The wild cost of invasive feral animals worldwide

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Highlights:

1. Invasive feral animals cost $141.95 billion globally, mainly impacting the agriculture sector.
2. Oceania, North America, and Europe recorded the highest economic burden
3. Islands face a higher economic cost ($83.40 billion) than mainlands, due to invasive feral livestock.
4. Damage costs outweighed management and mixed costs, totalling $124.94 billion.

5. Invasive feral species cost twice as much as their wild invasive species counterparts.

Abstract

Invasive non-native species are a growing burden to economies worldwide. While domesticated animals (i.e., livestock, beasts of burden or pets) have enabled our ways of life and provide sustenance for countless individuals, they may cause substantial impacts when they escape or are released (i.e., become feral) and then become invasive with impacts. We used the *InvaCost* to evaluate monetary impacts from species in the *Domestic Animal Diversity Information System* database. We found a total cost of $141.95 billion from only 18 invasive feral species. Invasive feral livestock incurred the highest costs at $90.03 billion, with pets contributing $50.93 billion and beasts of burden having much lower costs at $0.98 billion. Agriculture was the most affected sector at $80.79 billion, followed by the Environment ($43.44 billion), and Authorities-Stakeholders sectors ($5.52 billion). Damage costs comprised the majority ($124.94 billion), with management and mixed damage-management costs making up the rest ($9.62 and $7.38 billion, respectively). These economic impacts were observed globally, where Oceania, North America and Europe were the most impacted regions. Islands recorded a higher economic burden than continental areas, with livestock species dominating costs more on islands than mainlands compared to other feral species. The costs of invasive feral animals were on average twice higher than those of wild species. The management of invasive feral populations requires higher investment, updated regulations, and comprehensive risk assessments. These are especially complex when considering the potential conflicts arising from interventions with species that have close ties to humans. Effective messaging to raise public awareness of the impacts of feral populations and appropriate legislation to prevent or control such invasive feral populations will substantially contribute to minimizing their socioeconomic and environmental impacts.

Keywords: biological invasions; agriculture; non-native species; economic impacts; conservation; *InvaCost*

Introduction

For millennia, humans have domesticated animals which have improved well-being and advanced cultural and socio-economic development (Diamond 2002; Zeder, 2012). Domestication refers to the adaptation of animals to circumstances defined by humans and the establishment of a symbiotic relationship, although a clear and comprehensive definition is still debated (Kohane & Parsons, 1988; Zender, 2012; Purugganan, 2022). The earliest known domesticated animals were dogs *Canis lupus familiaris* more than 13,000 years ago (Sablin & Khlopachev, 2002), likely first tamed for hunting and protection, and goats *Capra hircus* to produce milk, meat, and wool (Ahmad et al., 2020). During the period of maritime exploration, sailors introduced domesticated animals such as goats and pigs to islands as a future food resource (Cheke, 2010). Cats were also introduced inadvertently, as hitchhikers on ships and often settling on these islands (Whinam, 2005). The global reliance on such species for food and economic security has since led humans to translocate increasing numbers of domestic species favoured in livestock farming around the world (Crosby, 1986; Bradford, 1999; Rostagno, 2009). Currently, it is estimated that humans, together with their livestock, comprise approximately 96% of terrestrial mammalian biomass on Earth, with profound implications for the environment (Bar-On et al., 2018). Furthermore, poultry biomass (principally the chicken *Gallus gallus*) is estimated to be three times higher than that of wild, i.e., non-domesticated birds (Bar-On et al., 2018). This pattern of reliance is expected to continue, with a sharp increase in the *per capita* consumption of animal-based food items by 2100, predominantly in low-income countries (Bradford, 1999; Rohr et al., 2019).

Non-native species are commonly defined as those which are translocated by human activities outside of their native range and where they have not naturally evolved (McNeill, 2003; Soto et al., 2023a). These non-native species then—in some cases—establish wild populations, spread, and cause negative ecological, economic, and/or social impacts (Blackburn et al., 2011). However, this non-native definition can be challenging to apply to animals with a long history of domestication (see Gurevitch & Padilla, 2004), owing to hybridisation events and adaptations that have produced distinct lineages (McHugo et al., 2019). In this context, domestic animals present a unique case: despite being domesticated and often introduced to new environments by humans, they are generally not perceived as 'foreign'. Furthermore, some domestic species can be already integrated into new ecosystems and thus considered as part of the natural environment (Gurevitch

& Padilla, 2004). This complicates their classification as either native or non-native by traditional definitions (Gurevitch & Padilla, 2004; Moutou & Pastoret, 2010). In this study we refer to populations of non-native domesticated animals as invasive feral species.

Despite the economic, social, and cultural benefits of domesticated species to their owners or public when confined to their human-constructed ecological niches (e.g., in farmland, homes, or aquaculture facilities; Purugganan, 2022), released or escaped domesticated animals that become feral can become a growing threat to ecosystems, biodiversity and global economies (Genovesi et al., 2012; Russell & Blackburn, 2017; Marra, 2019, but see Foley et al., 2005). For example, dogs and cats pose a substantial threat to biodiversity as both pets and feral animals (Doherty et al., 2017; Loss et al., 2022), prompting numerous debates around legislation and the implementation of management efforts (Riley, 2019; Trouwborst et al., 2020; Oedin et al., 2021). These ecological and socioeconomic impacts are particularly notable in insular habitats (Whittaker & Fernández-Palacios, 2007; Bellard et al., 2017; Bodey et al., 2022), with cats in particular driving population declines and extinctions of endemic vertebrates on more than 100 islands worldwide (Medina et al., 2011, 2014). While the impacts of cats—particularly colonies of stray cats—are massive and particularly severe on islands, obtaining reliable data on the ecological and economic impacts in mainlands is more challenging due to the complexities involved in monitoring and quantifying their effects in these environments (Trouwborst et al., 2020; Carrete et al., 2022). Domesticated animals can also be important vectors of pathogens, including *Salmonella*, *Toxoplasma*, and the influenza A virus and rabies, causing wildlife and human diseases, or even death (Pauwels & Pantchev, 2018; Lycett et al., 2019; Johnson & Johnson, 2021). Furthermore, domesticated species can cause significant damage to the agriculture sector (e.g., reduced crop yields or decreased productivity), resulting in a massive economic burden (Smith et al., 2007; McKee et al., 2020). These impacts may even surpass those from non-domestic species, which may be assumed to have a higher potential for harming local communities. This assumption is based on the idea that domestication typically involves selecting for favorable specific biological traits for human use and thus loss of certain behavior patterns, whereas non-domestic species lack this selective process (Price, 1984; Wright, 2015). Additionally, the extent to which a species' gene pool has been modified during domestication could also influence its ability to thrive in natural environments and thus their capacity to cause an impact (Price, 1984).

Despite the substantial economic impacts domesticated animals can have when they spread beyond their intended anthropogenic environments (e.g., farms, homes), research into these impacts has been limited to specific species or case studies, and no attempts have been made to comprehensively quantify the monetary costs they cause (but see Legge et al., 2020). This has resulted in estimates scattered across individual reports and studies that each have a narrow focus, inhibiting the search for broadscale drivers. This lack of research obscures the full range of monetary impacts that invasive feral species can have, hindering efforts to effectively manage and mitigate their potential impacts. In particular, the inclusion of economic costs can raise societal awareness about the risks these invasions pose (Diagne et al., 2020; Ahmed et al., 2023), and help to develop more responsible management practices (Cuthbert et al., 2022a).

Here, we used the *InvaCost* database — the most comprehensive and robust database on the economic costs of invasive alien species worldwide (Diagne et al., 2020, 2021) — to provide the first analysis of the economic costs of invasive feral animal species included in the *Domestic Animal Diversity Information System* (DAD-IS) database to date. The *InvaCost* database is instrumental in identifying gaps in current knowledge and guiding future research priorities in the field of invasive species management, enabling more effective strategies to mitigate the economic burden caused by these species. Given the long history of domestication, and consequent translocation, of a limited number of species, we expect: *i*) massive and widespread costs worldwide, being most prominent for a few high-profile taxa; *ii*) that most costs will be incurred through damages in industrial sectors such as agriculture while management expenditures will be scarce; *iii*) that reported costs will be biased towards particular regions due to differences in research effort, with particularly substantial discrepancies on islands; and *iv*), that the average cost associated with non-domestic 'wild' species (i.e., invasive without any domestication history) to be several orders of magnitude greater than invasive feral species due to a reporting bias in light of human reliance on domesticated species.

Methods

To quantify the economic costs of domesticated species, we used the *Domestic Animal Diversity Information System* (DAD-IS) database (last accessed on 20 January 2023) developed by the Food and Agriculture Organization of the United Nations to identify domesticated animal species (www.fao.org/dad-is). The main aim of DAD-IS is to support the conservation and sustainable use of domesticated taxa due to their importance for human populations and cultures. The DAD-IS database contains information on diverse breeds of domesticated animals worldwide (FAO, 2023). The domesticated species identified in DAD-IS were classified into three categories:

I. *Livestock:* Also known as "farm animals", are domesticated species used to produce a wide variety of products for consumption, such as meat, milk, fur, or eggs. Some notable species in this group are cattle *Bos taurus*, sheep *Ovis aries*, goats *C. hircus* and chickens *G. gallus*;

II. *Pets:* Species kept by humans for various reasons, such as companionship, protection, entertainment or to provide emotional support. Some notable species in this group are dogs *C. lupus* or cats *Felis catus*. We did not include animals which are kept by humans but which are arguably not domesticated (e.g., fish, crayfish, rodents);

III. *Beast of burden:* Also known as "working animals", are domesticated species that are used to perform physical tasks, such as carrying or transporting goods, materials, or people. Some notable species in this group are donkeys *Equus asinus*, camels *Camelus bactrianus* and llamas *Lama glama*.

To synthesise the economic costs of invasive feral species worldwide, we used the latest version of the *InvaCost* database (version 4.1) using the *getInvaCostVersion* function of the `invacost` R package (Diagne et al., 2020; Leroy et al., 2020). *InvaCost* is a "living" database that is regularly updated with new information and curated (e.g., removal of duplicate entries). *InvaCost* entries were obtained using specific search criteria (i.e., systematic review) to collate the costs associated with biological invasions (Diagne et al., 2020). This was enhanced by adding costs from sources in more than 20 non-English languages (Angulo et al., 2021; Kourantidou et al., 2023). This version contains 13,553 cost entries worldwide extracted from primary sources (original research studies, reports, and other documents with direct information on the costs of invasive species), and secondary sources (research articles, books, and other sources that synthesize or review the available cost information).

Each entry of *InvaCost* is standardised to a reference currency (US$) and year (2017) to control for inflation and allow for the direct comparison of costs over time and across currencies, although since costs dating from before 1960 could not be standardised in this manner, they were removed from our analyses. Each entry also includes a range of descriptors that provide additional information about the cost, such as the specific species, impacted sector, region(s) where the cost was incurred, and the methodology used to estimate the costs, among others (Diagne et al., 2020).

Data processing

Prior to analysing the data, we carried out a series of steps to clean and refine the database (Figure 1). We firstly removed entries that had incomplete temporal cost information, such as missing starting or ending years ("Probable_starting_year_adjusted" and "Probable_ending_year_adjusted", respectively). We then identified species in DAD-IS that had recorded costs in *InvaCost* by matching both databases based on the "Common_name" and "Species" columns in *InvaCost* and "Common name" and "Scientific name" columns of DAD-IS. Each species' name in DAD-IS was verified manually to ensure its accuracy to avoid any misclassifications. Entries representing multiple species (e.g., *Cervus nippon/Dama dama/Muntiacus reevesi*), which included one or more species not identified in DAD-IS, were excluded from the analysis, due to the inability to disentangle individual species' impacts.

