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Research Article

An invasive species cost review for New South Wales, Australia, highlights key drivers and limitations of economic cost estimates

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Abstract

Accounting for the costs incurred due to biological invasions is important for informing invasive species management policies and for understanding and mitigating future losses. InvaCost, a living review and large database of cost estimates, is a valuable open science resource that can support informed policy and management of invasive species and has been the basis of many regional and national cost assessments. This study used this existing database and an independent systematic literature review to conduct an expedited systematic review (or rapid review) for the state of New South Wales (NSW), Australia. This work aimed to comprehensively collate existing data to estimate the historical and current reported costs for the state and to assess the utility of InvaCost for smaller-scale regional assessments. Our findings show that invasive species costs within NSW are on the scale of billions of dollars annually and have increased substantially over time. Furthermore, most reported costs are attributed to agricultural or industry loss (e.g., control costs and production losses in pastoral, cropping, and forestry sectors). Cost estimates for losses to environmental assets or ecosystem services are almost entirely absent from the literature. This work highlights the ongoing economic damage that continues to be incurred due to invasive species in Australia, particularly for agriculture, and emphasises the need to consider non-market impacts in cost assessments. Finally, this work highlights the value of open science resources such as InvaCost for supporting biosecurity research and policy, including at more localised, subnational, and regional scales.

Key words: Biosecurity, economic loss, ecosystem services, InvaCost, invasive species, non-native, systematic review

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Introduction

Invasive species have wide-ranging impacts on invaded communities and ecosystems, including economic, environmental, social, and human health costs. In Australia, the biosecurity system can be considered to protect four broadly overlapping areas from these impacts (per Dodd et al. 2020; Schneider and Arndt 2020): the sustainability, productivity, and competitiveness of industry; the health of natural environments and the ecosystem services they provide; the health of people from mortality and morbidity; and communities, social assets, and amenity. International movement of people and goods is expected to increase with ongoing globalisation, and the geographic barriers that once kept Australia isolated and relatively pest-free are being continually eroded (Dodd et al. 2015; Seebens et al. 2017). Therefore, accounting for costs incurred due to invasive species is essential for understanding and mitigating potential future impacts.

Impacts of non-native species on economic sectors such as agriculture include direct production losses and control costs, infrastructure damage, or indirect effects such as market access losses (see, for example, Sinden et al. 2004; Murray et al. 2013; McLeod 2016). Serious effects on human health and community wellbeing have also been documented for species like red imported fire ants in the USA and increasingly in Australia (*Solenopsis invicta*; Wylie & Janssen-May, 2017) and parthenium in multiple countries in Asia and Africa, as well as in Australia (*Parthenium hysterophorus*; Allan et al., 2019). Environmental and ecosystem services impacts are also substantial but are more challenging to characterise. Invasive species can reduce abundances and increase extinction risk for native species, and alter structural or functional characteristics of ecosystems (e.g., loss of species richness, functional diversity, or habitat complexity; Ehrenfeld 2010; Simberloff et al. 2013; David et al. 2017). They can also have negative impacts on ecosystem services, which include products obtained from ecosystems ('provisioning services'), benefits obtained from ecosystem processes ('regulating services'), non-material benefits ('cultural services'), and underlying services ('supporting services'; per Reid et al. 2005; Pejchar and Mooney 2009; Postel et al. 2012; Shackleton et al. 2019). Therefore, there is a broad range of both market and non-market costs that may be considered when characterising the potential economic impacts of biological invasions (Yao and Wallace 2024).

The most significant attempt to aggregate invasive species cost estimates is InvaCost (Diagne et al. 2020). This major global database has been the foundation of numerous regional studies to estimate the current and cumulative costs of invasive species, including for the United States (Fantle-Lepczyk et al. 2022), North America (Crystal-Ornelas et al. 2021), Central and South America (Heringer et al. 2021), Europe (Haubrock et al. 2021), and Australia (Bradshaw et al. 2021). This database and associated reviews focus on estimating costs reported in monetary terms but allow for the inclusion of costs to broader societal and ecological sectors, including human health (e.g., medical costs, productivity losses), public and social wellbeing (e.g., recreational and public amenity losses), or the environment (e.g., ecosystem service impacts, degradation of natural habitats; see sectors defined in Diagne et al. 2022). Furthermore, contemporary methods for estimating the value of non-market assets allow researchers and decision makers to quantify a wide range of impacts across sectors that cannot be assessed using market data (e.g., biodiversity, cultural values, water quality). Many non-market valuation methods are now well developed and are commonly used to quantify the value of ecosystem services (Tinch et al. 2019), including in the context of biosecurity (Stoeckl et al. 2023; Yao and Wallace 2024). This allows a broader range of impacts to be incorporated into invasive species cost assessments.

The purpose of this review was to quantify the current and historically incurred costs from invasive species in New South Wales (NSW), Australia, which is the most populous state in Australia and responsible for almost one-third of Australia's gross domestic product. This study was conducted as a component of a broader NSW Invasive Species Management Review, which aims to inform invasive species policy and management in the state (led by the NSW Natural Resources Commission; NSW Government 2023). So, while this study is of limited geographical significance in the global context, its result is an example of a type of targeted fine-scale review that is likely to be valuable for domestic government agencies and policymakers in more localised jurisdictions. Costs specifically from public expenditure (e.g., governmental management programmes, public grants) were beyond the scope of this specific component of the broader review, as public expenditure could be more accurately estimated directly from government sources. This study, therefore, focused on aggregating existing cost estimates to industry, the environment, and the community, which are primarily based on private expenditure or the value of damage to private and public assets. The specific aims of this analysis were:

1. To create a comprehensive collection of reported monetary invasive species cost estimates for NSW by conducting a rapid review of reported costs in combination with existing databases (i.e., InvaCost).
2. To assess the utility of InvaCost for targeted regional invasive species cost reviews.
3. To qualitatively assess the relative contribution of (i) different species and taxonomic groups (e.g., terrestrial plants, terrestrial vertebrates) and (ii) sectors (e.g., industry or agricultural, environmental, human health) to the reported costs for NSW.

