NON-INDIGENOUS VERTEBRATES IN AUSTRALIA

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ABSTRACT

At least 80 species of non-indigenous vertebrates have established wild populations in Australia and over 30 of these species are pests. Direct short-term economic losses caused by these species are at least $420 million per year, mainly in lost agricultural production. Overgrazing and browsing by introduced herbivores also contributes to land degradation, which lowers the future productive capacity in many areas, but the value of this degradation has not been estimated. In addition, grazing, predation and competition by non-indigenous vertebrates are recognised as major threats to many endangered native species and communities, but these costs have not been quantified.

Control of non-indigenous vertebrate pests in Australia costs governments and landholders over $60 million each year. In addition around $20 million is spent annually on research to control these pest species.

INTRODUCTION

Continents and large land masses are typically less susceptible to exotic species invasions[1]. Australia is an exception. Over the past 200 years, many exotic animals have been deliberately imported, both legally and illegally into Australia for transport, food, wool, leather, sport, pets, pest control or by migrants who wanted to see familiar animals from their home countries. Other species, such as black rats and house mice, have been accidentally imported. Following import, some species, such as rabbits and foxes, were legally released into the wild; others, such as feral goats and pigs, escaped domestication; and others, such as Indian mynahs, were released illegally. Exotic vertebrate species that have successfully established wild populations on mainland Australia include 25 mammals, 20 birds (and a further 7 bird species which are established on offshore islands), 4 reptiles, 1 amphibian and at least 23 freshwater fish species (Table 1).

Exotic species that have established in Australia typically possess some or all of the following attributes: a good climate match between their overseas geographic range and Australia, a history of establishing exotic populations outside Australia; a high reproductive rate; a generalist diet; and an ability to live in human disturbed habitats[2,3]. Disturbance of environments, particularly clearing and modification of vegetation and the resultant fragmentation of habitats facilitated the establishment and spread of many species[4].

Many of the exotic species that have established widespread wild populations are now considered major pests of agriculture and the environment[5-11]. There is a legal requirement for private landholders to control agricultural pests and government conservation agencies have a responsibility to reduce the impacts of exotic species on endangered native species and communities.

Exotic animals have major direct impacts on Australia's livestock industries through predation and competition for pasture. In stable environments with reliable rainfall, the presence of feral herbivores often reduces carrying capacity and productivity of stock by reducing pasture biomass. In environments with highly variable rainfall, which are the norm in Australia's rangelands, pasture biomass varies greatly and competition between stock and feral animals only occurs when pasture biomass is low[12]. It is at these times that feral animals can cause severe land degradation, because graziers can de-stock paddocks, but ferals continue grazing until large areas are almost completely denuded of vegetation. This causes permanent degradation of soil and pastures.

Exotic animals can also act as reservoirs and vectors for diseases affecting native wildlife, domestic stock and people. There are also potential losses that would occur if new diseases entered Australia and established in feral animal populations. For example, rabies could establish in wild dogs and foxes and foot-and-mouth disease in feral pigs and feral goats. Prevention and preparedness for the entry of such exotic diseases is costly.

Environmental costs, such as threats to the survival of native species through competition and predation, are hard to establish and quantify. This is because the threat posed by introduced species is often one of a suite of factors threatening native species survival, with habitat disturbance and destruction and changed fire and water regimes also playing a significant role for many native species threatened by introduced vertebrates. Changes in the composition and cover of the vegetation caused by grazing vertebrate pests are likely to influence populations of ants, termites and topsoil micro-arthropods. Vegetation changes may have long-term effects in maintaining soil structure. Some exotic species hybridise with native species and so pose a threat to their survival.

As well as being pests, many introduced vertebrates are valued as a resource[13]. Hunters and fishers value deer and trout as important game species and in some areas fees are charged to take them. Feral horses, camels, goats and pigs are mustered or shot for their meat and hides and are an important commercial resource. Many landholders make significant profits from their harvests that can offset other control and damage costs. There is a valuable export industry in feral pig and feral goat meat for human consumption. The total value of exported goats and goat products was about $30 million in 1992–93[14] and this figure is probably now much higher due to increased prices for goat meat. The feral pig harvesting industry is valued at $10–20 million[13]. Deer, camels, horses and goats are sometimes harvested for domestication. In the past, Australia was one of the world's most important exporters of fox and cat pelts, which generated significant export income, but with the decline in world fur trade this no longer occurs. Rabbit fur is used to make felt hats. Rabbits and cats are also a significant subsistence food source for some Aboriginal groups providing high-quality fresh food and economic savings to the communities[15]. Trout are a significant resource for recreational angling and carp are harvested commercially for human consumption and the production of fish bait, pet and stock food and fertiliser.

This chapter addresses the impacts and economic costs of wild-living introduced vertebrates in Australia. Harm caused by domestic animals is not considered and the cost of environmental harm to indigenous species and communities is not quantified.

All dollar values presented in this paper have been converted to 1999–2000 Australian dollars.

DAMAGE AND CONTROL COSTS OF MAJOR PEST SPECIES

The figures presented for agricultural damage costs are based on extrapolations of government agency estimates, landholder surveys and other information referenced in the text.

Only qualitative accounts are given for environmental damage caused by introduced vertebrates in Australia and no attempt has been made to price such impacts, such as the threat many introduced vertebrates pose for endangered native Australian species, and the land degradation due to overgrazing and browsing. We recognise that the cost of this damage, in many people's perception, is probably at least equivalent to the short-term agricultural damage for which costs are estimated in this paper.

