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Editorial

Cat ecology, impacts and management in Australia

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Introduction

The domestic cat (*Felis catus*) is an invasive species with severe impacts on the world's biodiversity. It is also a much-loved pet, and has a large and vocal constituency that preference saving the lives of cats above wildlife conservation. Given these conflicting perspectives, the management of cats is a contested and polarising subject (Loss *et al.* 2018). Evidence is critical for resolving this debate and for developing more effective management options. This special issue of *Wildlife Research* aims to compile and integrate much of the recent proliferation of research into diverse aspects of cat ecology, impacts and management undertaken in Australia and nearby areas. We hope that this collation helps responsible agencies and the community, in Australia and elsewhere, to gain a better understanding of cats and their impacts, and how those impacts can be reduced.

There has been substantial global interest in the management of cats (Marra and Santella 2016), with many pivotal research papers, particularly on impacts, produced in the last decade (e.g. Loss *et al.* 2013; Nogales *et al.* 2013). But the Australian case is distinctive; impacts have been (and continue to be) especially profound. There is now a particularly robust evidence base on cat impacts (Read 2019; Woinarski *et al.* 2019), governments are demonstrating a high degree of responsiveness, and most of the community recognises the conservation problem posed by cats.

Following their introduction to Australia in 1788, cats took less than a century to spread across the continent, helping send more than 25 mammal species to extinction and causing population declines in many others (Woinarski *et al.* 2015). By the late 1800s and early 1900s, perceptive naturalists such as Archibald Campbell, Edwin Ashby, the Le Souef brothers and Charles Barnard were warning of the severe impacts of cats on birds, and relating the disappearance of local populations of species such as night parrots (*Pezoporus occidentalis*) and paradise parrots (*Psephotellus pulcherrimus*) to the arrival of cats. By the 1930s, Hedley Finlayson was lamenting the loss of mammalian fauna from the central deserts, and attributing this loss partly to cats (Woinarski *et al.* 2019).

Despite these early observations and warnings, research on the ecology, impacts and management of cats was slow to develop. The lack of research attention occurred partly because identifying the individual contribution of cats to the broad-scale subversion of Australia's biota has been challenging. The diaspora of cats was part of a medley of immense environmental changes that followed the colonisation of Australia by Europeans; many other alien species were introduced (e.g. foxes (*Vulpes vulpes*), rabbits (*Oryctolagus cuniculus*), camels (*Camelus dromedarius*), cattle (*Bos* spp.), horses and donkeys (*Equus* spp.)), and Indigenous Australians' careful custodianship of country and the factors that shape it (like fire) were disrupted or replaced with other land uses. In addition, cats are notoriously challenging to study; they are difficult to catch and highly cryptic. In Australia, they also came to occur almost everywhere, so there was little scope for discerning the difference in biodiversity between cat-occupied and cat-unoccupied areas. Nevertheless, scientific investigation into the impacts of cats began from about the 1970s, with important compilations that summarised what was known to that point, and where the research gaps lay, produced from the 1990s (e.g. Potter 1991; Dickman 1996).

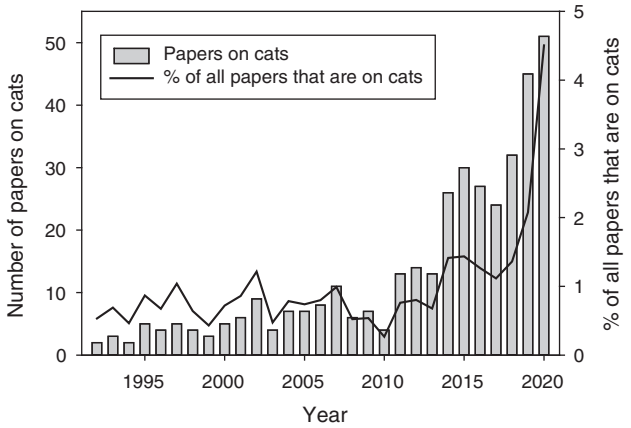

Fig. 1. The number of publications produced each year, and as a percentage of all publications, on cat impacts and management in Australia. The number of publications was collated from the Web of Science database by searching on the topic (i.e. title, abstract or keywords) for '*felis catus*' AND '*Australia*' AND ('*wildlife*' OR '*threatened species*' OR '*fauna*' OR '*conservation*' OR '*biodiversity*'). To account for the increasing number of Australian biodiversity and conservation papers over time, we also calculated the percentages of publications annually that were cat-related by dividing by the numbers of papers on the topic: '*Australia*' AND ('*wildlife*' OR '*threatened species*' OR '*fauna*' OR '*conservation*' OR '*biodiversity*').