Methods

Review methodology

Reported costs were systematically compiled using a “rapid review” or “expedited systematic review” approach (Ganann et al. 2010). Broadly, two data sources were used: (i) the InvaCost database, using the current version at the time of writing (v4.1; Diagne et al. 2022); and (ii) additional data records collected via an independent literature search using an approach modelled on the InvaCost systematic review methods. Our review process followed the general methods of a formal systematic review, including standardised guidelines and reporting standards for evidence synthesis studies (e.g., PRISMA and PRISMA-EcoEvo; O’Dea et al. 2021; Moher et al. 2009), while adopting strategies or excluding steps to complete the study within an accelerated time frame. This approach was necessitated by the short time frame for this study, but it may be well suited for localised reviews, as full systematic reviews may not be viable given their substantial time and cost demands (see Haddaway and Westgate 2019) nor justified given the existence of resources such as InvaCost. Data collection methods, processing steps, and all screening criteria and records for this review are described in detail in Suppl. material 1: part A and via Zenodo (https://doi.org/10.5281/zenodo.17836243).

Data sources

InvaCost is a ‘living’ review that has systematically collected reported invasive species costs using structured search queries for online databases (i.e., Web of Science (WoS), Google Scholar, and Google) and also includes a large contribution from non-systematic sources (e.g., grey literature, personal communications). The current version includes 2,597 cost estimates specific to Australia (v4.1, 22/Jan/2022; Diagne et al. 2022) and appears to have incorporated data from a recent Australia-specific review (Bradshaw et al. 2021). This database has also been expanded by an unpublished 2023 report by the Centre for Invasive Species Solutions ("CISS"; Canberra, Australia), which includes data extracted from several recent sources that post-date the latest InvaCost version. This report was shared privately with the authors of this study, and cost data were assessed against inclusion criteria and incorporated into analyses where relevant.

Independent literature searches were conducted to identify any additional data sources that may not yet have been captured by InvaCost, which may include more recent records or additional records that may be found through a more targeted review. We considered this necessary, as the last major Australian-focused data collection was conducted several years ago (Bradshaw et al. 2021), and new data may be available. In addition, most NSW-associated InvaCost data originate from a "Targeted Collection (TC)" instead of systematic searches, which includes a large amount of data identified from the Bradshaw et al. (2021) review. While InvaCost also used systematic data collection methods, it was not designed or reported as a formal systematic review (e.g., PRISMA; Moher et al. 2009). Therefore, while InvaCost represents a substantial and important resource, its completeness for a specific region such as NSW was unclear. Finally, given the more localised scale of this review, we expected that we would be able to conduct more targeted database searches than those used for InvaCost (see further details in Suppl. material 1: part A). Therefore, we expected that newer, more targeted searches might uncover some additional relevant cost data.

Searches were conducted in WoS and Scopus on 4/Jan/2024 from the University of Melbourne, using a standardised search query targeting monetary cost data for invasive species specifically in NSW or eastern or southeastern Australia. Records were extracted, processed, and deduplicated in R (v4.4.1; R Core Team 2013) via 'revtools' (v0.4.1; Westgate 2019). Additional non-systematic records were also included where they met the review criteria. These included more recent grey literature known to authors (Stenekes et al. 2022; Hafi et al. 2023). Finally, if cost estimates found from our database searches were non-original (i.e., they referred to another reference as the source for their cost estimate), those records were located and included where possible.

Record screening and inclusion criteria

Records were included for (i) any introduced plant and animal species that have been established in NSW; (ii) studies with monetary estimates of their costs or damages, where impacts on any sector are included (e.g., health, agriculture), provided they are estimated in monetary terms; and (iii) cost estimates for locations within or including NSW. We use the term 'invasive' here for consistency with the terminology used in preceding reviews (Diagne et al. 2020; Bradshaw et al. 2021) and the broader context for this study (see NSW Government 2023), which we define to include introduced species that are currently or have previously been established in NSW (consistent with the term 'established non-native', per Soto et al. 2024). Due to the pre-defined scope of the broader review, we also excluded: (i) introduced fungi, diseases or pathogens; (ii) marine invasive species; and, (iii) native Australian species that are considered 'pests' for some areas or industries (e.g., due to domestic spread beyond their natural range, or overabundance relative to natural historical levels, such as Queensland fruit fly, *Bactrocera tryoni*).

Title-abstract and full-text screening were completed by two authors (LYW, NPM), with partial double screening to assess inter-rater agreement. For further details of the literature search and screening process, see Suppl. material 1: part A. Inclusion and exclusion criteria were used to extract relevant data sources from the InvaCost data and to screen all additional records from database searches (including any non-systematic or secondary records). After screening, 217 references were identified across all sources that met these review criteria (InvaCost/CISS: 142 records; database searches and additional records: 97 records). Review records, including cost references and bibliographic information, are available via Zenodo (https://doi.org/10.5281/zenodo.17836243).

