The Missing Environmental Impacts in Invasive Species Cost Assessments – Insights from an InvaCost-based regional review

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Abstract

Accounting for the costs incurred due to biological invasions is important for informing invasive species management policies, and understanding and mitigating future losses. InvaCost, a living review and massive database of cost estimates, is a valuable open science resource that can support informed policy and management of invasive species and has since 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, Australia. This work aimed to comprehensively collate existing data to estimate the historical and current reported costs for the state, and assess the utility of InvaCost for smaller-scale regional assessments. Our findings show that invasive species costs within NSW are in the scale of billions of dollars annually and have increased substantially over time. Furthermore, the majority of reported costs are attributed to agricultural/industry loss, while value estimates for costs to environmental assets or ecosystem services are almost entirely absent from the literature. This work highlights the ongoing damage that continues to be incurred due to invasive species in Australia, particularly for agriculture, and emphasizes the need to also consider the environmental impacts in cost assessments. Finally, this work highlights the value of open science resources such as InvaCost for supporting biosecurity research and policy.

Keywords: invasive species, non-native, biosecurity, economic loss, ecosystem services, InvaCost, systematic review

1 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 Schneider & Arndt, 2020; Dodd et al., 2020): the sustainability, productivity, and competitiveness of industry; the health of natural environments and the ecosystems 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 globalization, and the geographic barriers that once kept Australia isolated and relatively pest-free are being continually eroded (Seebens et al., 2017; Dodd et al., 2015). Therefore accounting for costs incurred due to invasive species is essential for understanding and mitigating potential future impacts.

Economic impacts may include direct losses to agricultural production or pest control costs, infrastructure damage, or indirect effects such as market access losses. Serious effects on human health and community wellbeing have been documented from species like red imported fire ants, (or RIFA, *Solenopsis invicta*; Wylie & Janssen-May, 2017) and parthenium (*Parthenium hysterophorus*; Allan et al., 2019). Environmental and ecosystem services impacts are also substantial but are more challenging to characterize. 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 impact ecosystem services, which include (per Reid et al., 2005; Pejchar & Mooney, 2009; Postel et al., 2012); provisioning services (i.e., products obtained from ecosystems like food or timber); regulating services (i.e., benefits obtained from ecosystem processes such as pollination); cultural services (i.e non-material benefits through engagement with ecosystems); and supporting services (*i.e.*, additional services that support provisioning, regulating, cultural services). Importantly, while impacts are not always negative, evidence suggests that net costs of invasive species to ecosystem services tend to significantly outweigh any benefits (Shackleton et al., 2019; Pejchar & Mooney, 2009).

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). While this database and associated reviews have a focus on estimating the economic costs, impacts across other sectors such as environments, health, public and social welfare are included where they are estimated in monetary values. Contemporary methods for valuing non-market goods and services are well developed (Baker & Ruting, 2014), although their application in the context of invasive species impacts has been limited. One significant example is (Stoeckl et al., 2023), which estimated the current value of 16 ecosystem services across Australia and the potential damage from future invasions. However, there do not appear to be corresponding environmental cost valuations for existing established invasive species.

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 review was conducted as a component of a broader NSW Invasive Species Management Review which aims to inform and improve invasive species management in the state (led by the NSW Natural Resources Commission; NSW Government, 2023). This focused on aggregating existing cost estimates to industry, the environment, and the community, although public-expenditure-based costs were beyond the scope of this review (e.g., governmental management programs, public grants, etc.). The specific aims of this analysis were:

I. 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).

II. To assess the utility of InvaCost for targeted regional invasive species cost reviews.

III. To qualitatively assess the relative contribution of: (i) different species and taxonomic groups (e.g., terrestrial plants, terrestrial vertebrates, etc.); and (ii), sectors (e.g., industry/agricultural, environmental, human health, etc) to the reported costs for NSW.

2 Methods

2.1 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.e.,: (i) pre-existing databases, primarily InvaCost (Diagne et al., 2020); and, (ii) additional data records collected via an independent literature search. The rapid review followed the general process of a formal systematic review, including standardised guidelines/reporting standards for evidence synthesis studies (e.g., PRISMA/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 was necessitated by the limited 3-month period available for this review. As a result, this may also be considered a test case for the utility of InvaCost for supporting small-scale regional cost studies.

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), which is supplemented by large contributions from non-systematic sources (e.g., grey literature, personal communications, etc.). 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 (i.e., Bradshaw et al., 2021). This database has also been expanded on by the Centre for Invasive Species Solutions with data from several more recent reports (CISS, Canberra, Australia; unpub. report).

Independent literature searches were conducted to identify any recent data that may not have been captured by previous reviews and to provide an independent source of data to assess the comprehensiveness of InvaCost. Searches were conducted in WoS and Scopus on 4/Jan/2024 from the University of Melbourne, using a standardised search query targeting monetary costs data for invasive species specifically in NSW or eastern/southeastern Australia (see search details in Appendix A). Records were extracted, processed, and deduplicated in R (v4.2.3, 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, (Hafi et al., 2023; Stenekes et al., 2022). Finally, if cost estimates 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. For details of data sources and review methods see Appendix A.

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/damages, where impacts on any sector are included (e.g., health, agriculture, etc.), provided they are estimated in monetary terms; and, (iii) costs estimates for locations within or including NSW.

Due to the pre-defined scope of the broader review, records were excluded for: (i) introduced fungi, diseases or pathogens; (ii) marine pests; and, (iii) native Australian species that are considered pests for some areas or industries.

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 Appendix A. Inclusion/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 the Open Science Framework (doi: [to be confirmed]; URL: https://osf.io/35kc4/ [access via reviewer link: https://osf.io/35kc4/?view_only=53a8ac78fd5e492596d1d9cb039c8560]).

2.2 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. Nonetheless, for the majority of estimates we have 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 was 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 following quantitative analysis: (i) public-expenditure-based costs (which were addressed separately in the NSW Review); (ii) duplicated cost estimates; (ii) non-observed/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/control actions being implemented. These were excluded as these don't refer to invasive species costs that have actually been incurred); and, (iv) low-reliability costs (i.e., InvaCost data includes expert reviews to identify any estimates that may be considered unreliable, for example for 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 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(s) that the cost was estimated to occur in; 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 etc.). The list of invasive species included in analyses is available in Appendix B.

Spatial partitioning of costs

For cost data that was not specific to NSW (i.e., 90 national or regional estimates), the fraction 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/industry that is in NSW.

The overlap between the invasive species range and the impacted sector/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 range/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/regional location for the cost estimate (1 x 1 km resolution). The area of layers was calculated in R (package 'terra', v 1.7-71; Hijmans et al., 2022), and the proportion within NSW was used to calculate the cost fraction that could be applied to NSW (see Appendix 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/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 'invacost' package, v1.1-5; Leroy et al., 2022). Data was 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 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 fit (also 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 the minimum, i.e., a form of robust regressions 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 the uncertainty in the absence of underlying covariates from models that will influence costs and their future trends. Any predictions therefore should be treated with caution, and this warning is reflected in the prediction intervals provided alongside estimates.

3 Results

3.1 Review records

There were 217 cost data references identified from this review that met our criteria (see also Supplementary Fig. A.1). This included 142 references from existing databases (i.e., 136 from InvaCost 4.1; 6 via CISS), and 97 references from our independent searches (i.e., 56 records from database searches, 38 original data records and 3 non-systematic records). Of these 97 references, 22 had data extracted into InvaCost/CISS, and a similar proportion only reported secondary data that can 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/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/code repository.

3.2 Estimated costs

The total cumulative costs reported between 1970 – 2022 is $30.761 billion (excluding public-expenditure-based costs). Average annual costs are influenced by very high variation between years (see Fig. 3 and A.2). This is likely due to the incomplete reporting of costs as well as reporting biases, which would suggest 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 \$0.424 billion, while the costs for 2020 and 2021 were considerably higher (i.e., \$1.339 and \$1.379 billion). These years were more consistent with the average annual costs during the 2010s (i.e., \$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 \$3 billion (e.g., peaking at \$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 – \$25.51 million/year; 1980s – 299.21 million/year; 1990s – 456.22 million/year; and, 2000s – 661.22 million/year (see also Appendix A, Fig. A.2). Reported costs have consistently increased over this period and more than doubled between some decades (i.e., 1970 to the 1980s, and 2000s to 2010s). Furthermore, while this increase may partially be influenced by increases in reporting over time, this is likely to also 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 (i.e., terrestrial vertebrates) account for just one-fifth of that (Figure 1(a)). By sector, industry/agricultural losses account for 92.2.% of all reported costs (see Figure 1(b)). Heath, public and social welfare costs account for much of the remaining costs (7.4%), while other sectors represent $< 1\%$ of reported costs (e.g., private expenditure on research, and environmental costs, etc.).