Research on cats has proliferated since. A search of the Web of Science database for publications on cat ecology and impacts in Australia shows a fairly even trickle from the 1970s until 2010, when the number of publications in both absolute terms, and as a proportion of all publications on Australian ecology and conservation, began to flourish (Fig. 1). The increase is related to three key factors. First, some applied researchers had been working on programs to develop cat-management options or programs to conserve native animal species particularly susceptible to cat predation. Second, technological advances in telemetry, animal-borne cameras and motion-sensing cameras allowed a quantum leap in how wily feral cats could be tracked and observed. Third, socio-political attention sharpened on faunal extinctions, the role of cats in these losses, and the need to act to prevent further extinctions. For example, Australia's inaugural Threatened Species Strategy (Commonwealth of Australia 2015) highlighted feral cats as a threat for particular attention, with targets for policy initiatives, specific management interventions, new cat-control technology, as well as controversial cat-kill targets (Doherty *et al.* 2019). The Australian Government's National Environmental Science Program also began in 2015, with substantial investment in cat-related research made through the Threatened Species Recovery Hub (https://www.nespthreatenedspecies.edu.au/research/theme-1-0, accessed 9 October 2020). This pattern has been reflected in other jurisdictions; for example, a AU$20 million investment in cat research was made recently by the New South Wales Environmental Trust (https://www.une.edu.au/connect/news/2019/06/feral-cats-focus-of-$30-million-research-program, accessed 9 October 2020), and the Western Australia Biodiversity Science Institute released a comprehensive research prospectus that aims to reduce cat impacts in Western Australia (Webber 2020).

This special issue of Wildlife Research reflects not just the burgeoning interest in cats in Australia, and globally, from the research and broader community, but also our increasing capacity to manage the impacts of cats. The assembled papers contribute to our collective ability to conserve Australia's unique fauna; they cover advances in our understanding of the basic ecology of cats and their impacts, as well as trials of novel control methods and studies of adaptive management programs.

Cat ecology and impacts

In part following landmark studies in North America (Blancher 2013; Loss *et al.* 2013), over the past 4 years teams of researchers have performed a series of meta-analyses to synthesise fundamental information about cats in Australia. More so than elsewhere in the world, many separate studies have been gathered into a substantial evidence base on cat density and diet. This has allowed the following: robust analyses of cat distribution, population size and spatial variation in cat density across the Australian mainland and islands (Legge *et al.* 2017); estimates of the toll of predation of cats on animal groups; and identification of the native species most prone to cat predation (Woinarski *et al.* 2017*a*, 2017*b*, 2018; Murphy *et al.* 2019; Woolley *et al.* 2020). In this special issue, the final components of that series are presented, with estimates of the toll taken by cats in Australia on frogs (Woinarski *et al.* 2020) and invertebrates (Woolley *et al.* 2020). Fundamental statistics on cat population size and predation rates are now better described for Australia than for any other country. Cats cover the entire continent and most of its larger islands; there are an estimated 1.4–5.6 million feral cats in the Australian bush (depending on recent rainfall patterns through the arid zone), over 0.7 million feral cats in towns and cities, and 3.8 million pet cats in people's homes. Feral cats kill and eat over 2 billion vertebrates and over 1 billion invertebrates in Australia each year. One of the papers in this special issue turns the spotlight from feral cats onto pet cats, finding that Australian pet cats kill over 390 million vertebrates each year (Legge *et al.* 2020*b*).

The sequence of meta-analyses that is completed by the three papers in this special issue identified some data-poor areas, and work showcased in the special issue helps fill these gaps. For example, estimates of cat density or activity have been rare from some habitats including tropical rainforests and topographically rugged landscapes. Papers by Lavery *et al.* (2020) for the Solomon Islands and Rowland *et al.* (2020) in Queensland describe the density or occurrence of cats in rainforests, and McDonald *et al.* (2020) document cat density in rugged environments of central Australia. Hohnen *et al.* (2020*a*) and Miritis *et al.* (2020) estimate cat densities for Kangaroo Island and French Island respectively. This information is valuable because many islands (in Australia and globally) have very high conservation values, but cats reach higher densities on islands than on the mainland (Legge *et al.* 2017), and island-specific density information is required to inform cat-eradication efforts.