Cost data analysis

Cost data processing and exclusions

InvaCost/CISS cost records identified through the review were checked, and any obvious errors in the cost estimates entered into InvaCost were corrected where found. We extracted a small number of additional cost estimates from records that were already in the InvaCost references, as well as any NSW-specific estimates that could be extracted in place of non-NSW-specific values (see details in Suppl. material 1: part A). Nonetheless, for the majority of estimates, we primarily relied on the data entered in InvaCost and only made limited corrections where obvious errors or more specific NSW data could be found. Data were extracted from an additional 10 records (including 50 individual cost estimates) from our independent database searches and additional sources.

The following data are included in our review databases but have been excluded from the quantitative analysis: (i) public-expenditure-based costs (which were addressed separately in the NSW Review); (ii) duplicated cost estimates; (iii) non-observed or potential costs (e.g., InvaCost includes a substantial number of entries for 'Potential' or 'Avoided costs', which often refer to costs for proposed management actions that have not yet been implemented, or for costs that would have been incurred but for certain management or control actions being implemented. These were excluded as they do not refer to invasive species costs that have actually been incurred); and (iv) low-reliability costs (i.e., InvaCost data include expert reviews to identify estimates that may be considered unreliable, for example, cost estimates where the source or methodology supporting the value is not reported or described). A small number of potentially relevant cost estimates were also excluded, as there was no suitable method for extrapolating or partitioning those costs for NSW.

After exclusions and additional data extractions, the final dataset used in the quantitative analysis included 374 individual cost estimates from 50 records, which were primarily technical reports and peer-reviewed research articles. For each cost, this dataset includes taxonomic information; total and per-year monetary estimates; the year or years that the cost was estimated to occur in; and information about the location (e.g., within or including NSW), sector (e.g., agriculture, health, environment), and type of costs being incurred (e.g., control, production loss). The list of invasive species included in the analyses is available in Suppl. material 1: part B.

Spatial partitioning of costs

For cost data that were not specific to NSW (i.e., 90 national or regional estimates), the fractions of costs that could be attributed to NSW were estimated on a case-by-case basis. The primary method to estimate this fraction was based on the relative area of a species' range and the impacted sector or industry that is in NSW.

The overlap between the invasive species range and the impacted sector or industry was measured using the Biosecurity Commons platform (Biosecurity Commons 2024). Biosecurity Commons is a cloud-based decision-support platform for modelling and analysing biosecurity risk and response. Spatial layers of overlapping species ranges and impacted sectors were created within the platform using species distribution layers based on occurrence records from the Atlas of Living Australia (Belbin et al. 2021) with Australian Land Use and Management Classification layers (ABARES 2016). The 90 data points involved 44 species and various impacted sectors, which were grouped into agriculture, grazing, forestry, cropping, tree nuts, and pine production. Layers were created for the overlapping areas within NSW and the total overlapping area across the broader national or regional location for the cost estimate (1 × 1 km resolution). The area of layers was calculated in R (package 'terra', v 1.7-78; Hijmans et al. 2022), and the proportion within NSW was used to calculate the cost fraction that could be applied to NSW (see Suppl. material 1: part C for further details).

Cost data aggregation and modelling

All costs were also converted to yearly estimates. Where a single estimate was reported for periods longer than one year, this was split evenly over the starting and ending year range. Similarly, costs that were reported as an average annual cost over a period of multiple years were converted to individual annual costs applicable to each year within that period (via the '*invacost*' package, v1.1-6; Leroy et al. 2022). Data were transformed using inflation adjustments to 2023 values, using Consumer Price Index data (17th Series, accessed 14/02/2024; ABS 2024).

Using inbuilt functions within the *'invacost'* package, we calculated the observed cumulative and average costs over a specific period of time from the time interval 1970–2022. This period included all cost estimates found in the literature. Only a single estimate included costs for years earlier than 1970, so costs before 1970 were considered too sparse and under-reported to include in statistical analysis. Summary data were compiled for the cumulative costs associated with broad taxonomic groupings, impacted sectors, and species. Sector groupings were based on coarse aggregations of categorical groupings in InvaCost (e.g., Impacted sector and Type of cost), and taxonomic information was also based on InvaCost.

Several simple models were also fitted (via invacost), and their fit quality was checked. Most models are either simple regression models or variations of regression models accounting for heterogeneity of variance and autocorrelation and correcting for the influence of outliers. Here we chose the simplest (yet still appropriate) model that accounts for the heterogeneity of variance while keeping the influence of outliers to a minimum, i.e., a form of robust regression (e.g., Croux et al. 2004). Both linear and quadratic trends can be investigated and contrasted using linear robust regression and quadratic robust regression respectively.

This should not be used as a predictive model due to uncertainty in the absence of underlying covariates that influence costs and their future trends. Any predictions should therefore be treated with caution, and this warning is reflected in the prediction intervals provided alongside estimates.

Results

Review records

There were 217 cost data references identified from this review that met our criteria (see also Suppl. material 1: part A, fig. S1A). This included 142 references from existing databases (i.e., 136 from InvaCost 4.1; six via CISS) and 97 references from our independent searches (i.e., 56 records from database searches, 38 original data records, and three non-systematic records). Of these 97 references, 22 had data extracted into InvaCost/CISS, and a similar proportion only reported secondary data that could be traced to other records.

