping and cargo movement (Case *et al.* 1994; Carranza & Arnold 2006; Lever 2006; Rödder *et al.* 2008). *Hemidactylus frenatus* spreads as a stowaway, facilitated by its association with humans, small size and cryptic nature, the 'hardiness' of adults and eggs (which are hard-shelled and resistant to desiccation and tolerant of immersion and exposure to sea water), and the sperm storage capabilities of females (Brown & Alcala 1957; Case *et al.* 1994; Yamamoto & Ota 2006). *Hemidactylus frenatus* is now one the world's most widespread lizards. The introduced range currently includes parts of South-East Asia, Japan, parts of central America, Mexico and southern USA, Madagascar, Kenya, Australia, and many islands of the Pacific, Indian and Atlantic Oceans (Lever 2006; Rödder *et al.* 2008). The spread of *H. frenatus* continues at pace in these introduced regions, and the species continues to threaten to invade new regions. For example, *H. frenatus* has regularly been intercepted arriving in cargo at New Zealand ports, particularly since the mid 1980s (Gill *et al.* 2001). Climatic niche modelling predicts significant further global range expansion, particularly in South America and Africa, with further extension under a 2100 climate change scenario (Rödder *et al.* 2008).

WHY AUSTRALIA SHOULD BE CONCERNED

Current rate of spread and potential distribution of *Hemidactylus frenatus* in Australia

Hemidactylus frenatus has been present on some Australian island territories for some time (e.g. since the late 1930s on the Cocos (Keeling) Islands; Cogger *et al.* 1983), but here I focus on introduction and spread on the Australian mainland and adjacent islands. Figure 1 shows the accumulation of records across decades (see caption for sources). This accumulation of records is only an approximation of establishment and spread for the following reasons: the data are coarsely split by decade, effort is not equal across decades, *H. frenatus* may be present at a site for some time before detection or reporting, and it is not always possible to determine whether *H. frenatus* established and persisted at that site.

There are two records from the Australian mainland before 1960, one from Port Essington (on the Coburg Peninsula, Northern Territory) and one from Darwin (Fig. 1A). The Port Essington record, a specimen collected between 1838 and 1845, is the earliest account of *H. frenatus* in Australia (Greer 2006; Fisher & Calaby 2009). This settlement was established in 1838 and abandoned in 1849, following which *H. frenatus* apparently did not persist (Cogger 1975; Ehmann 1992; Fisher & Calaby 2009). The Darwin record is from before 1939 (collection date uncertain), but *H. frenatus* did not establish in Darwin at this time, as there are no subsequent records until the large number in the 1960s. The other records before 1960 come from the Crocodile Islands (off the Northern Territory) in 1948, and Moa and Thursday Islands (off Cape York) before 1922 and 1928, respectively (collection dates uncertain). At what point *H. frenatus* established on islands off northern Australia is hard to determine due to limited and sporadic surveys through time. Therefore, as for the pre-1960 mainland records, these one-off island records are not retained as established populations on the subsequent panel (Fig. 1B).

