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Review

We need to worry about Bella and Charlie: the impacts of pet cats on Australian wildlife

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Abstract. Research and management attention on the impacts of the introduced domestic cat (*Felis catus*) on Australian fauna have focussed mainly on the feral population. Here, we summarise the evidence for impacts of predation by pet cats on Australian wildlife. We collate examples of local wildlife population decline and extirpation as a result, at least in part, of predation by pet cats. We assemble information across 66 studies of predation by pet cats worldwide (including 24 Australian studies) to estimate the predation toll of pet cats in Australia, plus the predation pressure per unit area in residential areas. We compared these estimates to those published for feral cats in Australia. The *per capita* kill rate of pet cats is 25% that of feral cats. However, pet cats live at much higher densities, so the predation rate of pets per square kilometre in residential areas is 28–52 times larger than predation rates by feral cats in natural environments, and 1.3–2.3 times greater than predation rates per km^2 by feral cats living in urban areas. Pet cats kill introduced species more often than do feral cats living in natural environments, but, nonetheless, the toll of native animals killed per square kilometre by pet cats in residential areas is still much higher than the toll per square kilometre by feral cats. There is no evidence that pet cats exert significant control of introduced species. The high predation toll of pet cats in residential areas, the documented examples of declines and extirpations in populations of native species caused by pet cats, and potential pathways for other, indirect effects (e.g. from disease, landscapes of fear, ecological footprints), and the context of extraordinary impacts from feral cats on Australian fauna, together support a default position that pet cat impacts are serious and should be reduced. From a technical perspective, the pet cat impacts can be reduced more effectively and humanely than those of feral cats, while also enhancing pet cat welfare. We review the management options for reducing predation by pet cats, and discuss the opportunities and challenges for improved pet cat management and welfare.

Additional keywords: conservation, introduced species, management strategies, predation, prey selection.

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Introduction

Since their domestication ~4000 years ago in Egypt, people have moved domestic cats, *Felis catus*, extensively around the world. The status and ecological significance of cat populations is often defined in terms of their interactions with humans. Feral cats live independently across many habitats and environments, with a subset of these (sometimes called stray, or semi-feral) living in heavily modified environments and being at least partially provisioned by domestic garbage or supplemental feeding by people. In contrast, pet cats are owned by a household; some are allowed unrestricted roaming, and others are confined to their owner's premises at all times (for alternative definitions, see the glossary in Crawford *et al.* 2019). Feral (including stray or semi-feral) cats now occur on all continents except Antarctica, and on many of the world's islands (Atkinson and Atkinson 2000; Long 2003; Duffy and Capece 2012;

Nogales *et al.* 2013), whereas pet cats can claim a recent presence on every continent because they have been kept on some Antarctic bases (Roberts 2006; Sandall 2017). Cats have versatile diets, use a wide range of habitats, have high breeding rates and a wide thermal tolerance, and do not require free drinking water (Bonnaud *et al.* 2011; Bradshaw 2013; Doherty *et al.* 2014); these attributes make them superb invaders.

Introduced cats have had profound impacts on native faunas in many places, contributing to 26% of the total extinctions of mammals, birds and reptiles globally since 1600 (Doherty *et al.* 2016). The impacts of cats on native faunas have been greatest on islands, including large island nations such as Australia and New Zealand whose fauna evolved without exposure to felids (Salo *et al.* 2007; Campbell *et al.* 2011; Medina *et al.* 2011; Nogales *et al.* 2013). Cats affect native species mostly through predation, but also through disease transmission, hybridisation with other (native) species of *Felis*, and by affecting the behaviour of prey in ways that reduce their lifetime fitness (Beckerman *et al.* 2007; Dubey and Jones 2008; Medina *et al.* 2011; Doherty *et al.* 2016). Cats also interact with and compound the impacts of other threats such as changed fire regimes and pastoralism (McGregor *et al.* 2014; Legge *et al.* 2019).

Cats established in Australia following their introduction by European settlers from 1788 onwards (Abbott 2002; Abbott 2008; Koch *et al.* 2015; Spencer *et al.* 2016). Feral populations around settlements spread rapidly, covering the mainland within 70 years, aided by many deliberate releases to non-urban areas of cats in unsuccessful attempts to control other introduced species such as the introduced European rabbit, *Oryctolagus cuniculus* (Rolls 1969). Feral cats are now found across all of mainland Australia and Tasmania, and on all larger islands except Dirk Hartog Island (628 km^2) where cats were recently eradicated (Legge *et al.* 2017).

Cats are generalist ambush predators, capable of killing animals up to ~4 kg (Fancourt 2015). They are obligate carnivores, consuming almost no vegetative material. Cats mostly hunt species according to their relative abundance in an area (Doherty *et al.* 2015), but individual cats often specialise on particular species or species groups (Dickman and Newsome 2015; Moseby *et al.* 2015). Mammals make up the greatest proportion of cat diet, except in areas where mammals are rare or absent (such as some offshore islands), or where other prey types are more common. For example, reptiles make up a high proportion of cat diet in Australia's arid zone during summer months, when they are most active (Paltridge 2002; Doherty *et al.* 2015; Woinarski *et al.* 2018*b*).

Evidence that feral cats exert a detrimental impact on Australian fauna comes from a large range of studies on cat ecology and diet; on the spatial and temporal patterns of native species decline in relation to the spread of cats across the continent; from comparative analyses of the ecological and life-history correlates of decline; and from experiments where the response of native species is measured after cats are controlled or removed (reviewed in Doherty *et al.* 2017; Woinarski *et al.* 2019*b*). Cats have had a particularly profound impact on Australian mammals, causing or contributing to most of the >30 species extinctions in the past 250 years (Woinarski *et al.* 2015, 2019*a*; Woolley *et al.* 2019). Cats continue to cause declines in native fauna; a large proportion of extant native terrestrial mammal species are highly susceptible to predation from cats (Radford *et al.* 2018), and many of Australia's threatened mammals now occur only on small islands that were never invaded by cats or foxes, *Vulpes vulpes*, or as translocated populations to islands and small fenced mainland enclosures that exclude cats and foxes (Legge *et al.* 2018). Cats have also contributed to declines and extinctions of some bird populations on Australian islands, including island endemics (Taylor 1979).

In Australia, most cat-related extinctions and population declines have happened, or are happening, far from human residential areas. Research on, and management of, cat impacts has correspondingly focussed mostly on feral cats, rather than pet cats, even though pet cats also hunt and urban areas can be hotspots for threatened biodiversity (Ives *et al.* 2016). Population sizes and densities of pet cats can be enormous, eclipsing those of feral cats. In Australia, pet cats outnumber feral cats, at least in most years (3.77 million pet cats versus 2.8 million feral cats, Legge *et al.* 2017; AMA 2019). In the UK, 90% of all cats are pets (Woods *et al.* 2003). Globally, pet cat populations are increasing rapidly; pet cat numbers in the USA have tripled in the past 50 years (Kitts-Morgan 2015); they have increased by 13% per annum in the UK for the past 40 years (Beckerman *et al.* 2007) and are increasing by 10% per annum in China (Su *et al.* 2018). Likewise, the pet cat population in Australia increased by 6.5% between 2013 and 2016, mostly tracking human population growth (AMA 2019). Thus, if pet cats have detrimental impacts on native fauna, these impacts will inexorably increase unless we change the way we manage and care for pet cats, or reduce the rates of pet cat ownership.

Here, we summarise the available evidence for detriment to Australian wildlife by pet cats such as Bella and Charlie (the two most common names for female and male cats in Australia; Roetman *et al.* 2017). We focus on the impacts from predation, and discuss indirect impacts briefly. We estimate the toll of pet cats on native species by collating and interpolating information across 66 studies of predation behaviour and predation rates by pet cats (including 24 studies from Australia). Some studies have been published only in the grey literature, and there has been no previous attempt at a national collation. Although the Australian studies differ in methods, duration and sample size, and have not sampled exhaustively across Australian urban, peri-urban and rural environments, collectively, they represent a substantial research effort and include sampling from many locations. In addition to reviewing impacts, we review the management options for reducing those impacts, and their efficacy. Finally, we discuss the opportunities and challenges for improving pet cat management.