The figures presented for agricultural and environmental damage control costs are based on estimates supplied by government agencies. When such estimates are unavailable, we assume spending is equivalent to that in areas with similar pest numbers for which data are available. Estimates for landholder spending are based on the assumption that the average Australian landholder spends $250/farm/year, which is a conservative estimate and takes into account the following factors:

- not all enterprises have pest problems and pest damage and control activity varies between years (particularly for damage by mice and birds)
- due to economic and social factors, many farmers do not undertake pest control even when damage is evident
- some pest control actions (such as exclusion fences and nets) have a high initial outlay followed by relatively low annual maintenance costs.

Table 1. Introduced exotic vertebrate species that have established widespread populations on mainland Australia and their pest status. Other introduced species have only established localised populations on the mainland[a] or have only established on offshore islands[b]. Sources: birds[16]; mammals[17]; reptiles[18]; fish[19] and P.J. Kailola (pers. comm.); plus supplementary information referenced in text.

	Serious pest	Moderate pest	Minor or non-pest
Mammals	European rabbit *Oryctolagus cuniculus* Feral goat *Capra hircus* Feral pig *Sus scrofa* European red fox *Vulpes vulpes* Dingo/feral dog *Canis familiaris* Feral cat *Felis catus* House mouse *Mus domesticus*	Feral horse *Equus caballus* Feral donkey *Equus asinus* Feral buffalo *Bubalus bubalis* Feral camel *Camelus dromedarius* Feral cattle *Bos taurus* Black rat *Rattus rattus*	European brown hare *Lepus capensis* Brown rat *Rattus norvegicus*
Birds	European starling *Sturnus vulgaris* Indian myna *Acridotheres tristis*	Mallard *Anas platyrhynchos* Rock dove (feral pigeon) *Columba livia* Spotted turtledove *Streptopelia chinensis* Blackbird *Turdus merula* House sparrow *Passer domesticus* European goldfinch *Carduelis carduelis* Senegal turtledove *Streptopelia senegalensis*	Cattle egret *Ardeola ibis* Skylark *Alauda arvensis* Tree sparrow *Passer montanus* Nutmeg mannikin *Lonchura punctulata* Greenfinch *Carduelis chloris*
Amphibian	Cane toad *Bufo marinus*	-	-
Freshwater fish	European carp *Cyprinus carpio* Mosquitofish *Gambusia holbrooki* Mozambique tilapia *Oreochromis mossambicus*	Weather loach *Misgurnus anguillicaudatus* Tench *Tinca tinca* Redfin perch *Perca fluviatilis* Rainbow trout *Oncorhynchus mykiss* Brown trout *Salmo trutta*	Goldfish *Carasius auratus* Guppy *Poecilia reticulata*

[a] Localised mainland populations. Birds: ostrich *Struthio camelus*; red-whiskered bulbul *Pycnonotus jocosus*; song thrush *Turdus philomelos*; mute swan *Cygnus olor*; peafowl *Pavo cristatus*; Barbary dove *Streptopelia risoria*; redpoll *Carduelis flammea*. Mammals: Asian house rat *Rattus tunezumi*; Indian palm squirrel *Funambulus pennanti*; chital deer *Cervus axis*; rusa deer *Cervus timorensis*; banteng *Bos javanicus*; hog deer *Cervus porcinus*; fallow deer *Dama dama*; red deer *Cervus elaphus*; feral sheep *Ovis aries*; sambar deer *Cervus unicolor*. Reptiles: house gecko *Hemidactylus frenatus*; mourning gecko *Lepidodactylus lugubris*; red-eared slider *Trachemys scripta elegans*; flowerpot snake *Ramphotyphlops braminus*. Freshwater fish: three-spot gourami *Trichogaster trichopterus*; red devil/Midas cichlid *Amphilophus citrinellus*; three-spot cichlid *Cichlasoma trimaculatum*; Burton's haplochromine *Haplochromis burtoni*; Niger cichlid *Tilapia mariae*; roach *Rutilus rutilus*; one-spot live bearer *Phalloceros caudimaculatus*; sailfin molly *Poecilia latipinna*; platy *Xiphophorus maculatus*; brook trout *Salvelinus fontinalis*; green swordtail *Xiphophorus* helleri; Chinook salmon *Onchorynchus tshawytscha*; oscar *Astronotus ocellatus*.

[b] Offshore island populations. Birds: wild turkey *Meleagris gallopavo*; helmeted guinea fowl *Numida meleagris*; red jungle fowl *Gallus gallus*; California quail *Lophortyx californicus*; ring-necked pheasant *Phasianus colchicus*; chaffinch *Fringilla coelebs*; Java sparrow *Lonchura oryzivora*. Mammal: Pacific rat *Rattus exulans*. Reptiles: wolf snake *Lycodon aulicus*; skink *Lygosoma bowringii*.

The figures presented for research costs for vertebrate pest control are based on available records or estimates supplied by government and research agencies. When agencies were unable to provide estimates for individual species or states, we conservatively estimated expenditure based on equivalent spending for that pest in similar areas.

Control and research cost estimates are likely to be very conservative as they do not fully account for salaried positions and associated infrastructure.

A. Rabbit *Oryctolagus cuniculus*

European rabbits were imported with the first European settlers for food, fur and skins and have subsequently become Australia’s most widespread and significant pest animal. The rate of spread of the rabbit in Australia was the fastest of any colonising mammal anywhere in the world — advancing at up to 100 kilometres per year in the rangelands. The scale of the impact of the rabbit in Australia is considered to be unique in the history of exotic animal introductions[20].

Rabbit grazing results in fewer livestock, lower wool production, lower lambing percentages, lower weight gain and breaks in the wool, and earlier stock deaths during droughts. The extent to which rabbits reduce the carrying capacity for livestock is not well quantified. About 12–16 rabbits eat as much as one sheep, but competition between sheep and rabbits only occurs when pasture biomass is relatively low, for example, less than 250 kilograms per hectare in the sheep rangelands of New South Wales, which usually only occurs following periods of low rainfall[21].