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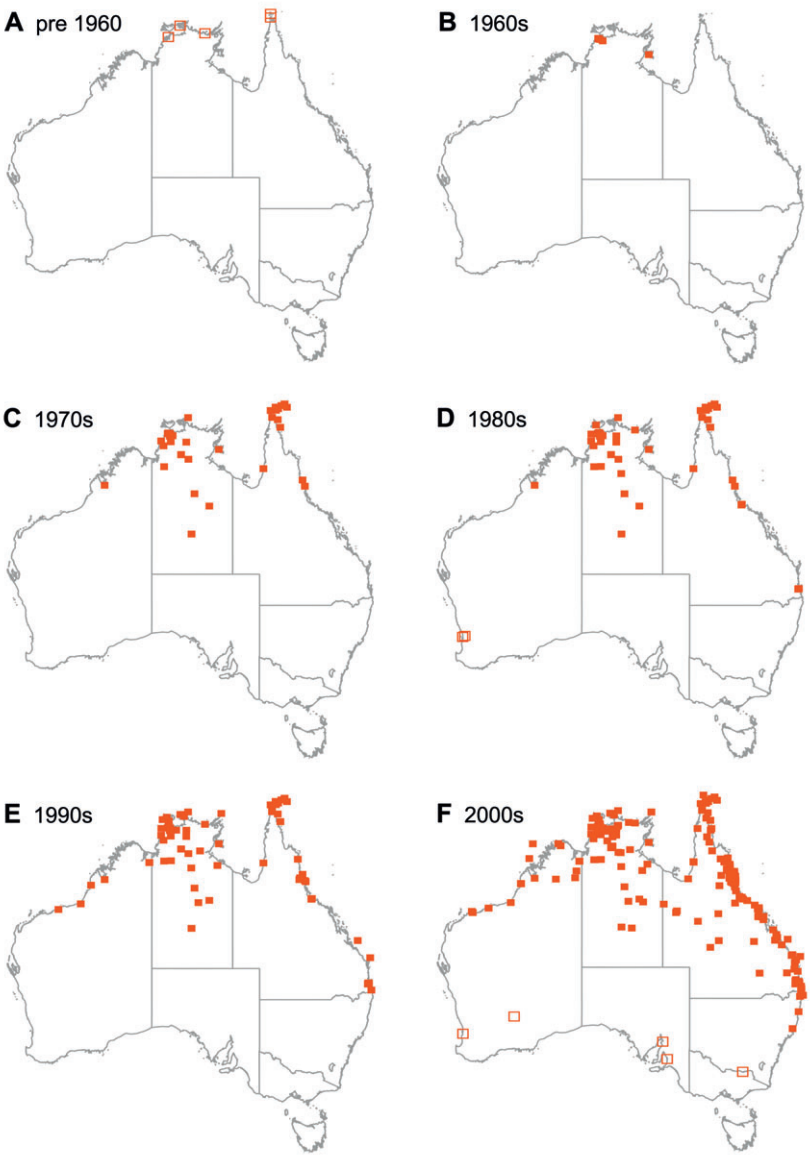

Fig. 1. The spread of *Hemidactylus frenatus* in Australia. The maps show (A) records before 1960, then (B–F) the accumulation of records in the following decades. Solid red squares represent records from established populations. Open red squares represent individuals collected from sites where *H. frenatus* did not establish at that point in time – these sites are not retained on the map of the following decade. Records come from museum specimen data (Queensland Museum, Australian Museum, Western Australian Museum, Museum and Art Gallery of the Northern Territory, South Australian Museum, Museum Victoria), my own records (1995–2009) and the literature (Cogger 1975; Wilson & Knowles 1988; Cook 1990; Wilson & Swan 2003, 2008, 2009; Greer 2006; McKay *et al.* 2009).

Hemidactylus frenatus established in Darwin in the 1960s, with a record in 1960 and then large numbers of records in the years following that (Fig. 1B). By the 1970s, it was well established in the north of the Northern Territory and had spread south along the Stuart Highway to a number of sites (Fig. 1C). By this time, it was also well established on islands of the Torres Strait and was present at a number of sites in north Queensland (e.g. Cairns). The first record from Western Australia also came in the 1970s (Derby in 1975). The 1980s saw continued expansion in the Northern Territory, establishment in Townsville and the first records for south-east Queensland (Fig. 1D). *Hemidactylus frenatus* appeared in Brisbane in 1983 at a container terminal at the Port of Brisbane and then at nearby wharves and storage areas (Low 1999; Couper *et al.* 2007). It remained localized and patchy in inner Brisbane into the early 1990s (Wilson & Czechura 1995) slowly radiating along transport corridors, then expanded massively from the mid 1990s

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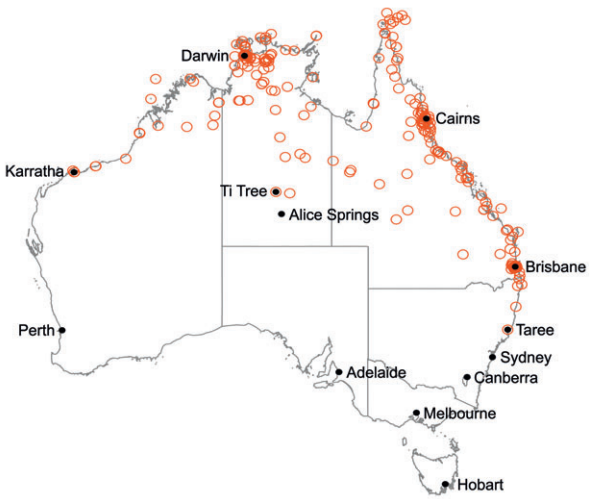

Fig. 2. The current distribution of *Hemidactylus frenatus* in Australia. This matches Figure 1F but only established localities are shown and open circles are used to better show density of records.