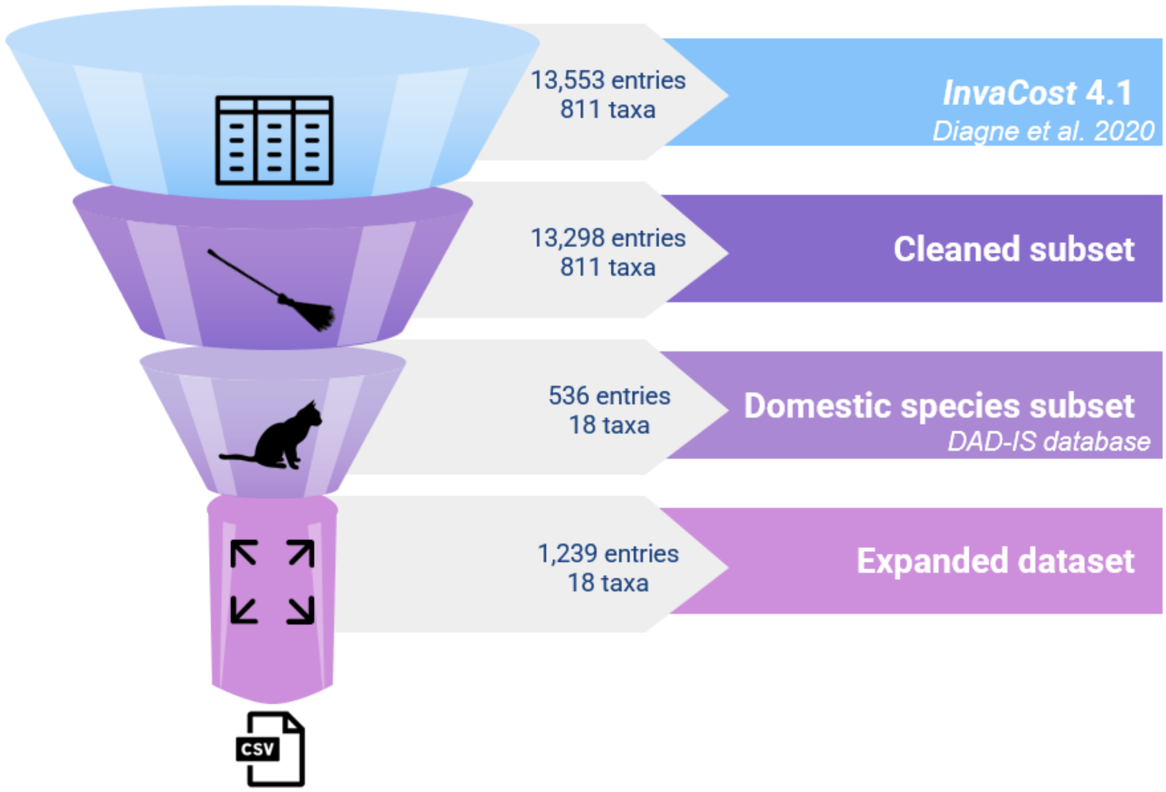

Figure 1. Flowchart outlining the steps for selecting and processing data of domesticated species in *InvaCost* version 4.1.

The final dataset contained 536 entries from 18 taxa. To annualize the data, the total cost for each estimate and species was divided by the duration of the cost entry. This allowed the costs to be spread out over the years they occurred or were estimated to have occurred, ensuring their total value was not inflated. For example, a reported total cost of $100,000 over five years would be transformed into five cost entries with a cost of $20,000 per year. The duration of the cost was determined using the time between the "Probable_starting_year_adjusted" and the "Probable_ending_year_adjusted" columns, and this process was performed using the *expandYearlyCosts* function of the `invacost` R package (Leroy et al., 2020). This process resulted in a total of 1,239 annual cost entries (Figure 1). Each cost entry was analysed according to different cost descriptors as currently defined in the *InvaCost*: Method reliability, Implementation, Species, Impacted sector, Type of cost merged, Islands and Geographic region (see Supplementary Note 1).

Feral vs. wild species comparison

All invasive feral species considered fell into the taxonomic classes Mammalia and Aves. Therefore, to test our hypothesis that invasive feral populations have lower economic costs than those of non-domestic wild species, we compared the average economic costs between these two categories across both originally domesticated (invasive feral species) and non-domesticated invasive species (wild species). We obtained costs of relevant wild species by filtering the tetrapods of *InvaCost* database (Bodey et al., unpublished data) considering only the relevant classes, i.e., Mammalia and Aves (column Class), excluding costs spread across multiple species where attribution to individual species was not possible, and finally excluding costs attributable to invasive feral species. This resulted in a total of 56 wild species together with our dataset of 18 invasive feral species. Further, the average cost of non-domesticated and domesticated species was calculated by dividing the total costs by the number of species identified in each category. In addition, the costs in both non-domesticated wild and invasive feral species were split according to their implementation and type of cost.

Results

Cost summary

A total cost of $141.95 billion (n = 1,239) arose from 18 invasive feral animals between 1960–2022. Of this total, $90.03 billion (n = 818) was attributed to 12 (out of 40 total) livestock species, $50.93 billion (n = 282) to the only two species categorized as pets by the DAD-IS (dogs and cats), and lastly, $0.98 billion (n = 139) to four (out of eight) beasts of burden (Table S1). For livestock species, a large proportion of costs ($79.08 billion, 87.83%) were from high reliability sources (n = 677), whereas only $10.95 billion (12.16%) were from low reliability sources (n = 141). Most of the economic costs for pet species ($50.83 billion, 99.80%) were from highly reliable sources (n = 196), whereas only $0.12 billion (0.20%) were from low reliability sources (n = 86). Of the total costs ($90.03 billion), most came from potential costs ($69.76 billion, 77.49%, n = 271), whereas only $20.27 billion (22.51%, n = 547) came from observed costs. In terms of implementation for pet costs, $50.70 billion (n = 261) came from observed costs (99.5% of costs) and $0.25 billion (n = 21) from potential costs (0.50% of costs). The majority of costs for beasts of burden were from low reliability sources ($0.88 billion, 89.79%, n = 15), and $0.10 billion

(10.21%) came from high reliability sources (n = 124). Most costs came from potential estimates ($0.87 billion, 88.77%, n = 32), while a minor part was attributed to observed costs ($0.11 billion, 11.23 %, n = 107) (Figure 2).

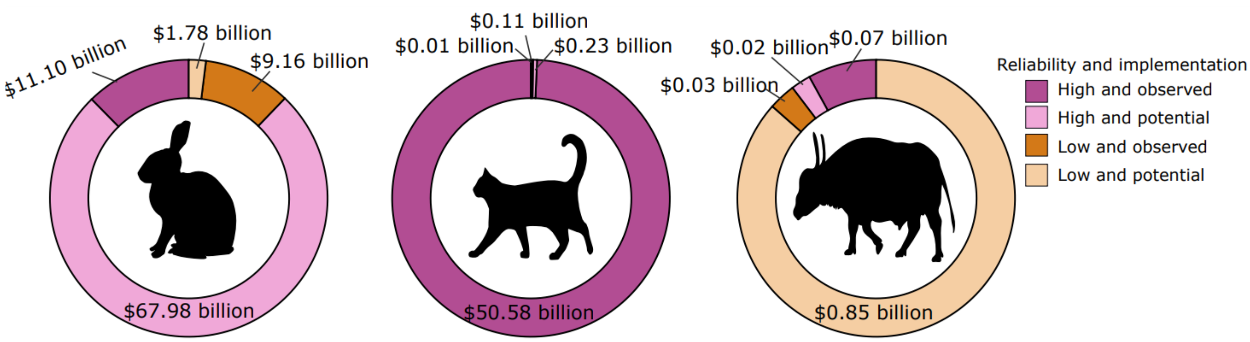

Figure 2. The proportion (%) of total economic costs for each group of domesticated species (livestock, pets and beasts of burden) split into four categories according to method reliability (high or low) and implementation (observed or potential).