Rabbit numbers declined greatly in Australia in 1997–1998, particularly in lower rainfall areas, due to the release of a biological control agent, rabbit haemorrhagic disease (RHD). So far there has been little recovery of rabbit populations. Before RHD was released, average densities of rabbits annually consumed 10 tonnes of dry pasture per square kilometre[22] and rabbits took more pasture than sheep in many areas[20]. Pastoralists were often unable to rest pasture because if stock were taken off, rabbit and kangaroo numbers built up. Due to recent declines in rabbit numbers caused by RHD[23] this high consumption rate is likely to have dropped, particularly in low rainfall areas.

Rabbit grazing leads to pasture degradation and lack of regeneration or destruction of important fodder trees, shrubs and perennial grasses, particularly during and following droughts. Perennial grasses and shrubs are replaced with less stable annual species. Rabbits also expose extensive areas of bare soil that leads to soil erosion, loss of soil fertility and siltation of dams[20].

Rabbits damage crops including cereal and horticultural crops. Rabbits also cause extensive losses to forestry and tree plantations, preventing regeneration and damaging tree plantings. This increases the cost of tree planting programs due to the need to erect tree guards. Damage from browsing rabbits can approximate one year's loss of growth, equivalent to $800/ha, at clear-felling and rabbit control costs in private forests can be as high as $80/ha during the period when trees are vulnerable to rabbit damage[20].

Rabbits threaten the survival of at least 17 native plants[8]. The replacement rate of many of the trees and shrubs in the southern rangelands was not sufficient to prevent their disappearance in the long term prior to the release of RHD[20]. Since RHD was released in 1996, many shrub and tree species have regenerated but it is too early to determine if RHD will keep rabbit numbers low enough for long enough to allow these new plants to survive to maturity[24]. Low rabbit numbers need to be sustained to prevent the extinction of several threatened native tree species. Even an apparently successful germination can be wiped out by rabbits up to 15 years after the event[25]. Mulga (*Acacia aneura*), which lives to 250 years, is very palatable to rabbits and stock[26]. It is the most important drought fodder tree in Australia. Rabbits, not domestic stock, are preventing regeneration of mulga.

Rabbits also threaten the survival of many native animal species, such as the greater bilby (*Macrotis lagostis*), a small burrowing mammal, through competition for food and habitat destruction[8,20]. The destruction of sandhill canegrass by rabbits reduces populations of birds such as the Eyrean grasswren (*Amytornis goyderi*). Overgrazing by rabbits modifies habitats making them unsuitable for the endangered plains-wanderer (*Pedionomus torquatus*), a small nocturnal wader. The distribution and abundance of many species of birds and other animals will be seriously affected if rabbits cause a long-term decline in tree and shrub populations in the rangelands.

Rabbits occur on 48 Australian islands and their environmental impacts can be catastrophic. Rabbits introduced onto Phillip Island caused the extinction of an endemic parrot (*Nestor productus*) and two endemic plants and severely reduced other vegetation. Since the eradication of rabbits on Phillip Island in 1986 the vegetation has shown considerable recovery. Many islands are important for seabirds, the nesting sites of which are affected by rabbits[20]. For example, the Gould's petrel (*Pterodroma leucoptera*) only nests on Cabbage Tree Island, and its long-term future is in doubt because of vegetation changes due to rabbits. Rabbits also maintain high predator numbers. For example, winter nesting seabirds no longer nest on Macquarie Island because of cat predation. Shooting of cats was ineffective but rabbit control is reducing cat numbers[27].

Rabbit agricultural costs

Estimates of agricultural losses due to rabbits vary. Annual crop losses to rabbits in South Australia were estimated at $7.5 million[28], annual Australian losses to sheep production due to rabbits were estimated at $130 million[29], and annual Australian losses to agricultural production were estimated at $600 million[30], including $300 million for wool losses, $70 million for sheep meat, $150 million for cattle and $80 million for crops. These estimates assume that markets would be available for any additional agricultural production occurring in the absence of rabbits, but this may not be true, particularly for wool. Since these estimates were made, the value of wool has declined and rabbit numbers have also declined due to RHD. The RHD-induced decline in rabbit numbers has been estimated to result in a benefit of at least $165 million a year to wool/sheep producers in Australia[31]. It is probable that annual losses to sheep and wool production due to rabbits are still around $100 million per year. Losses to other agricultural industries have probably benefited less from RHD; so total agricultural losses due to rabbits may still be at least $200 million a year.

Rabbit agricultural and environmental control and research costs

Governments are estimated to spend over $10 million per year on rabbit control. It is likely that landholders spend at least an equivalent amount so a conservative estimate for total annual rabbit control costs is over $20 million per year. Rabbit control research costs have been around $5 million per year for the last 5 years, much of it directed at biological control.

B. Fox *Vulpes vulpes*

Fox predation on lambs can be significant. A study in Victoria indicated that foxes took 7% of lambs[32]. Foxes reduced lambing success by an average of over 25% on two sheep properties in South Australia[33]. Foxes may account for up to 30% of all lamb mortalities in some areas in western New South Wales where foxes are common[34]. High lamb losses can occur where lambing is out of step with or isolated from neighbouring flocks. Foxes also prey on calves, goat kids and free range poultry although these losses are unquantified[32].

The fox is a serious threat to native wildlife, including many rare and endangered species[9,32]. In Western Australia, the removal of foxes in some areas has caused substantial and consistent population increases in some marsupial species[32]. After eight years of fox control in two rock wallaby (*Petrogale lateralis*) colonies, populations increased four to five-fold[35]. Following fox control on Dolphin Island, the sightings of Rothschild's rock wallabies (*Petrogale rothschildi*) increased nearly thirty-fold. Following fox control for five years in Dryandra State Forest, numbat (*Mymecobius fasciatus*) numbers increased significantly. In New South Wales, fox control has been shown to increase mallee fowl (*Leipoa ocellata*) survival.

Foxes were identified as a factor limiting success in seven out of ten mainland reintroductions of endangered native mammals[36]. Reintroductions to islands and mainland sites which had predators such as foxes and cats, had a success rate of only 8%, compared to a success rate of 82% on island sites with no predators.

There is no practical method for assessing the economic impact of foxes on wildlife although the impact may be considerable, particularly for eco-tourism for viewing native species such as kangaroos, koalas and penguins and rarer native species in wildlife parks as well as in the wild. Expensive fox control is often needed to allow this to occur[32]. For example, on Phillip Island there is a $50 million tourist industry viewing little penguin (*Eudyptula minor*) populations. For the period 1987 to 1992, 202 foxes were destroyed while in the same period 499 penguins were identified as having been killed by foxes[32].

Fox agricultural costs

If we assume that foxes take 5% of all viable lambs Australia wide; the annual cost of fox predation on lambs would be around $40 million.

Fox agricultural and environmental control and research costs

Governments are estimated to spend around $2 million on fox control annually and landholders probably spend around $5 million. Annual fox control research costs are around $4 million per year, mainly directed at baiting foxes with poisons or immunocontraceptives.

C. Feral Goat *Capra hircus*

Feral goats are a cost to primary producers because they contribute to long-term changes to perennial vegetation caused by overgrazing, especially during droughts. Feral goats contribute to damage to vegetation, soils, and native fauna in the large areas of pastoral land that are overgrazed, although their share is generally less than that of other herbivores[14]. Feral goats also affect perennial vegetation by eating established plants and by preventing regeneration of seedlings. Browsing by goats can kill established plants by defoliation. Goats are particularly prevalent in habitats with perennial shrubs and trees, many of which are palatable and most are ultimately eaten by goats.

At a density of two per square kilometre (the average density of goats in Australia in the early 1990s), feral goats annually consume 0.73 tonnes of dry matter per square kilometre[14]. This consumption by goats includes unpalatable vegetation and woody tissue not normally eaten by livestock and native fauna, and if not eaten by goats, much would be consumed by invertebrates, small vertebrates, and decomposers. Rangelands with 240 millimetres of rainfall can on average support at least 20 goat-sized herbivores per square kilometre. Therefore, at the average density of two per square kilometre, feral goats would consume about 10% of the food eaten by the suite of large herbivores present[14].

At four sites in south-west Queensland between 1994 and 1997, feral goats represented 3–30% of the total grazing pressure and all four sites had a total grazing pressure above the estimated safe total carrying capacity[37]. Livestock and kangaroos were the other main contributors to grazing pressure. In 1997–1998 the average cost of harvesting a feral goat was around $2 and the farm gate price was $16–$38 per goat. At this high price feral goats are not considered a pest by most landholders but are harvested for profit.

Costs to other production values include the costs to farmers of keeping feral goats from mating with their quality domestic goats and costs to production foresters caused by goat damage to their seedlings. Feral goats can damage fences and contaminate water bodies. The presence of feral goats in Australia also increases the contingent cost of insuring against the outbreak of exotic diseases of livestock[14].

Feral goats affect native fauna primarily by competition for resources such as food, water, and shelter, and by contributing to changes in ecosystems although these effects have not been quantified[10,14]. Feral goats now occur on only one Australian oceanic island, Lord Howe Island, which is a World Heritage Site.

Feral goat agricultural costs

Annual losses to agricultural production (mainly the pastoral industry) due to feral goats are around $20 million/year[14].

Feral goat agricultural and environmental control and research costs

Governments are estimated to spend around $2 million on feral goat control annually. Farmers also control feral goats, but the average price for harvested goats in recent years has been over $20[37], so the profits farmers make from selling the feral goats makes their control cost-neutral. Annual feral goat control research costs are around $1.5 million per year.

D. Feral Pig *Sus scrofa*

Feral pigs prey on newborn lambs. Feral pig predation on newborn lambs has been measured 32%[38] and 18.7%[39]. Feral pigs also eat or root up pasture, which could otherwise be used by domestic stock. This effect may be considerable in higher stable rainfall areas but is likely to be small (under 3%) in more arid variable rainfall areas[12].

Pigs damage water sources, including bore drains and bore outlets, water supply channels in irrigation areas, flood gates and levy banks around flood-prone property, and water troughs and distribution pipes[40]. They also foul farm dams and waterholes by wallowing and defecation[12]. Feral pigs also damage fences. Feral pigs also reduce yields of cereal grain, sugarcane, fruit and vegetable crops[40].

The most important environmental impacts that feral pigs are likely to have are habitat degradation and predation. Feral pig rooting leads to erosion and loss of regenerating forest plants. Erosion caused by pig rooting also leads to lowering of water quality and silting of downstream swamps[12]. Feral pigs eat native plants, including their foliage and stems, fruits and seeds, and rhizomes, bulbs, tubers and roots. The effect of pigs on rare or endangered plants and on plant succession in Australia is unknown. Animals reported to be eaten by feral pigs include earthworms, amphipods, centipedes, beetles and other arthropods, snails, frogs, lizards, snakes, the eggs of the freshwater crocodile (*Crocodylus johnstoni*), turtles and their eggs and small ground-nesting birds and their eggs[12]. Feral pigs are also reported to destroy the nests and eat the eggs and young of larger ground-nesting birds, such as cassowaries (*Casuarius casuarius*), scrubfowl (*Megapodius reinwardt*) and brush-turkeys (*Alectura lathama*). Feral pigs may also compete with brolga (*Grus rubicundus*) and magpie geese (*Anseranas semipalmata*) for food. The effect of this predation and competition on animal populations is unknown.

