Science of the Total Environment 819 (2022) 153404

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Biological invasion costs reveal insufficient proactive management worldwide

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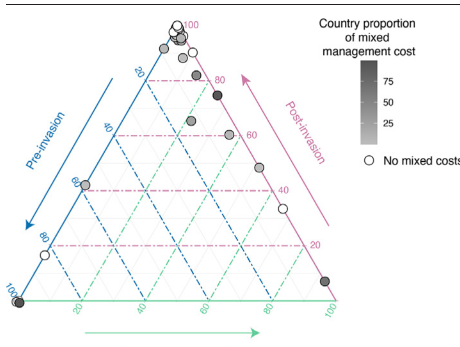
HIGHLIGHTS

- Since 1960, management for biological invasions totalled at least $95.3 billion.
- Damage costs from invasions were substantially higher ($1130.6 billion).
- Pre-invasion management spending is 25-times lower than post-invasion.
- Management and damage costs are increasing rapidly over time.
- Proactive management substantially reduces future costs at the trillion-$ scale.

GRAPHICAL ABSTRACT



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http://dx.doi.org/10.1016/j.scitotenv.2022.153404

ARTICLE INFO

Article history:
Received 20 December 2021
Received in revised form 21 January 2022
Accepted 21 January 2022
Available online 8 February 2022

Editor: Damià Barceló

Keywords:
Biosecurity
Delayed control and eradication
Global trends
InvaCost
Invasive alien species
Socio-economic impacts

ABSTRACT

The global increase in biological invasions is placing growing pressure on the management of ecological and economic systems. However, the effectiveness of current management expenditure is difficult to assess due to a lack of standardised measurement across spatial, taxonomic and temporal scales. Furthermore, there is no quantification of the spending difference between pre-invasion (e.g. prevention) and post-invasion (e.g. control) stages, although preventative measures are considered to be the most cost-effective. Here, we use a comprehensive database of invasive alien species economic costs (InvaCost) to synthesise and model the global management costs of biological invasions, in order to provide a better understanding of the stage at which these expenditures occur. Since 1960, reported management expenditures have totalled at least US$95.3 billion (in 2017 values), considering only highly reliable and actually observed costs — 12-times less than damage costs from invasions ($1130.6 billion). Pre-invasion management spending ($2.8 billion) was over 25-times lower than post-invasion expenditure ($72.7 billion). Management costs were heavily geographically skewed towards North America (54%) and Oceania (30%). The largest shares of expenditures were directed towards invasive alien invertebrates in terrestrial environments. Spending on invasive alien species management has grown by two orders of magnitude since 1960, reaching an estimated $4.2 billion per year globally (in 2017 values) in the 2010s, but remains 1–2 orders of magnitude lower than damages. National management spending increased with incurred damage costs, with management actions delayed on average by 11 years globally following damage reporting. These management delays on the global level have caused an additional invasion cost of approximately $1.2 trillion, compared to scenarios with immediate management. Our results indicate insufficient management — particularly pre-invasion — and urge better investment to prevent future invasions and to control established alien species. Recommendations to improve reported management cost comprehensiveness, resolution and terminology are also made.

1. Introduction

Invasive alien species (IAS) are those introduced to a novel range, where they establish and spread, often causing adverse ecological, social and/or economic impacts (Blackburn et al., 2011; Pyšek et al., 2020). Biological invasions have been identified as a major cause of native species extinction (Bellard et al., 2016), degradation of ecosystem functions and services (Vilà and Hulme, 2017), emergence and dissemination of infectious diseases (Ogden et al., 2019), and economic cost at the trillion-US$ scale worldwide (Diagne et al., 2021a). With invasion rates strongly related to rising globalisation (Bonnamour et al., 2021) and expected to keep increasing over coming decades from new source pools (Seebens et al., 2021; Cuthbert et al., 2022a), the burden of IAS on ecosystems and human wellbeing is also likely to rise.

Management of this steadily increasing number of IAS remains a major societal challenge for the 21st century (Seebens et al., 2017; Robertson et al., 2020). Among other national and international mandates, the Convention on Biological Diversity (CBD, 2010) and the United Nations Sustainable Development Goals (UN, 2015) emphasise the need to prevent new species introduction and reduce impacts of IAS, as well as to identify priority species for control or eradication. Approaches to IAS management can take several forms, broadly classified as prevention, rapid eradication, or long-term management (although definitions and terminology can vary; Robertson et al., 2020). This is because biological invasion is a stage-based process, defined through transport, introduction, establishment and spread of IAS (Blackburn et al., 2011). Management at early-invasion stages (e.g. biosecurity and prevention) is often driven by precaution based on evidence of adverse impacts elsewhere, whereas late-invasion stage management (e.g. control or eradication) is more often reactive, following the detection of impacts in situ (Simberloff et al., 2013).

Currently, theoretical evidence highlights the potential long-term economic benefits of acting early and prioritising investment in preventative measures (Ahmed et al., 2021), but bioeconomic risk models have found societies typically invest far less than is warranted in biosecurity actions (Leung et al., 2002). Given the impediments and costs associated with late-stage management (Simberloff et al., 2013), this may seem surprising. However, the difficulty in translating ecological, social and cultural IAS impacts into monetary terms (Hanley and Roberts, 2019), the need to further develop decision-making tools to optimise management efforts (Booy et al., 2020), and the lack of a sufficient understanding of the economic costs of biological invasions have likely contributed to inadequate spending on IAS management and inefficient decision-making (Diagne et al., 2020a, 2021a).

Recently, the InvaCost database has been compiled to fill this gap in collating and understanding reported economic costs of biological invasions in a globally standardised manner (Diagne et al., 2020b), allowing for relevant comparisons across different scales and contexts. