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Current and future threats from non-indigenous animal species in northern Australia: a spotlight on World Heritage Area Kakadu National Park

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Abstract. Non-indigenous animal species threaten biodiversity and ecosystem stability by damaging or transforming habitats, killing or out-competing native species and spreading disease. We use World Heritage Area Kakadu National Park, northern Australia, as a focal region to illustrate the current and potential threats posed by non-indigenous animal species to internationally and nationally recognised natural and cultural values. Available evidence suggests that large feral herbivores such as Asian swamp buffalo, pigs and horses are the most ecologically threatening species in this region. This may reflect the inherent research bias, because these species are highly visible and impact primary production; consequently, their control has attracted the strongest research and management efforts. Burgeoning threats, such as the already established cane toad and crazy ant, and potentially non-indigenous freshwater fish, marine invertebrates and pathogens, may cause severe problems for native biodiversity. To counter these threats, management agencies must apply an ongoing, planned and practical approach using scientifically based and well funded control measures; however, many stakeholders require direct evidence of the damage caused by non-indigenous species before agreeing to implement control. To demonstrate the increasing priority of non-indigenous species research in Australia and to quantify taxonomic and habitat biases in research focus, we compiled an extensive biography of peer-reviewed articles published between 1950 and 2005. Approximately 1000 scientific papers have been published on the impact and control of exotic animals in Australia, with a strong bias towards terrestrial systems and mammals. Despite the sheer quantity of research on non-indigenous species and their effects, management responses remain largely *ad hoc* and poorly evaluated, especially in northern Australia and in high-value areas such as Kakadu National Park. We argue that improved management in relatively isolated and susceptible tropical regions requires (1) robust quantification of density–damage relationships, and (2) the delivery of research findings that stimulate land managers to develop cost-effective control and monitoring programs.

Introduction

The establishment of non-indigenous plant and animal species often has severe impacts on natural or seminatural ecosystems (Cheke 1987; Ebenhard 1988). Introduced species that become invasive (i.e. widespread and locally dominant: Colautti and MacIsaac 2004) transform habitats, degrade ecosystem services, reduce biological diversity and are thus justifiably recognised as major environmental and economic threats (IUCN 2000; Baker *et al*. 2005). These species are considered among the greatest threats to biodiversity, along with habitat loss and over-exploitation by humans (Vitousek *et al*. 1996; Mack *et al*. 2000; Burbidge and Manly 2002; Blackburn 2004; Griffiths *et al*. 2004; Hampton *et al*. 2004; Clavero and García-Berthou 2005). Furthermore, these effects will likely be reinforced by the influence of global climate change through rising sea levels and changing rainfall patterns while increasing the potential range and spread of invading non-indigenous species (Dukes and Mooney 1999; Root *et al*. 2003).

Australia is a region that has been seriously affected by introductions of non-indigenous species. With its long history of geographic isolation and resultant high level of endemism, Australian biodiversity has suffered particularly acutely from the onslaught of introduced animal species such as foxes (*Vulpes vulpes*), cane toads (*Bufo marinus*) and feral pigs (*Sus scrofa*) (Strahan 1995; Moritz *et al*. 2001; Harvey 2002; James 2002). Indeed, many non-indigenous animal species in Australia have been documented as leading causes of population decline of

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native species and impediments to conservation and restoration efforts (Hobbs and Mooney 1998). Likewise, deliberate or accidental introductions of non-indigenous plant species that have become aggressive weeds (e.g. mimosa (*Mimosa pigra*) and gamba grass (*Andropogon gayanus*)) threaten many native species and ecosystems in northern Australia (Cook *et al*. 1996; Rossiter *et al*. 2003; Buckley *et al*. 2004; Setterfield *et al*. 2005). However, in this review we have restricted our analyses and discussion to animal species to avoid overlap with recent reviews of the ecological impacts of weedy plants in northern Australia (e.g. Lonsdale 1994; Parsons and Cuthbertson 2001; Grice 2004).

A great deal of research effort in Australia has been dedicated to understanding the effects of non-indigenous animal species on native biodiversity, the development of techniques to eradicate or control these species, and the potential for many of these to spread and threaten indigenous biota under the predictions of global climate change, changing land-use patterns and increasing human populations. However, there is a lack of consensus on, or even appreciation for, the magnitude of current and future threats to the biodiversity of northern Australia by invading species. Such knowledge gaps are serious impediments to the development of evidence-based interventions.

A comprehensive overview of current and future threats posed by non-indigenous animal species in northern Australia is therefore still sorely needed to contextualise their impact relative to other factors menacing biodiversity in this region of high endemicity and comparatively low post-settlement extinctions (Woinarski *et al*. 2006). Here we consider the main non-indigenous animal threats to native north Australian biota with emphasis on a region of particular biodiversity and cultural value – World Heritage Area Kakadu National Park (KNP) in the seasonal tropics of the Northern Territory. To do this, we (1) assess the current and potential range, diversity and intensity of risks posed by non-indigenous animal species to KNP's ecological integrity, (2) evaluate the costs and benefits of past, current and proposed management and restoration options in KNP, (3) consider the cultural, socioeconomic and logistic challenges for effective control of non-indigenous species within complex cross-cultural settings, and (4) frame these trends against the broader scientific emphasis on non-indigenous animal research in Australia by compiling a comprehensive list of the peer-reviewed scientific literature devoted to this topic since the 1950s.

Non-indigenous animal species introductions in the Northern Territory of Australia

In northern Australia, the most conspicuous populations of non-indigenous animals derive from introductions to support early European settlements (e.g. Fort Dundas, Melville Island and Victoria Settlement, Cobourg Peninsula) and in the subsequent development of agriculture. The first such settlement at Fort Dundas on Melville Island (Tiwi Islands) had, by 1826, a diverse complement of stock including cattle (*Bos* spp.), Asian water buffalo (*Bubalus bubalis*), pigs, goats (*Capra hircus*) and sheep (*Ovis aries*). Later, buffalo, pigs, banteng (*Bos javanicus*) and horses (*Equus caballus*) were introduced to the mainland at the Cobourg Peninsula (Fig. 1) and released when the settlement was abandoned shortly thereafter (Calaby 1975; Corbett 1995*a*). Some of these species have thrived in northern environments, achieving densities never observed in their native habitats (Freeland 1990). Buffalo have numbered in the hundreds of thousands (Bayliss and Yeomans 1989), and banteng, whose wild ancestors are now regarded as endangered in their Asian native habitats (Bradshaw *et al*. 2006), are sufficiently numerous to support a valuable safari hunting industry at Cobourg Peninsula (Brook *et al*. 2006). Feral pigs may be the most successful large non-indigenous vertebrate species at present, and they are perhaps one of the most difficult feral animal problems to resolve in Australia (Hampton *et al*. 2004). Estimates of their abundance are difficult to obtain and the likely costs of achieving control are high, largely because survey methods that give acceptable accuracy and precision are expensive (Choquenot 1995), but also because pigs have extensive dispersal capacity and high fertility rates (Caley 1993; Dexter 2003).

Following the failure of these and other early European settlements, the second wave of animal introductions to northern Australia occurred during a period of broad-scale pastoral settlement, with thousands of livestock being brought overland to provision newly granted properties. Given the lack of infrastructure such as fencing, cattle and horses established feral populations at many pastoral sites. Donkeys were used as pack animals, and now large feral populations are found in the subhumid regions of the western Northern Territory and have begun invading KNP (Graham *et al*. 1982). The remarkable success of feral stock is attributed to the lack of large predators, absence of some diseases and parasites, and limited competition from other large grazing animals (Freeland 1990). At high densities, these species damage the landscape substantially through physical disturbance, by selective grazing of palatable plant species, and by changing fuel loads and altering fire regimes (Freeland 1990).

Control, if it occurred at all, has been based on commercial use of some species. From the late 19th century, buffalo were harvested in large numbers for hides, horns and, less frequently, meat. Harvests varied with market demand, but sufficient numbers were taken at times to cause concern about depletion of the resource. Hunting of buffalo was greatly reduced in the 1950s after the hide markets collapsed. By the mid-1980s, the Northern Territory population of buffalo was thought to have exceeded 340 000 (Skeat *et al*. 1996). Public concern regarding the negative impacts of the most conspicuous non-indigenous animals increased in the late 1970s (Letts 1979). The types and extent of environmental damage and conflict with agricultural production were catalogued, and a proposed control program based on better assessment of the size of feral animal populations and their distribution was initiated. Subsequently, buffalo populations on pastoral lands were all but eliminated under the government- and industry-supported Brucellosis and Tuberculosis Eradication Campaign (BTEC) (Robinson and Whitehead 2003; Department of Environment and Heritage 2005). Implementation on a wider scale proved problematic principally because various sectors viewed feral animals differently and control was not attempted in areas where disease incidence was low as was the case in many parts of Arnhem Land.

Environmentalists saw buffalo as a conservation disaster, but many pastoralists viewed them as a useful wild or livestock resource (Robinson and Whitehead 2003), and whilst Aboriginal people were concerned about environmental damage, they also viewed them as an important source of food

(Altman 1982) and part of their recent history (Brockwell *et al*. 1995; Bowman and Robinson 2002). The predominantly positive views were reinforced by legislation that treated all feral and domesticated buffalo, cattle, and horses as stock – often with putative owners – rather than pests, irrespective of the animals' locations and concerns about environmental detriment. Furthermore, effective management and control of these species are still subject to changes in public perception (O'Brien 1987; Izac and O'Brien 1991), which may either support or hinder any action plan. These conflicting views and difficulties with eradicating populations at low densities have long-term consequences, as now seen by recent aerial surveys that have confirmed that buffalo populations remain high in and around the Arnhem Land plateau region of the Park, with a conservative population estimate of 80 000 (K. Saalfeld, NT Parks and Wildlife Service, pers. comm.), and a likely much higher population size to the east and south of KNP.

The feral heritage – Kakadu National Park

Kakadu National Park (Fig. 1) is a region of unique natural habitat, biota and cultural heritage and has been set aside for its conservation values. Measures to conserve and protect this region are formally declared under Australian law and listed under several conventions including the World Heritage Convention, the Convention on Wetlands of International Importance (RAMSAR), the Convention on Biological Diversity, the Conventions on Migratory Species, the National Wetlands Policy, the *Environmental Protection and Biodiversity Conservation Act 1999*, the *Environmental Protection and Biodiversity Conservation Regulations 2000*, the Memorandum of Lease for KNP, and the KNP Plan of Management. Its importance for the maintenance of Australian biodiversity is recognised internationally, so a detailed inventory of its current and potential non-indigenous species threats is an essential precursor to the effective management of its unique and representative biodiversity and cultural values.

Kakadu National Park, situated in the seasonal monsoon tropics of the Northern Territory, is Australia's largest national park, covering 19 804 km^2 (Fig. 1). The diversity of different plants and animals within the park and their interactions reflect complex geological and landscape processes. The park protects a community of ~1540 native plant species, more than 560 native vertebrates and over an estimated 10 000 invertebrate species, most of which are undescribed (Russell-Smith 1995). The park also has the lowest relative number of non-indigenous plant species of all Australian national parks (5.7%) (Russell-Smith 1995). The dominant vegetation includes *Eucalyptus* spp. (*E. miniata*, *E. tetrodonta*) open forest, and several different,

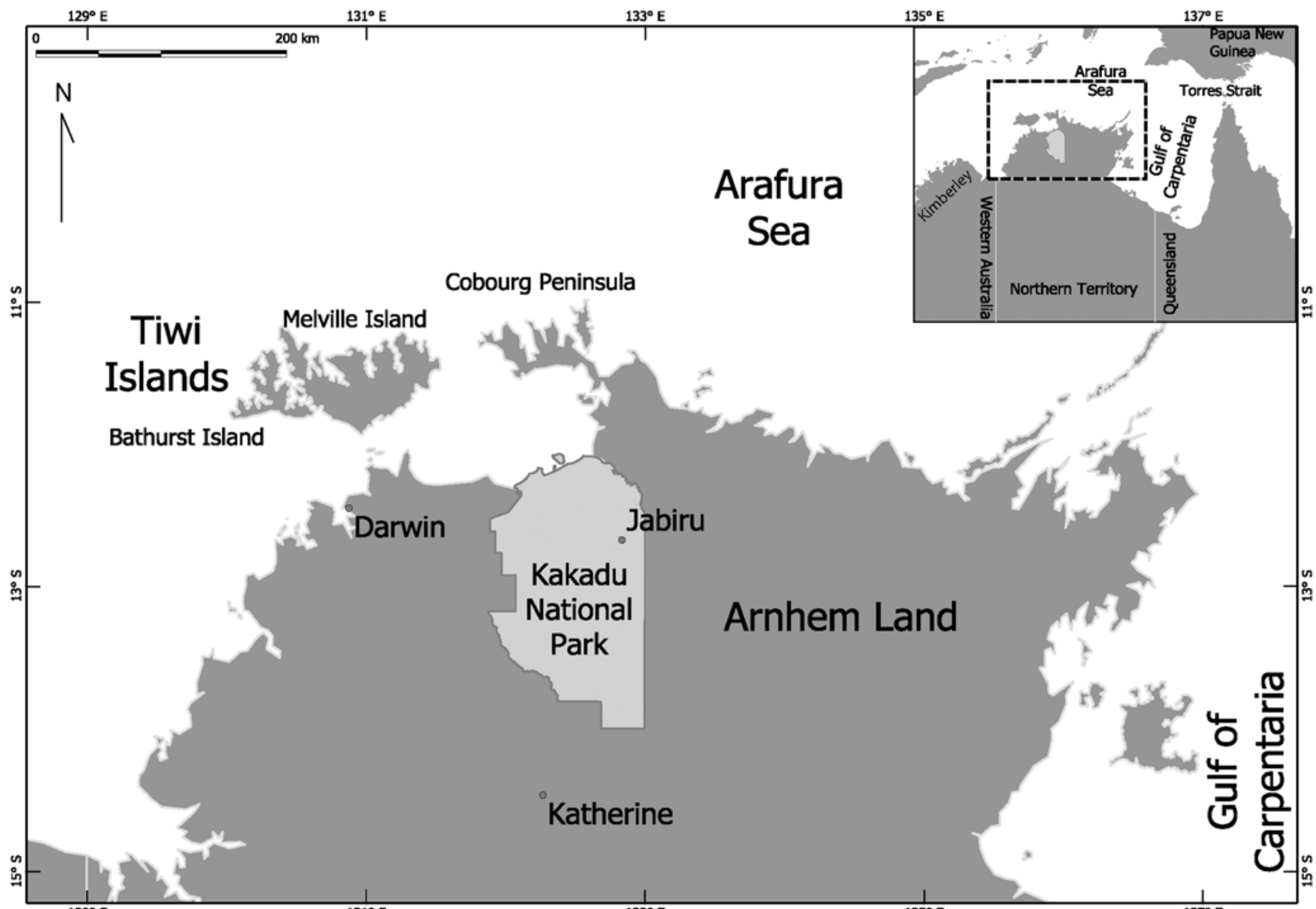

Fig. 1. Map of northern Australia showing the boundaries of Kakadu National Park.

floristically distinct *Eucalyptus* and low woodlands. Closed forests of mangroves, paperbark (*Melaleuca* spp.), and rainforest (lowland mixed forest or *Allosyncarpia ternata* escarpment forest) occur as patches of varying size in favourably moist, fertile or topographically fire-protected sites (Russell-Smith 1995). Owing to variation in the landscape, vegetation and animal species, this large national park boasts some of the greatest natural and cultural diversity in Australia.

The land on which the park has been set has probably been continuously inhabited by Aboriginal people for over 40 000 years (Mulvaney and Kamminga 1999). Over this time there have been large changes in the climate, sea level and ecosystems in the region that have been recorded in the rock art of the Arnhem Land escarpment and plateau and the record of material culture (Brockwell *et al*. 1995). For the conservation of its unique natural habitat, biota and cultural heritage, about one-third of the current area was proclaimed a national park in April 1979 after the land was leased by the Director of National Parks and Wildlife from the Aboriginal Traditional Owners. Kakadu National Park was subsequently enlarged in two major stages and recognised internationally for both its natural and cultural heritage with the entire park's inclusion as a World Heritage–listed area (listing took place between 1981 and 1992).

Kakadu National Park also has a substantial and growing human population of complex origins and diverse interests. Presently, the human population includes Aboriginal Traditional Owners and their families, other Aboriginal people with long-term connections to the park, more recent Aboriginal immigrants attracted by employment opportunities, non-Aboriginal people working in mining, tourism and basic services, park managers and associated staff, and other public servants working for the national, Northern Territory and local governments. In addition to the resident population, more than 150 000 people visit the park to use its facilities and recreational options each year. Many (unmeasured) also travel to and from Arnhem Land through the park to Jabiru or *en route* to major regional centres such as Darwin and Katherine (Fig. 1). This eclectic mix of people creates special challenges for the management of non-indigenous plant and animal species, especially managing the risks of deliberate or accidental introduction of biological materials into the park.