Impacts of predation by pet cats on local wildlife populations

Allowing pet cats to roam creates the potential for hyperpredation on local prey populations, because cat density and predation rates are decoupled from prey density (Courchamp *et al.* 2000; Woods *et al.* 2003). A range of studies on different native wildlife species from around the world has demonstrated substantial effects of predation from pet cats, including high rates of mortality, declines and even extirpations of local populations. Hunting by pet cats has caused bird population declines and extirpations at multiple habitat patches in California (Crooks and Soulé 1999). In a study in an English village, 30% of sparrow, *Passer domesticus*, mortality was attributed to pet cats (Churcher and Lawton 1987), and, in other studies in the UK and New Zealand, pet cats killed birds each year in numbers that were equivalent to the adult bird population in those areas (van Heezik *et al.* 2010; Thomas *et al.* 2012). Two separate studies of cat colonies that were fed daily and well by carers (i.e. similarly to a pet cat) also demonstrated impacts on populations of native species. In one case, a population of wedge-tailed shearwaters, *Ardenna pacificus*, declined as a result of higher adult mortality and lower breeding success, whereas adult mortality and breeding success were not affected in control areas (i.e. those without fed cats; Smith *et al.* 2002). In a Californian study, the abundance of native rodents and birds was reduced in the vicinity of the cat feeding area, but not in nearby control areas (Hawkins *et al.* 1999).

Detrimental impacts to wildlife populations from pet cat predation have also been reported from Australia, but the evidence is patchier. Pet cats were blamed for the decline of a local population of superb lyrebirds, *Menura novaehollandia*, at Sherbrooke Forest, Victoria; consequent changes to pet cat management regulations were associated with a recovery in lyrebird numbers (Pergl 1994; Dickman 1996). However, the improved pet cat management coincided with fox and feral cat control programs, so the relative contributions of pet cats versus introduced predators to the lyrebird declines are hard to disentangle (Sherbrooke Lyrebird Study Group 2019). Pet cats contributed to the extirpation of a population of threatened eastern barred bandicoots, *Perameles gunni*, in Victoria, by killing a high proportion of juveniles (Dufty 1994), but again, the relative contributions of pet cats and feral cats to this predation toll were unclear. Some studies have reported high mortality rates from pet cat predation on wildlife populations. For example, a study of radio-collared common ring-tailed possums, *Pseudocheirus peregrinus*, in Manly Dam Reserve near Sydney, showed that 37% of the population was killed by cats over three years (Warringah Shire Council 1998, cited in Eyles and Mulvaney 2014). In a second example, Paton (1993) estimated that pet cats in Adelaide were killing 80% of the standing crop of adult birds. The predation rates for both the ringtails and the Adelaide birds seem high, and a population viability analysis would help interpret the impacts of this predation on long-term viability. Similarly, attacks by pet cats are one of the most common causes of injury to animals brought to wildlife rescue centres, along with vehicle strike and dog attack, and the cat attacks tend to be concentrated on smaller species of mammal, reptile and bird (Shine and Koenig 2001; Koenig *et al.* 2002; Heathcote *et al.* 2019). However, inferring impact from these studies is challenging, partly because the population sizes of the affected species are unknown, and also because of strong biases in the sorts of animals that people attempt to rescue (towards species that people care about, are scared of, and that are large enough to be noticed).

There are some documented cases where just one or a few pet cats have driven population declines of native Australian species. Paton (1993) described the extermination of a local population of feather-tailed gliders, *Acrobates pygmaeus*, in south-eastern New South Wales, by a single pet cat. In suburban Canberra, a single pet cat killed enough olive legless lizards, *Delma inornata*, to reduce a local population to a 'non-detectable' level (W. Osbourne, pers comm., in Eyles and Mulvaney 2014). In Perth, Western Australia, a suburban garden population of the skink *Ctenotus fallens* was extirpated by one pet cat (Bamford and Calver 2012). Recently, disturbance by a single pet cat, and predation by a stray cat, caused the total breeding failure of a colony of more than 100 pairs of fairy terns, *Sternula nereis nereis*, at Mandurah, Western Australia (Greenwell *et al.* 2019). In New Zealand, the infamous extinction of the Stephens Island wren, *Traversia lyalli*, was caused by a single pet cat and its progeny (Galbreath and Brown 2004).

Broader studies that have looked for correlations between pet cat density and wildlife abundance have produced inconsistent results, or are hard to interpret (Grayson *et al.* 2007; Sims *et al.* 2008; Dickman 2009; Lilith *et al.* 2010). In practice, these correlative studies are often beleaguered by confounding factors, such as insufficient variation in pet cat density, gradients in other threats, uneven compliance with cat regulations, contrasts in vegetation and other biotic factors among sites, and whether the focus is on the bird community within the suburb or in adjacent bushland. These confounding factors, with a lack of adequate controls, make it hard to discern general patterns. Designing experimental manipulations such as adding pet cats to a cat-free area, or removing pet cats from entire suburbs, is infeasible. The lack of clear evidence of diminished faunal communities as a result of pet cat presence has hampered arguments that the impacts of pet cats need to be managed (e.g. RSPB 2019). The examples of wildlife population declines as a result of pet cat predation are highly suggestive, although these studies are few (especially so from Australia).

Impacts of pet cats on local populations of introduced species

Pet cats prey not only on native species, but also on introduced species, especially rodents, and this has led to the suggestion that pet cats could benefit wildlife because they may suppress the density of introduced rats and mice, which compete with, and prey on, native wildlife (Barratt 1997*b*; Matthews *et al.* 1999; Dickman 2009). This suggestion has been most strongly advanced in New Zealand, which has no native terrestrial mammals other than bats, and where bird nest predation by introduced rodents can be a major concern (Flux 2007, 2017). However, this is unlikely to be a general phenomenon in Australia. Even if pet cats kill introduced mice and rats in and around suburbs, they are also killing individuals of native species. So, for example, Dickman (2009) reported that pet cats seemed to reduce the rate of predation by introduced black rats, *Rattus rattus*, on bird nests in bushland fragments in Sydney, but high cat activity was also associated with lower bird species richness, presumably through the direct predatory impacts on birds by cats. Also, although pet cats can maintain low numbers of introduced rodents in local situations with specific conditions (e.g. Elton 1953), predation by pet and stray cats has not been shown to reduce the overall population size of introduced rodents across larger areas, although cat presence may change rodent behaviour (Parsons *et al.* 2018).

The predation toll of pet cats

Previous work has estimated the annual toll of cats in Australia on mammals, birds and reptiles, by combining estimates of the population sizes of cat in Australia with information on their predation rates from diet studies and cat owner surveys (Legge *et al.* 2017; Woinarski *et al.* 2017, 2018*a*; Murphy *et al.* 2019). Whereas variation in predation by feral cats was well represented by a large number of studies spread across Australia, information on predation by pet cats was more limited, being represented by three substantial Australian studies, and another four from overseas. Here, we attempt to improve our understanding of pet cat predation tolls by collating a larger set of studies conducted in Australia and overseas, using different subsets of these studies to derive the required statistics. Although it is difficult to extrapolate from tolls to impacts, we attempt to contextualise the potential impact of pet cats by converting the overall tolls into predation rates per unit area, and then comparing these predation rates with published equivalent estimates for feral cats, whose impacts are better described and understood.