Economic costs among species

The majority of costs (> 94.50%) was attributed to just three species: the European rabbit *Oryctolagus cuniculus*, the domestic cat, and feral pigs *Sus* spp. each exceeding $10 billion. For livestock species, most of the costs ($75.81 billion) were attributed to the European rabbit, followed by pigs ($10.64 billion), pigeons *Columba livia* ($3.32 billion), goats ($0.21 billion), and mixed deer *Cervus nippon*/*Hydropotes inermis* ($0.01 billion). For pets, the total was distributed between the domestic cat ($47.70 billion) and dog ($3.23 billion). For beasts of burden, costs were contributed from the water buffalo *Bubalus bubalis* ($0.88 billion), mixed donkey *Equus asinus* and horse *E. caballus* ($0.06 billion), dromedary *Camelus dromedarius* ($0.03 billion), donkey ($0.01 billion), and horse costs ($0.0006 billion; Figure 3a).

Considering only observed costs, pets superseded livestock as the costliest group overall, while the top five costliest invasive feral species remained the same, with pigs ($8.73 billion) causing more costs than rabbits ($8.01 billion). For beasts of burden the rank order changed, with water buffalo substantially reduced ($0.03 billion) such that mixed costs of donkeys and horses ($0.04 billion) were highest (Figure 3b).

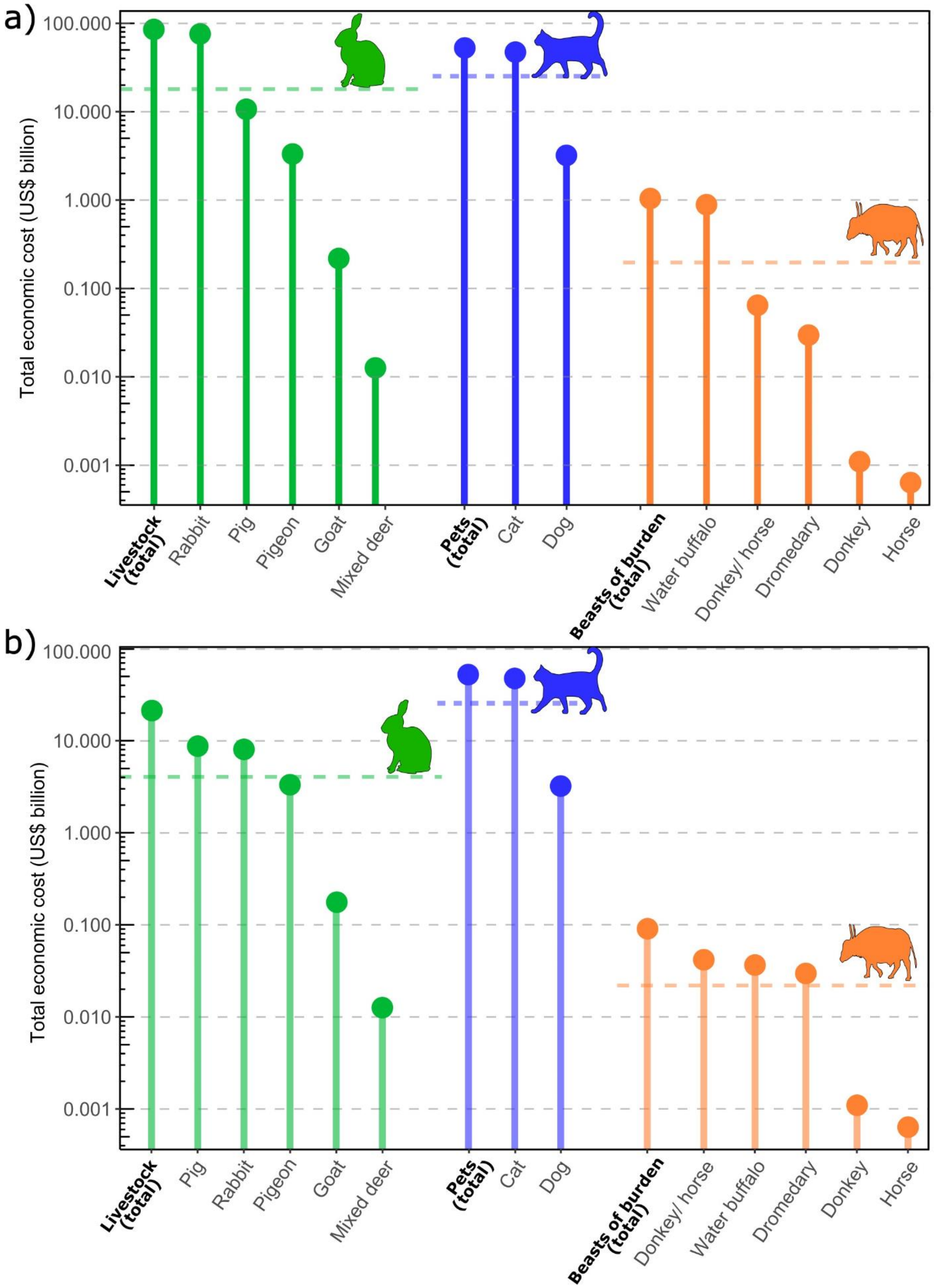

Figure 3. Top-5 costliest species (US$ billion) considering a) total economic costs (i.e., potential and observed costs combined) and b) observed costs only for livestock (green), pets (blue) and beast of burden (orange) categories of

domesticated species following the respective group's total cost. The coloured dashed line refers to the average cost per species for each group of domestic species. Note that costs (y-axis) are on a log-scale.

Impacted sectors and cost types

Overall, we found that the sectors most impacted by invasive feral species were Agriculture ($80.79 billion, n = 395), followed by the Environment ($43.44 billion, n = 22) and Authorities-stakeholders ($5.52 billion, n = 689). With respect to the type of cost, most costs ($124.94 billion, n = 424) were categorized as damages, followed by management spending ($9.63 billion, n = 797), and mixed damage-management costs ($7.38 billion, n = 9; Table 1). Only $0.005 billion (n = 9) was unspecified among types (Table 1).

Table 1. Monetary costs and numbers of database entries (rows) of groups of invasive feral species across impacted sectors and type of costs.

Impacted sector	Cost in US$ billion	Entries (n)	Domesticated group	Type of cost	Cost in US$ billion	Entries (n)
Environment	$43.39	5	**Pets**	Damage	$45.04	40
Health	$5.30	9		Mixed	$4.03	6
Authorities-Stakeholders	$1.85	233		Management	$1.86	236
Agriculture	$0.24	33				
Public and social welfare	$0.14	1				
Diverse	$0.01	1				
Agriculture	$79.62	326	**Livestock**	Damage	$79.84	344
Diverse	$4.58	50		Management	$6.83	462
Authorities-Stakeholders	$3.64	410		Mixed	$3.35	3
Forestry	$0.10	3		Unspecified	$0.005	9
Public and social welfare	$0.07	4				

Environment	$0.05	17				
Agriculture	$0.93	36	**Beasts of burden**	Management	$0.92	99
Authorities-Stakeholders	$0.03	46		Damage	$0.05	40
Public and social welfare	$0.01	33				
Diverse	$4.58	50				
Unspecified	$1.95	8				