Within KNP there is a highly diverse non-indigenous biota. Cowie and Werner (1993) provided an overview of weeds and, because non-indigenous animal species also pose a large threat to the landscape (Letts 1979; Australian National Parks and Wildlife Service 1991; Skeat *et al*. 1996), our review focuses only on animal species and their direct impacts. Despite our focus on non-indigenous animals it is important to note that they can contribute to threats from weedy species by the introduction and spreading of their seeds, over-grazing on native species and changing vegetation communities that all degrade the natural environment (Cook *et al*. 1996). It is for the above reasons, and under several international and national agreements and management plans, that non-indigenous species management is an ongoing focus for KNP. However, this is not a simple issue because of the size and range of habitats within the park and the cross-cultural views reflected in its management.

Non-indigenous animal species currently in Kakadu National Park

Many non-indigenous animal species are known to have established wild populations in KNP. Table 1 summarises the main ecological and control issues surrounding the management of the principal non-indigenous species currently occupying KNP – pigs, buffalo, cattle, horses, donkeys, cats (*Felis catus*), dogs (*Canis familiaris*), black rats (*Rattus rattus*), mice (*Mus musculus*), cane toads, ants and honeybees (*Apis mellifera*). Two non-indigenous reptiles also occur in KNP – the flower-pot snake (*Rhamphotyphlops braminus*) and the house gecko (*Hemidactylus frenatus*) – but their distributions and impacts are considered to be minimal (Cogger 2000), and so they are not discussed further in this review. Current control programs (and those planned for the foreseeable future) are likely to be set using control targets, funding availability, and the maintenance of public safety. The management challenges raised by these major non-indigenous animal populations in KNP are particularly problematic given the potential severity of their impacts and the diversity of interests and expectations from the broad range of interested groups.

Physical impacts

Damage arising from pigs mainly occurs as a result of digging for food in soft soils (Tisdell 1982), although other damage includes population-level effects on the wide range of plant, invertebrate and vertebrate prey that pigs consume. Pig predation was a cause of a substantial increase in snake-necked turtle (*Chelodina rugosa*) mortality in northern Australia (Fordham *et al*. 2006). Another example of the potential magnitude of pig impacts in KNP is that the costs associated with feral pig damage and control in the USA alone exceed AU$1 billion per year (Pimentel *et al*. 2001). In the Northern Territory, pigs have a limited effect on ground vegetation cover in monsoon forest remnants (e.g. Bowman and McDonough 1991; Bowman and Robinson 2002), although their impact is far greater in some isolated wetlands (e.g. Cobourg Peninsula: Bowman and Panton 1991). This type of damage is particularly acute in KNP's extensive wetland networks for which it has been listed, in part, as a World Heritage Area. In south-eastern Australia, by contrast, Hone (2002) demonstrated a strong relationship between pig density and damage caused by rooting, with plant species richness declining precipitously with intensive rooting. Feral pig populations in other parts of the world have been shown to (1) cause extensive damage to understorey plant cover in the eastern USA (Bratton 1975), although their impact varies by region (Singer 1981), (2) facilitate the invasion of weedy plants through the destruction of established native plant communities (Smith 1998), and (3) depress the biomass and density of soil microinvertebrates in Hawaii (Vtorov 1993).

After the collapse of the buffalo-hide industry in the 1950s, an unrestricted population explosion of feral buffalo caused severe damage to the lowland environment (Skeat *et al*. 1996; Mulrennan and Woodroffe 1998), which has only partially recovered in recent years. Adult buffalo are large animals (500–1200 kg) that consume up to 30 kg of food per day within relatively restricted home ranges (Tulloch and Cellier 1986). It is these habitual behaviours and high densities (up to 34 indi-

Table 1. A detailed description of the major ecological and management issues associated with the most important invasive species currently found in Kakadu National Park, northern Australia

These species include pigs (*Sus scrofa*), Asian swamp buffalo (*Bubalus bubalis*), cattle (*Bos* spp.), horses (*Equus caballus*), donkeys (*E. asinus*), cats (*Felis catus*), dogs (*Canis familiaris*), black rats (*Rattus rattus*), house mice (*Mus musculus*), cane toads (*Bufo marinus*), various ant species (*Pheidole megacephala*, *Solenopsis geminata*, *Monomorium destructor*, *M. floricola*, *M. pharaonis*, *Paratrechina longicornis*, *Tapinoma melanocephalum*, *Tetramorium bicarinatum*, *T. simillimum*) and honeybees (*Apis mellifera*). The table is divided into six main headings: (1) approximate densities and the relative ranking of densities among habitats, (2) the main habitat types in which the species is found in northern Australia, (3) the types of damage to the landscape and biodiversity inflicted, (4) the main diseases harboured and transmitted to wildlife and humans, (5) the types of control methods useful in reducing densities, and (6) the main management and sociopolitical issues concerning effective density reduction. Superscript numbers indicate reference source (author and year listing provided at end of table)

Species	Densities	Habitats	Damage	Diseases	Control	Issues
Pigs	Higher close to permanent water, in areas with subterranean foods and in areas with dense woody or grass shelter[1,2].	Floodplains flanked by dense *Melaleuca* spp. woodlands, vine thickets and forests[3].	Extensive digging causing erosion/siltation[3–5]. Weed Dispersal[3,6]. Predation on native species (turtles, yams)[6–8].	Japanese encephalitis virus[9,10]. Melioidosis[10]. Brucellosis[11,12]. Leptospirosis[1]. Foot-and-mouth disease[13].	Helicopter preferable due to poor ground access[14,15]. Costly[14,15]. Density reduction difficult[14–17]. Damage-density relationship unavailable.	General agreement on control. Adjacent uncontrolled areas are source of immigrants. Proving disease-free difficult[18].
Buffalo and cattle	Currently large population in Arnhem Land plateau[19]. Up to 34 per square km[20]; now <0.1 per square km[21].	All habitats, but higher densities in floodplains and channels, lowland forests and seasonally inundated areas[22].	Formerly one of greatest . threats to the region[16]. Severe damage to waterways (erosion, saltwater intrusion)[21,23–26]. High food consumption Altered ground cover and plant diversity.	Tuberculosis[28]. Brucellosis[28].	80 000 removed during BTEC[29] using mainly helicopters. 20 000 removed in KNP after[6]. Populations increasing and moving back into region[30,31]. Large density reduction possible, but high costs at low densities[32].	Buffalo farms with ~600 individuals to provide meat[33]. Important source of food and income for Aboriginals[29,34]. Full eradication culturally contested[29,34]. Adjacent uncontrolled areas source of immigrants.
Horses and donkeys	Less abundant than pigs/buffalo[32,35,36]. Densities unknown[25]. Population increase up to 80% per year[37].	Drier areas near sites of previous release[38]. High site fidelity. Can live farther from water than pigs/buffalo[39].	Less visible physical damage compared with buffalo/pigs. Erosion, weed dispersal, vegetation damage[25,37]. Possibly affects native herbivore densities[40].	Melioidosis[41]. Kunjin virus[42].	Damage-density relationship unavailable and controversial[43]. Ground/helicopter shooting plausible.	Highest controversy of control[44]. Many Aboriginals view as part of landscape[44]. Control questioned by many external groups[37,45,46].
Cats	Largely unknown. Abundance surveys difficult[47].	Throughout northern Australia[47]. Habitat associations uknown.	Consume wide range of . native fauna[48]. May compete with northern quoll (*Dasyurus hallucatus*)[48], snakes and goannas[49,50].	Toxoplasmosis[48] causing disease in wildlife and humans.	Poisoning[51]. Difficult to trap[52].	Control justification difficult given lack of data on associated declines of native fauna. Pets provide constant source of new feral individuals.
Dogs	Relatively lower than elsewhere in Australia[53]. No density estimates.	Wide distribution in northern Australia[53].	Source of hybridisation with dingoes[53,54]. Competition with, and direct predation of, native wildlife[53]. Impact less than cats[55].	Some threat of disease and parasites.	Tracking surveys, shooting, trapping, poisoning (1080), exlusion fences[53].	Stray pets source of feral individuals[53]. Control scrutinised by external groups[53].
Black rats	Unknown in KNP.	Common in agricultural land and human settlements.	Moderate pests of agricultural industry[6]. Omnivorous diet[56]. Can displace native species[56,57]. Bark stripping, root-system damage.	Salmonellosis and leptospirosis[56,58,59].	Poisoning. Making habitat less suitable. Trapping[37].	All stakeholders desire control, but lack of information on damage makes justification difficult.