Approach

To estimate the predation rates of pet cats in Australia, we conducted an unstructured search of the literature by using search terms 'pet cat' and 'cat predation', so as to collate information on the population size of pet cats, the percentage of pet cats that roam (i.e. have access to outdoors), the proportion of roaming pet cats that hunt, and the predation rates of those roaming, hunting cats. By breaking the analysis into these constituent steps, we were able to use data from more studies, because many studies report only on some steps in this sequence. In contrast to studies of the diet of feral cats, which are typically based on examination of stomach contents or faeces, most data on pet cat predation are gathered by keeping records of the prey items that pets bring home to their owners. However, most prey items killed by cats are not brought home; to account for the 'missing' prey, we collated information from studies that have used cat-borne video or scat analysis to directly compare the proportion of killed prey that is brought home. To convert the estimates of overall tolls into predation rates per unit area, we calculated a range of plausible values for the density of pet cats in and near residential areas. We explain each step in more detail below.

We characterised the uncertainty of estimates by simultaneously bootstrapping the datasets. For example, to derive an estimate for the overall toll of pet cats, we bootstrapped (1) the proportion of cats that roam, (2) the proportion of roaming cats that bring back prey, (3) for each cat that brings home prey, the number of prey items returned per year, and (4) the proportion of prey items that are brought home. The datasets were bootstrapped 10 000 times and, for each random sample of the data, the estimate of total predation was recalculated. We simultaneously accounted for uncertainty in the pet cat population size, by sampling a normal distribution with a mean of 3.77 million and standard deviation of 3% of the mean (following Loss *et al.* 2013). For clarity, confidence limits around estimates are presented in tables and figures, but not in the main text.

Pet cat population

The most recent estimate for the pet cat population size in Australia is 3.77 million, based on surveys of a large sample of households (AMA 2019). That study showed that 27% of households have pet cats, with an average of 1.4 cats per cat-owning household. These proportional figures have changed little since the 1990s, when a similarly broad survey estimated that cats occurred in 25.5% of households, with an average of 1.4 cats per cat-owning household (Reark 1994). Other studies conducted in smaller geographic areas have returned comparable values for the numbers of households with pet cats (Table S1, available as Supplementary material to this paper).

The Animal Medicines Australia survey censused households in urban areas and the 'rest of state' and then weighted the results accordingly, such that the representation of households in rural, regional and urban areas was sampled and incorporated into the population estimate. However, sampling was conducted online, and it is therefore likely that remote areas with poor internet access, including Indigenous communities, were not well sampled. It is possible that rates of pet cat ownership in remote areas differ from those of urbanised and rural areas; however, because the number of households in remote communities is small compared with the total number of households across Australia, differing cat ownership rates are unlikely to affect the overall population estimate for pet cats.

Pets that roam and hunt

Not all pet cats are allowed to roam freely outside, and not all roaming cats hunt. Across six Australian studies of pet cats, 71.1% roam outside (the remaining cats are contained indoors or within enclosed outdoor areas; Tables 1, S1). This may be an underestimate, because a detailed study of pet cat roaming behaviour found that many cat owners mistakenly believed that their pets did not roam outside their property; of 177 cats whom their owners believed were contained indoors at night, 39% actually had night-time ranges of over 1 ha (Roetman *et al.* 2017). Of those Australian cats that roam, an average of 78.4% bring prey back to their owner's house (across 10 studies; Tables 1, S1); this is likely to be an underestimate, because some cats hunt (and kill) without returning prey (e.g. Bruce *et al.* 2019). To estimate the overall predation rates of pet cats, we need to discount cats that are contained, and discount roaming cats that do not hunt; thus, the total population of 3.77 million pet cats is reduced to a minimum of 2.10 million roaming and hunting pet cats. We used Australian studies to derive the proportion of contained cats because the extent of cat containment varies markedly among countries (e.g. 3% of cats in the UK, 10% of pet cats in New Zealand, and around 30% of cats in the USA are contained; Bruce *et al.* 2019). We also used Australian studies to estimate the percentage of roaming cats that hunt, in case differences in pet care and prey availability across countries affect this figure. However, we note that the average percentage of roaming cats that hunt in overseas studies is remarkably similar (75.1% versus 78.4% for Australia: Tables 1, S1), perhaps suggesting that the hunting behaviour of well fed pets is similar regardless of their local ecological environment. Note that the 'breed' of cat is generally not defined in these studies; however, there may be some variable propensity for roaming and predation among different breeds of cats.

Pet cat density

We used the Catchment Scale Land Use of Australia (ABARES 2019) to estimate the total residential area across urban, rural

Table 1. Summary of the means and their 95% confidence limits, for each step used in the calculation of overall predation rates, from 10 000 bootstrapped values derived from the underlying datasets

The pet cat population was set at 3.77 million, with a standard deviation of 3% following Loss *et al.* (2013). Underlying data are based on Australian studies, except for 'proportion of prey killed that is brought home'. Details of contributing datasets, as well as comparable information for other countries, are given in Table S1

Item	Sample	Estimate	Lower 95%	Upper 95%
% of cats that roam	6	71.1%	67.0%	75.6%
% of roaming cats that hunt	10	78.4%	69.2%	85.8%
Prey items brought home per cat per year	12	28.1	16.9	40.1
Proportion of prey killed that is brought home	7	15.1%	7.8%	22.3%
Per capita predation rate per year for roaming-hunting cats (considering the % prey that is killed but not brought home)		186	97.7	378
Proportion of each class of prey				
Mammals	11	48.6%	40.6%	56.9%
Birds	11	30.1%	25.0%	35.9%
Reptiles	11	21.3%	14.7%	28.0%
% of prey that is native				
All prey	11	61.7	50.0	72.3
Within mammals	10	35.3	17.6	53.6
Within birds	10	67.8	54.7	80.0
Within reptiles	10	100	100	100
Total prey eaten per year by class (millions)				
Mammals		189	97.0	398
Birds		118	58.4	248
Reptiles		82.9	38.5	181
Total prey eaten per year (millions)		390	204	812
Total native prey eaten per year (millions)		241	122	502
Total native prey eaten per year by class (millions)				
Native mammals		66.9	25.5	157
Native birds		79.7	38.2	172
Native reptiles		82.9	38.5	181

and remote communities and farms (29 683 km^2; Table S2). Not all households have pet cats, and not all pet cats are allowed to roam outside, so it is possible that the area over which pet cats roam is smaller than the total footprint of residential areas in Australia. Nevertheless, to be conservative when estimating predation rates over unit area, we used the total residential area as the lower limit for the footprint over which pet cats roam.

Conversely, pet cats that have access to the outdoors may wander away from the household boundary, potentially making the total area over which pet cats roam larger than the cumulative residential area. To place an upper limit on the area over which pet cats roam, we recalculated the residential area plus a buffer of 80 m, which is the approximate radius for a circular home-range area of 2 ha. We chose 2 ha because it was the mean home-range size for a large sample of 428 cats tracked in South Australia (Roetman *et al.* 2017, 2018). Applying a buffer of 80 m around the residential areas in Australia returns an area of 54 201 km^2 (Table S2). We note that pet cat home-range size is variable, with reported values varying from 0.01 ha (Lilith *et al.* 2008) in high-density housing near Perth to 7.9 ha in suburban Canberra (Barratt 1997*a*). However, the distribution of home-range sizes tends to be skewed, with most cats having small ranges; for example, although the mean home-range size of pet cats in the South Australian study was 2 ha, the median was 1 ha.

Using the cumulative area of residential land as the lower boundary over which pet cats hunt, and the buffered area as the upper boundary, the average density of all pet cats in Australia is 69.5–127 cats km^{-2} (Table S3). However, considering only the subpopulation of pet cats that roams and hunts, the average density becomes 38.8–70.8 cats km^{-2} (Table S3). These values are lower than that reported in some other studies, such as 380 cats km^{-2} for Canberra suburbs (Barratt 1998), and 330 cats km^{-2} in Perth (Grayson *et al.* 2007). However, cat density varies substantially across residential areas in cities, towns, farms and remote communities. Paton (1990) reported a gradient in density of 200 pet cats km^{-2} in urban and suburban Adelaide, to 80 cats km^{-2} in country towns, and 0.01 cats km^{-2} in rural areas. Thus, the density range we calculated is plausible, reflecting the large variation between urban and rural areas.