Geographic regions and islands

Invasive feral species have global economic impacts, with costs recorded on all continents including Antarctica through sub-Antarctic islands ($0.96 million, n = 8). However, the highest economic burden came from Oceania (including Pacific Islands; $80.27 billion, n = 792), with almost all costs attributable to Australia, followed by North America ($54.28 billion, n = 187, with the United States of America being the costliest country with $54.25 billion) and Europe ($5.21 billion, n = 76, with the United Kingdom being the costliest country with $3.01 billion), with all other regions incurring substantially lower costs (< $2.22 billion; Figure 4). There was a notable gap in reported costs of feral populations in countries within Africa (with the exception of South Africa), Eastern Europe, the Middle East and Southeast Asia. For all animal groups, North America and Oceania incurred the highest costs: livestock, Oceania ($74.81 billion, n = 523), North America ($9.93 billion, n = 150); pets, North America ($44.27 billion, n = 31), Oceania($4.52 billion, n = 136); beasts of burden, Oceania ($0.94 billion, n = 133), North America ($0.04 billion, n = 6).

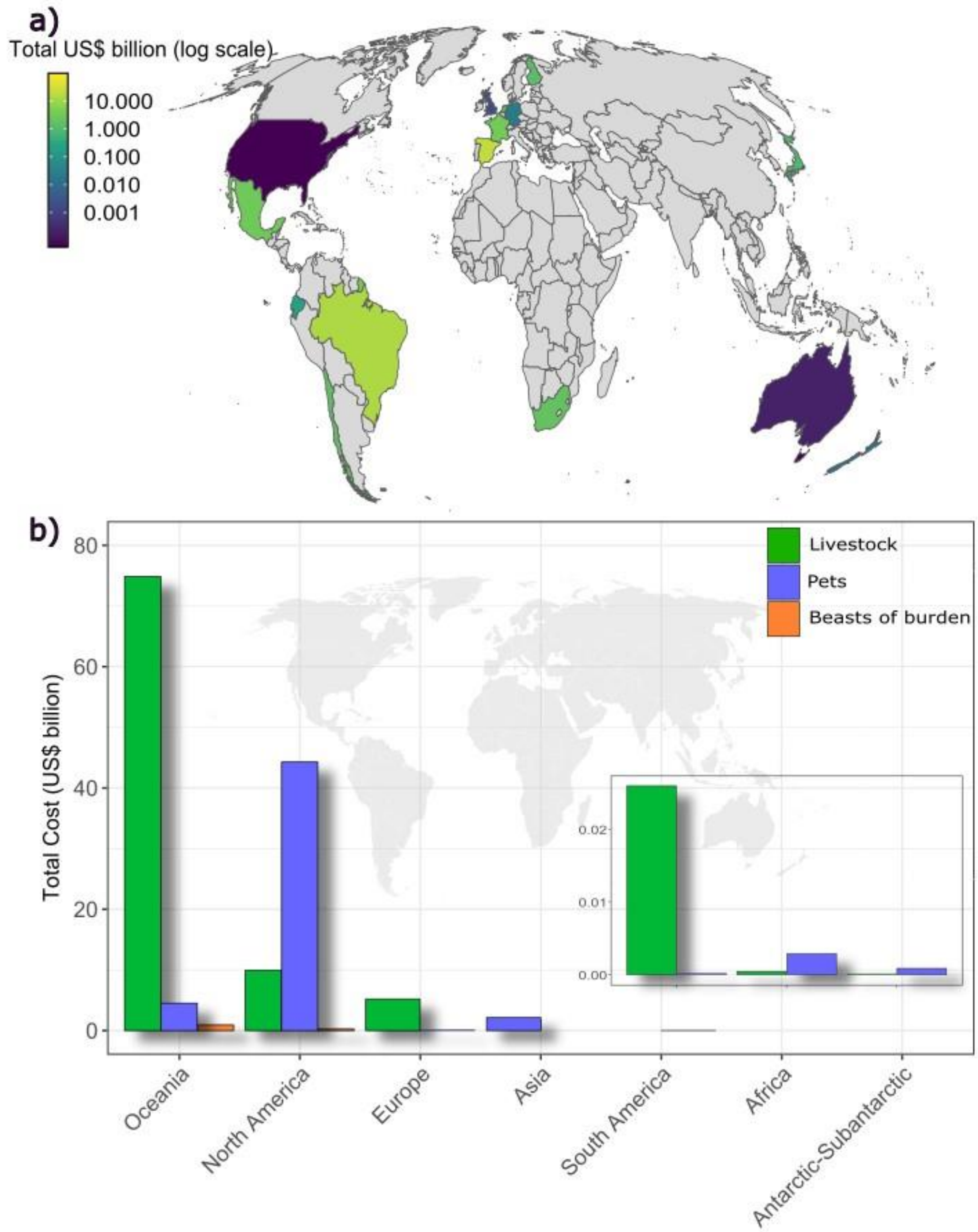

Figure 4. Geographical distribution of the economic costs of invasive feral species by country (a) and foreach group of domesticated species (i.e., pets, livestock, and beast of burden) across geographic regions (b).

Islands recorded higher economic costs associated with domesticated species ($83.40 billion, 58.73%, n = 1,087) than continental areas ($58.55 billion 41.27%, n = 152). The greatest proportion of costs on islands came from livestock species ($77.92 billion; 93.43%), with costs from pets totaling $4.54 billion (5.44%). However, continental areas had contrasting ratios with pets composing the greatest proportion at $46.39 billion (78.74%), with livestock at $12.11 billion (20.86%). While beasts of burden comprised only 1.05% of the total costs on islands at $0.94 billion, this figure comprised almost the entire recorded costs globally for this group (Figure 5).