Importantly, only data from a subset of these 217 references were used for our quantitative analysis of current costs below (i.e., excluding public-expenditure-based costs, potential costs, low-reliability estimates, duplicated or non-original costs, and estimates for which partitioning or extrapolating costs for NSW was not feasible). Bibliographic data for all records meeting the review criteria, and the cost data used in analysis, are provided in the accompanying data and code repository.

Estimated costs

The total cumulative costs reported between 1970 and 2022 is AU$30.761 billion (2023 value, excluding public-expenditure-based costs). Average annual costs are influenced by very high variation between years (see Fig. 1 and Suppl. material 1: part A, fig. S2A). This is likely due to incomplete reporting of costs as well as reporting biases, which suggests that this value is likely to be a large underestimate of the actual costs incurred over that period.

The raw aggregated reported costs for 2022 is AU$0.424 billion, while the costs for 2020 and 2021 were considerably higher (i.e., AU$1.339 and AU$1.379 billion). These years were more consistent with the average annual costs during the 2010s (i.e., AU$1.319 billion p.a.). The highest annual aggregate costs were also reported in the 2010s, with multiple years reporting a total cost of over AU$3 billion (e.g., peaking at AU$3.822 billion in 2019). The apparent drop in the average annual cost in the 2020s, and specifically in 2022, is most likely caused by a time lag between the occurrence of a cost and its reporting, instead of any actual fall in costs over recent years (e.g., 255 distinct cost estimates are included from the 2010s, while only 25 are included from the 2020s).

From 1970, there has been an increasing trend in the total value of reported costs for NSW each decade, from the 1970s – AU$25.51 million/year; 1980s – AU$299.21 million/year; 1990s – AU$456.22 million/year; and 2000s – AU$661.22 million/year (Fig. 1; see also Suppl. material 1: part A, fig. S2A). Reported costs have consistently increased over this period and more than doubled between some decades (i.e., 1970 to the 1980s and the 2000s to the 2010s). Fur-

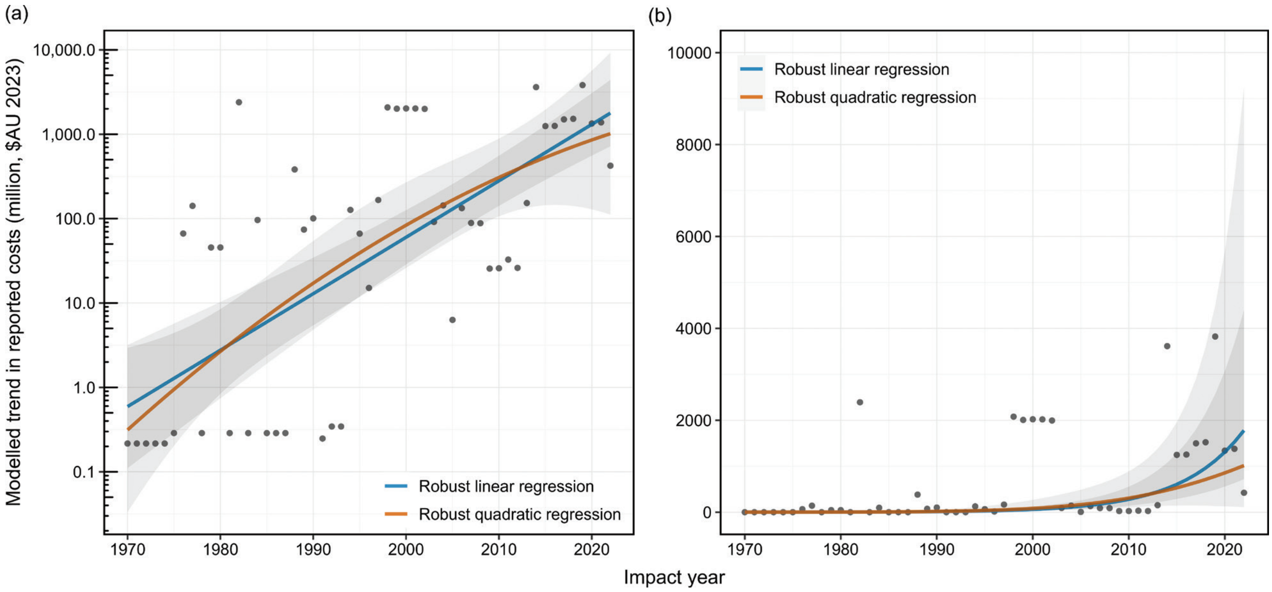

Figure 1. Modelled annual costs of established invasive species in NSW (1970–2022) for all non-public-expenditure-based costs, on (**a**) a logarithmic and (**b**) a linear scale. Both are included to show the trend in relation to the modelled unit (i.e., log-millions) and in relation to the dollar costs incurred. Shown are the annual total reported costs for each year (grey circles), the modelled trend via robust linear (blue line) and quadratic regression (orange line), and their 95% confidence intervals (grey bands).

thermore, while this increase may partially be influenced by increases in reporting over time, it is also likely to reflect a large increase in the actual costs of invasive species to NSW from 1970 to 2022.

Costs by taxonomic groups and impacted sector

The distribution of the total cumulative costs by taxonomic grouping shows that the majority (82.9%) of costs are attributed to terrestrial plants, while the next largest group (i.e., terrestrial vertebrates) accounts for just one-fifth of that amount (Fig. 2(a)). By sector, industry or agricultural losses account for 92.2% of all reported costs (see Fig. 2(b)), within which the dominant contributor by taxonomic group is terrestrial plants (89.8%), followed by terrestrial vertebrates (8.6%) and terrestrial invertebrates (1.3%). Health, public, and social welfare costs account for much of the remaining costs (7.4%), which are almost entirely made up of terrestrial vertebrates (98.9%). Other sectors represent under 1% of total reported costs (e.g., private expenditure on research, environmental costs).