Predation rates of pet cats

We used studies on predation by pet cats (in Australia and overseas) based on information provided by pet cat owners, by scat studies (which show prey items caught and consumed in the past 12–24 h), and by observational studies using cat-borne video (which show prey killed, irrespective of whether the prey is discarded, consumed or brought home). The collation included a small number of studies that reported prey returns of frogs and invertebrates; frogs and invertebrates were rarer prey items, when they were reported. In studies that did not report frogs and invertebrates, it was sometimes difficult to know whether this was because they were not recorded (e.g. remains too hard to identify) or whether they were not hunted. For consistency, we excluded frogs and invertebrates from prey-return rates, and from calculations of% prey type. This exclusion also allowed a fairer comparison with published predation rates of Australian feral cats, which at the time of this analysis was restricted to mammals, birds and reptiles. The studies reviewed here were of varying duration; to allow for comparison, we converted all tallies to annual rates.

The unweighted average number of prey items brought home by roaming, hunting pet cats across 47 studies globally was 38.9 prey items cat^{-1} year^{-1}. The unweighted average value for the subset of 12 Australian studies was 28.1 items cat^{-1} year^{-1} (Tables 1, S1); to be conservative, we use the Australian values for subsequent calculations.

Seven studies (non-Australian) compared the predation rates of pet cats as revealed by scat or cat-borne video to the prey-return rates; on average, only 15.1% of killed prey were brought home (Tables 1, S1). Accounting for the proportion of killed prey that is not brought home, the average predation rate for a roaming, hunting pet cat, therefore, needs to be scaled up from 28.1 to 186 prey items cat^{-1} year^{-1}. Considering the population of roaming, hunting pet cats, and multiplying this by the bootstrapped values for the predation rates per cat gives an average annual overall toll of 390 million individual vertebrates killed in Australia by pet cats (Table 1, Fig. 1*a*).

Composition of prey items

We collated studies that provided any information on the composition of prey items. We used only Australian studies, because prey availability, including the relative abundance of introduced versus native species, varies among countries. Eleven Australian studies recorded the species of prey returned by pet cats. These studies showed that the estimated annual toll of 390 million individual vertebrates per year comprises 189 million mammals, 118 million birds and 82.9 million reptiles (Table 1, Fig. 1*a*). The average per capita toll (186 prey year^{-1}) of a roaming, hunting cat comprises 90.2 mammals, 55.9 birds and 39.5 reptiles (Fig. 1*b*, Table S3).

Introduced animal species can be more abundant in towns and cities, and make up a proportion of the prey killed by pet cats. Across 11 Australian studies, 38.3% of all prey items were introduced species. Thus, the overall annual toll is 241 million native animals and 149 million introduced animals. For 10 studies that provided vertebrate class and native/introduced status for prey, the percentage of prey items that are from introduced species was highest for mammals (64.7%), then birds (32.2%; Table 1). No introduced species of reptile or amphibian were reported as killed by pet cats; studies report invertebrates only patchily, and generally not to species level (Table S1). The average annual tolls for native species in each class are, thus, 66.9 million mammals, 79.7 million birds and 82.9 million reptiles (Table 1, Fig. 1*a*). The estimates for the per capita tolls of roaming, hunting pet cats was partitioned into 115 individuals of native species (31.9 mammals, 37.9 birds, 39.5 reptiles) and 71 individuals of introduced species per year (58.3 mammals, 18 birds, 0 reptiles; Fig. 1*b*, Table S3).

Predation rates per area

Given the lower and upper densities for roaming, hunting pet cats (38.8–70.8 cats km^{-2}), the predation toll per unit area is

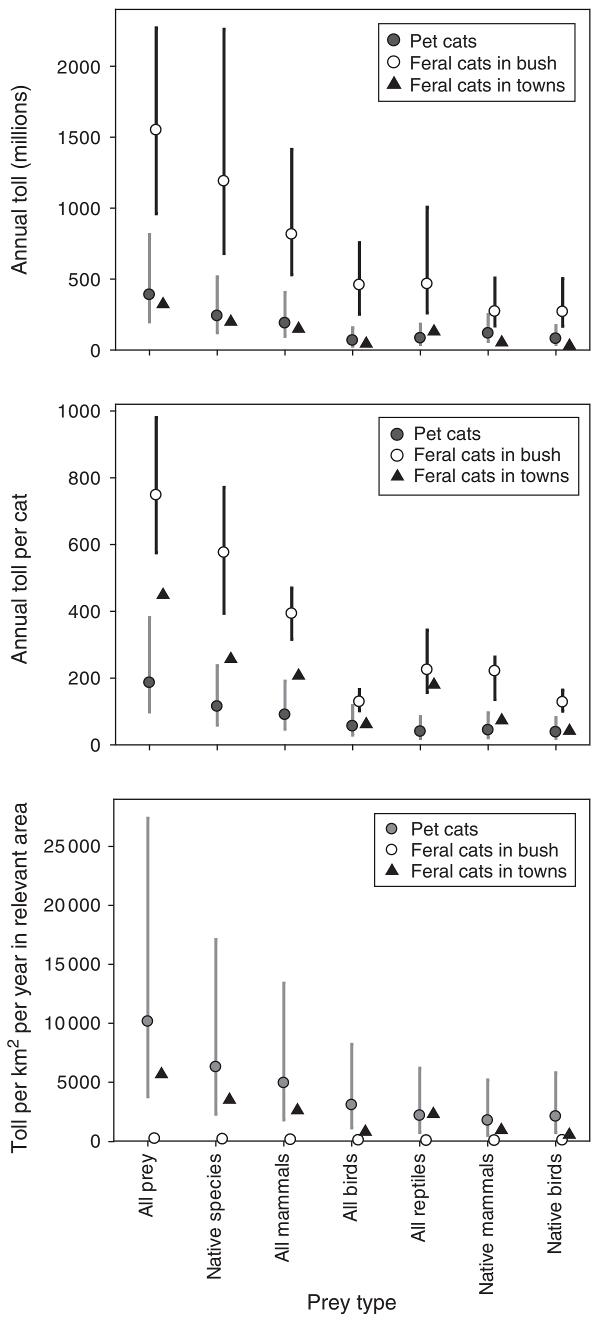

Fig. 1. Predation by feral cats (in the bush and in towns) and pet cats, presented as (*a*) the overall annual toll, (*b*) the annual per capita toll by feral cats and roaming, hunting pet cats, and (*c*) the predation toll per area, calculated for the area in which the cat type is found. In all cases, values are provided for the total toll, the toll on native species, the tolls across mammals, birds and reptiles, and across native species within those classes (native reptile values are not presented separately, because almost 100% of all recorded reptile prey are native species). Values show the mean estimate and the 95% confidence limits around that estimate, except for feral cats in towns, for which confidence limits were not available. For *c*, the displayed estimate is the mid-point between the two estimates derived from the plausible range of areas in which pet cats live; the confidence bars show the 2.5% quantile for the lower of the estimate, and the 97.5% quantile for the upper estimate.

7190–13 100 animals km^{-2} per year (including 4440–8110 native animals km^{-2} per year; Fig. 1*c*, Table S3). A few studies have attempted to estimate the predation toll by pet cats per unit area over smaller geographic areas, and their estimates are similar to that reported here. In Australia, Barratt (1998) derived estimates of 6660 prey km^{-2} year^{-1} for suburban Canberra, and Paton (1993) estimated 6000 vertebrates km^{-2} year^{-1} for urban Adelaide.