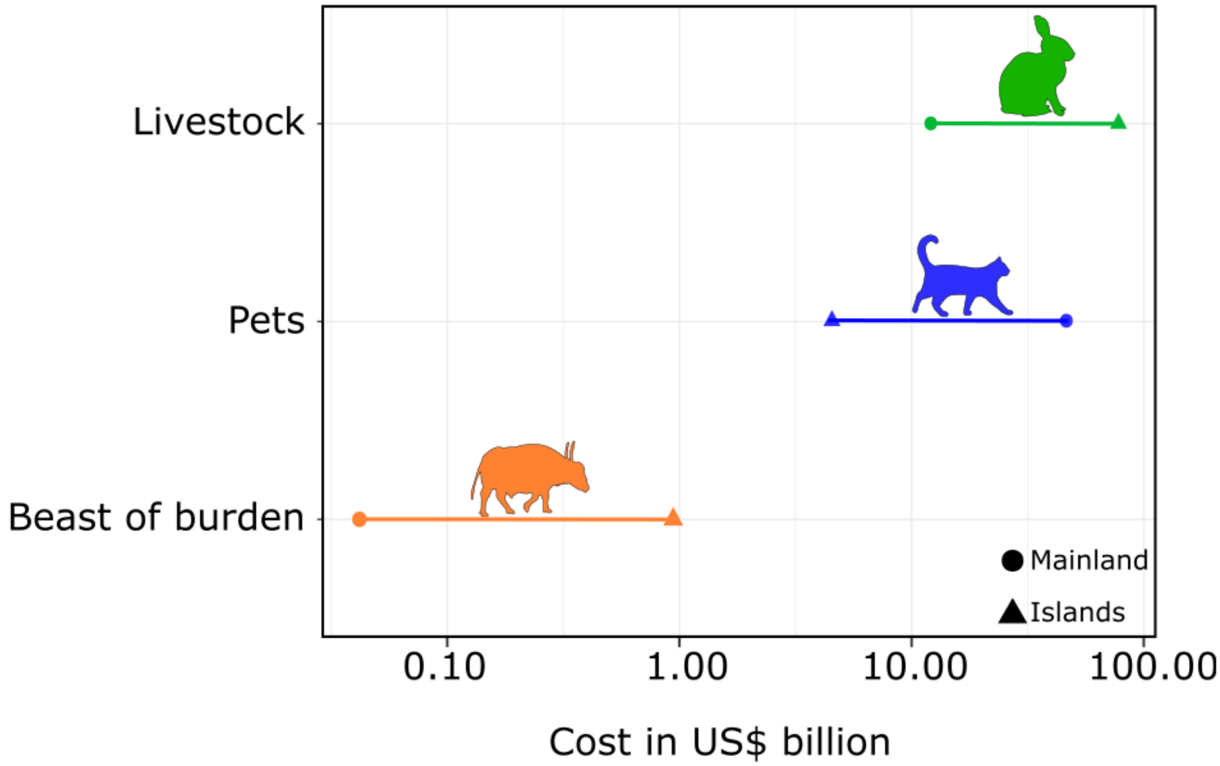

Figure 5. Total economic cost of each group of domesticated species (i.e., livestock, pets, and beasts of burden) between mainland and islands. Note that costs (x-axis) are on a log-scale.

Feral vs. wild species

Compared to the $141.95 billion total cost of invasive feral species across 18 species ($7.88 billion per species), invasive wild species were associated with $193.21 billion across 56 species ($3.45 billion per species). Interestingly, this means that invasive feral species were on average twice as costly as wild species, and this was not due to higher management costs. Indeed, the vast majority of the costs for invasive feral species and wild groups were due to damage ($124.94 billion and $166.13 billion, respectively), followed by management costs ($9.62 billion and $26.10 billion, respectively) and lastly, mixed costs ($7.38 billion and $0.92 billion, respectively). Albeit, the management investment for wild species was higher as a proportion of damage. In addition, a small portion of costs were classified as unspecified for invasive feral species and wild species (<$0.1 billion). The percentage shares of observed and potential costs from invasive feral species were similar, with $71.06 billion observed (50.07%; $3.94 billion per species), while higher shares were reported for wild species at $129.24 billion (66.89%, $2.30 billion per species) in observed costs.

Discussion

Although domestic species play an important role for human societies due to their contributions to agriculture, companionship, and labor, as well as their cultural and economic value (Ahmad et al., 2020), invasive feral populations of domesticated species have cost at least $141.95 billion to the global economy in the past 60 years. For livestock species, most of the costs were highly reliable but potential (i.e., expected in the future), whereas for pets, most of the costs were both highly reliable and observed. Beasts of burden, on the other hand, recorded the highest costs, which were of low reliability and potential. Pets primarily impacted the environment, while livestock and beasts of burden mostly affected the agriculture sector. Across all domestic groups, the most common type of cost was damage. In terms of geographical distribution, the United States and Australia stood out above other countries. Notably, only livestock and beasts of burden had a greater impact on islands than on mainlands. Lastly, wild species caused twice the economic costs as domestic species.

There was a notable disparity between the numbers of studies and associated costs for three categories of domesticated species (i.e., livestock, pets and beasts of burden), with livestock costing the most, followed by pets. This distinction may be attributed to the sheer numbers in which livestock species are introduced and the expansive areas they occupy (Anderson, 2006). Furthermore, their interactions with native species, competition for resources, and potential for habitat degradation have a significant impact on recipient ecosystems, where they are often considered “pests” and thus the target of eradication programs (Onuoha, 2008). While livestock as a whole took the forefront in terms of costs, the majority of these expenses stemmed from the European rabbit. Surprisingly, the economic toll from rabbits surpassed the combined costs from all pets or beasts of burden.

Method reliability and implementation

Most of the economic costs and entries of invasive feral species were retrieved from highly reliable sources, principally from governmental organizations. However, this was not the case for beasts of burden, for which information was primarily retrieved from low reliability (i.e., grey literature) sources. Together with the fact that the costs associated with beasts of burden were a very small fraction of the overall costs associated with invasive feral species, this suggests that costs and impacts have the potential to be substantially underestimated for these species as a result of both the complexity of defining their native and invasive ranges, and their long-standing and intricate history shared with humans (Crees & Turvey, 2015).

In terms of overall costs, an almost equal share was recorded as being directly observed compared to potential incurred (i.e., extrapolated or predicted future costs). Potential costs were higher than observed costs for livestock and beasts of burden, while the costs associated with pets were mostly observed. Despite the massive costs for domesticated species, the large potential costs being forecasted, particularly for livestock species, suggests that costs could increase further. Potential costs, although uncertain, might not have fully manifested yet. This underscores the importance of implementing improved monitoring and reporting mechanisms to track observed costs in these species groups.

Group differences in costs

Although there were relatively high numbers of monetary costs associated with the two pets included here, these costs are likely to still be substantially underestimated due to unquantified costs associated with this group (e.g., snakes or fish) as well as substantial geographic and taxonomic gaps in reported costs (Bush et al., 2014; Lockwood et al., 2019). Although most domesticated individuals remain in captivity — and so far many species have not established viable populations into the wild — there is a high risk of both escapes or releases of many species, and thus potentially unquantified damages (Vall-Llosera & Cassey, 2017; Stringham & Lockwood, 2018). Indeed, such elevated levels of propagule pressure through the continuous introduction of individuals increases the chances of successful establishment in the wild, which is further facilitated by e.g., climate change and human alterations to the environment (Lockwood et al., 2005, 2009; Kikillus et al. 2012).