through much of Brisbane and neighbouring urban centres and rural communities in south-east Queensland (Low 1999; Wilson 2006; Couper *et al.* 2007). The 1990s were also a period of expansion to other settlements along the Queensland coast and across northern Australia, including scattered sites in Western Australia (Fig. 1E). Expansion continued to fill in these bounds from 2000 to 2009, with considerable additional expansion in inland Queensland, north-west Australia and south along the New South Wales coast (Fig. 1F). *Hemidactylus frenatus* also continues to spread to new Australian islands, for example, becoming established on Norfolk Island in 2005 (Cogger *et al.* 2005).

Hemidactylus frenatus now has an extensive but patchy distribution across northern and eastern Australia, centred on urban areas and isolated settlements (Fig. 2). Areas of core distribution at present are the north of the Northern Territory and the Queensland coast from Cape York to south-east Queensland. *Hemidactylus frenatus* has spread so rapidly over such a large area of Australia because it is very easily translocated by accident. An analysis of reptiles intercepted being accidentally introduced to New Zealand showed that geckos (including *H. frenatus*) arrive regularly in ship and plane cargo from South-East Asia, particularly in personal effects, motor vehicles, timber, machinery, fruit and vegetables and manufactured goods (Gill *et al.* 2001). Introduction to Australia has most likely included (and probably continues to include) multiple independent introductions to major ports (e.g. Darwin, Brisbane) via ship cargo from South-East Asia. For example, the first Brisbane records come from the shipping container terminal at the Port of Brisbane (Low 1999; Couper *et al.* 2007). From these original points of introduction into Australia, *H. frenatus* expanded rapidly across urban areas and has been readily spread along transport networks to other areas of human habitation. This has resulted in a complex pattern of 'spot-fire' like spread rather than expansion along a single invasion front.

Based on the degree of spread in the last decade (Fig. 1F), the range of *H. frenatus* will continue to expand rapidly in north, east and central Australia. Climatic niche predictions suggest an extensive potential distribution across north and east Australia and potentially even parts of the south-east and south-west (Rödder *et al.* 2008; Csurhes & Markula 2009), with further extension under a 2100 climate change scenario (Rödder *et al.* 2008). *Hemidactylus frenatus* is occasionally detected at southern localities (primarily major ports and airports, e.g. Perth, Fremantle, Adelaide, Kalgoorlie and Albury; Fig. 1D,F) but it has not established in these areas, possibly because winters are too cold (Greer 2006). However, microhabitat selection, behavioural seasonality and other adaptive responses may facilitate establishment in these cooler areas, at least in urban environments, which are thermally buffered and have warm microhabitats ideal for *H. frenatus*. Robust prediction of potential distribution in Australia requires distribution modelling methods that incorporate physiological and ecological data, as outlined in Kearney and Porter (2009). The key question is: what is the current and potential range of *H. frenatus* in natural habitats?

Hemidactylus frenatus can invade natural habitats

Hemidactylus frenatus is one of five *Hemidactylus* that have undergone recent human-facilitated range expansions (Carranza & Arnold 2006). All are considered 'weedy' species due to their commensal existence with humans in disturbed areas (Kluge 1969), and concern in Australia has been limited for this reason. In Australia, *H. frenatus* is generally considered to be largely restricted to dwellings and other human structures, as supported by reports it disappeared from abandoned settlements in northern Australia (presumably referring to Port Essington) (Greer 1989; Cogger 1992; Ehmann 1992; Wilson & Swan 2008). There are, however, a number of points to consider. *Hemidactylus frenatus* occupies a range of natural habitats in its native range, and is increasingly documented from natural habitats across its introduced range, including in Australia. Additionally, within urban areas, *H. frenatus* can be abundant on natural features such as trees, rocks and cliffs (e.g. in Brisbane, Hoskin, pers. obs., 2009). Furthermore, just as many arboreal and rock-dwelling Australian geckos effectively utilize human

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structures (including *Gehyra* spp., *Oedura* spp., *Christinus* spp. and *Phyllurus platurus*), the reverse should be expected for *H. frenatus*.