Although a subset of reported costs are attributed to larger amalgamated groups of species (e.g., introduced weeds, freshwater pests, etc.), most estimates could be attributed to a specific species and/or genus. The five terrestrial plants, vertebrate and invertebrate species/genera with

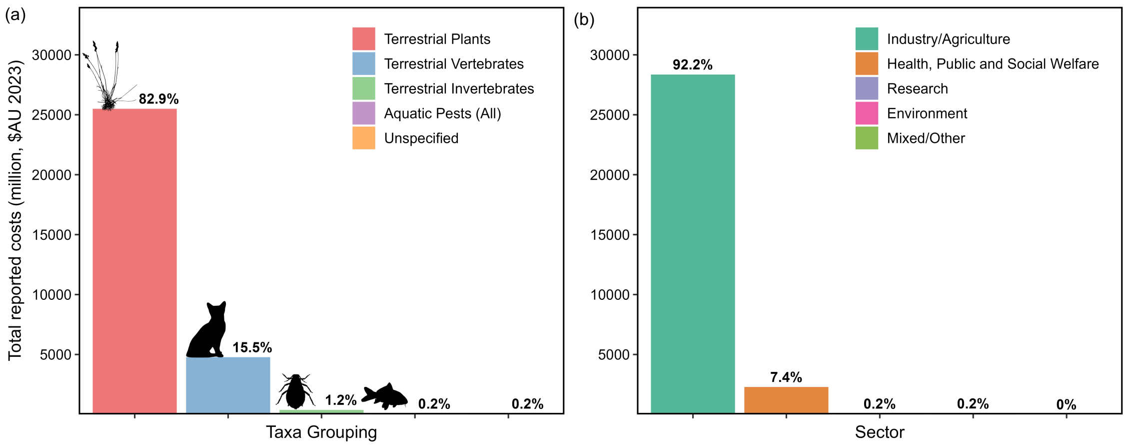

Figure 1: (a) Sum of reported non-public costs by environment and broad taxonomic groupings. Within the cost database, the number of cost data entries per group are: Terrestrial Plants = 252; Terrestrial Vertebrates = 95; Terrestrial Invertebrates = 21; Aquatic Pests (All) = 5; and, Unspecified = 1. (b) Sum of reported non-public costs by impacted sector/cost type. Industry/agricultural losses are predominately attributed to production losses and 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/infrastructure, road crashes, etc.). Environmental costs include estimates of the monetary value of damage to environmental assets/services, and the value of community/volunteer work on environmental programs.

the highest cumulative reported are shown in Figure 2. For terrestrial plants, the most costly taxa were serrated tussock (*Nassella trichotoma*; $322 million total reported costs up to 2022), blackberry (*Rubus fruticosus*; $305 million), ryegrass (*Lolium rigidum*; $153 million), fleabane (*Conyza* spp.; $130 million), and barnyard grass (*Echinochloa crus-galli*; $119 million).

The most costly terrestrial vertebrates were cats (*Felis catus*; $2.291 billion), European rabbits (*Oryctolagus cuniculus*; $443 million), wild dog (*Canis lupus*; $441 million), feral pigs (*Sus scrofa*; $420 million), and red foxes (*Vulpes vulpes*; $393 million). Oat aphids (*Rhopalosiphum spp.*; $47 million), blue oat mites (*Penthaleus major*; $42 million), lucerne fleas (*Dicyrtomina ornata*; $38 million), redlegged earth mites (*Halotydeus destructor*; $33 million), and cereal cyst nematodes (*Heterodera) spp.*; $31 million) were the most costly terrestrial invertebrates, while common carp (*Cyprinus carpio*; $30 million) was the only aquatic species for which species and/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/covariates, we used an extremely cautious modelling

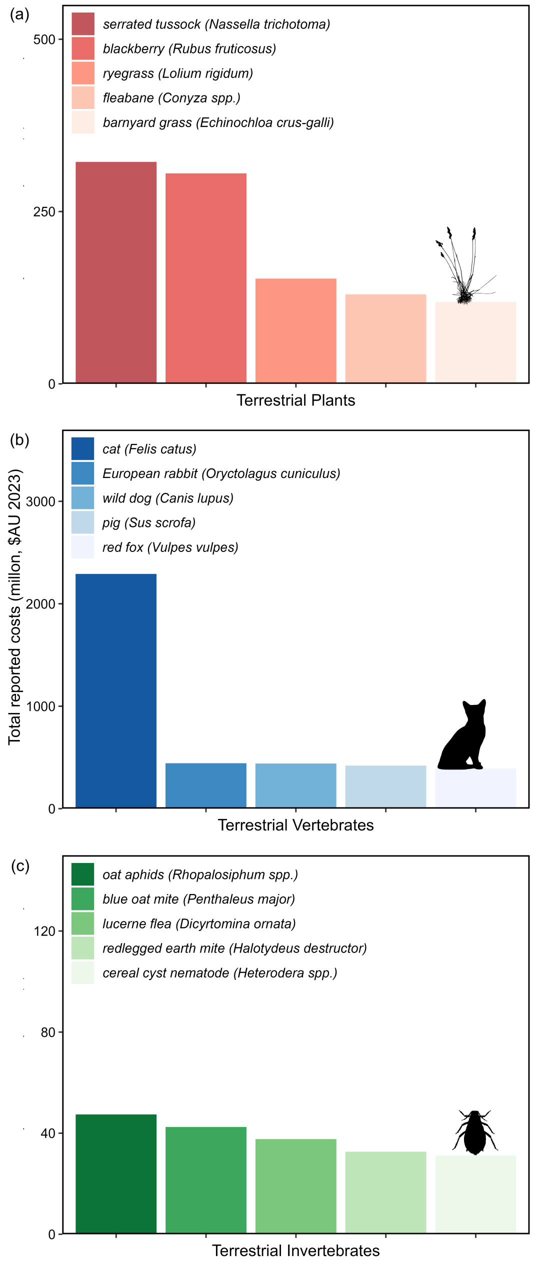

Figure 2: The five species with the highest reported costs for (a) terrestrial plants, (b) terrestrial vertebrates, and (c) terrestrial invertebrates. Aquatic pests are not included as only common carp had species-specific cost estimates. Note, that these cost totals are likely to be influenced by both reporting biases and actual differences in the costs of each species. Y-axis scales differ between panels.

approach. The two chosen models capture the general increasing trend since 1970 but do not over-fit to a tight pattern, as illustrated by the linear vs. quadratic robust regression models from Figure 3. The linear trend suggests a steeper recent increase than the quadratic model and less uncertainty. The modelled cost prediction amounts to $AU 2.076 [0.009, 495.596] billion, $AU 1.101 [0.005, 237.432] for the calendar year 2023 using a robust linear and quadratic model respectively.

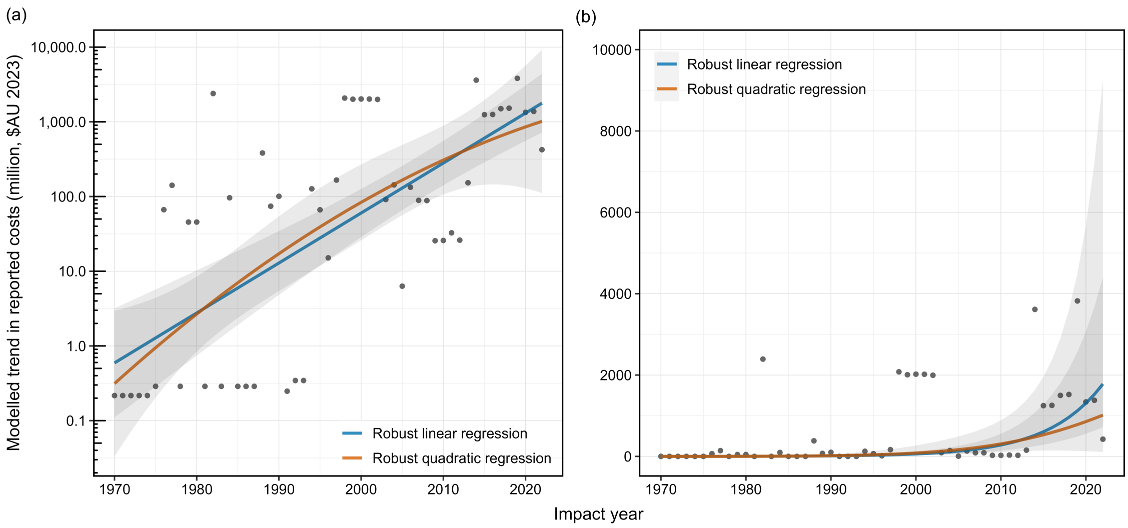

Figure 3: Modelled annual costs of established invasive species in NSW (1970 – 2022) for all non-public-expenditure-based costs, on (a) a logarithmic and (b) a linear scale. Both are included to show the trend both in relation to the modelled unit (i.e., log-millions) and in relation to the dollar costs 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).

4 Discussion

These estimates are broadly consistent with the recent Australia-wide review following similar methods (i.e., Bradshaw et al., 2021) and are comparable to a preceding economic analyses of Australian invasive species costs (i.e., Hoffmann & Broadhurst, 2016). While the Bradshaw estimate is somewhat higher, i.e., a US$5.25 billion annual cost for NSW-based reliable and observed costs (versus ∼1.10 - 2.08 billion here), this is not unexpected due to the more limited scope of our review (e.g., excluding pathogens, public expenditure, native species, etc.), and our very conservative approach to modelling costs (e.g., not accounting for reporting lags/ incomplete reporting). Like Bradshaw et al. (2021), our results show that the costs of invasive species to NSW are at least in the scale of billions of dollars per year 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 makes up almost half of the relevant cost records in InvaCost. Nonetheless, our searches were also able to identify cost records from additional sources that were not found in the database, highlighting the need to search for and include additional data to supplement InvaCost where possible. Additionally, there were some challenges using the database, including some 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).

Furthermore, costs were often extracted at larger aggregated spatial ranges (e.g., national estimates), where finer-scale state or regional estimates were also available. While this is appropriate for use in larger national or global impact assessments, re-extracting finer scale data and/or approximations of costs for sub-regions (e.g., spatial partitioning as used here) was required to apply this data for a state-level assessment. While the approach used here to spatially partition costs to NSW could efficiently estimate NSW-specific costs, there are limitations. For example, this does not account for temporal variation and spatial heterogeneity in the distribution of impacted sectors and the prevalence of the species within their range. The methods used here could be expanded on to incorporate those factors within Biosecurity Commons (Biosecurity Commons, 2024), although this was beyond the scope of this study and the approach used here was not expected to introduce a systematic over or underestimation of costs for NSW.

Although additional data was included through our independent literature review, incomplete reporting remains a major limitation of this study, such that estimates in this study (i.e., reported cost estimates) will be underestimates of the "true cost" of invasive species. For example, costs linked to feral pigs were first reported starting from 1979, yet from 1979 up to 2022, costs that are attributable to feral pigs are only available within our database for 21 (<50%) of those years (i.e., including costs either specifically attributed to pigs or attributed to terrestrial vertebrate pests generally). While tools to account for incomplete reporting and time lag effects are available, this was not considered viable here, given the smaller size of the dataset and was beyond the scope of the broader review.

Despite the limitations of relying on reported cost estimates, these results can also provide insights into what is missing from our historical understanding of invasive species costs. Most notably, environmental losses were extremely limited within the reported cost data for

NSW. This is not necessarily surprising, as the foundation reviews for this study are framed as assessments of the "economic costs" of invasions (i.e., Diagne et al., 2020; Bradshaw et al., 2021), and the former specifically cautions against aggregating non-market values alongside other economic costs citing their incomplete acceptance in academic and civil communities. Nonetheless, the scope of their reviews are broad enough to incorporate estimates to environmental assets provided the estimates are made in monetary terms using reliable methods, which are possible with the use of non-market valuation methods (e.g., contingent valuation, choice modelling, benefit transfer, etc.; Baker & Ruting, 2014; Stoeckl et al., 2023). A relatively small proportion of environmental costs were also estimated by Bradshaw et al. (2021), with $\sim$4.1% costs categorized as specific to the environment sector. However, this was a larger proportion than found in this study ($\sim$0.2%). This again may be due to the much more limited scope of this review (e.g., excluding public-expenditure based costs may exclude a proportion of direct expenditure on environmentally focused management programs).

The costs of invasive species to environmental assets are likely to be under-reported in the literature, likely due to the limited availability of the values of ecosystem services. It is challenging to evaluate ecosystem services, and the present data on the values of these services are unbalanced spatially and by category. There is little data, for example, for Russia, Central Asia, and North Africa and nearly no information on disease control, water base-flow maintenance, and rainfall pattern regulation (Brander et al., 2024). Although numerous methods are available (see for example Bennett, 2011; Pascual et al., 2012; Freeman III et al., 2014), estimating non-market value is non-trivial work and can often be time-consuming and expensive. Nonetheless, there are examples of such work. For instance, McLeod (2004) estimated the impact of invasive cat predation on native birds, derived from value estimates from the USA (Pimentel et al., 2000). A particularly comprehensive example is by Stoeckl et al. (2023), using a *value first then impact* approach to estimate the monetary value of numerous ecosystem regulating services associated with assets protected by the biosecurity system in Australia, including erosion control, flood control, gene pool, carbon sequestration, and toxin mediation. Their results show that the regulating services capture the majority of the benefit generated from the biosecurity system (i.e., $\sim$44%, compared with $\sim$25% for portfolio services, i.e., agriculture, forestry, and aquaculture and fishing combined), highlighting the need to consider ecosystem services for a whole-of-system assessment. This monetary data of ecosystem services can further enable us to predict the damages of exotic biosecurity threats (e.g., Dodd et al., 2020). The scarcity of reporting costs on the environment from invasive species not only creates a substantial data gap but may also lead to an underestimation of the overall damages of invasive species. Such underestimation will likely mislead judgments on and in terms of resource allocation and prioritisation by policymakers, with the consequences shared by both the public and the environment.

This study intentionally took a broadly conservative approach to aggregating and modelling incurred costs of invasive species, i.e., 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 of this available within the '*invacost*' package; Leroy et al., 2022) as well as approaches that incorporate impacts on environment and ecosystem service values will better allow us to quantify the true cost of biological invasions.

Data availability statement

All review records, datasets, analysis code, models and outputs are available via Open Science Framework (doi: [to be confirmed]; URL: https://osf.io/35kc4/ [access via reviewer link: https://osf.io/35kc4/?view_only=53a8ac78fd5e492596d1d9cb039c8560]).

Supplementary information

Additional supporting materials include the following:

A – Rapid Review Records

B – Taxa Included in Analysis

C – Spatial Partitioning of Costs via Biosecurity Commons

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Declarations

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Competing interests

The authors declare that they have no conflict of interest.

Authors' contributions (CRediT taxonomy)

NPM: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft

LYW: Conceptualization, Data curation, Investigation, Methodology, Validation, Writing – original draft

AMH: Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Writing – review & editing

TK: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing

References

ABARES. (2016). *Australian Land Use and Management Classification Version 8 (October 2016)* [Department of Agriculture, Fisheries and Forestry, Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES)]. Retrieved 2024-07-01, from https://www.agriculture.gov.au/abares/aclump/land-use/alum-classification

ABS. (2024). *Australian Bureau of Statistics, .Stat Data Explorer (BETA).* Retrieved 2024-02-14, from https://explore.data.abs.gov.au/

AEC Group. (2007). Economic impact of lantana on the Australian grazing industry. *Brisbane: Department of Natural Resources and Water*.

Allan, S., Shi BoYang, S. B., & Adkins, S. W. (2019, January). Impact of parthenium weed on human and animal health. *Parthenium weed: biology, ecology and management*, 105–130. Retrieved 2023-05-11, from https://www.cabidigitallibrary.org/doi/abs/10.1079/9781780645254.0105 doi: 10.1079/9781780645254.0105

Baker, R., & Ruting, B. (2014). *Environmental Policy Analysis: A Guide to Non-Market Valuation* (Productivity Commission Staff Working Paper). Canberra, Australia: Productivity Commission, Australian Government. Retrieved 2025-03-18, from https://www.pc.gov.au/research/supporting/non-market-valuation/non-market-valuation.pdf

Belbin, L., Wallis, E., Hobern, D., & Zerger, A. (2021). The Atlas of Living Australia: History, current state and future directions. *Biodiversity Data Journal*, *9*, e65023. Retrieved 2024-07-01, from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8081701/ doi: 10.3897/BDJ.9.e65023

Bennett, J. (2011). *The international handbook on Non-market Environmental Valuation*. Edward Elgar Publishing.

Binks, B., Kancans, R., & Stenekes, N. (2015). *Wild dog management 2010 to 2014–national landholder survey results* (ABARES report to client prepared for Australian Wool Innovation Ltd, Canberra). Canberra, Australia: Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES). Retrieved 2025-03-18, from https://pestsmart.org.au/wp-content/uploads/sites/3/2020/06/abares-wild-dog-management-2010-to-2014-national-landholder-survey-results.pdf

Biosecurity Commons. (2024). *Biosecurity Commons: A cloud-based decision-support platform for modelling and analysing biosecurity risk and response.* Retrieved 2024-07-01, from http://biosecuritycommons.org.au/ (https://doi.org/10.47486/PL021)

Bradshaw, C. J. A., Hoskins, A. J., Haubrock, P. J., Cuthbert, R. N., Diagne, C., Leroy, B., … Courchamp, F. (2021). Detailed assessment of the reported economic costs of invasive species in Australia. *NeoBiota*, *67*, 511–550. doi: 10.3897/neobiota.67.58834

Brander, L., De Groot, R., Schägner, J., Guisado-Goñi, V., Van't Hoff, V., Solomonides, S., … others (2024). Economic values for ecosystem services: A global synthesis and way forward. *Ecosystem Services*, *66*, 101606. (Publisher: Elsevier)

Cameron, N., Carnegie, A., Wardlaw, T., Lawson, S., & Venn, T. (2018). Economic appraisal of Sirex Wood Wasp (Sirex noctilio) control in Australian pine plantations. *Australian Forestry*, *81*(1), 37–45. doi: 10.1080/00049158.2018.1430436

Canyon, D. V. (2008). Historical analysis of the economic cost of dengue in Australia. *Journal of vector borne diseases*, *45*, 245–248.

Caughley, J. (1998). *Managing vertebrate pests: Rodents* (Tech. Rep.). Canberra, Australia: Bureau of Resource Sciences.

Charles, G. W. (1991). A Grower Survey of Weeds and Herbicide Use in the New-South-Wales Cotton Industry. *Australian Journal of Experimental Agriculture*, *31*(3), 387–392. doi: 10.1071/Ea9910387

Choquenot, D., McIlroy, J., & Koen, T. (1996). *Managing vertebrate pests: Feral pigs* (Tech. Rep.). Canberra, Australia: Bureau of Resource Sciences.

Cooke, B., Chudleigh, P., Simpson, S., & Saunders, G. (2013). The Economic Benefits of the Biological Control of Rabbits in Australia, 1950–2011. *Australian Economic History Review*, *53*(1), 91–107.

Craik, W., Palmer, D., & Sheldrake, R. (2017). Priorities for Australia's Biosecurity System–An Independent Review of the Capacity of the National Biosecurity System and its Underpinning Intergovernmental Agreement.'. *Commonwealth of Australia: Canberra, ACT*.

Croft, D., & Caughley, J. (1995). A survey of the MIA mouse plague-at what cost? *Farmers' Newsletter*, *145*, 40–41.

Croft, J. D., & Connellan, P. (1999). *Western Division rabbit control : information pack.* NSW Agriculture, Wagga Wagga. Retrieved from https://catalogue.nla.gov.au/catalog/1417461

Croux, C., Dhaene, G., & Hoorelbeke, D. (2004). Robust standard errors for robust estimators. *CES-Discussion paper series (DPS) 03.16*, 1–20. (Publisher: KU Leuven, Faculty of Economics and Applied Economics: Department of Economics)

Crystal-Ornelas, R., Hudgins, E. J., Cuthbert, R. N., Haubrock, P. J., Fantle-Lepczyk, J., Angulo, E., … Courchamp, F. (2021). Economic costs of biological invasions within North America. *NeoBiota*, *67*, 485–510. doi: 10.3897/neobiota.67.58038

David, P., Thébault, E., Anneville, O., Duyck, P. F., Chapuis, E., & Loeuille, N. (2017). Chapter One - Impacts of Invasive Species on Food Webs: A Review of Empirical Data. In D. A. Bohan, A. J. Dumbrell, & F. Massol (Eds.), *Advances in Ecological Research* (Vol. 56, pp. 1–60). Academic Press. Retrieved 2023-04-20, from https://www.sciencedirect.com/science/article/pii/S0065250416300502 doi: 10.1016/bs.aecr.2016.10.001

Diagne, C., Leroy, B., Gozlan, R. E., Vaissière, A.-C., Assailly, C., Nuninger, L., … Courchamp, F. (2020). InvaCost, a public database of the economic costs of biological invasions worldwide. *Scientific Data*, *7*(1), 277. doi: 10.1038/s41597-020-00586-z

Diagne, C., Leroy, B., Gozlan, R. E., Vaissière, A.-C., Assailly, C., Nuninger, L., … Ballesteros-Mejia, L. (2022). *InvaCost: Economic cost estimates associated with biological invasions worldwide (v4.1).* Retrieved 2025-01-15, from https://figshare.com/articles/dataset/InvaCost_References_and_description_of_economic_cost_estimates_associated_with_biological_invasions_worldwide_/12668570 (10.6084/m9.figshare.12668570.v5)

Dodd, A. J., Burgman, M. A., McCarthy, M. A., & Ainsworth, N. (2015). The changing patterns of plant naturalization in Australia. *Diversity and Distributions*, *21*(9), 1038 – 1050. doi: 10.1111/ddi.12351

Dodd, A. J., Stoeckl, N., Baumgartner, J., & Kompas, T. (2020). *Key Result Summary: Valuing Australia's Biosecurity System* (Tech. Rep. No. 170713). Melbourne, Australia: Centre of Excellence for Biosecurity Risk Analysis. Retrieved 2025-03-18, from https://cebra.unimelb.edu.au/__data/assets/pdf_file/0020/3535013/CEBRA_Value_Docs_KeyResultSummary_v0.6_Endorsed.pdf

Earl, J. (2003). The distribution and impacts of lippia (Phyla canescens) in the Murray Darling system. *Murray Darling Basin Lippia Working Group*, *91*.

Edwards, G., McGregor, M., Zeng, B., Saalfeld, W., Vaarzon-Morel, P., & Duffy, M. (2008). *Overview of the project Cross-jurisdictional management of feral camels to protect NRM and cultural values* (Desert Knowledge CRC Report No. 45). Alice Springs, Australia: Desert Knowledge Cooperative Research Centre. Retrieved 2025-03-18, from https://www.nintione.com.au/resource/DKCRC-Report-54-Overview-of-the-project-Cross-jurisdictional-management-of-feral-camels-to-protect-NRM-and-cultural-values.pdf

Edwards, G. P., Zeng, B., Saalfeld, W. K., & Vaarzon-Morel, P. (2010). Evaluation of the impacts of feral camels. *The Rangeland Journal*, *32*(1), 43–54.

Ehrenfeld, J. G. (2010). Ecosystem Consequences of Biological Invasions. *Annual Review of Ecology, Evolution, and Systematics*, *41*(1), 59–80. Retrieved 2023-05-05, from https://doi.org/10.1146/annurev-ecolsys-102209-144650 doi: 10.1146/annurev-ecolsys-102209-144650

Environment Australia. (1997). *Community involvement in off-reserve and on-reserve management of environmental weeds* (Report). Canberra, Australia: Environment Australia. Retrieved from https://weeds.org.au/wp-content/uploads/2020/04/involvement.pdf

Fantle-Lepczyk, J. E., Haubrock, P. J., Kramer, A. M., Cuthbert, R. N., Turbelin, A. J., Crystal-Ornelas, R., ... Courchamp, F. (2022). Economic costs of biological invasions in the United States. *Science of The Total Environment*, *806*, 151318. doi: 10.1016/j.scitotenv.2021.151318

Freeman III, A. M., Herriges, J. A., & Kling, C. L. (2014). *The measurement of environmental and resource values: theory and methods*. Routledge.

Ganann, R., Ciliska, D., & Thomas, H. (2010). Expediting systematic reviews: methods and implications of rapid reviews. *Implementation Science*, *5*(1), 56. Retrieved 2023-12-11, from https://doi.org/10.1186/1748-5908-5-56 doi: 10.1186/1748-5908-5-56

Gong, W., Sinden, J., Braysher, M., Jones, R., & Wales, N. (2009). *The economic impacts of vertebrate pests in Australia* (Tech. Rep.). Invasive Animals Cooperative Research Centre Canberra. Retrieved 2025-08-03, from https://pestsmart.org.au/wp-content/uploads/sites/3/2020/06/IACRC_EconoImpactsSummary.pdf

Gouldthorpe, J. (2006). *Gorse National Best Practice Manual: Managing Gorse (Ulex europaeus L.) in Australia* (Tech. Rep.). Hobart, Australia: National Gorse Taskforce. Tas Dept of Primary Industries and Water. Retrieved 2025-03-18, from https://vicgorsetaskforce.com.au/wp-content/uploads/2021/11/2-Gorse-National-Best-Practice-Manual.pdf

Hafi, A., Arthur, T., Medina, M., Warnakula, C., Addai, D., & Stenekes, N. (2023). *Cost of established pest animals and weeds to Australian agricultural producers* (ABARES research report No. No. 23.29). Canberra, Australia: Australian Bureau of Agricultural and Resource Economics and Sciences, Department of Agriculture, Fisheries and Forestry. Retrieved 2023-12-18, from 10.25814/xve7-s985

Haubrock, P. J., Turbelin, A. J., Cuthbert, R. N., Novoa, A., Taylor, N. G., Angulo, E., ... Courchamp, F. (2021). Economic costs of invasive alien species across Europe. *NeoBiota*, *67*, 153–190. doi: 10.3897/neobiota.67.58196

Heringer, G., Angulo, E., Ballesteros-Mejia, L., Capinha, C., Courchamp, F., Diagne, C., ... Zenni, R. D. (2021). The economic costs of biological invasions in Central and South America: a first regional assessment. *NeoBiota*, *67*, 401–426. doi: 10.3897/neobiota.67.59193

Hijmans, R. J., Bivand, R., Forner, K., Ooms, J., Pebesma, E., & Sumner, M. D. (2022). *Package 'terra'*. Vienna, Austria. Retrieved 2024-07-01, from https://cran.uni-muenster.de/web/packages/terra/terra.pdf

Hoffmann, B. D., & Broadhurst, L. M. (2016). The economic cost of managing invasive species in Australia. *NeoBiota*, *31*, 1–18. doi: 10.3897/neobiota.31.6960

Jones, R., & Vere, D. (1998). The economics of serrated tussock in New South Wales. *Plant Protection Quarterly*, *13*, 70–75.

Kalisch-Gordon, C. (2014). *The Economic Costs of Weeds in NSW* (Tech. Rep.). Sydney, Australia: Grain Growers Limited. Retrieved 2025-03-18, from https://www.nrc.nsw.gov.au/Weed%20management%20-%20Economic%20cost%20of%20weeds%20in%20NSW%20-%20Grain%20Growers%20-%20May%202014.pdf?downloadable=1

Legge, S., Taggart, P. L., Dickman, C. R., Read, J. L., & Woinarski, J. C. (2020). Cat-dependent diseases cost Australia AU $6 billion per year through impacts on human health and livestock production. *Wildlife Research*, *47*(8), 731–746.

Leroy, B., Kramer, A. M., Vaissière, A.-C., Kourantidou, M., Courchamp, F., & Diagne, C. (2022). Analysing economic costs of invasive alien species with the invacost r package. *Methods in Ecology and Evolution*, *13*(9), 1930–1937. Retrieved 2024-01-29, from https://onlinelibrary.wiley.com/doi/abs/10.1111/2041-210X.13929 (_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/2041-210X.13929) doi: 10.1111/2041-210X.13929

Llewellyn, R., Ronning, D., Ouzman, J., Walker, S., Mayfield, A., & Clarke, M. (2016). *Impact of weeds on Australian grain production: the cost of weeds to Australian grain growers and the adoption of weed management and tillage practices* (Tech. Rep.). Canberra, Australia: Grains Research & Development Corporation.

Long, K., & Robley, A. (2004). *Cost Effective Feral Animal Exclusion Fencing for Areas of High Conservation Value in Australia: A Report* (Tech. Rep.). Melbourne, Australia: Arthur Rylah Institute for Environmental Research, Department of Sustainability and Environment.

Martin, G. (2014). *Cost benefit analysis of winegrape rootstock research, development and extension* (Tech. Rep.). Canberra, Australia: Australian Grape and Wine Authority. IDA Economics PTY Ltd. Retrieved 2025-03-18, from https://www.wineaustralia.com/getmedia/5ad34d17-4c57-4748-935a-60ccf80933a3/GWR-1308

Martin, T. G., & van Klinken, R. D. (2006). Value for money? Investment in weed management in Australian rangelands. *The Rangeland Journal*, *28*(1), 63–75.

McKenzie, J., Mifsud, G., Dall, D., Woolnough, A., Hall, J., & Jackson, M. (2014). *National Wild Dog Action Plan: Promoting and supporting community driven action for landscape-scale wild dog management* (Tech. Rep.). Sydney, Australia: Australian Wool Innovation Ltd.

McLaren, D., Ramasamy, S., Lawrie, A., Morfe, T., & Pritchard, G. (2006). Assessing the extent of serrated tussock resistance to the herbicide, flupropanate in Australia. Wagga Wagga, NSW. Retrieved 2024-01-22, from https://grasslandnsw.com.au/news/wp-content/uploads/2010/08/McLaren-Ramasamy-Lawrie-Morfe-Pritchard-2006.pdf

McLeod, R. (2004). *Counting the cost: impact of invasive animals in Australia, 2004* (Tech. Rep.). Canberra, Australia: Cooperative Research Centre for Pest Animal Control.

McLeod, R. (2016). *Cost of pest animals in NSW and Australia, 2013–14.* (Tech. Rep.). Sydney, Australia: eSYS Development Pty Ltd; NSW Natural Resources Commission. Retrieved from https://invasives.com.au/wp-content/uploads/2019/02/Cost-of-Pest-Animals-in-NSW-and-Aus-2013-14-web-HR.pdf

McLeod, R. (2018). *Annual costs of weeds in Australia* (Report). Canberra, Australia: eSYS Development Pty Ltd, Centre for Invasive Species Solutions,. Retrieved 2025-03-18, from https://invasives.com.au/wp-content/uploads/2019/01/Cost-of-weeds-report.pdf

McLeod, R. (2023). *Annual costs of feral deer in Australia* (Tech. Rep.). Canberra, Australia: eSYS Development Pty Ltd, Centre for Invasive Species Solutions. Retrieved 2025-03-18, from https://pestsmart.org.au/wp-content/uploads/sites/3/2023/07/Invasives-Cost-of-Feral-Deer-Final-Report.pdf

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & Group, T. P. (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *PLOS Medicine*, *6*(7), e1000097. doi: 10.1371/journal.pmed.1000097

Murray, D. A. H., Clarke, M. B., & Ronning, D. A. (2013). Estimating invertebrate pest losses in six major Australian grain crops. *Australian Journal of Entomology*, *52*(3), 227–241. Retrieved 2023-12-20, from https://onlinelibrary.wiley.com/doi/abs/10.1111/aen.12017 doi: 10.1111/aen.12017

Murray, G. M., & Brennan, J. P. (2009). *The current and potential costs from diseases of wheat in Australia* (Tech. Rep.). Canberra, Australia: Grains Research and Development Corporation. Retrieved from https://grdc.com.au/__data/assets/pdf_file/0026/203957/disease-loss-wheat.pdf.pdf

NSW Government. (2023). *NSW Invasive Species Management Review - Terms of reference.* Retrieved 2024-06-25, from https://www.nrc.nsw.gov.au/invasive

O'Dea, R. E., Lagisz, M., Jennions, M. D., Koricheva, J., Noble, D. W., Parker, T. H., ... Nakagawa, S. (2021). Preferred reporting items for systematic reviews and meta-analyses in ecology and evolutionary biology: a PRISMA extension. *Biological Reviews*, *96*(5), 1695–1722. Retrieved 2021-09-30, from https://onlinelibrary.wiley.com/doi/abs/10.1111/brv.12721 doi: 10.1111/brv.12721

Page, A., & Lacey, K. (2006). *Economic impact assessment of Australian weed biological control* (Tech. Rep.). Adelaide, Australia: CRC for Australian Weed Management. Retrieved 2025-03-18, from https://weeds.org.au/wp-content/uploads/2020/02/tech_series_10.pdf

Parkes, J., Henzell, R., Pickles, G., & Bomford, M. (1996). *Managing vertebrate pests: Feral goats* (Tech. Rep.). Canberra, Australia: Bureau of Resource Sciences.

Pascual, U., Muradian, R., Brander, L., Gómez-Baggethun, E., Martín-López, B., Verma, M., ... others (2012). The economics of valuing ecosystem services and biodiversity. In *The economics of ecosystems and biodiversity: Ecological and economic foundations* (pp. 183–256). Routledge.

Pejchar, L., & Mooney, H. A. (2009). Invasive species, ecosystem services and human well-being. *Trends in ecology & evolution*, *24*(9), 497–504. (Publisher: Elsevier)

Pimentel, D., Lach, L., Zuniga, R., & Morrison, D. (2000). Environmental and Economic Costs of Nonindigenous Species in the United States. *BioScience*, *50*(1), 53–65. doi: 10.1641/0006-3568(2000)050[0053:EAECON]2.3.CO;2

Postel, S., Bawa, K., Kaufman, L., Peterson, C. H., Carpenter, S., Tillman, D., … Goulder, L. (2012). *Nature's services: Societal dependence on natural ecosystems*. Island Press.

R Core Team. (2013). *R: A language and environment for statistical computing.* Vienna, Austria. Retrieved from https://www.r-project.org/

Reid, W. V., Mooney, H. A., Cropper, A., Capistrano, D., Carpenter, S. R., Chopra, K., … Hassan, R. (2005). *Ecosystems and human well-being-Synthesis: A report of the Millennium Ecosystem Assessment*. Island Press.

Saunders, G., & Fleming, P. (1988). *Interaction between feral pigs, wild dogs and agriculture on the tablelands and coast of NSW, Unpublished Final Report on Project DAN 15P to the Wool Research and Development Fund* (Tech. Rep.). Australia: Wool Research and Development Fund.

Schneider, K., & Arndt, E. (2020). *Evaluating the health of Australia's biosecurity system* (Report). Melbourne, Australia: Centre of Excellence for Biosecurity Risk Analysis, University of Melbourne. Retrieved 2023-05-03, from https://cebra.unimelb.edu.au/__data/assets/pdf_file/0011/3423278/Endorsed-CEBRA-170714-Final-Report-June2020.pdf

Seebens, H., Blackburn, T. M., Dyer, E. E., Genovesi, P., Hulme, P. E., Jeschke, J. M., … Essl, F. (2017). No saturation in the accumulation of alien species worldwide. *Nature Communications*, *8*(1), 14435. doi: 10.1038/ncomms14435

Shackleton, R. T., Shackleton, C. M., & Kull, C. A. (2019). The role of invasive alien species in shaping local livelihoods and human well-being: A review. *Journal of Environmental Management*, *229*, 145–157. doi: 10.1016/j.jenvman.2018.05.007

Simberloff, D., Martin, J.-L., Genovesi, P., Maris, V., Wardle, D. A., Aronson, J., … Vilà, M. (2013). Impacts of biological invasions: what's what and the way forward. *Trends in Ecology & Evolution*, *28*(1), 58–66. doi: 10.1016/j.tree.2012.07.013

Sinden, J., Jones, R., Hester, S., Odom, D., Kalisch, C., James, R., … Griffith, G. (2004). *The economic impact of weeds in Australia* (Tech. Rep.). Adelaide, Australia: CRC for Australian Weed Management. Retrieved 2025-03-18, from https://weeds.org.au/wp-content/uploads/2020/02/tech_series_8_summary.pdf

Singleton, G. R. (2000). Ecologically based rodent management integrating new developments in biotechnology. In *Nineteenth Vertebrate Pest Conference, Proceedings* (pp. 221–227).

Sloane, Cook and King Pty Ltd. (1988). *The economic impact of pasture weeds, pests and diseases on the Australian Wool Industry* (Tech. Rep.). Sydney, Australia: Australian Wool Corporation.

Stenekes, N., Kancans, R., & Binks, B. (2017). *Pest animal and weed management survey - National landholder survey results* (Report). Canberra, Australia: Australian Bureau of Agricultural and Resource Economics and Sciences.

Stenekes, N., Ticehurst, J., & Arthur, T. (2022). *Pest Animal and Weed Management Survey 2016/2019/2022: National land manager survey results* (ABARES research report to client). Canberra, Australia: Australian Bureau of Agricultural and Resource Economics and Sciences, Department of Agriculture, Fisheries and Forestry. Retrieved 2024-01-11, from https://doi.org/10.25814/pff0-1a62

Stoeckl, N., Dodd, A., & Kompas, T. (2023). The monetary value of 16 services protected by the Australian National Biosecurity System: Spatially explicit estimates and vulnerability to incursions. *Ecosystem Services*, *60*, 101509. doi: 10.1016/j.ecoser.2023.101509

Tisdell, C. A. (1982). *Wild pigs: environmental pest or economic resource?* Sydney, New South Wales: Pergamon Press.

Tracey, J., & Saunders, G. (2003). *Bird damage to the wine grape industry* (Tech. Rep.). Orange, Australia: NSW Agriculture. Retrieved 2025-03-18, from http://www.pestsmart.org.au/wp-content/uploads/2010/03/9245.pdf

Vere, D., & Campbell, M. (1978). The economic loss caused by serrated tussock (Nassella trichotoma) in New South Wales. In *Proceedings of the First Conference of the Council of Australian Weed Science Societies* (pp. 422–425). Parkville, Australia: Council of Australian Weed Science Societies.

Vere, D., Jones, R., & Saunders, G. (2004). The economic benefits of rabbit control in Australian temperate pastures by the introduction of rabbit haemorrhagic disease. *Agricultural Economics*, *30*, 143–155. doi: 10.1016/j.agecon.2002.10.002

Vere, D. T., & Campbell, M. H. (1979). Estimating the economic impact of serrated tussock (Nassella trichotoma) in New South Wales. *Journal of the Australian Institute of Agricultural Science*, *45*(1), 35–43. Retrieved 2023-12-18, from https://eurekamag.com/research/000/653/000653488.php

Walker, S. R., Taylor, I. N., Milne, G., Osten, V. A., Hoque, Z., & Farquharson, R. J. (2005). A survey of management and economic impact of weeds in dryland cotton cropping systems of subtropical Australia. *Australian Journal of Experimental Agriculture*, *45*(1). doi: 10.1071/ea03189

Watkinson, A., Freckleton, R. P., & Dowling, P. M. (2000). Weed invasions of Australian farming systems: from ecology to economics. In *The Economics of Biological Invasions. Edward Elgar Publishing, Cheltenham* (pp. 94–116).

Westgate, M. J. (2019). revtools: An R package to support article screening for evidence synthesis. *Research Synthesis Methods*, *10*(4), 606–614. doi: 10.1002/jrsm.1374

Williams, C. K., Parer, I., Coman, B., Burley, J., & Braysher, M. (1995). *Managing vertebrate pests: Rabbits* (Tech. Rep.). Canberra, Australia: Bureau of Resource Sciences.

Wise, R., Van Wilgen, B., Hill, M., Schulthess, F., Tweddle, D., Chabi-Olay, A., & Zimmermann, H. (2007). *The economic impact and appropriate management of selected invasive alien species on the African continent* (Tech. Rep.). Nairobi, Kenya: Global Invasive Species Programme.

Wylie, F., & Janssen-May, S. (2017). Red Imported Fire Ant in Australia: What if we lose the war? *Ecological Management and Restoration*, *18*(1), 32–44. doi: 10.1111/emr.12238

Supplementary materials: The Missing Environmental Impacts in Invasive Species Cost Assessments – Insights from an InvaCost-based regional review

Nicholas P. Moran, Lu-Yi Wang, Anca M. Hanea, Tom Kompas

A Rapid Review Records

An overview of the review methodology, including all sources used to collate cost data for NSW is included in Fig A.1. InvaCost/CISS records refers the data references extracted from the InvaCost 4.1, along with additional records from the Centre for Invasive Species Solutions (unpub. report). Database search records are those collected via our independent literature search. Additional records include recent reports known to authors that were not captured by other sources (referred to as "non-systematic records") and records identified as the original source of cost data in studies found in our independent database searches (referred to as "original data records").