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Table 1. (*Continued*)

Species	Densities	Habitats	Damage	Diseases	Control	Issues
House mice	Normally low, but 'plague' outbreaks can occur[60–63]. Plagues unlikely in KNP, but possible after heavy rains in drier regions[64].	All habitat types, but higher densities in agricultural areas and human settlements[64,65].	Major pests of agricultural industry[64]. Thought to be greater threat to biodiversity than rats[37].	Some threat of diseases to wildlife and humans.	Baiting with strychnine, but serious side-effects for native wildlife[37]. Possible fertility control[66].	All stakeholders seek control, but lack of information on damage makes justification difficult.
Cane toads	Can exceed 2000 animals km^{-2} in favourable conditions[67].	Throughout northern NT[68–70].	Reduction of survival and densities of native reptiles[69–81] through predation and poisoning. Increased competition with native wildlife. Changes in plant and animal communities[70,72,79,80,82].	Possible transmission of disease to native amphibians[83].	Trapping, but time-consuming and expensive[82]. Possibility of fertility control[82].	All stakeholders agree that control is warranted, but difficult to implement.
Ants	Densities unknown.	Wide dispersal capability, but generally localised outbreaks. Highly invasive[84].	Threats to invertebrate diversity[85,86]. Agricultural & urban pests.		Eradication campaign in KNP successful using poisons[86]. Ongoing monitoring vital to identify new outbreaks.	Little community or government interest in control.
Honeybees	Many feral colonies in northern Australia. Densities unknown	Range in KNP unknown.	Inefficient pollinators compared with native bees[87–89]. Competition with native bees and birds[90]. Reduction of 'sugar bag' harvested by Aboriginal people[91].		Control through destruction of hives, poisoning, insecticide strips, but less effective in fragmented landscapes[92,93].	Proposals to limit distribution of commercial hives not implemented. Damage generally ambiguous, so control difficult to justify.

Cited references: [1]Choquenot and Dexter 1996; [2]Choquenot and Ruscoe 2003; [3]Tisdell 1982; [4]Bowman and McDonough 1991; [5]Bowman and Panton 1991; [6]Department of Environment and Heritage 2005; [7]Whitehead *et al.* 2000; [8]Fordham *et al.* 2006; [9]Department of Health and Ageing 2004; [10]Communicable Diseases Unit 2005; [11]Cronin and Frazer 2004; [12]McCool and Newton-Tabrett 1979; [13]Animal Health Australia 2001; [14]Choquenot *et al.* 1999; [15]Hone 1986; [16]National Office of Animal and Plant Health 2000; [17]Braysher 1993; [18]Wilson and O'Brien 1989; [19]Saalfeld 1999; [20]Ridpath *et al.* 1983; [21]Skeat *et al.* 1996; [22]East 1990; [23]Mulrennan and Woodroffe 1998; [24]Taylor and Friend 1984; [25]Letts 1979; [26]Petty *et al.* 2007; [27]Tulloch and Cellier 1986; [28]Department of Environment and Heritage 2004; [29]Robinson and Whitehead 2003; [30]Chibeba 2003; [31]Field *et al.* 2006; [32]Bayliss and Yeomans 1989; [33]Riley 2005; [34]Robinson *et al.* 2005; [35]Graham *et al.* 1986; [36]Graham *et al.* 1982; [37]Caughley *et al.* 1998; [38]McLaren and Cooper 2001; [39]Department of Environment and Heritage 2004; [40]Matthews *et al.* 2001; [41]Cheng and Currie 2005; [42]Mackenzie *et al.* 2003; [43]Symanski 1994; [44]Australian National Parks and Wildlife Service 1991; [45]Rose 1995; [46]English 2001; [47]Edwards *et al.* 2000; [48]Dickman 1996; [49]King and Green 1993; [50]Shine 1991; [51]Short *et al.* 1997; [52]Short *et al.* 2002; [53]Fleming *et al.* 2001; [54]Corbett 1995; [55]Cook *et al.* 1996; [56]Watts 2002; [57]Ramanamanjato and Ganzhorn 2001; [58]Levett *et al.* 1998; [59]Thumen *et al.* 2002; [60]Chapman 1981; [61]Krebs *et al.* 1995; [62]Mutze 1991; [63]Saunders and Giles 1977; [64]McLeod 2004; [65]Singleton 2002; [66]Pest Animal Control CRC 2004; [67]Freeland 1986; [68]Freeland and Martin 1985; [69]van Dam *et al.* 2002; [70]Griffiths *et al.* 2004; [71]Catling *et al.* 1999; [72]Watson and Woinarski 2003; [73]Phillips and Shine 2006; [74]Phillips and Shine 2005; [75]Phillips *et al.* 2004; [76]Phillips *et al.* 2003; [77]Burnett 1997; [78]Lever 2001; [79]Oakwood 2004; [80]Crossland 2000; [81]Crossland and Alford 1998; [82]Taylor and Edwards 2005; [83]Laurance *et al.* 1996; [84]Baskin 2002; [85]Williams 1994; [86]Hoffmann and O'Connor 2004; [87]Westerkamp 1991; [88]Vaughton 1996; [89]Paton 1996; [90]Paini 2004; [91]Sugden and Pyke 1991; [92]Oldroyd 1998; [93]Aizen and Feinsinger 1994.

viduals km^{-2}) that make buffalo particularly efficient at damaging their environment. The types of damage inflicted have been studied extensively (Letts 1979; Taylor and Friend 1984; Skeat *et al*. 1996; Robinson and Whitehead 2003; Petty *et al*. 2007) (Table 1). Damage caused by feral horses has never been studied directly in northern Australia; however, anecdotal and photographic evidence supports claims that they contribute to erosion, damage vegetation and disperse weeds (Letts 1979; Caughley *et al*. 1998). In the eastern USA, feral horses can cause over-grazing pressure on dune vegetation, to the point of causing extensive dune erosion (De Stoppelaire *et al*. 2004). Donkeys are likely to have similar impacts on the vegetation and land degradation as feral horses, although their distribution may be limited currently to drier (southern) regions within the park.

Feral cats consume a wide range of native vertebrate fauna (Dickman 1996), and it has also been suggested that they are potential competitors with some native carnivorous predators for prey. Among native predators in KNP, the already endangered northern quoll (*Dasyurus hallucatus*) has the closest dietary overlap with feral cats and may coexist in forest and woodland habitats (Dickman 1996). Feral cats may also compete with some species of elapid snakes and goannas (*Varanus* spp.) (Shine 1991; King and Green 1993). With no information on cat densities it has proven difficult to demonstrate their association with observed declines of native species in northern Australia, although they are suspected to play a role. This is most likely due to the difficulty of implementing effective control with which to test their capacity to reduce native species abundance and diversity.

The diet of feral dogs in KNP is likely to be similar to that of dingoes, and their foraging may have an impact on the native wildlife by increasing both competition for food with other native predators and by reducing the densities of prey species important for endangered or threatened native predators (Fleming *et al*. 2001). However, their impact is thought to be less than that of feral cats (Cook *et al*. 1996). Specifically within KNP, a greater problem may be the postulated hybridisation between feral dogs and native dingoes. The incidence of dingo–domestic dog hybridisation is highest in the more densely human-populated areas of Australia, with more pure-bred dingoes found in northern regions of the country (Wilton *et al*. 1999; Corbett 2001). However, increasing numbers of domestic dogs in the north are probably causing a higher incidence of cross-breeding, which threatens to erode the dingo's genetic diversity and uniquely evolved phenotypes (Wilton *et al*. 1999). This is especially disconcerting considering the recent evidence that healthy, high-density dingo populations appear to restrict populations of smaller invasive predators such as cats and foxes, which are considered responsible for the extinction of many of Australia's endemic mammals (Johnson *et al*. 2007).

Black rats are pests that have a large economic impact on Australian agriculture industries (Department of Environment and Heritage 2005). In the eastern forests of Australia, black rats are omnivorous (Watts 2002) and it has been suggested that in undisturbed or largely unmodified areas, black rats can displace native species (Ramanamanjato and Ganzhorn 2001; Watts 2002). In unmodified habitats, black rats exhibit destructive behaviour that may have ecosystem-wide consequences, such as stripping bark from trees and the consumption of plant root systems. Elsewhere in the world, black rats have particularly acute impacts on species such as colonially nesting seabirds on smaller islands, although these effects are reduced as island size increases (Atkinson 1977; Martin *et al*. 2000). There is little information on the impacts of house mice, although this species is considered to be a greater threat to biodiversity than black rats given their relatively higher ecological flexibility (Caughley *et al*. 1998), and there is recent evidence that mice can cause island seabird populations to decrease (Wanless *et al*. 2007).