Feral pigs may help spread rootrot fungus (*Phytophthora cinnamomi*), responsible for dieback disease in native vegetation. The spread of the fungus has also been associated with soil disturbance and reduction of litter cover by pigs.

Feral pigs can be hosts or vectors of several diseases and parasites currently present in Australia that affect livestock and people. The major diseases of concern are leptospirosis (*Leptospira* spp.), brucellosis (*Brucella suis*), melioidosis (*Pseudomonas pseudomallei*), tuberculosis (*Mycobacterium* spp.), porcine parvovirus, sparganosis (*Spirometra erinacei*), Murray Valley encephalitis and other arboviruses[12]. Feral pigs are the wild vertebrate species of most concern in Australia for their potential to harbour or spread exotic diseases and parasites of livestock should such diseases breach Australia's quarantine barriers[12]. The most significant exotic disease of concern is foot-and-mouth disease (FMD), a highly contagious viral disease of ungulates (including pigs, cattle, sheep, goats and deer). Other diseases of concern include swine vesicular disease, African swine fever, Aujeszky's disease, trichinosis (or trichinellosis), and classical swine fever. Outbreaks of any of these diseases or parasites could have severe repercussions for livestock industries[41]. For example, an outbreak of FMD could cost Australia more than $3 billion in lost export trade, even if the outbreak of the disease was eradicated immediately[12]. If the outbreak persisted, continuing losses could be $0.3–4 billion a year, depending on whether trade was affected in just one state or territory or countrywide.

Feral pig agricultural costs

Annual losses to agricultural production (mainly the pastoral industry) due to feral pigs are around $100 million/year[12]. This includes contingent cost of insuring against the outbreak of exotic diseases of livestock of about $5 million per year.

Feral pig agricultural and environmental control and research costs

Governments are estimated to spend around $2.5 million on feral pig control annually and landholders probably spend an equivalent amount bringing the total control costs to around $5 million/year. In addition research on feral pig control averages around $1.5 million per year.

E. House Mouse *Mus musculus*

Mice form plagues in grain growing areas and do most damage when winter crops are sown and when they flower and set seed and when summer crops mature[42]. Nearly all crop types can be damaged during plagues, particularly grain and oilseed crops and many horticultural crops.

Apart from the damage to crops, mice damage farm equipment, machinery and vehicles, building insulation, household items and personal possessions. The average loss to grain growers of the three most recent major plagues is estimated conservatively to be around $48 million[42]. Major plagues now occur every year or two[42]. In addition, there is damage from local plagues, such as one in 1994 in the Murrumbidgee Irrigation Area of New South Wales which caused an estimated $7 million damage to rice, maize and soybean crops[43]. Even at non-plague densities mice can cause millions of dollars worth of damage to crops.

Mouse plagues also cause losses to pig and poultry farmers, due to increased feed costs (rising by up to 50% during the 1993 Victorian plague), stress and attacks by mice causing injuries. The total losses experienced by intensive livestock producers during the 1993 mouse plague were in the order of $600 000 in the worst affected area in north-west Victoria[42]. Depletion of pastures is commonly reported by graziers during mouse plagues[42].

Mouse plagues also cause damage in rural townships, including damage to equipment (particularly electrical equipment), spoiling and consumption of products, lost business opportunities from not stocking and selling products at risk (such as packet food and grain) and the cost of protecting goods and cleaning to maintain health and hygiene standards. The most significant cost is the labour required to mouse-proof, bait, trap, clean, and search for and dispose of carcasses. Rural suppliers, food retailers, hospitality outlets, schools, hospitals and telephone communications and grain handling facilities record high losses. Estimated total costs to retailers, community services and residents in a 1993 plague in South Australia exceeded $1 million[42].

In a mouse plague in 1984, the rodenticide market was valued at $27 million, compared to $5 million in a non-plague year[44].

Mouse agricultural costs

The average annual loss to grain growers is at least $27 million[42]. Additional losses to other agricultural products and off-farm losses due to mouse plagues probably average at least $0.5 million per year.

Mouse agricultural and environmental control and research costs

Governments are estimated to spend around $2 million on mouse control annually. Landholders spend more, with total annual control costs of around $8 million/year. Government spending on mouse control research is an additional 2.5 million of which about half is directed at developing an immunocontraceptive biocontrol agent.

F. Wild dog *Canis familiaris familiaris*

The threat of predation of livestock by wild dogs (including feral dogs, dingoes and their hybrids) determines the distribution of sheep and cattle in Australia and sheep are not run in many areas that would be suitable for them without wild dogs. Wild dogs often kill far more sheep than they eat, so even a few wild dogs can cause heavy stock losses. To minimise wild dog predation, 12% of respondents to a survey in eastern Australia said they reduced sheep numbers or did not run sheep[45]. Sheep are the most commonly attacked animal, followed by cattle and goats[46]. Attacks on young calves are the major cause of cattle losses to wild dogs. In Queensland, 30% losses of calves caused by predation by wild dogs have been suggested[47].

Losses other than direct maimings and killings of livestock caused by wild dogs are difficult to quantify. Wild dogs sometimes chase sheep without following through with an attack which can lead to harm such as mismothering of lambs. Rams sometimes survive severe scrotal injuries, with some being fully castrated by wild dogs.

Predation by wild dogs may have an impact on the survival of remnant populations of endangered fauna. For example, predation by the dingo was implicated in the extinction of the Tasmanian native-hen (*Gallinula mortierii*) from mainland Australia[48]. Hybridisation between introduced feral dogs, which were introduced by Europeans about 200 years ago, and the dingo (*Canis familiaris dingo*) which was introduced to Australia by indigenous peoples about 3.5 thousand years ago, threatens the survival of the dingo on the mainland.