Most Australian research on cat impacts has focussed on predation, for a good reason, but cats can affect native animals via other pathways. Cats can alter the behaviour of potential prey

(Bonnington *et al.* 2013), leading to compromised lifetime reproductive success and potential population declines (Greenwell *et al.* 2019). Studies of dietary and habitat overlaps suggest that cats compete with native predators. Cats can also facilitate the transmission of disease-causing pathogens, including those that depend on cats for part of their life cycle, and which, therefore, would not exist in Australia had cats not been introduced. Papers in this special issue help improve our knowledge of these less-studied cat impacts. Taggart *et al.* (2020) document the high rates of infection by the protozoan *Toxoplasma gondii* in macropods on Kangaroo Island. Cats are the definitive host for this parasite, and it causes morbidity and mortality in some Australian animals, although its effect at the population level is still unclear. Taggart *et al.* (2020) relate the high infection rates to the high cat density on the island. Any warm-blooded animal can be a secondary host for *T. gondii* and, in another paper, Legge *et al.* (2020*a*) examine the economic costs of this parasite, and other cat-dependent pathogens, through their impacts on human health and livestock production in Australia. They estimate an annual cost of over AU$6 billion, and suggest that reducing the population size of cats (both feral and pets) and breaking transmission pathways could reduce disease burdens on people and agriculture.

In the past few years, the interaction of cats with other threats has become much more widely recognised. Research in north-western Australia has demonstrated that cats hunt more efficiently in heavily grazed and severely burnt areas, and as a result cats are drawn from far-afield to hunt in such areas (McGregor *et al.* 2014, 2015, 2016). The combination of increased cat density and hunting success causes the mortality rates of small mammals living in such places to increase dramatically (Leahy *et al.* 2015; McGregor *et al.* 2016), with population-level effects occurring (Legge *et al.* 2019). The synergistic interaction between invasive predators and major disturbances has been similarly documented in Victorian forests (Hradsky *et al.* 2017). In this special issue, Davies *et al.* (2020) extend the generality of these observations yet further, by showing that the abundance of feral cats on Melville Island, Northern Territory, is positively related to increased disturbance from high frequencies of intense fire and heavy grazing by feral stock. This corroborates another recent study from northern Australia that found that feral cats were less likely to be present in productive habitats unless those habitats experienced high fire activity (Stobo-Wilson *et al.* 2020*a*).

Understanding how cat impacts are influenced by co-occurring threats is extremely important, because it informs management approaches that can be used to reduce these impacts without ever touching a cat, potentially over very large areas. Fire and grazing can be managed to retain structural complexity in ground-layer vegetation, and thus reduce cat hunting success. The paper by Miritis *et al.* (2020) shows how long-nosed potoroos (*Potorous tridactylus*) on French Island 'use' this principle, sticking to denser cover in areas with high cat activity. In a different example, Stobo-Wilson *et al.* (2020*b*) suggest that controlling rabbits, themselves being a threat to many native plant species, in the Flinders Ranges of South Australia may be the most effective way to reduce cat impacts on native species, because cat density is inflated by the ready availability of rabbits.

Controlling cat populations

Until quite recently, reducing cat populations was typically relegated to the 'too-hard' basket. However, increasingly over recent decades, a range of control options has been developed and applied. Some of the papers in this special issue further our understanding of the circumstances under which they work best. Other papers present findings from trials of novel control options.

Cat eradications from Australian islands began modestly in the 1960s, but are now occurring on increasingly large islands (e.g. 630 km^2 Dirk Hartog Island in north-western Australia – the world's largest successful island eradication of cats), including inhabited islands. Their mainland analogues, namely, fenced areas from which cats and other feral animals have been removed, have been established in Australia from the late 1990s, and construction of new fenced areas has accelerated in the past decade or so. Cat-free islands and fenced areas have prevented the extinction of eight Australian mammal species, and further expansion should extend protection to other species that are highly susceptible to cat predation (Legge *et al.* 2018). The ark network has focussed on threatened mammals and birds (especially on islands), but Roshier *et al.* (2020) describe the effects of a large mainland fenced area on other species, showing that small mammals benefited from the exclusion of feral animals, but small reptiles did not, possibly because the reintroduced mammals competed with resources important to the reptiles, or preyed on the reptiles directly.

Poison-baiting became a viable option for cats, which are live-prey specialists, when innovators in Western Australia developed a bait formulation and strategy that was attractive even to feline fussy eaters (Algar *et al.* 2011). Eradicat baits, a sausage laced with the poison 1080, are being used successfully to control cats and support recovery of threatened mammal populations in south-western Australia, where native fauna has high tolerance to the 1080 toxin, because it occurs naturally in a common group of plants in that region. However, the utility of Eradicat elsewhere in Australia depends on several factors, including the likelihood that native animals without this elevated tolerance will consume the baits. Several papers in the special issue build the body of evidence for when Eradicat can and cannot be safely used, with studies of the extent of non-target impacts in south-western Australia (Friend *et al.* 2020), the Pilbara (Cowan *et al.* 2020) and Kangaroo Island (Hohnen *et al.* 2020*b*).