Cane toads are regarded as one of the greatest problem species in KNP because of their predatory behaviour and, more particularly, their capacity to poison and kill their predators (Table 1). Although no native Australian species is known to have been pushed to extinction by the invasion, the arrival of cane toads appears to have substantially reduced the abundance of monitor (*Varanus* spp.) species on some islands within the Great Barrier Reef (Burnett 1997; Lever 2001), and there is anecdotal evidence for a decline in goanna species (including *Varanus gouldii* and *V. panoptes*) in north Queensland (Burnett 1997). Recent radio-tracking work just east of Darwin has confirmed a strong effect of cane toad presence on reducing survival of *Varanus* spp. (T. Griffiths, unpubl. data). Further, a large decrease in the monitor *V. panoptes* has been observed following the arrival of cane toads to the Northern Territory (Doody *et al*. 2006). Cane toad tadpoles are also poisonous, with a 100% mortality observed in a freshwater snail species (Crossland and Alford 1998). Species known to be preferred as prey by cane toads have also been shown to decline subsequent to invasion (Catling *et al*. 1999; Lever 2001; Taylor and Edwards 2005), especially where these taxa were already restricted in occurrence.

The African big-headed ant (*Pheidole megacephala*) eliminates native ants and many other invertebrates from rainforest sites (Hoffmann *et al*. 1999), which probably has negative repercussions for other fauna and flora. For non-indigenous honeybees, the most important issues are their potential for competition with native birds and insects and, hence, interference with pollination of plants dependent on native pollinators. European bees are thought to be inefficient pollinators of many plants (Westerkamp 1991), and high densities can cause lower pollination rates and compromised seed production in Australian native plants (Paton 1996; Vaughton 1996). Some Aboriginal people in northern Australia have expressed concern over the potential for feral honey bees to displace native social bees and so reduce the abundance of 'sugarbag', the so-called honey made by native *Trigona* spp. bees (Sugden and Pyke 1991). If there are similar effects in northern Australia with the local *Trigona* species, then harvest of sugarbag may be compromised.

Disease

Feral pigs, buffalo and horses are prominent reservoirs for exotic and endemic disease and parasites that can affect native wildlife, stock, and humans (Table 1). Perhaps the greatest disease concern is the Japanese encephalitis virus that has been tracked across south-east Asia over the past 20 years and has been found recently in Torres Strait pig populations (Department of Health and Ageing 2004). Pigs are the important amplifier hosts that do not show signs of infection and allow transmission to humans through mosquitoes (Department of Health and Ageing 2004).

In southern Africa, buffalo (*Syncerus caffer*) are one of the major reservoir hosts of bovine tuberculosis (BTB, *Mycobacterium bovis*), with other native and domesticated ungulates, and their predators, particularly vulnerable to its effects (Keet *et al*. 1996; Cross and Getz 2006). The disease is currently re-emerging as one of the more difficult management problems for major biodiversity reserves such as Kruger National Park in South Africa (Cross and Getz 2006). The Brucellosis and Tuberculosis Eradication Campaign (BTEC) (Robinson and Whitehead 2003) saw the destruction of ~80 000 buffalo from KNP between 1980 and 1989 and was considered largely successful in eradicating BTB from Australia. BTB is an airborne pathogen that causes chronic and progressive bacterial disease from which few animals recover (Bengis *et al*. 1996). The disease's potential economic implications for Australia are massive – costs of AU$8–13 billion for eradication and lost exports would be felt by the Australian livestock industry if a disease such as BTB or worse, foot-and-mouth disease, were to become established in wild or domesticated ungulates in Australia (www.daff.gov.au; see also Table 1).

Management and control challenges

The threats and damage caused by many of the aforementioned species are overt and severe enough that most people desire some form of control. Control options for large herbivores are generally restricted to broad-scale helicopter shooting campaigns, although the technique is expensive and labour-intensive (Hone 1986; Choquenot *et al*. 1999). Budget restrictions and opportunistic culls can often result in no more than a sustained off-take that does not reduce target species densities or landscape damage (Braysher 1993). Another problem that may arise when attempting to justify the high costs of maintaining effective control is the lack of quantitative studies examining the relationship between animal density reduction and the hypothesised decrease in environmental damage expected, even though the amount of damage and threat to native biodiversity may appear intuitive.

Furthermore, efforts to control damage are likely to be compromised by entry of animals from neighbouring regions whose human occupants either lack interest or funds to implement broad-scale control, have reservations given the lack of evidence for general density–damage relationships, or have fundamentally different management goals. For some species, there are competing cultural, ethical and political interests that render the decision to reduce non-indigenous animal densities controversial. For example, buffalo have become an important source of food and income for Aboriginal Traditional Owners, pastoralists and entrepreneurs, and so may be regarded as an integral part of the landscape and food source by some Aboriginal people (Bowman and Robinson 2002). Buffalo are also a relatively minor commercial source of meat (compared with beef) in the region and for export markets.

Management of feral horses elicits particular controversy in KNP because whilst horses have the potential to cause large-scale environmental and economic damage, many Aboriginal people have accepted them as part of the landscape and their presence is not considered unusual (Australian National Parks and Wildlife Service 1991). As such, horses are now partially protected by Aboriginal people by exercising their rights to biological resources. Thus, widespread shooting is not seen as an acceptable management option in many parts of KNP. This is also the case elsewhere in Australia where control programs for horses also tend to attract close attention from both rural and urban people, including animal welfare, Aboriginal and horse-protection groups (Rose 1995; Caughley *et al*. 1998), and are often accompanied by intense scrutiny and political lobbying (English 2001).

As with many other feral species, it is difficult or impossible to defend control programs when there has been no clear demonstration of detriment from a non-indigenous species' presence (Symanski 1994), even though anecdotal and photographic evidence may be convincing (e.g. mission grass growing from horse droppings). It is certainly difficult to justify costly large-scale density-reduction programs for species such as cats, dogs, rats and mice when there is little information on population densities or evidence for a harmful threat to native wildlife. Furthermore, proposals for control of cats and dogs may be controversial because of their popularity as pets amongst both indigenous and non-indigenous Australians. When strong poisons are used to kill the target animal (e.g. strychnine for mice, 1080 for dogs), there may be serious ramifications for non-target native species. In these cases, new technologies such as viruses and poisons to reduce fertility are being developed to minimise the negative impacts on non-target species (Pest Animal Control CRC 2004). Another major impediment to effective management is when the target species is particularly difficult to survey and kill or trap directly (Edwards *et al*. 2000). In these cases (e.g. cats, dogs, cane toads), the effectiveness of control is difficult to demonstrate even if assessed in terms of reducing numbers.

Future exotic animal threats to Kakadu National Park

The life-history attributes of any invading species (e.g. survival rate, fecundity, dispersal capacity: Rejmánek and Richardson 1996; Buckley *et al*. 2003; Hamilton *et al*. 2005), prior modification of habitats (either physically or by loss of native species: Lonsdale 1999), or the assiduousness of attempts at introduction ('propagule pressure': Jeschke and Strayer 2006) can all be important determinants of establishment and success of spread (Arthington and Mitchell 1986). Several non-indigenous species have established populations in the regions surrounding KNP (Table 2), but many have yet to establish in the park. Those that pose the greatest risk to KNP include yellow crazy ants (*Anoplolepis gracilipes*), mosquito fish (*Gambusia holbrooki*) and rock pigeons (*Columbia livia*) (Table 2). Although it is unlikely that management of KNP will have much influence on the introduction and spread of non-indigenous species outside of the park's boundaries, it is in the interest of the park to make some investment into reducing their potential spread across northern Australia. Failure to take interest in such issues may ultimately expose the park to costly and intrusive management responses. Table 2 provides an outline of the major exotic mammalian, avian, fish and invertebrate species currently threatening Kakadu National Park with invasion.

Mammals

In KNP's recent history, it has been the large, hard-hoofed herbivorous mammals (i.e. pigs, buffalo, cattle, horses, donkeys) that have caused greatest concern and physical damage, but there are few other feral ungulate species in the region that are likely to pose major threats (Table 2). This is a result of the restricted distributions of such species and relative ease of detection. Smaller ungulates such as goats and smaller deer (e.g. rusa deer) are present only on islands off the Northern Territory's coastline (Letts 1979), presumably because they are vulnerable to predation by dingoes and are therefore less likely to emerge as an important threat in a reserve managed in part to maintain healthy dingo populations. If any new large vertebrate invaded KNP, sustained control programs should be established with the aim of a rapid and total elimination to prevent establishment of viable populations. If intensive cattle ranching develops on the western border of KNP, then adding to, and strengthening, existing fencing will be an important measure to limit the spread of stock into the park.