Although generally considered a human commensal (a 'house gecko') across much of its native range, *H. frenatus* also inhabits trees and rocks in a wide variety of natural and disturbed habitats (Loveridge 1946; Taylor 1966; Das 2006). In introduced populations, invasion beyond human habitation has been patchy, with invasion of natural habitats (in some cases to become the most abundant gecko) in some areas (e.g. the Mascarene Islands, Cole *et al*. 2005; Guam, Wiles *et al*. 1989; Hawaii, McKeown 1996; Phillipines, Keim 2002) but not others (e.g. Fiji, Case *et al*. 1994; Morrison 2003; Japan, Goris & Maeda 2004; New Guinea, F. Kraus, pers. comm., 2009). Invasion of forested habitats across Pacific Islands has been patchy and this has been attributed to variation in insect abundance (Petren & Case 1998). Environments that *H. frenatus* has been recorded in across its introduced range include: a variety of undisturbed and disturbed forest types (Grant 1957; Chou 1974; Wiles *et al*. 1989; Bauer & Vindum 1990; McCoid 1996; McKeown 1996; Petren & Case 1998; Bauer & Sadlier 2000; Cole *et al*. 2005); isolated trees, shrubs and rocks in open fields and grassland (McCoid 1996; Wiles & Guerrero 1996); coastal vegetation including coconut palms (Wiles *et al*. 1989; Bauer & Sadlier 2000); rocky terrain, including piled rock, basalt, coralline rock and compacted tuff (Grant 1957; Bour & Moutou 1982; McKeown 1996; Cole *et al*. 2005); and ground debris such as timber (McKeown 1996).

The extent of invasion of natural habitats in Australia remains poorly known. Research to date suggests invasion is patchy and localized, but at high density in some areas. *Hemidactylus frenatus* has been recorded in a variety of disturbed and undisturbed natural habitats, including: eucalypt woodland, riparian and coastal monsoon forests, coastal forests (including those dominated by *Casuarina*), *Melaleuca* swamp forests, mangroves, areas rich in *Pandanus* palms, coconut palms along beaches, rocky gullies, and among beach debris such as coral boulders, palm fronds and logs (Kikkawa & Monteith 1980; Cogger *et al*. 1983; Gambold & Woinarski 1993; Keim 2002; McKay *et al*. 2009; museum specimen records; Hoskin, pers. obs., 1995–2009). All these records come from northern Australia, with no evidence yet of invasion of natural habitats in more southerly areas of the current distribution (e.g. south-east Queensland, Couper *et al*. 2007). In the Northern Territory, McKay *et al*. (2009) report localized presence in a variety of forest types (particularly denser forests) at a number of sites in the far north of the Northern Territory. These records generally came from within 500 m of anthropogenic structures, but a few also came from deeper in natural habitats, including two individuals found over 1 km from human structures (McKay *et al*. 2009). In north Queensland, *H. frenatus* is generally absent from natural habitats; however, at some sites it occurs at high density in forest habitats considerable distances from human habitation (Hoskin, unpubl. data, 2009).

Keim (2002) investigated *H. frenatus* abundance across the interface between suburban housing and native forest in Brisbane and Darwin. In Brisbane, *H. frenatus* was present on houses but not in adjacent bushland (see also Couper *et al*. 2007), whereas at some Darwin sites it was present at considerable densities up to 150 m into bushland. *Hemidactylus frenatus* density was not assessed further into forest than this. Although at some sites densities in forest habitats were as high as those in suburbia, suburban densities were generally higher, leading Keim (2002) to suggest presence in forest may be driven by dispersal pressure from the suburban populations rather than establishment in forest habitats (i.e. source-sink). Presence in forest habitats in Darwin but not Brisbane was attributed to several possible reasons: longer occupation of Darwin (approx. 40 years *vs.* 20 years), competition with native geckos, and the more tropical climate of Darwin (Keim 2002). Variation in density in forest sites across Darwin was attributed to differences in habitat characteristics, but this was not tested in detail.

Therefore, both overseas and in Australia *H. frenatus* is patchily invading a wide variety of natural habitats, and in some cases at high density. The question is: will invasion remain localized or will more comprehensive infiltration of natural habitats occur with time? In northern Australia at least, it appears that *H. frenatus* is increasingly being detected in habitats away from human habitation. Why *H. frenatus* invades natural habitats in some areas and apparently not in others is unresolved. Where *H. frenatus* is present in natural habitats, it is generally at lower densities than in urban areas (e.g. Petren & Case 1998; Keim 2002); and this could be taken to suggest that it is not well-suited to these habitats and hence not a threat to native species. However, native geckos that use human dwellings also generally occur at higher density (or are more easily detected) on these than in surrounding natural habitats (Hoskin, pers. obs., 1995–2009), so lower relative densities of *H. frenatus* in natural habitats does not necessarily indicate low suitability habitat or insignificant densities *versus* native species.

Prolific urbanization, habitat fragmentation and a desire for people to live in 'bush' settings may facilitate invasion of natural habitats. *Hemidactylus frenatus* has been spread to thousands of dwellings in or adjacent to bushland in northern and eastern Australia, resulting in large areas of interface between high-density populations on dwellings and adjacent natural habitats. In the process, *H. frenatus* is inadvertently being introduced to a wide variety of habitat types, some of which may be more suitable than others and providing

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countless staging grounds for potential adaptation. Furthermore, the disturbed edge around human habitation may provide a gradient of environmental conditions into natural habitats that may facilitate invasion (Keim 2002). Additionally, although *H. frenatus* is currently largely absent from natural habitat in remote areas such as national parks, it is often present in these areas on structures such as picnic shelters and toilet blocks (Hoskin, pers. obs., 1995–2009); presumably transported in on building materials. This issue is magnified by increasing pressure to improve user access and facilities in protected areas.

Hemidactylus frenatus can out-compete other geckos, both in man-made and natural settings

Hemidactylus frenatus has been implicated in displacing resident geckos from the house gecko niche in many regions, particularly *L. lugubris*, *Gehyra* spp. and *Hemidactylus* spp. on islands of the Pacific and Indian Oceans (Cogger *et al.* 1983; Bauer & Vindum 1990; Petren *et al.* 1993; Case *et al.* 1994; Petren & Case 1996; McCoid 1999; Bauer & Sadlier 2000; Lever 2006). The interaction with *L. lugubris* on dwellings on Pacific islands has been studied in detail. *Hemidactylus frenatus* displaces *L. lugubris* through a number of mechanisms, including aggression – with *L. lugubris* in some cases excluded by *H. frenatus* from prime refuge and feeding sites (Bolger & Case 1992; Case *et al.* 1994; McKeown 1996; Brown *et al.* 2002), predation of *L. lugubris* juveniles by *H. frenatus* (Bolger & Case 1992; Case *et al.* 1994), and potential indirect competition through negative effects of *H. frenatus* exudates or faeces on *L. lugubris* fecundity (Brown *et al.* 2002). The primary mechanism, however, appears to be exploitative competition, with *H. frenatus* being a faster, more pursuit-orientated forager (Petren & Case 1996, 1998). Experiments of competition between *H. frenatus* and *L. lugubris* have shown that the competitive advantage to *H. frenatus* is reduced in structurally complex environments (walls with baffles *vs.* flat walls) and when food is dispersed rather than clumped (dispersed lights *vs.* a single light; Petren & Case 1998). These results have led to the suggestion that *H. frenatus* should be a less superior competitor against *L. lugubris* in natural habitats because insect resources will be less clumped, structural complexity is less suitable to pursuit-orientated foraging, and the advantage of being larger and faster may diminish in a dispersed resource environment (Petren & Case 1998). Indeed, on some Pacific Islands it has been observed that although displacement of resident geckos has been complete in urban areas, it has been incomplete or absent in rural or forested areas on the same islands (Petren & Case 1998).

Few studies have been conducted regarding competition in natural settings. Following introduction to Guam, *H. frenatus* was initially restricted to urban dwellings and almost entirely absent from forest habitats (Sabath 1981), but it subsequently became abundant in all habitat types, including grasslands and forested areas, where it is implicated in the decline of *Gehyra mutilata* (McCoid 1996). McCoid (1996) attributed invasion of forest to habitat disturbance and the effect of introduced predators on native geckos. The most thoroughly studied example of competition between *H. frenatus* and native geckos in natural settings regards the *Nactus* gecko radiation in the Mascarene Islands (Cole *et al.* 2005). Here *H. frenatus* has invaded nearly all natural habitats at high density and has out-competed *Nactus* through aggressive exclusion from daytime refugia, which increases the risk of predation and exposure to adverse weather conditions (Cole *et al.* 2005). The asymmetric aggression also results in injury to *Nactus* (toe and tail loss), potentially affecting growth, survival and fecundity (Cole *et al.* 2005). This has led to catastrophic declines in *Nactus* populations wherever *H. frenatus* has invaded, and the extinction of three species (Cole *et al.* 2005). The only place where *Nactus* is known to survive in the presence of *H. frenatus* is a small area of powdery tuff on one island (Cole *et al.* 2005). In this habitat *H. frenatus* movement and foraging abilities are impaired by the loose particular nature of the substrate, with particles adhering to the toe setae and reducing gripping ability (Cole *et al.* 2005). *Nactus* have toes with longer claws enabling them to grip the solid substrate beneath the powdery surface. Also in the Mascarene Islands, *H. frenatus* has been reported to be displacing the endemic day gecko *Phelsuma ornata* from native ebony forest on Ile Aux Aigrettes (Harris 2000, sourced from Lever 2006).