In recent years, dingoes have become a major tourist attraction at sites in 'outback' Australia and Fraser Island in particular. Consequently, many visitors and residents feed dingoes to encourage contact for close viewing and photographs. This has led to many dingoes and other wild dogs losing their fear of people and occasionally attacking them[45].

The prevalence of hydatidosis (causal agent *Echinococcus granulosus*), a fatal disease in humans, is often linked to sylvatic cycles in wild dogs and wildlife. Hydatidosis also leads to the condemnation of offal from up to 90% of slaughtered cattle from endemic areas in Victoria[45]. In south-eastern Queensland, bovine hydatidosis prevalences of 2.2–55.7% have been reported. Prevalences of 0.5–7% were found in north-eastern Victoria despite an extensive hydatid control program aimed at domestic and farm dogs[45]. Where wild dogs co-occur with foxes, for example, in coastal south-eastern Australia, the control of human hydatidosis becomes difficult.

Wild dogs and foxes pose a risk of maintaining and spreading rabies if it were introduced to Australia. If rabies were to become endemic in Australia, interaction between free-roaming domestic dogs and wild dogs would be the most likely avenue for rabies transmission to humans.

Wild dog agricultural costs

Annual losses to agricultural production (mainly the pastoral industry) due to wild dogs are at least $20 million/year[45].

Wild dog agricultural and environmental control and research costs

Governments are estimated to spend at least $4 million on wild dog control annually and landholders probably spend at least $2.5 million in direct control plus maintenance of the wild dog control fence costs up to $10million per year. This fence was established in the early 20th Century and currently extends 5614 kilometres across three states. The current costs of replacing or extending the fence are up to $8500 per kilometre and ongoing inspection and maintenance costs $300–2000/kilometre/year. Wild dog control research expenditure is around $1.5 million/year.

G. Feral cat *Felis catus*

Field experiments have shown that cat predation causes major declines in small vertebrate populations[49]. The effects of feral cat predation on native fauna were evaluated[50]. On the Australian mainland, 38 species of mammals, 47 species of birds, 48 species of reptiles, and 3 species of amphibians have been recorded in the diet of feral cats. Nineteen species of endangered or vulnerable mammals, 6 species of endangered birds, and 2 species of endangered or vulnerable reptiles are at high risk from feral cat predation on mainland Australia[50]. On offshore islands, 4 species of endangered or vulnerable birds are at high risk from feral cat predation. There is also a potential for feral cats to compete with native predators but no scientific evidence is available.

Two pathogens, which use the cat as a definitive host, can cause disease in many native species[50]. *Spirometra erinacei* is a large tapeworm that infests the gut of carnivores. *Toxoplasma gondii* produces toxoplasmosis, which can cause lethargy, poor coordination, blindness, and death. Antibodies and signs of infection have been recorded in at least 30 species of native mammals[51] and several species of birds. Toxoplasmosis can also be transmitted from feral cats to domestic stock and people and can cause lamb carcases to be condemned[52]. Feral cats can also assist in the spread of sarcosporidiosis, which causes economically significant condemnations of sheep in Australia, particularly on Kangaroo Island.

Cat environmental damage costs

No estimates have been made of the cost of feral cat predation on native fauna. Cats are not an agricultural pest.

Cat environmental control and research costs

Governments are estimated to spend at least $1 million on feral cat control annually. Annual cat control research costs are also around $1 million per year.

H. Feral Donkey *Equus asinus*

Donkeys compete with stock for water and pasture in northern Australia and also denude ground cover and contribute to erosion[6]. The effect of donkeys on native fauna is unknown, but habitat destruction may be a problem. Their potential role in spreading livestock diseases is limited by their remoteness.

Donkey air and ground shooting campaigns have been conducted and large numbers have been shot including an estimated 76,000 between 1980 and 1982[6]. Reinfestation is a major problem. There is little current government spending on feral donkey control and no estimates are available of landholder spending.

I. Feral horse *Equus caballus*

Horses on rangelands destroy fences, foul watering points and consume fodder, hence reducing productivity for livestock[53]. Their grazing and fouling of water may also have a detrimental impact on native species. Feral horses also have a potential role in exotic disease spread, although this is limited by their remoteness from significant domestic horse populations. Control costs are not quantified but methods include mustering and despatching to abattoirs, and shooting, mainly from helicopters[6,53].

J. Feral buffalo *Bubalus bubalis*

In 1985–86 feral buffalo numbers in northern Australia were estimated at 350,000. Since then their numbers have been greatly reduced by a large scale control program to eliminate brucellosis and bovine tuberculosis from Australia, the Brucellosis and Tuberculosis Eradication Campaign[6]. The spread of these livestock diseases posed a threat to Australia's meat industry[54]. Buffalo are shot from helicopters or rounded up into corrals, using four-wheel-drives and helicopters, for transport to abattoirs.

Prior to their widespread control feral buffalo extensively damaged freshwater swamps by forming trails between tidal rivers and floodplains which allowed sea water to enter and kill large areas of paperbark *Melaleuca* spp. forest[6]. They also selectively ate native grass (*Hymenachne acutigluma*) and changed the structure of monsoon forest. They trampled nesting grounds of the rare pig-nosed turtle (*Carettochelys insculpta*). Buffalo damage was especially significant in areas that have major conservation values such as Kakadu National Park[6].

K. Feral camel *Camelus dromedarius*

Camels can damage fences and watering points but the impact is probably small[6]. There is little competition between camels and livestock. Their potential role in spreading livestock diseases is insignificant because of their low density and remoteness. It is possible that browsing and grazing by feral camels reduces shelter for small desert mammals. Camels are sometimes controlled on cattle stations, usually by trapping at water points, mustering and shooting[6].

