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Ecology, impacts and management of wild deer in Australia

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Introduction

Deer (Family Cervidae) have long been highly valued by people for their economic and resource values, as well as for aesthetic, cultural and spiritual reasons (Baker *et al.* 2014). Consequently, deer have been translocated far and wide, both within their ancestral strongholds in Eurasia and the Americas and, Antarctica aside, to all other continents (Long 2003; Nugent *et al.*, in press). For Australia, the main motivation for the initial introductions in the 1800s and early 1900s appears to have been a combination of an enthusiastic interest in exotic species and a desire to recreate a resource symbolic of the wealth, power and prestige long associated with deer hunting in Europe in general (and Britain in particular) but more accessible to the common person. That motivation was clearly strong, because importing non-native deer into Australia in the 1800s was a major undertaking, involving long sea voyages in small sailing ships, with deer survival often depending on luck.

Acclimatisation societies established captive breeding populations of deer so that more individuals could be released (Bentley 1998). Following release, these new deer populations were sometimes strictly protected from hunting for decades to help ensure their establishment and spread, a practice that continued until as recently as the 1980s. Indeed, the establishment of a new fallow deer (*Dama dama*) population on public land at Koetong, north-east Victoria, was actively supported by the state government during the 1970s and 1980s (Phillips 1985), and deer are today managed as game in Victoria and Tasmania.

The advent of deer farming as a profitable enterprise in the 1970s and 1980s led to deer being captured from the wild, bred in captivity and then moved around the country to establish new farms. New wild populations have established from deer escaping from farms, and also from the deliberate (but now illegal) release by people wanting to establish new populations for hunting (Moriarty 2004). Wild deer are now present in all Australian states and territories.

With the benefit of hindsight, the effort spent establishing wild deer populations in Australia now seems misplaced, but it is only in the last two decades that there has been a focus on understanding and managing the undesirable impacts of deer in Australia. For example, a review of mammal pests in the late 1990s did not specify undesirable impacts for any of the six species of wild deer established in Australia (table 1 in Cowan and Tyndale-Biscoe 1997). A 2004 review of the economic costs of vertebrate pests did not consider deer in any depth but noted that 'so far they are only minor agricultural pests but their range and abundance is increasing' (McLeod 2004: p. 63). Since then, two national workshops, in 2005 (McLeod 2009) and 2016 (Forsyth *et al.* 2017), have brought public land managers, researchers and other stakeholders together to identify common issues and knowledge gaps. The latter workshop led to the Federal Government coinvesting [with state government agencies in Victoria, New South Wales (NSW), Queensland and South Australia] in research into the impacts and management of wild deer in Australia. The Australian Research Council has also invested in Linkage Projects investigating the impacts and ecology of wild deer.

This special issue of *Wildlife Research* aims to compile some of the recent research into the ecology, impacts and management of wild deer in Australia. We hope that this collection of research helps government agencies, land managers and community members to better understand deer and their impacts and management.

Impacts of wild deer

The increasing governmental interest in wild deer has focused more on increases in abundance and distribution than on documenting adverse impacts. This is in contrast to the situation for non-native predatory mammals for which the impacts on native fauna are relatively well-documented [e.g. feral cat (*Felis catus*); Legge *et al.* 2020]. Examples of long-term increases have been provided by licenced hunter harvest statistics for sambar deer (*Cervus unicolor*[1]) (Forsyth *et al.* 2018; Moloney *et al.* 2022) and spotlight counts for fallow deer in Tasmania (Cunningham *et al.* 2022*a*). Qualitative mapping of deer across NSW has revealed recent range expansions there (Crittle and Millynn 2020).

Davis *et al.* (2016) characterised the likely direct and indirect impacts of deer in Australia, with the main impacts expected to be on plants in natural and agricultural environments, with subsequent impacts on native fauna and livestock through habitat alteration and competition. Some plant species appear particularly vulnerable to deer herbivory, but the broader concerns are that high densities of deer can greatly alter the structure and composition of plant communities in their non-native ranges (Wardle *et al.* 2001). That has long been a far greater concern in New Zealand than Australia, mainly because New Zealand's vegetation evolved in the absence of mammalian herbivores, whereas native plant communities in Australia could be expected to be relatively more resilient, having evolved with ground-dwelling marsupial browsers. Nevertheless, overabundance is, by definition, damaging, regardless of the herbivore's origin. Also, fire and drought are more important in Australian than New Zealand ecosystems (Bradstock *et al.* 2012). As well as shaping plant community dynamics, large-scale high-severity fire can greatly affect deer population dynamics (Forsyth *et al.* 2012; Legge *et al.* 2023).