Hemidactylus frenatus has been implicated in displacing native geckos from the house gecko niche in Australia – *Gehyra australis* and *Oedura rhombifer* in Darwin (Greer 1989; Keim 2002; Wilson 2006; Wilson & Swan 2009) and *Gehyra dubia* in Townsville (Wilson & Swan 2009). The same appears to be occurring regarding *G. dubia*, *Oedura robusta* and *Oedura jacovae* in parts of Brisbane (Hoskin, pers. obs., 2006–2009). It has been suggested that large Australian geckos (e.g. *Oedura*) are unlikely to be impacted because they will be physically dominant over the relatively smaller *H. frenatus* and because they may predate on *H. frenatus* juveniles (e.g. Keim 2002; Cogger *et al.* 2005; Newberry & Jones 2007). For example, Keim (2002) found that *H. frenatus* was common on houses in a Brisbane suburb except those near forest, on which several native species were common. Keim (2002) suggested this may indicate competitive exclusion or predation by native geckos on *H. frenatus* on these houses. However, *H. frenatus* is now abundant on houses

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adjacent to forest in this suburb and native species are now rare (Hoskin, pers. obs., 2006–2009). If the primary impact of *H. frenatus* is exploitative competition for food resources (as in the Pacific, e.g. Petren & Case 1996, 1998), then body size may not confer the expected benefits in a competitive interaction (Stamps 1983; Case *et al*. 1994). Reports of coexistence between *H. frenatus* and natives on houses in Brisbane (Keim 2002; Couper *et al*. 2007; Newberry & Jones 2007) likely reflect temporary coexistence following recent arrival of *H. frenatus*.

Competition in natural habitats has not been assessed in Australia. Arboreal and rock-dwelling species in a range of habitats, particularly tropical sclerophyll and monsoon forests, across the northern half of Australia are potentially at risk of being displaced. I believe species in the following genera may be impacted (ordered from most to least likely impacted; number of Australian species in brackets): *Lepidodactylus* (2), *Oedura* (15), *Gehyra* (18), *Nactus* (4), *Heteronotia* (3), *Pseudothecadactylus* (3), *Cyrtodactylus* (1), *Christinus* (3), *Phyllurus* (8), *Orraya* (1) and *Saltuarius* (6). This list is based on distribution (northern and eastern Australia; localized *vs.* widespread), ecology (arboreal/rock-dwelling *vs.* terrestrial), habitat (dry forest types *vs.* rainforest), body size, and behaviour ('apparent' aggression). Competitive displacement in natural environments will depend on the degree to which *H. frenatus* invades habitats and how successful it is as a competitor in each of these habitats.

Hemidactylus frenatus carries novel parasites

Hemidactylus frenatus has been recorded carrying a wide range of parasites (Hanley *et al*. 1995; Hanley *et al*. 1998; Greer 2006), many of which will be novel to areas where *H. frenatus* is introduced. In Hawaii, parasites are known to have transferred from introduced *H. frenatus* to a resident gecko *L. lugubris* (Hanley *et al*. 1995). Foreign parasites and pathogens can have significant impacts on naïve hosts or may affect competitive interactions through differential effects on native and introduced species (Combes & Le Brun 1990; Hanley *et al*. 1995). We know little about the parasite fauna introduced into Australia with *H. frenatus*, or its potential to transfer to and impact Australian reptiles. At least two ectoparasitic *Geckobia* mites (*G. bataviensis* and *G. keegani*) appear to have been introduced into Australia on *H. frenatus* (Domrow 1991, 1992; Keim 2002; Walter & Shaw 2002). Both species have wide host specificity (Hirst 1926; Combes & Le Brun 1990) so may potentially shift to native hosts (Keim 2002; Walter & Shaw 2002). Mites can transfer blood parasites between individuals (Lewis & Wagner 1964; Walter & Shaw 2002) so introduced mites represent a potential vector for invasive blood parasites (Keim 2002; Walter & Shaw 2002). Barton (2007) found the pentastome blood parasite *Raillietiella frenatus* in *H. frenatus* in the Northern Territory, a parasite recorded from *H. frenatus* throughout South-East Asia and the Pacific Islands. The only other record of this parasite in Australia is a probable individual from a *Gehyra australis* from Darwin, potentially representing host-switching from *H. frenatus* (Barton 2007). Pentastome parasites feed on the host's blood and can potentially impact competition, reproduction and survival (Bush *et al*. 2001; Barton 2007).