L. Black rat *Rattus rattus*

Black rats cause losses as high as 30% in macadamia orchards in some years, equivalent to around 100 tonnes or $350 000 worth of nuts on some individual farms[42]. Annual average losses are probably around 5% so at this level of damage the total national damage is of the order of $3 million per year[42]. The macadamia industry in Australia is rapidly expanding, so this figure could increase substantially unless effective control methods are developed and implemented. Black rats also damage citrus, avocado and banana crops, but the extent and severity have not been evaluated.

The potential impact on owls (*Circus*, *Ninox* and *Tyto* spp.) from the use of anticoagulant rodenticides in orchards has raised concern[42].

Predation by black rats on offshore islands is suggested to adversely affect native species including eight native birds, two reptiles and one insect[55] and is also thought to have contributed to the extinction of two additional bird species. Competition by black rats on islands may also adversely affect two mammal species[55].

M. Cane Toad *Bufo marinus*

The diet of cane toads is primarily composed of arthropods and effects on invertebrate communities have not been quantified but it is possible they compete for food with some native species. Cane toads also take bees around commercial hives but the economic costs are unquantified.

Cane toads may compete with native species for habitat[56]. They may also eat native frogs and their eggs although this appears to be uncommon[57]. As cane toads are toxic they can poison native predators that attempt to eat them. Native frogs that eat cane toad eggs or tadpoles could be poisoned but there is little evidence for this[58]. There is anecdotal evidence that local populations of four quoll species (*Dasyurus* spp) and 16 goanna species (*Varanus* spp) that eat cane toads are threatened[59] but there is little clear evidence that cane toads are the principal cause of declines in these species[7].

Cane toad control and research costs

Governments spend around $0.5 million on cane toad research annually. There are no significant cane toad control programs.

N. European starling *Sturnus vulgaris*

European starlings cause high levels of damage to fruit crops, particularly grapes and stone fruit and they attack winter-sown cereals at germination[60]. Crop damage due to starlings is difficult to quantify as it is usually combined with damage caused by other birds but average bird damage losses to grape crops have been estimated at around 10% and starlings would be a significant contributor to this total damage[61]. Damage is caused by grape removal or damage or by secondary spoilage through moulds, yeasts, bacteria and insect damage. Bird damage can also cause undesirable early harvests with resultant downgrading of premium fruit.

Starlings also take feed from cattle feed lots, piggeries and poultry farms[60]. In addition to the food they take, they spoil much more with their droppings. There is also a risk that they could assist in the spread of diseases such as salmonella and tuberculosis at these sites[62]. Starlings nest in roof and ceiling cavities causing fire hazards and parasite infestations and deface buildings with their droppings.

European starlings compete for food and nesting hollows with native birds, in many cases displacing them[60,63].

Bird agricultural costs

Starlings are the worst introduced bird pest of agriculture in Australia. No estimates are available of total agricultural losses caused by introduced birds but they are likely to be at least $10 million/year.

Bird control and research costs

Governments and landholders are estimated to spend at least $3 million on bird pest control and probably around half of this is directed at introduced birds such as starlings. An intensive monitoring and control program in Western Australia has prevented starlings from establishing there. Governments spend around $0.5 million on bird pest research.

O. House sparrow *Passer domesticus*

House sparrows damage fruit, vegetable, grain and oilseed crops[16, 61]. They also deface buildings with their droppings and block gutters and downpipes although this damage is minor. Sparrows congregate at feedlots, piggeries and poultry farms and they could assist in the spread of diseases such as salmonella and tuberculosis at these sites[62].

House sparrows are aggressive around their nests and compete with native birds for nest sites and food[64].

P. Indian myna *Acridotheres tristis*

Indian mynas are still colonising Australia and do not yet occur in large numbers. Mynas compete with native birds, such as the crimson rosella (*Platycercus elegans)*, and mammals, such as the sugar glider (*Petaurus breviceps*), for nest hollows[65]. Mynas are also minor pests of some fruit, such as grapes and figs. They can also nest in building cavities (especially chimneys) and bring irritating bird mites into buildings. In Hawaii the Indian myna is a major disperser of seeds of the introduced harmful weed *Lantana camara*[66]. This weed is a serious threat to native communities in Australia and it is likely that the Indian myna could play a similar role here.

Q. European blackbird *Turdus merula*

Blackbirds damage grapes and stone fruit[61]. They can also spread weeds such as blackberry (*Rubus* spp) and sweet pittosporum (*Pittosporum undulatum*) and damage garden plants. Blackbirds are aggressive towards native birds and they may compete with them for food and displace them but there is no published evidence.

R. Mallard *Anas platyrhynchos*

Mallards interbreed with the native Pacific black duck (*Anas superciliosa*) and the hybrid offspring are fertile. Hence mallards are a conservation risk for this native duck and may eventually replace it[63]. The Pacific black duck is also an important game bird in Australia and hunters prefer it to mallard.

S. Nutmeg Manikin *Lonchura punctulata*

Nutmeg manikins compete with native birds for food and it is believed the species may be replacing native finches, such as the chestnut-breasted finch (*Lonchura castaneothorax*) in some areas[63].

T. European Carp *Cyprinus carpio*

Carp occur in huge numbers and biomasses in the waterways of the Murray–Darling Basin, Australia's most productive agricultural region. They increase costs to domestic and irrigation water suppliers, agriculture, recreational and commercial fisheries and tourism.

Carp contribute to increased nutrient, algae and suspended sediment concentrations. This reduces water quality for stock, and increases pump wear and the cost of water treatment. The costs have not been estimated.