Although a subset of reported costs are attributed to larger amalgamated groups of species (e.g., introduced weeds), most estimates could be attributed to a specific species or genus. The five terrestrial plant, vertebrate, and invertebrate species or genera with the highest cumulative reported costs are shown in Fig. 3. For terrestrial plants, the most costly taxa were serrated tussock (*Nassella trichotoma*; AU$322 million total reported costs up to 2022), blackberry (*Rubus fruticosus*; AU$305 million), ryegrass (*Lolium rigidum*; AU$153 million), fleabane (*Conyza* spp.; AU$130 million), and barnyard grass (*Echinochloa crus-galli*; AU$119 million).

The most costly terrestrial vertebrates were cats (*Felis catus*; AU$2.291 billion), European rabbits (*Oryctolagus cuniculus*; AU$443 million), wild dogs (*Canis lupus*; AU$441 million), feral pigs (*Sus scrofa*; AU$420 million), and red foxes (*Vulpes vulpes*; AU$393 million). Oat aphids (*Rhopalosiphum* spp.; AU$47 million), blue

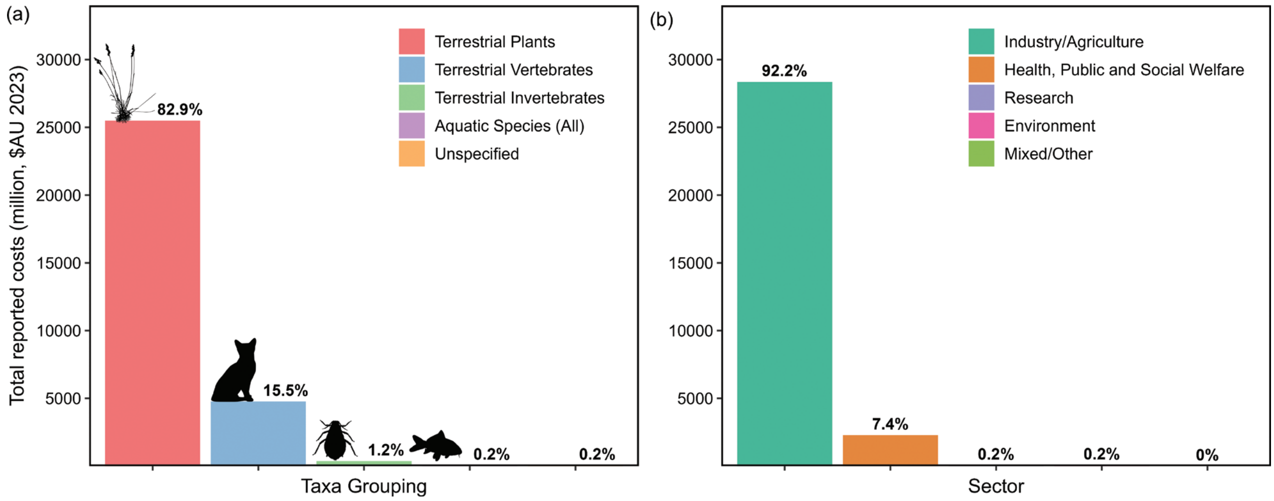

Figure 2. (**a**) Sum of reported non-public costs by environment and broad taxonomic groupings. Within the cost database, the number of cost data entries per group are: Terrestrial plants = 252; Terrestrial vertebrates = 95; Terrestrial invertebrates = 21; Aquatic species (all) = 5; and Unspecified = 1. (**b**) Sum of reported non-public costs by impacted sector or cost type. Industry or agricultural losses are predominately attributed to production losses and pest control costs. Research costs are research and innovation expenditures by industry representative bodies. Health and public welfare costs include medical costs, as well as costs to community-based assets (e.g., Indigenous communities or infrastructure, road crashes). Environmental costs include estimates of the monetary value of damage to environmental assets or services and the value of community or volunteer work on environmental programmes.

oat mites (*Penthaleus major*; AU$42 million), lucerne fleas (*Dicyrtomina ornata*; AU$38 million), redlegged earth mites (*Halotydeus destructor*; AU$33 million), and cereal cyst nematodes (*Heterodera* spp.; AU$31 million) were the most costly terrestrial invertebrates, while common carp (*Cyprinus carpio*; AU$30 million) was the only aquatic species for which species- or genus-specific cost estimates were found.

Modelled costs

Due to the variability in the costs, the incompleteness of the data, and the lack of information about other predicting variables or covariates, we used an extremely cautious modelling approach. The two chosen models capture the general increasing trend since 1970 but do not overfit to a tight pattern, as illustrated by the linear versus quadratic robust regression models in Fig. 1. The linear trend suggests a steeper recent increase than the quadratic model and less uncertainty. The modelled cost prediction amounts to AU$2.076 billion [0.009, 495.596] and AU$1.101 billion [0.005, 237.432] for the calendar year 2023 using a robust linear and quadratic model, respectively.

Discussion

These estimates are broadly consistent with the recent Australia-wide review following similar methods (Bradshaw et al. 2021) and are comparable to a preceding economic analysis of Australian invasive species costs (Hoffmann and Broadhurst 2016). Notably, Bradshaw et al. (2021) estimated NSW costs to be somewhat lower, that is, a US$5.25 billion total cost at 2017 value for NSW-specific, highly reliable, observed costs. This contrasts with the AU$30.761 billion (2023 value) total estimated here, which is almost four times higher in the equivalent currency. This is despite the more limited scope of our review (e.g., excluding pathogens and

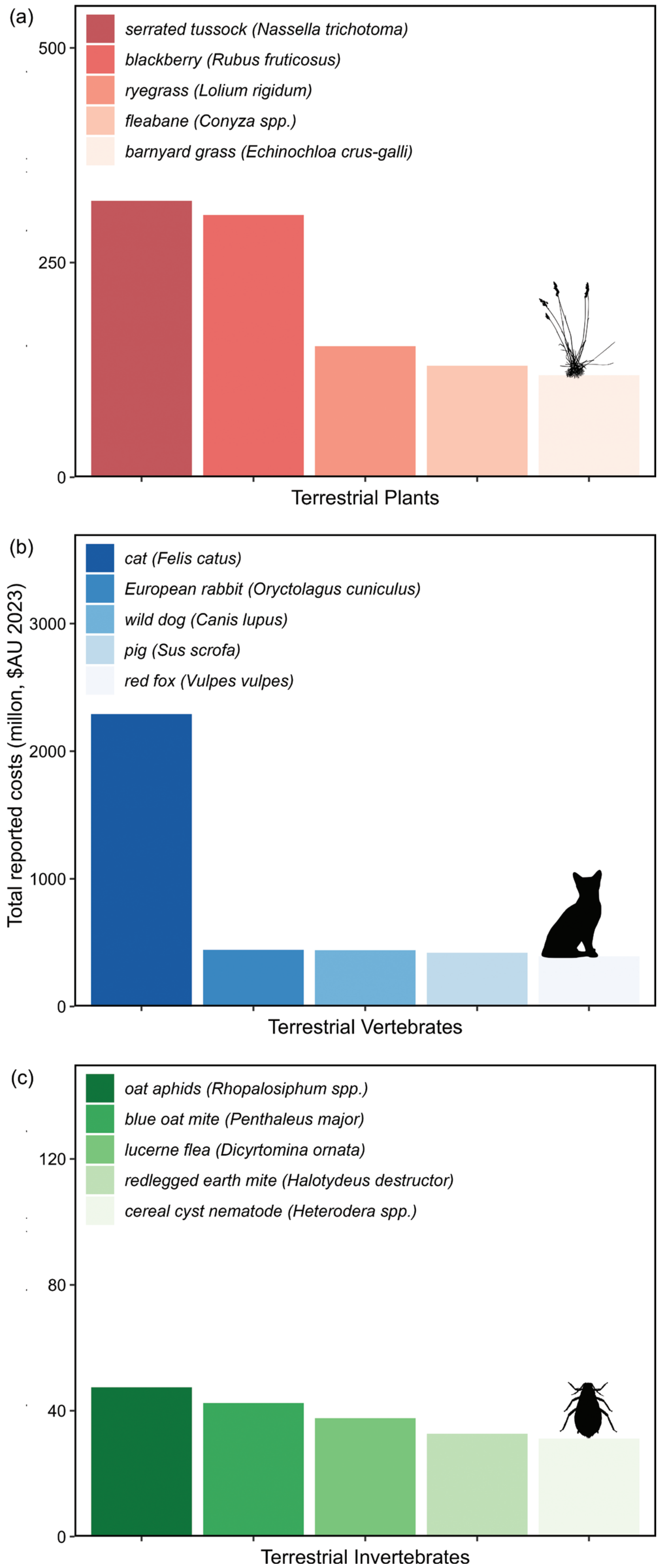

Figure 3. The five species with the highest reported costs for (**a**) terrestrial plants, (**b**) terrestrial vertebrates, and (**c**) terrestrial invertebrates. Aquatic species are not included, as only common carp had species-specific cost estimates. Note that these cost totals are likely to be influenced by both reporting biases and actual differences in the costs of each species. Y-axis scales differ between panels.

public expenditure). The key drivers of our higher estimate were the inclusion of non-NSW-specific estimates through Biosecurity Commons (~50% of the total cost estimate) and the inclusion of additional cost estimates from sources that are not yet incorporated into InvaCost (~two-thirds of the total cost estimate). The inclusion of new data from several recent major agricultural cost surveys was particularly influential (Stenekes et al. 2022; Hafi et al. 2023), as were several previous cost analyses found through our literature searches (Sinden et al. 2004; Kalisch-Gordon 2014). For some studies included in InvaCost, we were also able to extract NSW-specific data from the original source material in place of national estimates (e.g., Sloane Cook & King Pty Ltd. 1988), which expanded the base of cost data that could be included in our total. Nonetheless, our work is not a direct comparison with Bradshaw et al. (2021), and the purpose of the state-level estimates in that study appears to be to highlight the relative or proportional contributions of each state, rather than to estimate a total value for each state. Importantly, while our additional literature review and data partitioning steps produced a higher total estimate, both studies demonstrate that the costs of invasive species to NSW are on the scale of billions of dollars and continue to increase.

Our new database searches only found a subset of the data sources in InvaCost. This supports the use of InvaCost as the foundation for our analysis, as that database includes a substantial number of cost estimates that are unlikely to be identified through traditional systematic literature searches. This is particularly the case for grey literature, which comprises almost half of the relevant cost records in InvaCost. Bradshaw et al. (2021) also identified a substantial amount of data from grey literature, which suggests that targeted engagement with local experts, agencies, and land managers would be valuable for future local cost reviews. This study had limited capacity to formally engage with and identify additional data directly from these local sources; however, several key references were identified through both the knowledge of authors and collaboration with the NSW Natural Resources Commission. Ultimately, our searches identified cost records from additional sources that were not found in that database (~22% of records included in the analysis were not from InvaCost), highlighting the need to search for and include additional data where possible. As described above, these additional references also contributed a large proportion of the total reported costs, so our estimates would be considerably lower without these additional searches and data extractions. There were some challenges using the database, including some apparent data duplication, difficulty tracing data to sources (e.g., multiple Reference IDs for single sources), and limited transparency around data extraction and processing decisions (e.g., additional non-extracted estimates could be extracted from several sources in the database, such as Murray et al. 2013 and Edwards et al. 2008; for further details on review records, reference checks, and data checks or changes, see Suppl. material 1: part A). Nonetheless, this study demonstrates that InvaCost is a valuable open science resource that can support local invasive species cost studies, and it provides a simple roadmap for conducting robust, transparent, and reproducible regional cost reviews (see Fig. 4).

Furthermore, costs were often extracted at larger spatial scales, commonly at the national level, even where finer-scale state or regional estimates were also available (e.g., from McLeod 2016 and Sloane Cook and King Pty Ltd. 1988). While this is appropriate for use in larger national or global impact assessments, re-extracting finer-scale data or approximations of costs for subregions (e.g., spatial partition-

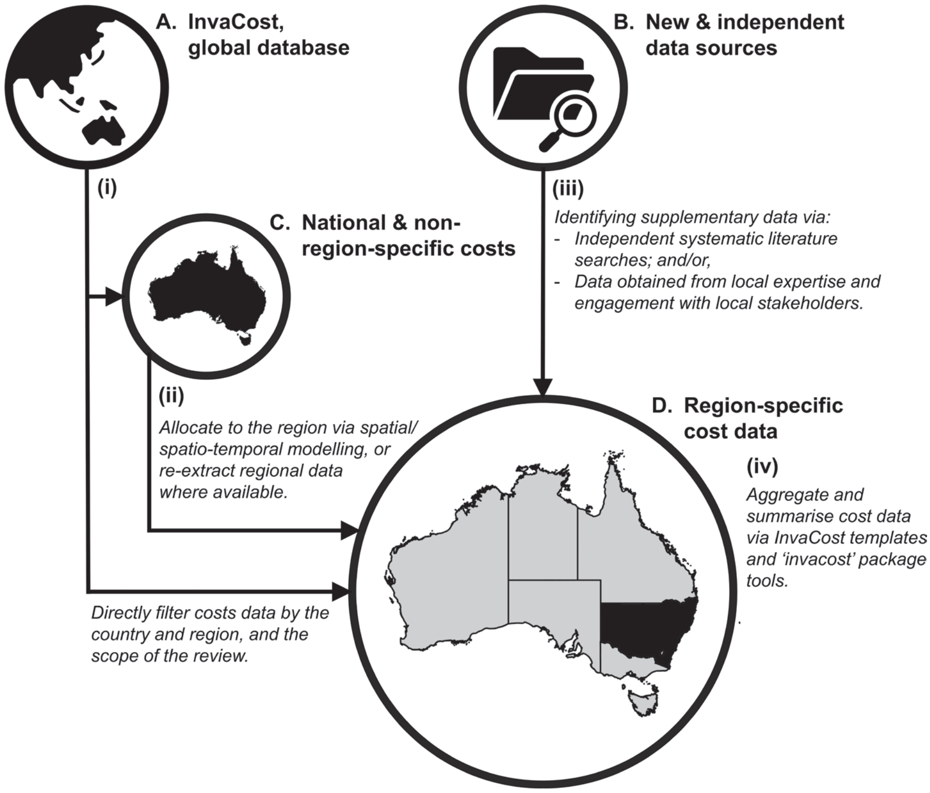

Figure 4. Steps for conducting a regional review for NSW based on InvaCost, including: (**i**) filtering the InvaCost data to the relevant country or region, and scope of the study (e.g., subsetting out specific taxa and cost types, using the many available InvaCost descriptors); (**ii**) partitioning cost data for broader areas to the specific region (e.g., via Biosecurity Commons), or re-extracting finer-scale estimates from the original reference material where they are available; (**iii**) supplementing InvaCost with new or additional sources through independent reviews or additional data that are either known to the authors or local experts (as with ABARES data used here), or from direct engagement with local stakeholders or experts (e.g., NSWNRC); and (**iv**) aggregating and analysing data using InvaCost resources and *'invacost'* R package tools to allow data to be readily incorporated back into the global database.

ing as used here) was required to apply these data for a state-level assessment. Our method for partitioning costs to NSW via Biosecurity Commons was able to efficiently estimate NSW-specific costs based on the intersection of species occurrence and impacted sectors, yet there are limitations to this approach. Impacts are spatially and temporally heterogeneous; for example, the value and resulting costs to impacted sectors vary regionally (e.g., agricultural production). Similarly, the prevalence of non-native species and their impacts vary within their range, and relying on current Atlas of Living Australia occurrence records and Australian Land Use and Management Classification layers does not account for these forms of heterogeneity. The methods used here could be expanded with additional data to incorporate those factors (e.g., by modelling non-native species distributions over time and using temporally explicit occurrence–sector layers), which may be implemented using simple spatial modelling tools (e.g., for species distribution modelling via Biosecurity Commons 2024; see Suppl. material 1: part C for further implementation details). However, the approach used here was not expected to introduce a systematic over- or underestimation of costs for NSW, and this was considered beyond the scope of this study.

Although additional data were included through our independent literature review, incomplete reporting remains a major limitation of this study, meaning that estimates presented here (i.e., reported cost estimates) will be underestimates of the true cost of invasive species. For example, within the dataset used for this analysis, there are eight references reporting costs for feral pigs, including costs either specifically attributed to pigs or attributed to groups of terrestrial vertebrate species that include pigs. Following the same approach as InvaCost to allocate costs to specific impact years, costs could be applied to 21 separate years, from the first reported costs for feral pigs in 1979 (via Tisdell 1982) up to 2022. While it is reasonable to expect that the economic impacts of feral pigs were ongoing throughout this period, this analysis only includes data for the years in which costs have been reported. Relying on the availability of costs from the literature means these data gaps are common, which can lead to biases in cost estimates over time and between species. Time lag effects are apparent, highlighted by relatively lower annual totals from 2020–2022 relative to the decade prior, which is likely due to common lags in the availability of estimates (e.g., due to the length of the academic publication process or for technical reports to undergo review and become public). While tools to account for incomplete reporting and time lag effects are available, this was not considered viable here given the smaller size of this dataset and was beyond the scope of this study.

Despite the limitations of relying on reported cost estimates, these results can also provide insights into what is missing from past accounting of invasive species costs. For example, the reported cost data for NSW are heavily focused on industry and agricultural costs, and other non-market costs were not well quantified (e.g., environmental impacts and human health and social wellbeing costs). This is not necessarily surprising, as the Diagne et al. (2020) and Bradshaw et al. (2021) reviews are focused on synthesising monetary cost data, which are more commonly and easily applied to estimate market-based losses and damage. The former study specifically cautions against aggregating non-market values alongside other economic costs, citing their incomplete acceptance in academic and civil communities. Nonetheless, the scope of these reviews is broad enough to incorporate estimates using non-market valuation methods (e.g., contingent valuation, choice modelling, benefit transfer; Tinch et al. 2019; Stoeckl et al. 2023). A relatively small proportion of environmental costs was also estimated by Bradshaw et al. (2021), with ~4.1% of costs categorised as specific to the environment sector. However, this was a larger proportion than found in this study (~0.2%). This again may be due to the more limited scope of this review (e.g., excluding public-expenditure-based costs may exclude a proportion of direct expenditure on environmentally focused management programmes).

The costs of invasive species to environmental assets are particularly likely to be under-reported. It is challenging to evaluate ecosystem services, and the present data on the values of these services are unbalanced spatially and by category (Brander et al. 2024). Although numerous methods are available (see Bennett 2011; Pascual et al. 2012; Freeman III et al. 2014), estimating non-market value is non-trivial, time-consuming, and can be expensive. Nonetheless, examples exist. McLeod (2004) estimates the impact of invasive cat predation on native birds based on value estimates from the USA (Pimentel et al. 2000). A comprehensive example is Stoeckl et al. (2023), which estimates the value of numerous ecosystem regulating services protected by the biosecurity system in Australia, including erosion control, flood control, gene pool protection, carbon sequestration, and toxin mediation. Their results show that the regulating services capture a large proportion of the benefit generated from the biosecurity system (~44%, compared with ~25% for portfolio services, i.e., agriculture, forestry, aquaculture and fishing combined), highlighting the need to consider ecosystem services for a whole-of-system assessment. This monetary information on ecosystem services can further enable predictions of the damages posed by exotic biosecurity threats (e.g., Dodd et al. 2020). The scarcity of reported non-market costs from invasive species may lead to an underestimation of the overall damages of invasive species, which may then mislead policymakers in terms of resource allocation and prioritisation.

This study intentionally took a broadly conservative approach to aggregating and modelling incurred costs of invasive species, that is, focusing on aggregating and estimating the extent of reported costs only. Further work to address gaps in reporting, including modelling approaches that can account for incomplete reporting and time-lag bias (see examples available within the *'invacost'* package; Leroy et al. 2022), as well as approaches that incorporate impacts on environmental and ecosystem service values, will better allow us to quantify the true cost of biological invasions. Finally, the ability to undertake this review within a limited time frame and apply a global dataset to NSW demonstrates and value of InvaCost as a foundation for smaller-scale reviews. These methods for partitioning costs and identifying supplementary data are also a potential guide for researchers and biosecurity policymakers to apply InvaCost in the context of regional or subnational jurisdictions and increase the utility of the database.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

This research did not require ethics approval.

Use of AI

No AI tools were used in this study.

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Author contributions

NPM: Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualisation, Writing – original draft. LYW: Conceptualisation, Data curation, Investigation, Methodology, Validation, Writing – original draft. AMH: Conceptualisation, Formal analysis, Investigation, Methodology, Supervision, Writing – review and editing. TK: Conceptualisation, Funding acquisition, Methodology, Project administration, Supervision, Writing – review and editing.

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Data availability

All review records, datasets, analysis code, models and outputs are available via Zenodo (https://doi.org/10.5281/zenodo.17836243).

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Supplementary material 1

Supplementary review records, results and methodological details

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Data type: pdf

Explanation note: Additional supporting information includes the following: **A** – Rapid Review Records; **B** – Taxa Included in Analysis; **C** – Spatial Partitioning of Costs via Biosecurity Commons.

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