Wallowing by sambar deer threatens the integrity of peatlands in south-eastern Australia (Comte *et al.* 2022), and it has been suggested that shooting would reduce these impacts (Parliament of Victoria 2017). However, control and monitoring of deer are difficult in forested alpine country, prompting research into control efficiency. Two papers in this special issue address the ability of ground- and helicopter-based shooting to reduce sambar deer populations in Victoria (Comte *et al.* 2023*b*, this issue; Ramsey *et al.* 2023, this issue; see sections below).

The impacts of wild deer on food available to domestic livestock during severe drought led to federal government funding of shooting to control chital deer (*Axis axis*) in north Queensland (Pople *et al.* 2023, this issue) and fallow deer in north-west NSW (Davis *et al.* 2023, this issue). Analysis of the diet of deer shot in those control programs revealed that the forage consumed by 100 chital deer would have supported 14 and 25 cattle in the dry and wet seasons, respectively (Watter *et al.* 2020a), and that the fallow deer population was equivalent to ~60 Dry Sheep Equivalents per km^2 – and reduced the potential stocking rate of domestic livestock by ~50% (Davis *et al.* 2023, this issue). These livestock equivalents can guide expenditure on deer control, but the conversions are an oversimplification. Competition between wild deer and domestic livestock will only occur when the common food supply is limiting, such as in drought or during the dry season. Control should be conducted to anticipate these periods of food shortage.

McLeod (2023) estimates that the annual economic cost of wild deer in Australia in 2021 is within the broad range of A$45–206 million, with a mean of $91 million. In that analysis, agricultural losses were estimated to cost $69 million and deer–vehicle collisions to cost $3 million annually. An estimation of agricultural production lost to deer was based on data from landholder surveys. These estimates do not account for unwanted impact on native biodiversity, but they are a starting point. At least for the major and high-cost primary industries, the expected costs should be more accurately determined through quantitative research. This would allow primary producers and pest managers to weigh up the costs and benefits of deer control more confidently.

Wild deer can be hosts of a wide range of parasites and pathogens that could harm the deer themselves, livestock and humans (Cripps *et al.* 2018). Fortunately, there is no recent evidence of high profile zoonotic and/or agriculturally important diseases such as bovine tuberculosis and foot and mouth disease. However, a new review (Huaman *et al.* 2023, this issue) confirms the presence of a wide range of parasitic and viral pathogens in Australian deer, including some new species, and that wild deer could act as reservoirs for multi-host pathogens including *Pestivirus*, *Neospora caninum* and *Entamoeba bovis*. Next-generation sequencing has enabled novel viruses such as *Picobirnavirus* and a novel species of the genus *Bopivirus*, both of which pose transmission risks for domestic animals, to be discovered in the serum, plasma and faeces of wild deer in Australia (Huaman *et al.* 2023, this issue). Continued advances in high-throughput sequencing and bioinformatics would further increase our ability to identify and understand viruses and parasites in wild deer, and how they interact with domestic livestock.

In North America and Europe, collisions between native deer and vehicles have major economic and human health impacts (Langbein *et al.* 2011; Cunningham *et al.* 2022*b*). In Australia, collisions between rusa deer and both road and rail vehicles were partly responsible for the establishment of a culling program in the Illawarra Local Government Area (First Person Consulting 2016; Dawson 2017). An investigation of spatial variation in genetic diversity in rusa deer in the Illawarra region aimed, in part, to help target that deer

[1]There is debate about the taxonomy of deer. For consistency, nomenclature throughout this special issue follows Jackson and Groves (2015).

control effort (Li-Williams *et al.* 2023, this issue). The growing numbers and the expansion of the distribution of deer in Australia increase the risk of collision with vehicles, and there are greater consequences for deer–vehicle collisions than for collisions of vehicles with other wildlife, given the average body size of deer is larger than that of macropods and other native wildlife. The risk of deer–vehicle collisions has been modelled in Victoria (Davies *et al.* 2020), but there would be value in assessing this risk in other regions, for both the current and predicted Australian distributions of deer, particularly along the eastern seaboard. That analysis would help with the planning and implementation of mitigation measures.

Ecology of wild deer

Robustly estimating deer abundance or density is difficult (Forsyth *et al.* 2022), but several papers in this issue attempt to do that. Helicopter mark–recapture distance sampling (MRDS) at nine sites in eastern Australia revealed that deer [predominantly fallow deer but also red deer (*Cervus elaphus*)] densities could be as high as 39 per km^2 in agricultural landscapes (Bengsen *et al.* 2023, this issue). In northern Queensland, helicopter MRDS showed that chital deer were patchily distributed, with local densities exceeding 50 per km^2 (Pople *et al.* 2023, this issue). Ramsey *et al.* (2023, this issue) applied catch–effort models to kill data and flight-path data from helicopter-based shooting operations to estimate sambar deer densities in mostly native forest habitat in eastern Victoria, where the maximum pre-shoot sambar deer density was 2.8 per km^2. These estimates supplement the earlier use of spatial mark–resight models with images from grids of motion-sensitive cameras to estimate the densities of 13 deer populations comprising four deer species in eastern Australia (Bengsen *et al.* 2022).

Spotlight counts along 172 transects in Tasmania during 1985–2019 suggest that the fallow deer population there increased by 11.5% annually (Cunningham *et al.* 2022*a*). However, the population did decline during a 4-year period of below-average rainfall (Cunningham *et al.* 2022*a*). In northern Queensland, spotlight counts of chital deer declined 80% in just 10 months during severe drought (Pople *et al.* 2023, this issue). Necropsies of shot samples confirmed an associated decline in adult body condition and fecundity (Pople *et al.* 2023, this issue). Analysis of the rumen contents of a sample of the fallow deer shot in the Bengsen *et al.* (2023, this issue) study suggested that browsing, including on *Eucalyptus*, likely helped fallow deer to persist at high densities during the severe drought of 2018, when properties had destocked (Davis *et al.* 2023, this issue).

Genetic data can be used to clarify patterns of gene flow and may be useful for assessing deer dispersal rates and distances. If there is spatial variation in population genetic structure, then there could be barriers to dispersal, knowledge of which could help in the design of control programs. One example of this is provided by analysis of kinship in hog deer (*Axis porcinus*) in eastern Victoria using single nucleotide polymorphisms (SNPs) (Hill *et al.* 2023*a*, this issue). That study found that most interpair distances were 5–10 km (maximum 30 km) and that movement by deer was not strongly influenced by sex. The implication was that hog deer dispersal rates were relatively low. Another example is an analysis of SNPs that showed the genetic diversity of rusa deer in the Illawarra region was highest in the north, nearer the original introduction site at Royal National Park (Li-Williams *et al.* 2023, this issue). Three spatially distinct genetic clusters were identified, indicating reduced mixing of deer from each cluster with deer from outside the cluster (Li-Williams *et al.* 2023, this issue).

Genetic data can also help clarify the origins of specific deer populations and identify ongoing human-assisted translocations. Sambar deer in Australia and New Zealand are genetically distinct, but both populations are more genetically similar to sambar deer in the west of the native range (the South and Central Highlands of India, and Sri Lanka) than they are to those in the east (eastern India and throughout Southeast Asia) (Rollins *et al.* 2023, this issue). A second genetic study of sambar deer used SNPs and identified four genetically distinct groups across south-eastern Australia, as well as the presence of sambar and rusa deer hybrids in three geographically separated regions (Hill *et al.* 2023*b*, this issue).

Managing wild deer

The main methods used to control wild deer in Australia are ground- and helicopter-based shooting. Ground-based shooting can be conducted by volunteers or contractors, but there are few examples of either method substantially reducing deer populations or deer impacts (Bengsen *et al.* 2020). A 5-year trial in the Australian Alps revealed that contract shooters killed four times more sambar deer per unit effort than did volunteer shooters, but that the cost per deer killed was only 10% higher for the former (Comte *et al.* 2023*b*, this issue). Both shooter types hunted mainly near roads and tracks, with more remote areas less or not hunted. Recreational hunting of deer is an important activity in some states (Moloney *et al.* 2022) and usually involves ground-based shooting for meat or trophies. This undoubtedly has some effect on deer abundance in the most easily hunted and accessible areas, but probably only minimal impact in rugged, remote and fully forested areas. However, in Victoria, recreational hunting of sambar deer using teams of dogs is a popular recreational pastime suited to steep forested areas with good vehicle access (Hampton *et al.* 2023*a*, this issue).

Helicopter-based shooting is now used to control deer in Queensland, NSW, the Australian Capital Territory, Victoria, South Australia and Tasmania. This control tool can substantially and quickly reduce deer populations over large geographic areas, with the magnitude of the reduction dependent on initial densities and the extent of forest cover, and the effort (hours of shooting) per deer per km^2 (Bengsen *et al.* 2023, this issue; Ramsey *et al.* 2023, this issue). For large rugged or remote areas, helicopter-based shooting is the only practical available option for controlling deer. However, helicopter-based shooting becomes less effective as concealing cover (e.g. canopy and subcanopy trees or shrubs) increases, although a thermal camera can increase the probability of detecting deer in such cover.

The extent to which controlling deer reduces their undesirable impacts is less clear. The most straightforward context is where deer are damaging crops or competing with livestock for food. The total value of lost production can be high, but the key questions are whether the costs of deer control outweigh the benefits, and how much control is required, driving research into the quantification of costs and benefits [e.g. in north-west NSW, helicopter-based shooting reduced the fallow deer population by 26%, increasing the stocking rate by 22.0% (in areas of complete overlap) or 13.8% (discounting for the proportion of browse that likely would not be eaten by domestic livestock) (Davis *et al.* 2023, this issue)].

Controlling deer to reduce adverse environmental impacts is more complex because the benefits are much more difficult to quantify in economic terms – largely because the impacts of deer on conservation values are complex and the relationships between deer density and their impacts are often not well known (Bennett *et al.* 2022). However, a 5-year experiment in Alpine National Park showed that ground-based shooting reduced some – but not all – of the impacts of sambar deer on alpine peatlands (Comte *et al.* 2023*a*). Another complexity is antipathy from recreational hunters to deer being culled by ground-based contract shooters or helicopter-based shooters; hunters have suggested that recreational hunting could provide the desired level of control.

Managing the risks to human health posed by deer is likewise complex, particularly in peri-urban areas, where a multitude of landholders and land use types lead to myriad societal concerns and place limitations on the deer control tools that can be used. Ground-based shooting reduced native white-tailed deer (*Odocoileus virginianus*)–vehicle collisions in peri-urban areas in the USA (DeNicola and Williams 2008). In the long-running Illawarra Wild Deer Management Program, there is strong focus on minimising the actual and perceived risks of contract vehicle-based shooting to people (Dawson 2017), and on minimising adverse animal welfare outcomes of shooting (Hampton *et al.* 2023*c*, this issue).

More broadly, maintaining social licence for deer control tools requires that adverse animal welfare outcomes are minimised or eliminated. Two studies have addressed this issue. For helicopter-based shooting, the best animal welfare outcomes are achieved when a fly-back procedure with multiple shots to the head and thorax is mandated (Hampton *et al.* 2022). Independent assessment of the welfare outcomes of vehicle-based shooting of rusa deer by contract shooters indicated that the frequency of non-fatal wounding (considered the worst possible welfare outcome) was 3.5% for those deer that were hit (Hampton *et al.* 2023*c*, this issue). Other research has sought to mitigate some potential adverse aspects of shooting, such as the demonstration that using non-lead ammunition does not substantially increase animal welfare consequences (Hampton *et al.* 2023*b*, this issue).

Where next?

During our almost 2 years of editing this Special Issue, we have identified the following areas as especially deserving of further investigation. We note that Davis *et al.* (2016), the 2016 national workshop (Forsyth *et al.* 2017) and Cripps *et al.* (2018) identified knowledge gaps, and that some of those are yet to be addressed.