Birds

The Northern Territory is relatively free of non-indigenous birds, and those that have established have done so mostly in the largest urban centre in the region (Darwin). Most species detected (Table 2) have been brought under control by shooting and poisoning. Nonetheless, some populations exist and escapees from aviaries will probably maintain some sort of presence indefinitely. Most of the non-indigenous birds present in Australia have first established in highly modified environments and have only expanded their ranges from these footholds. There is no evidence that the extinction of any native species or even a large change in conservation status of native birds can be attributed to the presence of non-indigenous birds in northern Australia (Garnett and Crowley 2000).

Fish

The factors determining successful establishment of exotic fish species remain ambiguous, just as for most other taxa. Freshwater ecosystems in north Australia are generally in better condition than in most other parts of the nation. Few rivers in the Northern Territory are modified extensively by human activities, and they are usually embedded within landscapes that retain a large proportion of their native vegetation cover and have few sources of pollution. In contrast to Queensland where 17 species of non-indigenous fish have established self-sustaining populations, the Northern Territory presently has only one known non-indigenous fish species in the wild – the eastern gambusia or mosquito fish (*Gambusia holbrooki*). Its impacts on native fauna in the Northern Territory have not been described, but elsewhere gambusia may contribute to declines in native fishes by competing for similar foods or other resources and preying on eggs and young (Howe *et al*. 1997; Margaritora *et al*. 2001). Five of 10 freshwater fish identified as threatened in Australia by interaction with exotic fish are thought to have been affected by gambusia (Wager and Jackson 1993; Fairfax *et al*. 2007).

The absence of larger non-indigenous freshwater fish is probably due to the unsuitability of conditions in tropical Australia for familiar exotic sports fish such as trout, and, perhaps more importantly, the limited public pressure to introduce non-indigenous predatory fish given the successful native sport-fishing industry. The relatively recent establishment of the aquaculture industry, with its interest in preserving native populations, may also be a factor. The 'healthy' condition of most rivers and streams may provide ecological safeguards against

Table 2. Description of the main mammalian, avian and invertebrate species thought to represent an invasive threat to Kakadu National Park, northern Australia, if insufficient monitoring or control measures are not established

Superscript numbers indicate reference source (author and year listing provided at end of table)

Taxon	Species	Issues
Mammals	Sambar deer (*Cervus unicolor*)[1]; rusa deer (*Cervus timorensis*)[1]; banteng (*Bos javanicus*)[2]; goats (*Capra hircus*).	Many species available for invasion. Likelihood of successful invasion low due to restricted ranges and specific habitat associations. Detailed monitoring and efficient targeted control measures reduce the risk of successful establishment. Cattle fencing could restrict invasion.
Birds	Rock pigeon (*Columba livia*); collared doves (*Streptopelia risoria*); tree sparrows (*Passer montanus*); house sparrows (*P. domesticus*); spice finches (*Lonchuria punctulata*); Indian mynah (*Acridotheres tristis*)[3]; Indian house crow (*Corvus splendens*)[4].	Shooting campaign of pigeons in urban centres successful. Successful invasive species likely to colonise urban centres first. Potential invasions from Asia likely (e.g. *Corvus splendens*).
Fish	Mosquito fish (*Gambusia holbrooki*)[5]; *Oreochromis mossambicus*; tilapia (*Tilapia mariae*); rosy (*Puntius conchonius*); tiger barb (*Capoeta tetrazona*); several cichlids (Cichlidae); swordtail (*Xiphophorus halleri*); platy (*Xiphophorus maculatus*); guppy (*Poecilia reticulata*); sailfin molly (*Poecilia latipinna*).	Freshwater fish species most likely potential invasives. Difficult to detect; more difficult to eradicate. Aquarium trade likely source of many invasive fish. Aquaculture poses major threat
Invertebrates	Yellow crazy ant (*Anoplolepis gracilipes*)[6,7]; black-striped . mussel (*Mytlopsis sallei*)[8].	*A. gracilipes* already present in region; not yet in KNP. Intervention and monitoring key to successful detection and eradication.

Cited references: [1]Letts 1979; [2]Choquenot 1993; [3]Pell and Tidemann 1997; [4]Brook *et al*. 2003; [5]Wager and Jackson 1993; [6]Young *et al.* 2001; [7]O'Dowd and Lake 2003; [8]Marshall *et al.* 2003.

invasion (Moyle and Leidy 1992) by reducing overall ecosystem 'invasibility' (Lonsdale 1999), although there is considerable debate on this issue (e.g. Ortega and Pearson 2005). However, the popularity of aquarium fish will ensure that there are many opportunities for mostly smaller exotics to become established (Table 2). For example, in the United States, the aquarium trade is thought to have been the source of at least 27 exotic species now established in the wild, many of which are found in the warm waters of Florida (US Congress Office of Technology Assessment 1993).

Invertebrates

Non-indigenous invertebrate species pose a serious threat because these small invaders may go undetected in the region and have time to establish viable populations that resist eradication attempts. One species already present in the region and thus a cause for concern is the yellow crazy ant (*Anoplolepis gracilipes*). This species has been in northern Australia for decades and has the potential to out-compete or depredate other invertebrates (O'Dowd and Lake 2003). It has established colonies in north-eastern Arnhem Land over an area of ~2500 km^2 (Young *et al*. 2001), and the absence of intervention may encourage its continued spread into KNP and beyond. The introduction of the exotic black-striped mussel to marinas of Darwin illustrates the risks posed by exotic fouling organisms associated with the movement of water craft into and within northern Australian waters. That incident provoked a strong and effective reaction from both local and national authorities, which eradicated the pest from the enclosed waters in which it had established large populations (Marshall *et al*. 2003). As a poignant comparison, the zebra mussel (*Dreissena polymorpha*), a native of the Caspian and Black Seas, has invaded and spread throughout much of Western Europe, the United Kingdom, Canada and the USA. This highly successful species has modified freshwater ecosystems throughout much of the Northern Hemisphere and severely threatens many native freshwater taxa (Nalepa *et al*. 1996; Ricciardi *et al*. 1998). The cost of control, damage to infrastructure and loss of ecosystem services resulting from this species' rapid invasion in the USA have been estimated in the tens of millions of dollars (Leung *et al*. 2002). However, such animals represent only the 'high-profile' members of a much larger suite of non-indigenous fouling organisms (e.g. Wyatt *et al*. 2005). Most of such non-indigenous species appear to be introduced by pleasure craft, although no studies have been carried out in any part of the northern Australian coastline, so the marine pathway is likely to assume increasing importance as the abundance and distribution of readily transported non-indigenous marine invertebrates continues to increase in Australian waters.

Trends in research on non-indigenous species in Australia

An analysis and review of the research on non-indigenous animal species in Australia demonstrates the changing priority that Australian biodiversity research and management has placed on non-indigenous species over time. We compiled an exhaustive bibliography of the peer-reviewed literature devoted to this topic in Australia since 1950. Our first aim was to document the increasing importance of non-indigenous species research in Australia and to provide a resource for researchers and land managers struggling with the challenging task of mitigating the damage to biodiversity values caused by non-indigenous species. Our subsequent aim was to appraise any taxonomic or environmental (milieu) biases associated with such research so that poorly studied taxa and habitats could be identified.

We searched the major online databases for peer-reviewed journal articles published between 1950 and 2005: Google Scholar (scholar.google.com), ISI Web of Science (www.isinet.com), CSA Illumina (www.csa.com), and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Publishing database (www.publish.csiro.au). Books, book chapters, government reports and non-peer-reviewed literature sources were excluded to standardise the method for isolating key scientific contributions in this field, although we acknowledge the important contribution of reports, books and online sources (see also Discussion below). We restricted our search terms to include the keywords 'feral', 'invasive', 'exotic' or 'alien' and 'Australia'. We ignored articles dealing exclusively with weedy plant species because our focus was on animals. A thorough inspection of the identified articles required some decisions as to which were most pertinent to the issue of non-indigenous species research and management. Therefore, we focussed primarily on studies dealing directly with the dynamics or control of such species and those examining how native species are affected by non-indigenous species. We excluded all research pertaining to native Australian species invading regions outside of Australia. We also excluded all articles on micro-organisms given that our focus was not necessarily on epidemiological or medical topics.