Innovation in poison-baiting has not stopped with Eradicat; an alternative toxin (para-aminopropiophenone, or PAPP) is now available, and ways of presenting either toxin to reduce the risk of non-target impacts are being developed. For example, encapsulating the toxin in a controlled-release pellet within the bait should reduce intake by native animals, and a promising trial of this approach using PAPP is presented by Johnston *et al.* (2020). Another example of innovative toxin delivery is documented by Moseby *et al.* (2020) who tested the capability of the new Felixir grooming trap to reduce the density of feral cats, while minimising the impact on co-occurring native animals. The Felixir holds much promise for controlling cats in localised areas, because it can be set out in the field for extended periods without maintenance.

As cats spread across Australia, they replaced some native animals in the diet of Indigenous Australians. Hunting cats for food is still a favoured activity for some families in the western deserts. Paltridge and her co-authors, including Pintupi Traditional Owners (Paltridge *et al.* 2020), describe the history of cat hunting in that region, and attempt to quantify the efficacy of traditional cat hunting in terms of reducing cat numbers and supporting populations of bilbies (*Macrotis lagotis*) and great desert skinks (*Liopholis kintorei*). Cat hunting by Indigenous tracking experts could be used more widely. Indigenous ranger groups are being supported to manage an increasingly large proportion of Australia, and investment in land-management activities such as these, which fulfil aspirations for managing country more broadly, has substantial environmental and linked social benefits (Social Ventures Australia 2016).

One of the papers in the special issue, by Garrard *et al.* (2020), represents the first attempt to summarise the extent of cat control occurring nationwide. These authors estimate that over 300 000 feral cats are killed annually, with much of that effort happening outside the traditional conservation sector. Of course, interpreting a change in impact from feral predators as a direct result of the killing of pests is notoriously fraught, but Australian conservation programs are increasingly integrating monitoring into cat management to inform adaptive responses. Examples include a long-running program to control cats around remnant populations of western ground parrots (*Pezoporus flaviventris*; Comer *et al.* 2020), a program to control foxes and cats in the Flinders Ranges (Stobo-Wilson *et al.* 2020*b*), a program to monitor non-target responses to cat baiting at Matuwa-Lorna Glen (Wysong *et al.* 2020), and a study to check for perverse outcomes from attracting cats to the perimeter of a successful fenced area at Arid Recovery in South Australia (McGregor *et al.* 2020).

Where to next?

The papers in the special issue reflect the quality of applied ecological research into cat impacts and management that has developed over the past few years. Although continuing research is critical, the knowledge gaps that have long impeded cat management are shrinking. Innovation is continuing, with current research exploring options such as more targeted cat control (e.g. using 'toxic trojans', and predator profiling); immunocontraception, disease and gene drive technology for reducing cat populations; and accelerated natural selection to enhance the anti-predator behaviour of native species (summarised in Woinarski *et al.* 2019).

For pet cats, given enough political and public support, the available technical solutions for reducing impacts are simple; responsible cat ownership includes actions such as early age desexing, keeping pets indoors or in a securely contained outdoor area, and designating suburbs adjacent to high conservation-value areas as cat-free. Reducing the numbers of feral cats living in towns and cities is more challenging, but tighter management of refuse and sites of high food subsidy should reduce cat numbers substantially. As well as reducing cat impacts on 'urban' wildlife, reducing the numbers of pet and feral cats wandering at large will also reduce transmission rates of cat-dependent pathogens. Managing the impacts of feral cats in the bush remains challenging, but significant progress has been made, and continues to be made. As the special issue goes to press, two highly relevant parliamentary inquiries are underway in Australia: a Senate Inquiry into 'Australia's faunal extinction crisis' (https://www.aph.gov.au/Parliamentary_Business/Committees/Senate/Environment_and_Communications/Faunalextinction, accessed 9 October 2020), and a House of Representatives Inquiry into the 'Problem of feral and domestic cats in Australia' (https://www.aph.gov.au/Parliamentary_Business/Committees/House/Environment_and_Energy/Feralanddomesticcats, accessed 9 October 2020). We hope that the flourishing of knowledge about cat impacts and management, showcased in this special issue, will encourage the recent policy support initiated by the Australian and other governments, and be matched by a step-up in strategic management, investment and delivery, so that further declines and extinctions of native species are prevented.

Conflicts of interest

Sarah Legge is an associate editor for *Wildlife Research* and was the guest Editor-in-Chief for this special issue. John Woinarski, Chris Dickman, Tim Doherty, Hugh McGregor and Brett Murphy were also guest editors for this special issue. The authors have no further conflicts of interest to declare.

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