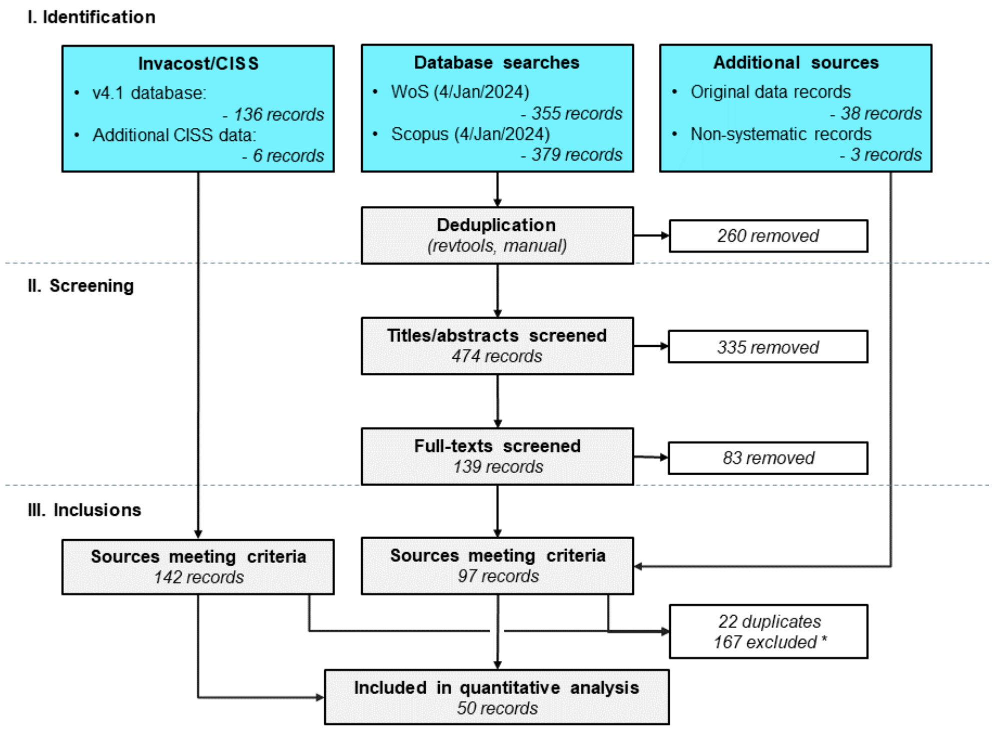

Figure A.1: Rapid review PRISMA diagram, including data sources, processing and screening. (*Cost records identified through our review were excluded from quantitative analysis where they included only publicly funded costs, costs estimates that were rated as low reliability, duplicated/ non-original estimates, or potential/unrealised costs.).

Independent literature review records

WoS searches were conducted with the Web of Science Core Collection (A&HCI , BKCI-SSH , BKCI-S , CCR-EXPANDED , ESCI , IC , CPCI-SSH, CPCI-S , SCI-EXPANDED , SSCI), based on titles, abstracts, author keywords and keywords plus. Searches in Scopus for titles, abstracts, author keywords and indexed keywords also followed the same query. Advanced search functions were used with a standardised query adapted for each database (i.e., WoS query: *TS=(econom* OR cost OR monetary OR dollar OR *expens*) AND TS=(pest OR weed OR ((exotic OR invasi* OR invad* OR alien OR introduc* OR nonnative OR non-native OR non-indigenous) NEAR/5 (species OR animal OR plant))) AND TS=(”New South Wales” OR ”NSW” OR ((east* OR southeast*) NEAR/5 Australia))*; Scopus query: *TITLE-ABS-KEY(econom* OR cost OR monetary OR dollar OR *expens*) AND TITLE-ABS-KEY(pest OR weed OR ((exotic OR invasi* OR invad* OR alien OR introduc* OR nonnative OR non-native OR non-indigenous) W/5 (species OR animal OR plant))) AND TITLE-ABS-KEY(”New South Wales” OR ”NSW” OR ((east* OR southeast*) W/5 Australia))*). This query followed a similar structure to that used in InvaCost, but with a broader set of terms to capture the types of costs (i.e., expenses, dollar, etc.) and invasive species (e.g., alien plants, non-indigenous species, etc.), as well as a regional term to limit results to NSW or south-eastern Australia.

From our database searches, the titles and abstracts of records were screened by two authors (LYW, NPM). Records were included for full-text screening where they met or appeared likely to meet the above criteria. Initially, 5% of records were double screened to assess agreement levels (17/24, 71% agreement). To ensure that inclusion/exclusion decisions were consistent, a second 5% of records were double screened (21/24, 88% agreement). Any conflicting decisions were discussed and resolved collaboratively. The remaining records were screened by a single author.

Full-text records were then assessed against the inclusion criteria. If is was unclear whether a record where met the criteria, both reviewers made a final decision collaboratively. All records from additional sources (e.g., non-systematic and original data records) were also checked against our inclusion criteria.

InvaCost/CISS records

The primary source of data was InvaCost (v4.1, published 22/Jan/2022; Diagne et al., 2022). Data checks confirmed that all data from the subsequent Australia-specific review (Bradshaw et al., 2021) has been incorporated into the most current version of the InvaCost database.

InvaCost data were filtered in R to include only estimates from Australia that apply to areas that are within or include New South Wales. Entries for fungi and viruses were excluded (e.g., Wheat streak mosaic virus, Banana bunchy top virus, etc.). We also excluded data for taxa that are native to Australia [e.g., native bollworms (*Helicoverpa spp.*), windmill grass (*Chloris truncata*), koalas (*Phascolarctos cinereus*), etc.] or that are exotic to NSW [e.g., screw-worm fly (*Cochliomyia hominivorax*), mimosa (*Mimosa pigra*), banana skipper butterfly (*Erionota thrax*), etc.]. Similarly, CISS data was manually checked to confirm that the locations and species for cost data met these criteria.

Review data summary

The aggregated cost data for NSW identified in the rapid review is shown in Figure A.2. Individual data points are total annual costs for each year (i.e., the sum of all individual cost

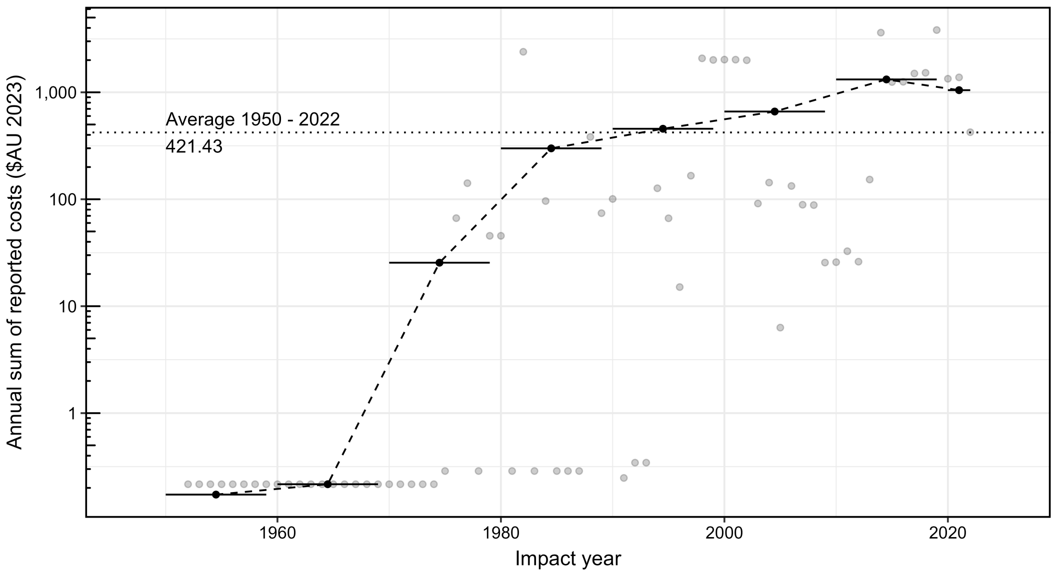

Figure A.2: Aggregated total reported costs of established invasive species in NSW, for all non-public expenditure based costs (e.g., private control costs, production losses, health impacts and environmental costs). Shown are the annual total costs for each year (grey circles), the average annual cost per decade from 1950 to current (black circles with horizontal bars). The dashed line represents the average total cost per year over the full data period.

estimates for that year). Horizontal bars mark the average average annual cost for 10-year intervals. The full range of cost data is from 1952 - 2022. Only a single cost estimate is applicable to dates prior to 1970, and there is a clear surge in reporting of cost estimates from the 1970s on. Therefore analysis of these costs was limited to the 1970s onwards.