To determine whether temporal trends in the number of non-indigenous animal publications in Australia mirrored or diverged from general publication rates within the major journals consulted, we compiled publication rate data from 10 journals listed in ISI Web of Science. These journals were those in which a large proportion (49%) of the sourced papers were published, and they included 6 Australian journals (*Austral Ecology* [formerly *Australian Journal of Ecology*], *Australian Journal of Zoology*, *Australian Veterinary Journal*, *Emu*, *Marine and Freshwater Research* [formerly *Australian Journal of Marine and Freshwater Research*], and *Wildlife Research* [formerly *Australian Wildlife Research*]), and 4 major international journals (*Biological Conservation*, *Conservation Biology*, *Journal of Applied Ecology*, and *Oecologia*). ISI Web of Science only indexes publications from 1992, so publication rate data are presented from 1992 to 2005 only.

In total, we identified 1000 peer-reviewed articles published between 1950 and December 2005 (a full reference list is provided as an Accessory Publication on the Wildlife Research website). There was a clear increase over time in the number of publications dedicated to non-indigenous species (Fig. 2), although it is possible that some articles published before the 1970s were missed by the online databases searched. For example, ISI Web of Science provided articles from 1992 to the present and CSA Illumina from 1990 to the present. Google Scholar was the best online resource for articles published before 1990, with many older articles identified from the CSIRO Publishing journals search engine. The increase in publication number per year for the 1000 articles identified was greater than that observed for general publication rates over the

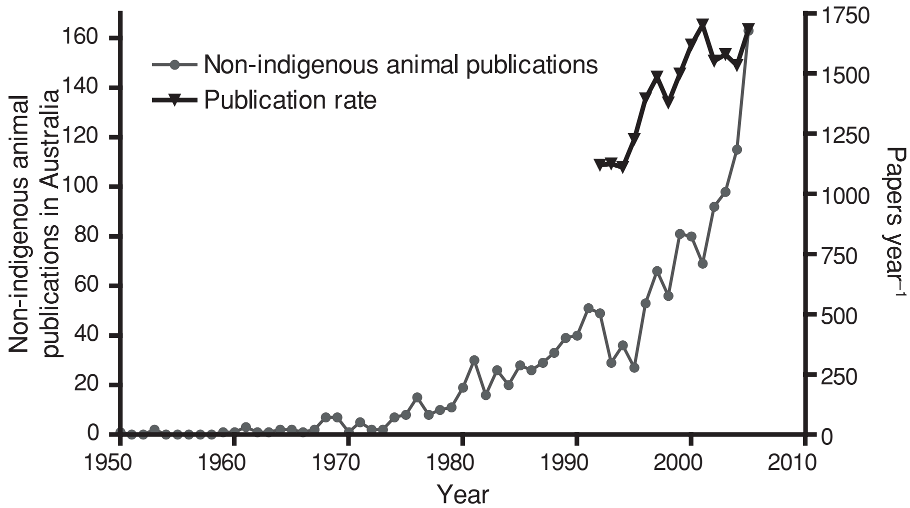

Fig. 2. The temporal distribution of 1000 peer-reviewed articles published between 1950 and December 2005 that examined or discussed non-indigenous animal species in Australia. Articles were identified from online databases (Google Scholar, ISI Web of Science, CSA Illumina, CSIRO Publishing database) using the keyword search terms 'feral', 'invasive', 'exotic' or 'alien' and 'Australia'. A full reference list is provided in an online Appendix. A comparative increase in the general publication rate from 10 Australian and international journals (see text) still does not account for the increasing emphasis placed on non-indigenous animal species in the scientific literature.

same period (Fig. 2), although some of the increase can be attributed to a general trend of increasing publication rates in this field.

Four major environmental milieus of principal focus were identified for each article: terrestrial, marine, freshwater (including estuaries and saline lakes) and coastal (transition zone between terrestrial and marine). A fifth category was included to cover articles dealing with several milieus simultaneously ('various'). Most articles (85%) dealt with terrestrial species and systems (Fig. 3*a*), with freshwater, marine, coastal and 'various' categories all consisting of ≤10% of the publications identified (Fig. 3*a*). We also classified each publication according to the main taxonomic group of focus (in reference to the non-indigenous culprit): mammals, birds, reptiles, amphibians, fish and invertebrates (again with an additional category 'various' for those articles covering two or more taxonomic groups simultaneously. The category with the highest number of publications was mammals (56%). Invertebrates (21%) were the next highest, with all remaining groups consisting of <10% of the publications identified (Fig. 3*b*).

The results of this literature review demonstrate the increasing importance of non-indigenous species research in Australia, even accounting for higher publication rates with time (cf. Linklater and Cameron 2001) (Fig. 2). The taxonomic breakdown demonstrates the predominance of studies associated with terrestrial mammals, followed closely by invertebrates. The mammalian group largely comprised studies examining the effects of terrestrial carnivores such as cats, foxes and dogs, herbivores such as European rabbits (*Oryctolagus cuniculus*), Asian swamp buffalo, goats and feral cattle, and omnivores such as pigs, rats and house mice. Most of the invertebrate studies examined insect pests in agricultural systems (e.g. fruit flies), non-indigenous ant species (e.g. fire ants – *Solenopsis* spp.), livestock pests (e.g. screwworm flies – *Chrysomya bezziana*) and feral honeybees (*Apis mellifera*). All publications dealing with non-indigenous amphibians investigated the introduced cane toad. The low number of marine species identified probably reflects both the relatively lower number of species and systems affected by non-indigenous marine animals (e.g. the

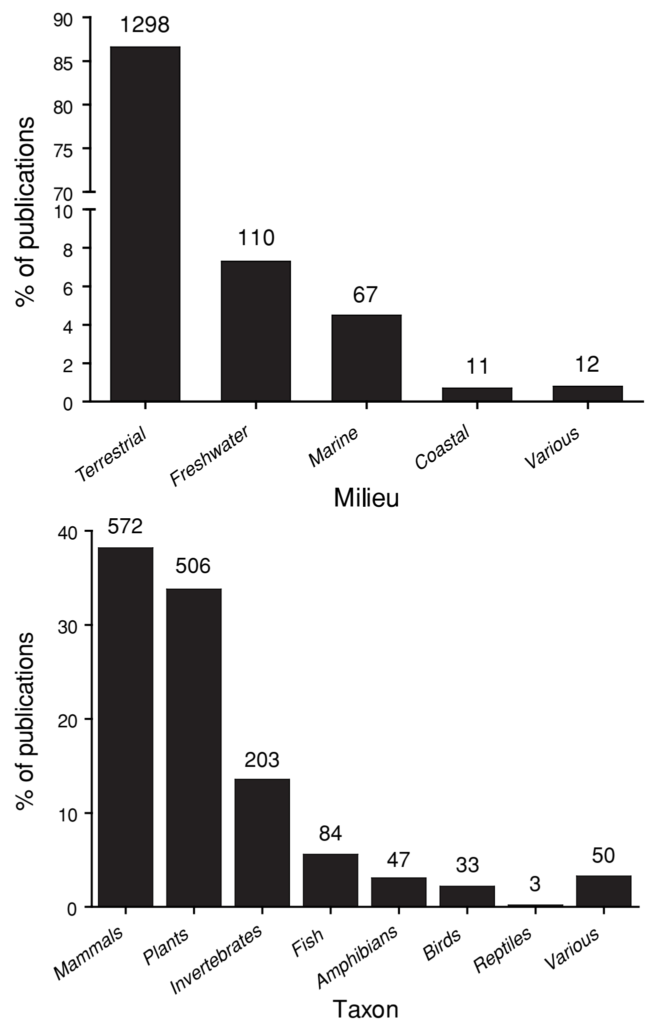

Fig. 3. Distribution of 1000 peer-reviewed articles published between 1950 and December 2005 that examined or discussed non-indigenous species in Australia divided by (*A*) major environment and (*B*) main taxonomic group, of principal focus.

gastropod *Maoricolpus roseus*) in Australia, but also a lower detection probability and historical ignorance of the threats that these taxa pose. Similarly, the low number of non-indigenous fish species studied suggests that Australian freshwater systems in general have not received the same level of threat as some more infamous freshwater systems (e.g. the threat to cichlid communities in Lake Victoria, southern Africa: Verschuren *et al*. 2002).

Discussion

This review has outlined some of the major threats posed by non-indigenous animal species to northern Australia's biodiversity, and illustrates some of the ecological and socio-economic problems they pose using World Heritage Area Kakadu National Park as a focal region of particularly high natural and cultural value. The damage ultimately inflicted by non-indigenous species to KNP will depend on the resources devoted to their mitigation, management and control. However, our review has highlighted that the challenges associated with control or eradication of non-indigenous animal species extend well beyond the logistical and financial constraints normally associated with non-indigenous species' management. Indeed, one of the greatest challenges is the integration of the contemporary values of Aboriginal Traditional Owners with the conservation values of park managers and the incorporation of these into cost-effective, adaptive management strategies. This situation is not unique to northern Australia: similar constraints exist elsewhere in Australia and the rest of the world (see Stevens 1997; West *et al*. 2006) when trying to control non-indigenous species on state and adjacent privately owned land occupied by groups with divergent values.