Carp have detrimental effects on aquatic plants and invertebrates and lower water quality[67]. The role of carp in the decline of Australian native fish populations has been the subject of much speculation, but scientific evidence is lacking. There may be some competition between carp and native fish for both food and habitat and carp may make aquatic habitats less suitable for other fish. Carp may have contributed to the decline of several threatened species including dwarf galaxias (*Galaxiella pusilla)*, trout cod (*Maccullochella macquariensis)*, Yarra pygmy perch (*Edelia obscura*) and variegated pygmy perch (*Nannoperca variegata)* [68].

Recreational fishing in Australia is worth billions of dollars per year. Few anglers seek carp and some may cease visiting areas where carp are abundant which could have substantial negative impacts on industries supported by recreational fishing[67]. In Tasmania, the image of a high quality trout fishery has been tainted by the introduction of carp. In an analysis of the effects of carp in the Gippsland Lakes in Victoria, a rough estimate of the costs to the community over five years was $175 million[67]. This included losses to the native commercial fishery and losses to recreational fishing, tourism and commerce.

Carp control and research costs

Governments are estimated to spend around $1 million on carp control/year. In addition governments spend around $0.5 million on carp control research.

U. Brown Trout *Salmo trutta* and Rainbow Trout *Onchorynchus mykiss*

Brown trout and rainbow trout are aggressive and territorial and adversely affect many species of native fish through competition for food and habitat, predation and habitat alteration and are thought to have replaced native species in some habitats[69, 70].

Competition for food between brown trout and native species such as Macquarie perch (*Maquaria australasica*), river black fish (*Gadopsis marmoratus)*, trout cod (*Maccullochella macquariensis*) and some Galaxiids (*Galaxias* spp) have led to a severe decline in the numbers of these species[69,71,72]. Brown trout also prey on invertebrates such as yabbies, beetles, and tadpoles and can reduce their numbers[71,72].

V. Mosquitofish *Gambusia holbrooki*

There is circumstantial evidence that mosquitofish harm native fish and frogs by competing for food and habitat, aggressive behaviour, and predation on eggs and hatchlings[19,73,74]. Declines in native fish populations have been observed in most places where mosquitofish have been introduced[75].

W. Tilapia *Oreochromis mossambicus*

Tilapia prey on and compete with native fish species for food and habitat[76]. They also remove plants, which may lower habitat quality for native fish. Tilapia are thought to pose a major threat to native fish species in Australia but the species is still in the early stages of establishing here and its impacts have been little studied[77].

SUMMARY AND DISCUSSION

Agricultural costs due to the major introduced vertebrate pests in Australia are difficult to accurately estimate due to a shortage of reliable data but total at least $420 million/year for direct short-term losses (Table 2). Longer-term losses are also likely to be large.

Table 2 Estimated agricultural damage costs and agricultural and environmental control and research costs for the major vertebrate pests in Australia.

Species	Agricultural losses $million	Control costs $million	Research costs $million
European rabbit	=200	20	5
Red fox	40	7	4
Feral goat	20	2	1.5
Feral pig	100	5	1.5
House mouse	=27	10	2.5
Feral dog and dingo	=20	=10	1.5
Feral cat	0	1	1
Non-indigenous birds	=10	1.5	0.5
Cane toad	0	0	0.5
European carp	?	1	0.5
TOTALS	**=$417 million**	**=$57.5 million**	**$18.5 million**

Landholders and governments in Australia spend over $60 million/year controlling introduced vertebrate pests. In addition to the resources spent on control an additional cost is the value of lost opportunities to take profit from alternative investment of this expenditure[12]. There are also flow-on effects to related industries and the community which are unquantified. Governments also spend around $20 million/year on research to control these pest species. Another cost to governments is the reduced tax revenue due to the reduced income of primary producers.

Two major impacts of introduced vertebrates in Australia, for which damage costs are not estimated in this paper, are the contribution to long-term land degradation caused by introduced herbivores[20] and the contribution to declines and extinctions of small native mammals caused by introduced carnivores, particularly foxes and cats[78]. Grazing and browsing species, particularly rabbits, are responsible for preventing the regeneration of trees and shrubs that hold sandy soils together in Australia's dry interior[26]. The introduction of myxomatosis as a rabbit biological control disease in the 1950s and the later introduction of RHD in the 1990s allowed some trees and shrubs to regenerate. But field strains of myxomatosis have become less effective and rabbits have developed genetic resistance to this virus and such effects will probably also occur with RHD. No biological control agents are available for foxes or cats. Conventional control methods, such as warren ripping for rabbits and poison baiting, trapping and shooting for carnivores, are expensive. There are also animal welfare concerns associated with such control measures and they often have harmful effects on non-target species.

There are likely to be significant changes in community and political attitudes to the presence, impact and management of non-indigenous animals in Australia over the next 20 years. For example, recent surveys in Australia have shown that some introduced species are already accepted by many people as a normal part of the landscape, despite the harm they cause. There is also increasing pressure to make pest control more humane and safer.

Community attitudes towards genetic modification and viruses will affect the ability of scientists to introduce potentially safer and more humane biological control techniques for pest animals, such as viral vectored immunocontraception[79]. If developed, such techniques could enable more cost-effective population control over large areas. This is particularly important for a country such as Australia where large property sizes often make pest control using conventional techniques unfeasible. Expanding the range of pest control techniques available will also overcome the possibility of pest species becoming resistant to current control techniques. However, it is too early to determine whether biotechnology research will deliver such effective new control techniques.

Awareness of the harm done by introduced vertebrates also has consequences for managing the risk of new exotic species being introduced and establishing[2]. Particular caution is required for species with attributes similar to those that have already established as pests and with a good climate match to Australia[3].

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