Long-term impacts of deer on plant communities and ecosystems

Setting targets for deer control requires understanding of the relationship between deer density and impact (Putman *et al.* 2011), and this is likely to vary throughout the wide range of environments in which deer occur in Australia (i.e. from tropical and coastal to high-elevation peatlands, and peri-urban). The need to understand the long-term impacts of deer on plant communities and ecosystems was highlighted by Davis *et al.* (2016), but to our knowledge there has been little progress on this. The long timeframes (decades and potentially centuries) over which impacts could manifest in some ecosystems could be a disincentive to begin this priority work. However, an emerging priority globally in recent decades is the need to determine the long-term impacts of deer (and other herbivores) on carbon stores, particularly in tall forests (Tanentzap and Coomes 2012).

Potential distributions of deer in Australia

Predictions of the potential Australian distribution of deer (Moriarty 2004; Davis *et al.* 2016) have been based on climate-matching models that compare the climate of a species' native range (and potentially other geographic ranges) with the climate in Australia. Other environmental variables such as vegetation, soil and topography will influence the potential distribution and also need to be incorporated in the modelled predictions. Determining new areas into which deer will spread will also depend on proximity to extant populations. This broader habitat and climate modelling has been undertaken at a regional scale for fallow deer in Tasmania (Cunningham *et al.* 2022*a*) and at a continental scale for all six of the wild deer species in

Australia (Kelly *et al.* 2023). These predicted distributions need to be incorporated into deer management planning, with location-specific aims to slow or prevent spread, reduce density or, in some cases, eradicate populations.

Eradicating deer populations

Eradication requires complete removal of all deer and prevention of reinvasion. There are, however, few examples of deer eradication globally (Nugent *et al.*, in press). To date, the only documented successful Australian deer eradication program is for fallow deer on Kangaroo Island (Masters *et al.* 2018), but there is an eradication program underway for rusa deer on Wild Duck Island (A. Pople, pers. obs.) and a proposal to eradicate hog deer from Wilsons Promontory National Park (Hill *et al.* 2023*a*, this issue). There are likely to be rapid knowledge gains from both successful and unsuccessful deer eradication programs, particularly regarding the effectiveness and costs of the control and monitoring tools employed (Macdonald *et al.* 2019; see following theme).

Emerging techniques for detecting deer

The use of thermal- and night-vision equipment can increase the effectiveness of ground-based deer shooters (Pulsford *et al.* 2023; Comte *et al.* 2023*b*, this issue). A thermal camera mounted in a helicopter can detect deer for subsequent targeting by a helicopter-based shooter (Cox *et al.* 2023; Pulsford *et al.* 2023), or it can provide data for estimating deer abundance and density (T. Cox, pers. comm.). A thermal camera mounted on a remotely piloted aircraft system ('drone') has detected rusa deer in peri-urban Brisbane (Sudholz *et al.* 2021). Identifying individual deer from their DNA in faeces has been used to estimate deer abundance and density for more than a decade (Brinkman *et al.* 2011), but has yet to be used in Australia. It will be important to understand when emerging technologies become cost-effective to use relative to existing methods, but the former are likely to be particularly cost-effective for finding the last few deer in eradication programs.

Biology and ecology of deer in Australia

Relative to the other large vertebrate pests in Australia, such as feral pigs (*Sus scrofa*), little is known about the biology and ecology of some of the six deer species in Australia. For the two species that are common in Europe (i.e. fallow and red deer), much of the information has been documented there and would likely apply in Australia. For the four species native to Asia (sambar, rusa, chital and hog), much is unknown in both their native and Australian ranges. The aseasonal and variable reproductive output of chital deer over several years in north Queensland has been described and was linked to rainfall (Kelly *et al.* 2022). This contrasts with the unvarying seasonal breeding of the two temperate species. The ability of deer to persist in more variable, arid environments outside their current ranges needs to be assessed. Quantifying home range sizes (Amos *et al.* 2022), seasonal movements (Comte *et al.* 2022), breeding (Watter *et al.* 2020*b*) and survival and dispersal rates will improve our ability to predict range expansions and to understand the effectiveness of existing and new management tools and strategies.

Concluding statement

The research published in this Special Issue and elsewhere shows that there has been substantial progress in addressing many of the key knowledge gaps identified in Davis *et al.* (2016) and Forsyth *et al.* (2017). Given that there are six species of deer in Australia, and that wild deer occur in all states and territories and occupy a wide range of environments, deer management in Australia is complicated. There is no simple set of solutions so management approaches will need to be further tested, reported and revised.

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