Research is required to resolve what parasites and pathogens have entered (or could enter) Australia in or on *H. frenatus*, and the potential impacts on native reptiles. Introduced *Geckobia* mites could also impact native *Geckobia* species that are present on Australian geckos (Keim 2002; Walter & Shaw 2002).

Other potential issues – predation on geckos and invertebrates

In addition to competition and novel parasites, there are a number of other potential impacts to consider. *Hemidactylus frenatus* has been recorded preying on the eggs, hatchlings and juveniles of other gecko species (Church 1962; Hunsaker 1966; Bolger & Case 1992; Case *et al*. 1994; Brown *et al*. 2002; Cole *et al*. 2005; Dame & Petren 2006), particularly *L. lugubris* under lab settings. However, such predation appears rare in the wild (Bolder & Case 1992; Newberry & Jones 2007) and is unlikely to pose a threat to native geckos. The effect of *H. frenatus* predation on invertebrate populations is not known at all. Like most geckos, *H. frenatus* is a generalist predator, and, where it invades natural habitats, it is likely to be filling a similar niche to native geckos. Of consideration would be if *H. frenatus* were to invade habitats containing highly localized invertebrate species, for example, boulder-field habitats of north Queensland (Couper & Hoskin 2008), and exert elevated or novel predation pressure. Additionally, predation pressure by high density populations of *H. frenatus* could impact the broader ecology of natural habitats they invade.

WHAT HAS BEEN DONE IN AUSTRALIA?

Despite rapid and conspicuous spread in Australia and recognized impacts overseas, the invasion of *H. frenatus* has so far raised little concern in Australia. This is in sharp contrast to the conspicuously negative attitude regarding many other invasive species, such as cane toads, foxes and fire ants. The general lack of concern towards *H. frenatus* relates to: a general ignorance towards its introduced status; its 'cute' and 'friendly'

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appearance and call; enjoyment (particularly amongst children) in having geckoes around the house; the fact that it does not harm people or pets; the perception that it has a positive effect in reducing pest insect numbers (mosquitoes, flies, cockroaches and spiders) around houses (*H. frenatus* has been shown to be an effective predator of mosquitoes, Canyon & Hii 1997); the fact that native geckos are often rare, inconspicuous or absent on houses prior to *H. frenatus* so displacement is not obviously witnessed; and the fact that it is not an obvious threat to primary industries. Amongst scientists, managers and naturalists, *H. frenatus* has raised little concern because it is generally considered to be restricted to houses and unlikely to spread beyond urban areas into natural habitats (e.g. Wilson & Knowles 1988; Greer 1989; Ehmann 1992; Low 1999; Cogger 2000; Wilson 2005; Wilson & Swan 2008).

There has been little research or discussion regarding *H. frenatus* in Australia. As reviewed above, competitive displacement of native geckos from the house gecko niche has been reported (Cogger *et al.* 1983; Greer 1989; Keim 2002; Wilson 2006; Wilson & Swan 2009), localized assessments of invasion of natural habitats have been conducted (Keim 2002; Newberry & Jones 2007; McKay *et al.* 2009), and preliminary data have been collected on introduced parasites associated with *H. frenatus* (Domrow 1991, 1992; Keim 2002; Walter & Shaw 2002; Barton 2007). Evidence for invasion into natural habitats has led to recent concern regarding potential impacts of *H. frenatus* on native geckos (Keim 2002; Wilson 2006; Couper *et al.* 2007; Worthington Wilmer 2007; McKay *et al.* 2009). The Queensland Museum recently launched a web survey to ascertain public attitude towards *H. frenatus* and monitor its spread (http://www.southbank.qm.qld.gov.au/learning/nsw/geckos/index.asp). At the national level, *H. frenatus* is not listed as a 'pest animal' or an 'animal of concern', and its legislative listing varies across Australian states and territories. The Queensland Government recently conducted a pest animal risk assessment of *H. frenatus*, which concluded that it is a 'serious threat species' that will continue to spread in northern and eastern coastal Australia, mainly in urban areas, and may out-compete native geckos in these areas (Csurhes & Markula 2009).