Comparison of predation by pet and feral cats

Figure 1 and Table S3 compare predation parameters calculated for pet cats to analogous figures for feral cats living in natural environments (the 'bush') and feral cats living in heavily modified ('town') environments (available from recent published studies; Woinarski *et al.* 2017, 2018*b*; Murphy *et al.* 2019). An average pet cat kills fewer animals than does a feral cat: a pet's predation rate is 14–25% that of a feral cat, depending on whether all pet cats, or only the subset of pets that roam and hunt, are considered. On average, a roaming and hunting pet cat kills 186 mammals, birds and reptiles each year (including 115 native animals), which is about a quarter of what an average feral cat kills in the bush (748 mammals, birds and reptiles, including 576 native) per year. But pets occur at a high density in small areas, so local predation pressure can be substantial; in those areas in which they occur, pet cats collectively kill 28–52 times more animals per square kilometre than do feral cats in natural environments, and 1.3–2.3 times more animals per square kilometre than do feral cats living in urban environments. The prey of pet cats includes almost twice the proportion of introduced species in the prey of feral cats (38% for pets versus 23% for ferals, with most of the difference owing to mammals; Table 1). Nevertheless, the toll on native animals by pet cats per square kilometre (in the areas in which they occur) still far exceeds that of feral cats (Fig. 1*c*, Table S3).

The estimated annual per capita predation toll shared across all pet cats (rather than just the roaming, hunting pets) is 103 mammals, birds and reptiles, with this total comprising 50.3 mammals, 31.2 birds and 22 reptiles (Table S3). This is slightly higher than are the analogous estimates (a toll of 76, comprising 46 mammals, 16 birds, 14 reptiles) produced from a smaller number of collated studies by Woinarski *et al.* (2017, 2018*b*) and Murphy *et al.* (2019). The pet cat predation estimate presented here is still based on a small number of studies; however, we note that the estimate sits well within the range of pet cat predation rates from a larger number of studies from overseas (Table S1), and the annual per-capita predation toll of a roaming–hunting Australian pet cat (186) is very similar to that of pet cats in other countries, measured by scat or cat-borne video (169; Table S1).

We attempted to derive the overall predation toll and the toll per unit area realistically and conservatively. In estimating overall tolls, we excluded from our tallies those pet cats that are contained, and those that roam but do not hunt. For the remaining subset of roaming, hunting cats, we used a lower per capita annual predation rate than the global average (28.1 from Australian studies, compared with a global average of 38.9). Our estimate of the proportion of prey that is returned home, based on scat and cat-borne video studies, is conservative; scat studies omit prey that are killed but not eaten; scat and video studies omit prey that are not killed, but die later from their injuries (Mcruer *et al.* 2017). We partitioned the toll by pet cats into introduced and native species, which further reduces the estimates for predation on native species. Finally, in estimating the predation toll per unit area, we used the entire residential area across urban, rural and remote Australia as the lower limit for the area over which cats roam, even though only one-third of Australian households have pet cats.

Other impacts from pet cats

We have focussed on the impacts of predation by pet cats, but there are other potential pathways for impacts from pet cats. For example, some authors have argued that the indirect effects of pet cats on the feeding behaviour, breeding behaviour and success of local populations may exceed the direct impacts from predation. In these scenarios, wild animals may change their ranging behaviour, including feeding or breeding in suboptimal areas so as to avoid cats, or they may reduce provisioning rates to nestlings to reduce risk of predation (on themselves or nests), but with consequences for the growth and survival of their young. These effects can drive population decline even if the level of direct predation by cats is low (Beckerman *et al.* 2007; Bonnington *et al.* 2013).

Another pathway for pet cats to affect local wildlife populations is through disease. Cats are carriers for dozens of viral, bacterial, fungal and parasitic diseases, some of which have significant impacts on wildlife, human health and livestock production (Day *et al.* 2012). In Australia, the cat-borne disease that has received the most attention is toxoplasmosis, caused by a protozoan parasite *Toxoplasma gondii*. Felids are the only definitive host (so the widespread occurrence of the disease in Australia is due solely to the introduction of domestic cats); however, almost all birds and mammals can act as secondary hosts if they ingest eggs (which are shed by the cat), eat infected prey, or via the placenta for placental mammals. The symptoms of infection vary from negligible to extreme morbidity and death (Hill and Dubey 2002), and include effects on behaviour and the nervous system, which combine to make individuals more prone to being preyed on, for example by increasing risk-taking behaviour (Lamberton *et al.* 2008).

Toxoplasma is prevalent in Australian wildlife (Pan *et al.* 2012; Hillman *et al.* 2016) and can cause disease in infected individuals of many native mammal and bird species (Canfield *et al.* 1990; Mason *et al.* 1991; Skerratt *et al.* 1997). *Toxoplasma* infections contributed to high mortality in a trial translocation of eastern barred bandicoots, *Perameles gunnii*, to French Island (Groenewegen *et al.* 2017), and may have contributed to declines in a larger bandicoot population in Tasmania (Obendorf *et al.* 1996), but its contribution to population declines in Australian wildlife more generally remains unclear (Fancourt and Jackson 2014; Hillman *et al.* 2016). *Toxoplasma* prevalence has been found to be higher in areas with declining populations, but both the decline and the higher prevalence could be explained by exposure to higher densities of cats (Fancourt *et al.* 2014).

Pet cats, as well as feral cats, carry *Toxoplasma*, with prevalence varying with environment (higher in wetter areas because the eggs persist in the environment for longer), diet (which affects the likelihood of eating infected prey), and level

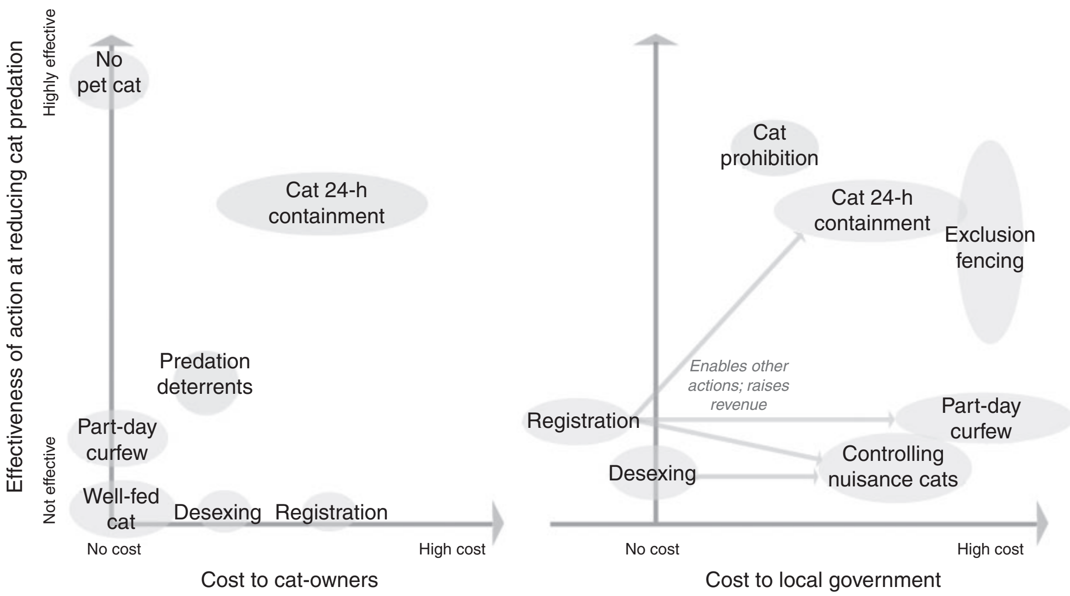

Fig. 2. The effectiveness of actions to reduce the predation impacts of pet cats against their cost for pet cat owners (left) and local government (right). The diagram shows relative differences, and axes are not to scale. Actions that are the choice of the owner (although local government could influence by communication programs) are shown in the left diagram; actions that require local government responsibility or coordination are shown in the right diagram. The shape of the shaded ellipses provides some information on variability; for example, the cost of exclusion fencing is highly variable, depending on a range of factors, including topography, size, vegetation and so on. Similarly, the effectiveness of containment will vary depending on the success of communication and participation, and enforcement.

of containment (pet cats kept indoors have lower infection rates than pets allowed to roam freely outside) (Brennan 2015; Must *et al.* 2015). When the parasite undergoes sexual reproduction within the cat gut, cats shed enormous quantities of eggs in their faeces; tens of million oocysts are shed per cat over a 2-week period (Dubey 2002; Dabritz *et al.* 2007). In suburban areas, the densities of oocysts in the environment can be staggering because of the high prevalence of *Toxoplasma* and the high density of pet cats; for example, studies in urban areas of North and Central America estimated that 94–4671 oocysts m^{-2} were deposited per year (Sousa *et al.* 1988; Dabritz *et al.* 2007). Thus, if *Toxoplasma* infections do contribute to wildlife population declines, the impacts may be amplified in residential areas with high densities of roaming pet cats.