Regarding livestock species, only 12 out of the 40 species included in DAD-IS (Table S1) had recorded monetary impacts. Of them, the majority of costs were inferred by the European rabbit. They are listed among "the 100 world's worst" invasive non-native species due to their massive impacts on ecosystems (Lowe et al., 2000). Such identification can lead to a greater research focus, which may contribute to the high costs recorded for this species (Cuthbert et al., 2022b). Most costs associated with rabbits were recorded as impacts on pastures and crops in Australia (Gong et al., 2009). In some countries such as the United Kingdom, rabbits are considered to be a 'naturalised' pest, rather than an invasive non-native species as a result of the long timeframe since their original introduction, and such classifications can result in underestimates of invasive species' impacts (Cuthbert et al., 2021; Diagne et al., 2023). For beasts of burden, four out of eight species in DAD-IS had recorded economic costs. The vast part of these costs came from the water buffalo and were incurred in Australia (e.g., Ridpath & Waithm, 1988). The relatively small pool of invasive beasts of burden can be due to the decreased likelihood of detecting their impacts in regions with lower research effort, but also by the nuanced distinction between native and invasive species. The association of domesticated species with beneficial human activities (e.g., farming practices) can lead to shifted perceptions of "native" status for domesticated species (Nance, 2015). For instance, species that have been part of agricultural systems for centuries may begin to be perceived as "native" by the public in the context of human-altered ecosystems, despite having impacts that we show to be akin to more conventional invasive species when feral. While acknowledging that not all the species will cause a significant economic burden, the scarcity of cost data across all groups and most of geographic regions highlights the lack of quality data available for these groups. As a result, the estimates presented here are likely conservative with regard to the full extent of their economic impact.

Impacted sectors and cost types

Introduction pathways play a defining role in the establishment and spread of non-native populations (Turbelin et al., 2021). It is now recognized that when domesticated species accidentally escape into the wild, they are able to survive, thrive and establish feral populations, as for example, cats. This can lead to substantial impacts on various primary sectors such as agriculture or forestry, alongside negative ecological consequences (Gong et al., 2009). Paradoxically, agriculture, which often relies on domesticated species for its success, emerges as the sector most negatively impacted by these feral populations. These impacts are principally through crop damage, where overgrazing contributed to reductions in vegetation cover, soil erosion, and loss of biodiversity (Filazzola et al., 2020). In addition, several management actions can be hampered by pressure from different stakeholders, generating social conflicts around conservation issues, control of invasive species that have become part of cultural practices in invaded ranges, or those with socio-economic benefits (Massei et al., 2011; Crowley et al., 2017).

Geographic distribution of economic costs

Despite the widespread and massive economic costs of domesticated species, these were unevenly spread globally, with costs particularly identified within Australia, the United States of America, and the United Kingdom. This geographic pattern in cost reporting biases towards North America, Oceania and Europe is a pervasive pattern reported on other invasive taxa (e.g., Haubrock et al., 2021; Angulo et al., 2022), and likely reflects current and historic differences in research efforts and economic activity (Nuñez et al., 2022). Countries characterized by growing economies and substantial dependence on agricultural practices are anticipated to confront formidable challenges. These countries must allocate resources towards domesticated species-centric production endeavors to uphold food security. However, they face heightened vulnerability to the potential collapse of their industries resulting from the impacts of invasive alien species (Turbelin et al., 2023).

For livestock species, the largest share of economic costs originated from Oceania, particularly from rabbits in Australia (Vere et al., 2004). The economic costs of livestock species in other geographic regions were a share of ~17%, suggesting geographic knowledge gaps with e.g., only 13 cost entries in Africa. These knowledge gaps are accentuated for beasts of burden, with only two geographic regions having available cost data (North America and Oceania). The reason for these knowledge gaps could be traced back to the history of domestication, which is intrinsically linked to colonialism. Most of the domestication processes for these species began in the Eurasian region, influencing the geographical distribution of economic costs associated with them. Consequently, our understanding and quantification of the economic impacts are confined to specific regions, neglecting the potentially considerable impacts in under-studied areas.

The impacts of domesticated species are particularly important on islands due to their unique and vulnerable ecosystems. Among domesticated species, rabbits and cats are the most impactful on islands — being also the driver of many animal extinctions (Medina et al., 2013). For example, those impacts caused by cats on islands, where they have contributed to the extinction of >60 native species (Meli et al., 2010; Doherty et al., 2016), are rarely translated into monetary costs, or if translated, typically comprise relatively low management costs rather than a record of damages to resources (Cuthbert et al., 2022a). Many other domestic species have caused drastic damage to the islands invaded such as goats, pigs and sheep (Courchamp et al., 2003). These species cause habitat degradation by reducing the vegetation cover, loss of native biodiversity through competition, and alterations in ecosystem functions, and are thus considered among the most destructive feral mammals (Courchamp et al., 2003). Due to their massive ecological impacts, these species have become the target of multiple eradication programs (Courchamp et al., 2003; Barrios-Garcia & Ballari, 2012; Jones et al., 2016). The economic costs found here can also be due to a history of species introduction on islands, for farming, hunting, or biocontrol of previous invasive feral species (Courchamp et al., 2003).

Feral vs. wild species

Surprisingly, invasive feral species recorded twice higher average economic costs than wild species. This result suggests that due to the close association between domestic populations and human societies, their impact has likely been more easily observable and quantifiable. Furthermore, it is worth noting that these economic impacts are typically observed in human-structured environments, which are more inclined towards assessing the impacts of domestic species, but also more prone to economic costs (Pimentel et al., 2005). In contrast, the economic impacts on wild species are often overshadowed, as their effects tend to be more ecological in nature rather than directly tied to human economic activities (Pejchar & Mooney, 2009). These ecological impacts encompass changes in biodiversity, ecosystem functioning, and ecological services, which are complex to quantify and may not translate directly into monetary terms (Naeem et al., 2012; Bacher et al., 2018). However, it is also worth highlighting that the sentience and charisma of species matters—independently of their potential impacts—whereby laws around management of invasive feral species (e.g., eradication programs) can encounter opposition from the public and from animal rights groups (Simberloff et al., 2013). A clear example is the case of stray cat colonies in Spain, which are protected by national laws motivated by public perception and animal rights groups, thereby potentially obscuring the scientific evidence around their impacts (Carrete et al., 2022). It should also be highlighted that most domestic species actually belong to different species with respect to their wild counterparts (e.g., *L. glama* and *L. guanicoe*), and accordingly their impacts—when becoming invasive—can be different from those of their wild relatives (Zeder, 2012). These differences can be attributed to the distinct evolutionary paths taken by domestic species, often resulting in varied behavior, ecological needs, and adaptability (Driscoll et al., 2009; Larson & Fuller, 2014). Furthermore, it should be highlighted that this analysis is restricted to mammals and birds, although the inclusion of other species could further magnify the differences found between both groups (i.e., invasive feral and wild species).