WHAT CAN AUSTRALIA DO?

More awareness and research is required. The first step is to recognize that *H. frenatus* is a potential threat to the ecology and biodiversity of Australia. The second step is to work out the level of threat posed by this species. In order to understand the spread and impacts of *H. frenatus*, the following research is required: (i) monitor spread; (ii) resolve the genetic composition of the Australian populations to determine the origins, number of independent introductions, and genetic diversity; (iii) assess invasion of natural habitats and potential for competition with native geckos and other impacts in these habitats; (iv) determine physiological tolerances and adaptation across Australian populations; (v) model potential distribution incorporating physiological and ecological data; and (vi) resolve which parasites have been (or could be) introduced into Australia with *H. frenatus* and their potential impact on native lizards. Only once the potential impacts have been assessed will it be possible to determine the response warranted.

A practical current measure is to attempt to limit further spread, particularly into natural habitats. Attention should be paid to whole regions not yet affected, for example, south-west Australia, from which *H. frenatus* may be excluded by thorough quarantine and public awareness. It is not feasible to attempt to control numbers or spread in urban areas where *H. frenatus* is already established or will soon invade from nearby areas. Killing *H. frenatus* on urban houses will have no effect – they will rapidly recolonize from next door. *Hemidactylus frenatus* is here to stay in urban areas and in these environments they may as well be enjoyed for the endearing animals they are. In contrast, removing them when they appear on houses in more sparsely settled areas may be beneficial in reducing the potential for local spread into bushland areas. However, manual removal may not be effective even in these areas; and there is the issue of confusion with native geckos. One area where removal should be encouraged is in wild areas (e.g. national parks), where *H. frenatus* is often present on structures. They may not spread into surrounding natural habitats at these sites but a precautionary principle should be followed. In these areas, careful checks of building materials are required to stop *H. frenatus* being introduced when toilet blocks, picnic shelters and other structures are built, and regular checks of these structures are required to remove any *H. frenatus*.

The introduction of *H. frenatus* into Australia serves as a warning regarding the potential for other foreign species to establish. Globally, at least 36 gecko species have been spread outside their natural range (Lever 2006), and climatic modelling of one of these, *Hemidactylus mabouia*, predicts potential occurrence over large areas of Australia (Rödder *et al.* 2008). The total count for naturalized reptiles and amphibians internationally is approximately 185 and 83, respectively; and many of these have had significant impacts in their introduced ranges (Lever 2006). Australia has thus far suffered few reptile and amphibian introductions but, with continued increases in international cargo movement, it will take rigorous quarantine inspection to prevent further species establishing. The spread and potential impacts of *H. frenatus* in Australia also serves

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as a warning to other regions with diverse and 'ancient' gecko faunas, such as New Caledonia (where *H. frenatus* has established in man-made and some natural habitats; Bauer & Sadlier 2000) and New Zealand (where *H. frenatus* is regularly introduced accidentally but has yet to establish; Gill *et al*. 2001).

CONCLUSION

Australia should be more concerned about the potential impact of *H. frenatus*. It has spread rapidly across urban areas, settlements and isolated dwellings in northern and eastern Australia; and this continues at pace. In these environments, it will most likely replace native geckos from the house gecko niche. Of greater importance is the degree to which *H. frenatus* will infiltrate natural environments (both undisturbed and disturbed) and compete with native geckos, as has happened in some overseas populations. Indications so far suggest that *H. frenatus* is establishing in some natural habitats in Australia, but how extensive this is and with what impacts remain unresolved. The continued extensive urbanization and fragmentation of eastern and northern Australia is likely to be facilitating invasion of natural habitats by providing thousands of invasion fronts across a comprehensive range of natural habitats. *Hemidactylus frenatus* may pose a threat to species in its own right or may represent a significant impact on top of other impacts such as habitat destruction and fragmentation, and introduced predators. Research is required to determine the likely impacts of *H. frenatus* in Australia, strategies to manage these impacts, and the degree of investment warranted. Continued vigilance is also required to prevent further reptile and amphibian introductions.

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