A more diffuse, yet substantial indirect impact to wildlife from pet cats, comes from their considerable 'ecological pawprint' (how much land is needed to sustain the pet cat, and to process the waste associated with the cat's existence) (Satriajaya 2017; Su *et al.* 2018). Su *et al.* (2018) estimated that, in China, 0.4–0.6 ha was farmed to provide the material for commercial food to feed an average pet cat for a year. Other studies have estimated that the land requirements for producing the commercial dried cat food for the top 10 cat-owning countries covers an area six times that of New Zealand (Vale and Vale 2009). Similarly, a high proportion of seafood products end up in cat food; estimates suggest that over 13% of the global catch of forage fish end up in canned and dry cat food (De Silva and Turchini 2008). Cat owners in Australia spend AU\$962 per cat per year, or AU\$3.62 billion overall, on pet food and care, with over half of those costs (AU\$491 of AU\$962 per cat) going to cat food (AMA 2019). Pet cats, therefore, cause effects on wildlife through the exploitation, habitat loss and degradation, water impacts, soil loss and carbon emissions that are necessary just to produce their food.

A final example of a pet cat-related impact other than direct predation, is their potential to sustain, as a result of unwanted breeding or pet dumping or straying, dense populations of feral cats in urban environments (strays; Denny 2005; Spencer *et al.* 2016).

Pet cat management options

The high density and, therefore, very high predation toll of pet cats relative to feral cats, set against the backdrop of extraordinary impacts from feral cats on Australian fauna (Woinarski *et al.* 2019*b*), justify a precautionary position that the biodiversity impacts of pet cats are serious and should be reduced (see also Grayson and Calver 2004; Lilith *et al.* 2006; Calver *et al.* 2011). Moreover, although reducing the numbers and impacts of feral cats is notoriously challenging and expensive (Woinarski *et al.* 2019*b*), the impacts of pet cats can, theoretically, be reduced much more efficiently and effectively and humanely through husbandry practices. There are several non-exclusive options for reducing the impacts of pet cats. Some actions can be taken by cat owners, some by local government, and most require participation from both cat owners and local government to be most effective. In practice, combinations of these actions are likely to be most useful, depending on the specific situation. These actions are described below, and the relative trade-offs in effectiveness versus cost of these actions are shown for cat owners and local government in Fig. 2.

Keeping pet cats well fed

At least in some situations, hunting rates by pet cats can be related to their body condition (Silva-Rodríguez and Sieving 2011), hunger (Biben 1979), or to the amount of meat in their diet (Robertson 1998). Inadequate feeding of pet cats predominantly kept for vermin control on Polish farmsteads has been linked to high predation rates on birds and mammals (Krauze-Gryz *et al.* 2019). However, being well fed does not alter cat ranging behaviour (Hall *et al.* 2016*c*), and even well fed and sated cats will hunt (Adamec 1976; Biben 1979). Opportunity may be a key factor for determining hunting events. Several studies have noted that predation rates are higher in cats living closer to natural habitats than in cats in heavily urbanised areas (Churcher and Lawton 1987). For example, in Canberra and Adelaide, predation rates by pet cats increased with proximity to woodlands (Paton 1991; Barratt 1997*b*). Therefore, even though proper feeding has low additional costs to the cat owner, and may contribute to a decreased need to hunt, the action has little effectiveness because pet cats may still hunt opportunistically, and particularly so when natural hunting habitats are available nearby (Fig. 2).

Desexing

Desexing has limited or no effect on the predation impacts of pet cats, as desexing does not alter the ranging behaviour of cats (Hall *et al.* 2016*c*), nor their propensity to hunt (Robertson 1998; Meek 2003). However, desexing is an important component of responsible pet ownership in many countries; it reduces many of the welfare and ethical issues associated with uncontrolled breeding in cats (Reichler 2009), and may reduce movement of pets into the stray cat population (Stavisky *et al.* 2012). The age at which pet cats are desexed is critical. Although desexing rates for pet cats are high in Australia (Lilith *et al.* 2006; Hall *et al.* 2016*a*), there is evidence that many cats are desexed at $\geq$2 years of age, which is well after the onset of puberty and breeding (Johnson and Calver 2014). Furthermore, there is division among veterinary professionals within Australia and internationally on the ideal age to desex pet cats, with the option of early age desexing (younger than 4 months) being popular in animal shelters whereas traditional age desexing (4–6 months old) and mature age desexing ($>$6 months old) are more common in private practices (Welsh 2018; Crawford and Calver 2019). Reasons for the discrepancy include professional judgement, recommendations of veterinary associations (the Australian Veterinary Association encourages desexing to tackle the problem of unwanted animals, but leaves the question of age to practitioner discretion; AVA 2017*a*), and concern about loss of business if fewer cats have litters for adoption. In sum, these may place some professionals at odds with increasing numbers of Australian local government jurisdictions that require desexing of pet cats by 3 months of age to prevent any non-commercial breeding (Crawford and Calver 2019). Although desexing is not effective at reducing predation by the desexed cat, and imposes a modest cost to the cat owner, it may result in reduced costs to local government if nuisance cat incidents decrease (Fig. 2).

Registration and identification

Similarly, registration and identification of pet cats does not stop them hunting, but the financial investment by the cat owner does support a more responsible attitude to pet cat ownership, and facilitates other management options such as cat containment because cats that escape from their homes can be quickly returned and the owners cautioned or fined. Registration can also provide a subsidy for local government to help with the management of pet and stray cats, thus contributing to more effective cat management (Fig. 2).

Predation deterrents on cats

Various devices are available to reduce predation by pet cats. Early studies appeared to show that bells on cat collars do not reduce cat predation rates (Paton 1993; Barratt 1998; Morgan *et al.* 2009). However, these correlative surveys did not account for hunting differences between cats, and owners may put bells only on cats that are the most proficient hunters. Experimental studies have demonstrated some, but variable, benefits of collar-worn predation deterrents, including bells, motion-activated alarms (sound or lights) attached to pet cats' collars, colourful collar covers that warn prey with good colour vision, and pounce protectors (neoprene devices that hang from the collar and interfere with prey capture; Ruxton *et al.* 2002; Nelson *et al.* 2006; Calver *et al.* 2007; Gordon *et al.* 2010; Hall *et al.* 2015). Some owners are reluctant to use such collar-worn devices because of a perception that collars are unsafe for cats, although research indicates that properly fitted collars that are checked regularly for fit and condition are very safe (Calver *et al.* 2013). However, even if deterrents do reduce cat predation success, they never remove the risk entirely and cannot prevent cats from harassing prey and affecting fitness, even if hunting is unsuccessful. It is also unlikely that these devices reduce roaming by pet cats (Hall *et al.* 2016*b*). The costs of cat-borne predation deterrents are carried solely by cat owners (Fig. 2).