Costs data references

The following 50 references contributed cost data to the quantitative analysis of invasive species costs for NSW (cited here for inclusion in the reference list): (AEC Group, 2007; Binks et al., 2015; Cameron et al., 2018; Canyon, 2008; Caughley, 1998; Charles, 1991; Choquenot et al., 1996; Cooke et al., 2013; Craik et al., 2017; D. Croft & Caughley, 1995; J. D. Croft & Connellan, 1999; Earl, 2003; G. Edwards et al., 2008; G. P. Edwards et al., 2010; Environment Australia, 1997; Gong et al., 2009; Kalisch-Gordon, 2014; Gouldthorpe, 2006; Hafi et al., 2023; Jones & Vere, 1998; Legge et al., 2020; Llewellyn et al., 2016; Long & Robley, 2004; G. Martin, 2014; T. G. Martin & van Klinken, 2006; McKenzie et al., 2014; McLaren et al., 2006; McLeod, 2016, 2018, 2023, 2004; G. M. Murray & Brennan, 2009; D. A. H. Murray et al., 2013; Page & Lacey, 2006; Parkes et al., 1996; Saunders & Fleming, 1988; Sinden et al., 2004; Singleton, 2000; Sloane, Cook and King Pty Ltd, 1988; Stenekes et al., 2017, 2022; Tisdell, 1982; Tracey & Saunders, 2003; D. Vere & Campbell, 1978; D. T. Vere & Campbell, 1979; D. Vere et al., 2004; Walker et al., 2005; Watkinson et al., 2000; Williams et al., 1995; Wise et al., 2007).

B Taxa Included in Analysis

Cost analysis included any species for which there were private/non-public expenditure based cost estimates attributable to NSW, for species that are currently or have previously established in NSW. This included the following species/genus. Note, some cost estimates were attributed to broader aggregated groupings of species, which are not included here.

Terrestrial plants:

- serrated tussock (*Nassella trichotoma*)
- blackberry (*Rubus fruticosus*)
- ryegrass (*Lolium rigidum*)
- fleabane (*Conyza* spp.)
- barnyard grass (*Echinochloa crus-galli*)
- wild oats (*Avena* spp.)
- barley grass (*Hordeum* spp.)
- melons (*Curcumis* spp.)
- common heliotrope (*Heliotropium europaeum*)
- lantana (*Lantana camara*)
- silver grass (*Vulpia* spp.)
- panic grass (*Panicum maximum*)
- lippia/frog fruit (*Phyla* spp.)
- Brassica weeds (*Brassica* spp.)
- St John's wort (*Hypericum perforatum*)
- Paterson's curse / salvation Jane (*Echium* spp.)
- feathertop Rhodes grass (*Chloris virgata*)
- sweet summer grass (*Brachiaria eruciformis*)
- common sowthistle (*Sonchus oleraceus*)
- scotch, stemless and Illyrian thistles (*Onopordum* spp.)
- brome grass (*Bromus* spp.)
- wild radish (*Raphanus raphanistrum*)
- brown-top bent grass (*Agrostis capillaris*)
- skeleton weed (*Chondrilla juncea*)
- saffron thistle (*Carthamus lanatus*)
- black bindweed (*Fallopia convolvulus*)
- fireweed (*Senecio madagascariensis*)
- mint weed (*Salvia reflexa*)
- caltrop (*Tribulus terrestris*)
- wild mustard (*Sisymbrium officinale*)
- wireweed (*Polygonum aviculare*)
- capeweed (*Arctotheca calendula*)

- Xanthium burrs (*Xanthium* spp.)
- spiny emex/docks (*Rumex* spp.)
- phalaris (*Phalaris aquatica*)
- parthenium (*Parthenium hysterophorus*)
- gorse (*Ulex europaeus*)
- goosefoots (*Chenopodium spp.*)
- horehound (*Marrubium vulgare*)
- Mexican poppy (*Argemone mexicana*)
- giant rat's tail grass (*Sporobolus pyramidalis*)
- parkinsonia (*Parkinsonia aculeata*)
- onion weed (*Asphodelus fistulosus*)
- prickly lettuce (*Lactuca serriola*)
- deadnettle (*Lamium* spp.)
- buffel grass (*Cenchrus ciliaris*)
- mesquite (*Prosopis* spp.)

Terrestrial vertebrates:

- cat (*Felis catus*)
- European rabbit (*Oryctolagus cuniculus*)
- wild dog (*Canis lupus*)
- pig (*Sus scrofa*)
- red fox (*Vulpes vulpes*)
- deer (*Cervus* spp.)
- mouse (*Mus musculus*)
- rat (*Rattus* spp.)
- goat (*Capra hircus*)
- camel (*Camelus dromedarius*)
- horse/donkey (*Equus spp.*)

Terrestrial invertebrates:

- oat aphids (*Rhopalosiphum* spp.)
- blue oat mite (*Penthaleus major*)
- lucerne flea (*Dicyrtomina ornata*)
- redlegged earth mite (*Halotydeus destructor*)
- cereal cyst nematode (*Heterodera* spp.)
- root lesion nematodes (*Pratylenchus* spp.)
- sirex wood wasp (*Sirex noctilio*)
- spotted alfalfa aphid (*Therioaphis trifolii*)
- yellow fever mosquito (*Aedes aegypti*)
- grape phylloxera (*Daktulosphaira vitifoliae*)

Aquatic pests:

- common carp (*Cyprinus carpio*)

C Spatial Partitioning of Costs via Biosecurity Commons

Within the Biosecurity Commons platform (Biosecurity Commons, 2024), spatial layers were created for the overlap of the species distribution and the impacted sector/industry, both within NSW and across the broader national or regional location for which the cost estimate applies. Figure C.1 shows an example for the invasive plant common heliotrope (*Heliotropium europaeum*), and overlapping with the impacted sector (i.e., cropping, based on the secondary Australian Land Use and Management Classification "3.3.0 Cropping"). This estimated an overlapping area of 187,894km^2 within NSW and 427,207km^2 across Australia, therefore a fraction of 0.439819572 was applied to partition the associated national cost estimate to NSW. Importantly, this approach only provides an estimate of the portion of costs that could be applied to NSW, without accounting for spatial heterogeneity in impacts within the invasive species' range, or temporal variation in a species' impacts or their invasive range. Extensions to this method accounting for these factors are viable, but were considered beyond the scope of this project.

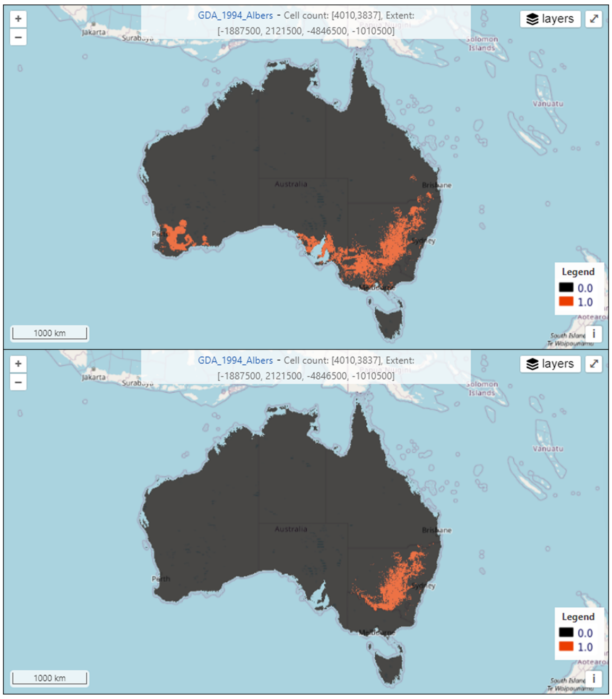

Figure C.1: Spatial layers created via Biosecurity Commons, of the overlap in the distribution of common heliotrope and cropping areas (upper) across Australia and (lower) within NSW.