Conclusions

This study confirms our initial expectations regarding the substantial economic impacts of invasive feral animals with an estimated global cost of at least $141.95 billion over the past 60 years. However, it is also important to note that some of our predictions were only partially fulfilled due to existing knowledge gaps across taxa and biogeographic regions in the *InvaCost* database (Balzani et al., 2022; Jiang et al., 2022; Soto et al., 2022). Therefore, our results are a conservative estimate of the actual costs, suggesting that the true economic burden may be even higher. Here, we aim to emphasize the possible economic consequences of irresponsible animal husbandry and discourage the acquisition, and particularly the release, of invasive feral species — even those not officially banned. Management of feral populations of domestic animals is fraught with social, ethical, and political complexities. Ownership of these populations is often a subject of debate, but is an issue that is crucial to advance knowledge and direct management. Therefore, we underline the importance of risk assessments including both ecological and economic impact (Soto et al., 2023b) in developing effective laws and tools for managing domesticated species and addressing escaped and stray individuals. Regulations for domesticated pets should focus on controlling feral populations, while risk assessments are needed for livestock and beasts of burden to ensure responsible introductions that minimize impacts on biodiversity and economies. Public awareness and education are crucial, as legislation alone does not guarantee compliance (Patoka et al., 2018).

Acknowledgments

We would like to express our gratitude to PresentationGO for providing the free PowerPoint funnel chart template, which was adapted for use in Figure 1 of this study. IS is supported by the Grant Agency of the University of South Bohemia, project number 065/2022/Z. RNC is funded by the Leverhulme Trust (ECF-2021-001).

Data availability statement

All data and R codes can be found under https://github.com/IsmaSA/Domestic-InvaCost-topic.

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Supplement Note 1. Description of the descriptors used in the *InvaCost* database

Cost descriptors

I. *Method reliability:* This descriptor assesses the reliability of the methods used to estimate the costs of alien species. The costs can be classified as high reliability (e.g., from official reports or peer-reviewed articles with repeatable traceable methods), otherwise classified as low reliability;

II. *Implementation*: The cost estimates can be classified as either observed or potential. Observed costs refer to incurred costs, while potential costs refer to costs that are predicted or extrapolated over time and/or space, but have not yet been incurred;

III. *Species:* This descriptor provides the specific invasive alien species to which the incurred costs are attributed;

IV. *Impacted sector:* This descriptor provides information about which sector or sectors are affected by the presence and spread of alien species, such as agriculture, forestry, or health. In the case of several sectors, these groups were grouped into the category "Diverse";

V. *Type of cost merged:* This descriptor provides the type of costs (damage, management or mixed) derived from the invasion. Damage costs refer to damages or losses incurred due to the invasion (e.g., costs for damage repair, resource losses or medical care). Management costs refer to investments or expenditure on related activities (e.g., monitoring, prevention, control, eradication). Mixed costs do not distinguish between damage and management costs;

VI. *Islands:* This descriptor provides information about whether the costs of alien species are present on islands or mainland regions. Those entries recorded as “unspecified” were filled by checking each reference to determine if the costs were produced in islands. Following the classification of *InvaCost*, Australia was considered as an island;

VII. *Geographic region:* This descriptor provides information about the location(s) where the recorded costs were incurred;

VIII. Official country: This descriptor provides the specific information about country(s) where the recorded costs were incurred.

Description of each category in Impacted sector:

Sector	**Description**
Agriculture	Considered at its broadest sense, food and other useful products produced by human activities through using natural and/plant resources from their ecosystems (e.g., crop growing, livestock breeding, beekeeping, land management)
Authorities-Stakeholders	Governmental services and/or official organisations (e.g,. conservation agencies, forest services, associations) that allocate efforts for the management sensu lato of biological invasions (e.g., control programs, eradication campaigns, research funding)
Environment	Impacts on natural resources, ecological processes and/or ecosystem services that have been valued by authors such as disruption of native habitats or degradation of local habitats
Fishery	Fish-based activities and services such as fishing and aquaculture
Forestry	Forest-based activities and services such as timber production/industries and private forests
Health	Every item directly or indirectly related to the sanitary state of people such as vector control, medical care and other derived damage on human productivity and well-being
Public and social welfare	Activities, goods or services contributing - directly or indirectly - to the human well-being and safety in our societies, including local infrastructures (e.g., electric system), quality of life (e.g., income, recreational activities), personal goods (e.g., private properties, lands), public services (e.g., transports, water regulation), and market activities (e.g., tourism, trade)

Supplementary Material

Table S1: List of domestic species based on *Domestic Animal Diversity Information System* database (DAD-IS).

Scientific name	**Common name**	**Classification**
Anas platyrhynchos	Duck	Livestock
Anser anser	Goose	Livestock
Axis axis	Chital or axis deer	Livestock
Bison bison	American Bison	Beast of burden
Bos grunniens	Yak	Beast of burden
Bos indicus	Cattle	Livestock
Bos taurus	Cattle	Livestock
Bos frontalis	Cattle	Livestock
Bubalus bubalis	Buffalo	Beast of burden
Cairina moschata	Muscovy duck	Livestock
Camelus bactrianus	Dromedary Bactrian Camel	Beast of burden
Camelus dromedarius	Dromedary	Beast of burden
Canis lupus familiaris	Dog	Pet
Capra hircus	Goat	Livestock
Casuarius casuarius	Cassowary	Livestock
Cavia porcellus	Guinea pig	Livestock
Cervus albirostris	Thorold's deer	Livestock

Cervus elaphus	Red deer	Livestock
Cervus nippon	Sika deer	Livestock
Columba livia	Pigeon	Livestock
Cyrtonyx montezumae	Montezuma quail	Livestock
Dromaius novaehollandiae novaehollandiae	Emu	Livestock
Equus asinus	Ass/ Donkey	Beast of burden
Equus caballus	Horse	Beast of burden
Felis catus	Cat	Pet
Gallus gallus	Chicken	Livestock
Hydropotes inermis	Water deer	Livestock
Lama glama	Llama	Livestock
Lama guanicoe	Guanaco	Livestock
Lama pacos	Alpaca	Livestock
Meleagris gallopavo	Turkey	Livestock
Numida meleagris	Guinea fowl	Livestock
Oreortyx pictus	Mountain quail	Livestock
Oryctolagus cuniculus	Rabbit	Livestock
Ovis aries	Sheep	Livestock
Pavo cristatus	Peacock	Livestock
Pavo muticus	Peacock	Livestock

Perdix perdix	Partridge	Livestock
Phasianus colchicus	Pheasant	Livestock
Rangifer tarandus	Deer	Livestock
Rhea americana	Nandu	Livestock
Struthio camelus australis	Ostrich	Livestock
Struthio camelus massaicus	Ostrich	Livestock
Struthio camelus syriacus	Ostrich	Livestock
Struthio molybdophanes	Ostrich	Livestock
Sus sp.	Pig	Livestock
Synoicus chinensis	Quail	Livestock
Vicugna vicugna	Vicuña	Livestock

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