Part-day curfews and containment

In Australia, some local governments have established bylaws that aim to reduce the impacts of cats on high-value environmental assets, or to reduce the public nuisance value from wandering cats. Relevant bylaws include cat curfews (where cats must be contained for part of the day, usually overnight) or 24-h containment requirements (McCarthy 2005; RSPCA 2018). A 2011 review of council bylaws in South Australia reported that two councils out of 27 had cat curfews (summarised in RSPCA 2018). Toukhsati *et al.* (2012) stated that 30% of Victorian councils have cat-confinement legislation, without citing the source for this figure. Seventeen suburbs in Canberra are now designated cat-containment suburbs (ACT Government 2019).

Night-time curfews are widely perceived as protecting wildlife. For example, studies in Victoria and in South Australia both found that pet cat owners were more likely to contain their pets overnight than during the day (Toukhsati *et al.* 2012; Roetman *et al.* 2017). However, time-bound curfews of cats are unlikely to prevent cat impacts. Cats that roam at night may encounter different species of animals (typically, more mammals) than cats that wander during the day (typically, more birds); day or night curfews may, therefore, change the type of animal caught, but not the overall predation rates (Barratt 1997*a*; Perry 1999). For example, night-time cat curfews in residential areas near Sherbrooke Forest, Victoria, were associated with a decrease in reported cat attacks on possums, but an increase in the incidence of cat attacks on diurnal birds (Pergl 1994). In New Zealand, where the only native mammals are bats, Flux (2017) opined that diurnal curfews would be more effective than nocturnal ones in protecting native wildlife because they would reduce attacks on birds and lizards, while maintaining rodent predation.

Total containment indoors or within enclosed outdoor areas (as opposed to time-bound curfews) should reduce the impacts of pet cats on native species. Some cat owners have successfully trained their cats to be walked on a leash, but not all cats enjoy this or 'agree' to be walked. Containment could incur costs to the cat owners, if they build containment structures outdoors, and purchase cat toys and other equipment for behavioural enrichment.

Compliance, and responding to non-compliance, in both cat curfew or containment areas are significant issues (McCarthy 2005), even if fines are imposed on owners who allow their cats outdoors (Baker 2001; Micromex Research 2011; Eyles and Mulvaney 2014). Indeed, there have been reports of increases in the numbers of roaming cats collected from cat containment suburbs (Brown 2017). Both curfew and containment bylaws impose resourcing burdens on local government, which needs to police the laws and maintain staff and facilities to care for impounded cats (Pert 2001; Brown 2018). Local governments with cat curfew or containment regulations have generally been unable to demonstrate reductions in complaints about roaming cats, or the incidence of roaming cats, following the introduction of the regulations (RSPCA 2018). In part, this is due to the lack of monitoring for compliance and outcomes, as well as the fundamental issues of non-compliance. Containment bylaws can be effective only if compliance is monitored, if non-compliance is detected and penalised, if infrastructure, staffing and a process for impounding and handling wandering cats are all in place, and if accompanied by ongoing education about the need for cat containment (Moore 2001). Thus, the effectiveness of curfews and containment are likely to be correlated with local government investment, particularly so for complete containment, which is easier to police than are part-day curfews (Fig. 2).

Cat prohibition

Cat prohibition occurs in some local government areas, but it is hard to gather information on the frequency and outcomes of this approach (Buttriss 2001; McCarthy 2005; Lilith *et al.* 2010). Cats now occur on ~100 Australian islands, many of which support (or supported) many endemic wildlife species and significant breeding colonies of seabirds; almost all of these occurrences of cats on islands arose from importation of pet cats. Some populated islands such as Christmas, French, Phillip and Kangaroo islands have committed to long-term goals of becoming entirely cat-free, or free of feral cats (Commonwealth of Australia 2015), so local cat prohibition may become more common in Australia in the future. Some populated islands, such as Rottnest Island, have already become cat-free (Algar *et al.* 2011). Far easier than eradicating island cat populations is to enact regulations or legislation to prevent any introductions of pet cats to islands not currently populated by cats. Policing cat prohibition (or any other cat restriction) on an island is likely easier than on the mainland, but experience from the mainland indicates that compliance does need to be monitored and enforced. For example, a designated cat-free suburb near Cranbourne in Victoria has appreciable rates of non-compliance, with households keeping unregistered pet cats in suburbs that are supposed to be cat-free (Blair *et al.* 2016). Cat prohibition may be most critical to establish in urban areas or regional communities in or adjoining sites with significant conservation values, and in new residential areas (such that councils are not taking away rights already established).

Although most local governments with cat-containment or -prohibition bylaws lack monitoring data on effectiveness (e.g. Moore 2001), Tweed Shire Council on the northern coast of New South Wales is an exception, and data comparing the efficacy of differing cat restrictions are available. Tweed Shire Council has prohibitions on cats in five locations, cat containment in one location, and overnight cat curfews in a further four locations. Cat prohibition is also proposed for other new housing developments in the Shire. The Council has monitored for cats in bushland adjacent to some of these locations, for up to 3 years. Pet cats are repeatedly and regularly detected in bushland adjacent to locations with partial cat restrictions, but cat prohibition appears to markedly reduce incursions to adjacent bushland (Tweed Shire Council, unpubl. data). As well as being more effective than containment or curfews, cat prohibition is also less costly to police, because even with background rates of non-compliance, the total population of pet cats is much lower in a prohibition situation than in a containment or curfew situation (Tweed Shire Council, pers. comm.; Fig. 2).

If cat prohibition is to be used more widely, better guidance on the width of buffer areas next to environmental assets would be useful. Studies at different locations have proposed buffers from 360 m to 2.4 km wide (Lilith *et al.* 2008; Metsers *et al.* 2010). It is likely that the required buffer width will vary with a host of site-related factors.

Physical barriers to exclude cats

Cat exclusion has become an essential conservation tool for preventing the extinction of Australian native mammal species that are highly vulnerable to predation by cats (and usually also foxes; Legge *et al.* 2018). Most fenced exclosures are constructed in remote areas, but some are close to urban centres, such as Mulligan's Flat, a 400-ha fenced area surrounded by suburbs in Canberra. Mulligans Flat has 19 unlocked gates that allow access to the community. The suburbs surrounding Mulligan's Flat also have 24-h cat containment laws to reduce the frequency of cats attempting to breach the fence (ACT Government 2019). Fences that aim to exclude cats must entirely encircle an area. Linear stretches of fence, for example along an urban–bushland interface, have been trialled in some places and shown to be ineffective (WES 2018). The fence construction needs to meet exacting standards because cats are proficient climbers, and fences need ongoing maintenance to maintain those standards (Long and Robley 2004; Hayward *et al.* 2014). Gates are a potential weakness in fencing because cats may slip through when gates are opened for vehicle access. Sonic repellents, which are moderately effective in deterring unwanted cats from suburban gardens (Nelson *et al.* 2006; Crawford *et al.* 2018), may increase security at gates. The effectiveness and cost of fencing is highly variable, depending on its configuration (linear versus encircling), its construction, and its ongoing maintenance. Even well constructed fences that encircle an area only reduce cat predation within that area, whereas other cat management options such as cat prohibition can reduce predation by pet cats over a larger area (Fig. 2).

Poisoning, trapping, shooting of nuisance cats

The management of feral cats (and other introduced predators) in Australia focuses on a mixture of toxic baiting, trapping and shooting, with these mechanisms resulting in variable success. While poisoning and shooting are not used deliberately to control pet cats in Australia, roaming pets may be at risk during control operations for feral animals (RSPCA 2019), or they may suffer deliberate, illegal persecution. Trapping regulations for pet cats vary across Australia. In some cases, pet cats may be caught in traps intended for strays, whereas in other cases, local governments may supply traps to householders to trap cats, including pets, that are causing a nuisance on private property (e.g. see trapping provisions under Western Australian legislation; Barry 2017). Internationally, regulations are far more diverse. For example, under Poland's *Animals Protection Act*, landholders may 'shoot free-ranging cats and dogs found at least 200 m from the nearest household' if they appear 'abandoned (feral), undernourished and could be a threat to wildlife' (quoted in Wierzbowska *et al.* 2012). Grayson and Calver (2004) gave examples from the USA of trapping pet cats that were causing a nuisance on neighbouring properties. Dealing with nuisance cat complaints can be a time-consuming and costly action for local government, with only modest effects on overall predation rates. Other actions that tend to decrease the incidence of nuisance cats, such as registration, desexing, cat containment and cat prohibition, can, therefore, save effort and money for the local government (Fig. 2).