Joint or participatory environmental management (Kapoor 2001) is a process that has been adopted around the world to broker the differences of opinion and relative values placed upon biodiversity in national parks (West *et al*. 2006). While evidence for successful joint management of invasive non-indigenous species in national parks of high biodiversity value is comparatively rare, there are many examples of participatory cross-cultural management achieving sound benefits for biodiversity despite conflicts between traditional owners and park managers (e.g. Makalu-Barun National Park in Nepal: Furze *et al*. 1996; Te Urewera National Park in New Zealand: Coombes and Hill 2005; Gates of the Arctic National Park in Alaska: Catton 1997). However, indigenous participatory management in ecological restoration projects has proven to be difficult because as the biodiversity crisis accelerates it is often seen to take precedence over indigenous rights and needs, as is the case in Te Urewera National Park in New Zealand (Hill and Coombes 2004), in national park buffer zones in Nepal (West *et al*. 2006), in oryx reintroduction areas in the Arabian Peninsula (Chatty 2002), and in protected areas in Syria (Rae *et al*. 2002). Debate surrounding these complexities will probably intensify with increasing threats from invasive species.

The joint-management arrangement in KNP is designed to incorporate the extensive historical experience of Aboriginal Traditional Owners in land management. Although Aboriginal people are interested in land management and concerned with damage to habitats, some feral animal populations are regarded as 'belonging to country' (Rose 1995) and, as such, have acquired subsistence, economic and cultural value to indigenous people. This adds to the complexity of contemporary wildlife and national park management because some indigenous custodians do not necessarily share the conservation values of government park managers, scientists or non-indigenous land owners. Thus, Aboriginal people often do not see the need to reduce or eradicate feral animal populations (Davies *et al*. 1999). Nonetheless, it can be argued that the mainstream view of all interested groups, including Aboriginal people, is that a demonstration of how non-indigenous species threaten ecosystem and cultural values more than they enhance them is required before there is an acceptance of broad-scale control (Davies *et al.* 1999). However, motivations differ for historical and cultural reasons, and many Aboriginal people categorically require this evidence more than non-Aboriginal land managers, who often accept that the (largely unmeasured) damage already

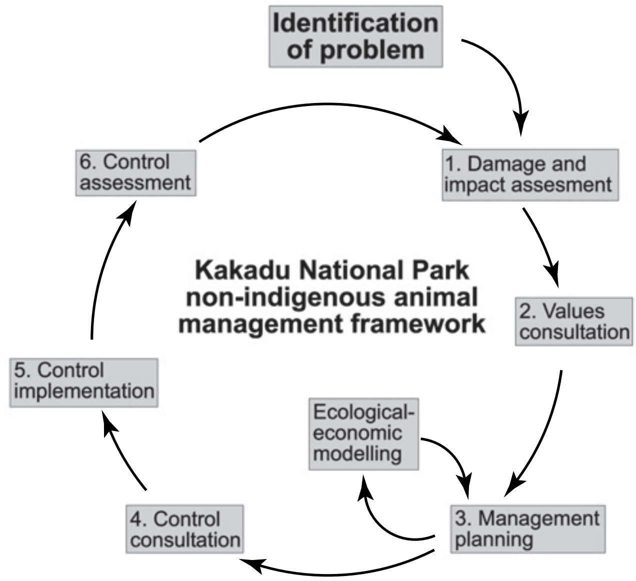

Fig. 4. The joint-management decision-based framework proposed for non-indigenous animal management planning and control in Kakadu National Park (Field *et al*. 2007). This management strategy and framework facilitates integration of conservation and indigenous values through the process of consultation and negotiation between Aboriginal Traditional Owners and Parks Australia North senior staff. The initial stage of this management strategy and framework allows for non-indigenous animal risk assessment to be done for current and potential threats to KNP and prioritises management responses to them. The framework then suggests damage and impact assessments (Step 1) that can be used for management planning (Steps 2–4) as the basis for consultations and negotiation between Traditional Owners and Parks Australia North senior staff for the integration of conservation and indigenous values. These stages allow the use of ecological–economic modelling for realistic and imaginative budgeting and resolution mechanisms for conflicting interests. Once control targets have been agreed upon, control operations can begin (Step 5) for a prescribed period and then evaluated (Step 6). This is an important, often-overlooked component of management strategies that permits an assessment of whether the control plans have had or are having the desired effect on the landscape. This will lead to ongoing monitoring programs based on results of the current control operations so that approaches can be refined to reach the desired (often evolving) management goals.

exists. As such, our collation of the available historical and contemporary data on the distribution and damage caused by exotic animal species can be used by land managers to assist in justifying the allocation of restricted resources. We argue that good inventories of existing data, and comparisons to analogous international situations, will assist in convincing all interested parties of the value in controlling invasions of non-indigenous species and reducing the population densities of those already firmly established in the park.

The field of invasion biology is growing rapidly in tandem with increasing focus on determining the drivers of species extinction risk. Our review of the Australian literature shows a clearly increasing trend in the emphasis on the biodiversity implications and dynamics of non-indigenous species in Australia, even when compared with the generally increasing trend of publication rate within this field of biology (Fig. 2). This trend demonstrates the growing need for up-to-date information on the current and potential threats Australia's sensitive ecosystems face with the continued invasions by non-indigenous species. Our analysis also demonstrates obvious taxonomic and habitat biases in research focus, with the overwhelming majority of studies published pertaining to terrestrial systems and mammals. However, our relatively restricted search criteria (only peer-reviewed journals indexed by the major online databases) did not necessarily permit a full evaluation of all the relevant non-indigenous species literature in Australia. For example, there exists a host of government (national and state) and non-governmental organisation reports (e.g. Arthington and Blühdorn 1995; Dickman 1996; Long and Robley 2004; Olsen *et al*. 2006; Robinson *et al*. 2006), books and book chapters (e.g. Mooney and Hobbs 2000; Wittenberg and Cock 2001; Clout and Veitch 2002; De Poorter *et al*. 2005) and online databases (e.g. National Introduced Marine Pest Information System 2002; Database on Introductions of Aquatic Species 2007; Global Invasive Species Database 2007) that provide information on the extent, threat, ecology, distribution and control of non-indigenous species in Australia and globally. Continued development of published and online resources and the accumulation of species-specific data to identify current and future threats will be an integral part of managing the non-indigenous species' threats to northern Australia, and KNP in particular.

Kakadu National Park provides an illustrative yet challenging example of how non-indigenous species alter and interact with natural and cultural values within a culturally contested and highly valued landscape. Many of the perceived and potential threats to native ecosystems, especially in remote regions of Australia, have a low management priority because of the paucity of basic information such as species' distributions, variation in density over different habitat types, survival rates and other life-history characteristics, and population rebound potential. Perhaps more importantly, there has been insufficient development of cost-effective control techniques that are not only an essential component of density-reduction programs over the long term, but can also be used to reduce animal densities experimentally to quantify the magnitude of negative impact – a key to successful adaptive management. Our review has highlighted that the most important and consistent gap in knowledge concerns the relationship between the population density of non-indigenous species and landscape/ecosystem damage, and we recommend this area as most in need of further research. Only with long-term longitudinal data (monitoring) on habitat–densities–damage relationships will wildlife scientists and managers be able to overcome the hurdles facing the reduction and possible eradication of non-indigenous animals, both from a logistic perspective and as a means to argue for control when controversy surrounds their perceived impacts.

However, new knowledge alone will not resolve the complexity of management of non-indigenous species in KNP and elsewhere in tropical Australia. Data need to be analysed within the appropriate quantitative frameworks to provide robust appraisals of the threats of non-indigenous species (risk analysis) and the options for control (cost–benefit analyses). Perhaps more fundamentally, a common language is required to translate scientific data and analyses into a mode of discourse that other interested parties can understand, and thus become equal participants in the decision-making process. This will require some form of an adaptive-management cycle (Field *et al*. 2007), where consultation, monitoring, analysis, interventions, evaluation and policy (re)formulation become part of an ongoing and interactive process (Fig. 4). While such a process carries a heavy transactional cost (i.e. requiring dedicated staff and excellent communication amongst all parties), such an approach has a far higher likelihood of achieving effective management outcomes than short-term bursts of activity that have typified past control programs.

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