Reduced ownership rates for pet cats

The overall impact of pet cats on Australian wildlife can be reduced not only through more effective management of pet cats, but also through reduction in the ownership rate and, hence, total population size of pet cats. Increased recognition of the detriment of pet cats, and more awareness of environmental concerns, may help change society's desire for the keeping of such introduced predator species. The proportion of households in Australia owning cats did decline around the turn of the century (Perry 1999; Chaseling 2001; Baldock *et al.* 2003), but has more recently recovered (AMA 2019). Pet cats are big business, with AMA (2019) estimating that Australians spent, on average, AU$962 for each cat owned that year. The Australian Veterinary Association publicises the health benefits of pet ownership via press releases (e.g. AVA 2017*b*), and many veterinarians worry about possible declines in cat-related clinical work if the pet population falls (McGreevy *et al.* 2002). Given the economic incentives for pet cat ownership, reducing the number of pet cats in Australia will be challenging unless the costs of irresponsible pet cat ownership to society (individuals, communities, local government) and wildlife are fully considered and transparent. Nevertheless, it remains a truism that choosing not to have a pet cat is the most cost-effective option that would-be cat owners can take to reduce impacts from pet cats (Fig. 2).

Conclusions: opportunities for better pet cat management

Cats have been devastating to Australian fauna, and, in recognition of this, 'predation by feral cats' is listed as a key threatening process in Australia's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). In 2015, the Australian Government released an updated Threat Abatement Plan to guide coordinated management of feral cats (Department of the Environment 2015) and the inaugural Threatened Species Strategy (Commonwealth of Australia 2015) committed to a range of targets to reduce the impacts of cats and support the recovery of native species affected by cats. As well as detailing strategies, actions and targets relating to the management of feral cats, these national documents recognise the need to engage with the public to enhance awareness of cat impacts, and build support for responsible pet ownership.

Nevertheless, feral cats have been the primary focus of most of the research and management attention, partly because most of the species extinctions that cats have contributed to have occurred in remote Australia. However, urban areas can support high levels of biodiversity, including threatened species (Ives *et al.* 2016). The estimates for predation tolls presented here, and evidence from other focal studies, show that pet cats are capable of driving declines in local populations of native wildlife species. We need to broaden the discourse about cat impacts and management to include pets. This discussion needs to include multiple sectors of the community (McLeod *et al.* 2019), so as to avoid polarising the public in the manner that has been singularly divisive and counterproductive in places such as the USA (Marra and Santella 2016).

Australia has a starting advantage; the Australian public are more aware of cat impacts on wildlife, and more supportive of actions to reduce those impacts, than are those in many other countries (Zito *et al.* 2015; Hall *et al.* 2016*a*). Most Australians support tighter regulation of pet cats, including desexing, microchipping and curfews (Scriggins and Murray 1997; Grayson *et al.* 2002; Grayson and Calver 2004; Lilith *et al.* 2006; Micromex Research 2011; Blair *et al.* 2016; Roetman *et al.* 2017). Support for cat prohibition (cat-free zones) is more variable, with some studies reporting less support for this management option (Grayson *et al.* 2002; Lilith *et al.* 2006), whereas other studies have reported strong support for cat-free zones near areas of high conservation value (Blair *et al.* 2016; Travaglia and Miller 2018). The cited reasons for supporting cat curfew and containment laws include (usually in this order) protecting native wildlife, protecting the pet cat from injury, preventing nuisance behaviour and preventing unwanted breeding (e.g. Toukhsati *et al.* 2012; Travaglia and Miller 2018). Of particular note, Australian cat owners are just as likely as non-cat-owners to cite protection of wildlife as the primary reason for cat containment (Toukhsati *et al.* 2012). Greenwell *et al.* (2019) noted the willingness of cat owners in Mandurah, Western Australia, to take prompt action to prevent their cats harassing a breeding colony of fairy terns.

What though, of those owners who discount the significance of predation by their cats, or value or take pride in their cats' hunting? For example, Roetman *et al.* (2017) reported that while 66% of 4314 respondents in their Adelaide study indicated that their cats hunted, only 22% of all respondents considered that hunting by their cats was a problem. Reducing wildlife impacts would not be a motivation for action by these owners. In other cases, owners may keep cats for vermin control and be unsympathetic to any attempts to reduce hunting (Ramón *et al.* 2010). Furthermore, although we believe that this review presents clear evidence that predation by pet cats is a threat to wildlife conservation, not all commentators agree. In Australia, Rand *et al.* (2018, 2019) suggested that predation by cats in Australian cities is overstated as a threat to wildlife, and should not be used as an argument against trap–neuter–return (TNR) programs for semi-feral (stray) cats. With TNR, semi-feral cats are trapped, desexed, sometimes vaccinated or given other veterinary care, before release at the point of capture, sometimes in association with on-going supplemental feeding. The issue of the management of semi-feral cats, especially given arguments to implement TNR in Australia (Rand *et al.* 2018, 2019; Riley 2018; Swarbrick and Rand 2018) is a matter of special concern. In the UK, the Royal Society for the Protection of Birds (RSPB 2019) has taken the position that '… despite the large numbers of birds killed by cats in gardens, there is no clear scientific evidence that such mortality is causing bird populations to decline'. In New Zealand, on the basis of observations of just two pet cats, Flux (2007, 2017) concluded that predation by pet cats was beneficial because of rodent control and he did not believe that his pets' predatory histories had harmed wildlife populations.

Rather than contesting the view that pet cats are not a threat to wildlife, an alternative route to encourage confinement of pet cats to their owners' properties at all times (which gives high protection to wildlife, while still allowing vermin control on the owner's property) might be to focus on the benefits of containment to pet cat welfare. Road accident trauma, poisoning and fighting are major causes of death and injury for roaming pet cats internationally (Kolata *et al.* 1974; Kolata 1980; Moreau *et al.* 2003; Egenvall *et al.* 2009, 2010) and present a strong welfare argument for containing pet cats. McLeod *et al.* (2015, 2017, 2019) presented strategies that could be used to encourage behaviour change on the basis of a welfare approach.

The public awareness of cat impacts, and their support for managing cats accordingly, suggests that management options that are minimally contentious, including predation-deterrent devices, desexing, registration and identification, could be more actively propagated. Cat containment requirements imposed by local government are slowly becoming more common, and with sensitive communication, including significant weighting to cat welfare concerns, this option could be further expanded. The most effective management approach, namely, cat prohibition, could be considered in new residential developments that are close to sites of high conservation significance. Although cat prohibition could put off some potential home buyers, it might attract others who place a premium on those conservation values. Whereas the management of feral cats across the Australian landscape remains challenging, the options for reducing the impacts from pet cats are technically much more feasible, but will require careful engagement with the human community and more resources than typically available to or allocated by local government authorities (Gramza *et al.* 2016; McLeod *et al.* 2019).

Conflicts of interest

Sarah Legge is an associate editor for *Wildlife Research* and was the guest Editor-in-Chief for this special issue. Chris Dickman, Brett Murphy and John Woinarski were guest Associate Editors for this special issue. Despite this relationship, they did not at any stage have editor-level access to this manuscript while in peer review, as is the standard practice when handling manuscripts submitted by an editor to this journal. *Wildlife Research* encourages its editors to publish in the journal and they are kept totally separate from the decision-making process for their manuscripts. The authors have no further conflicts of interest to declare.

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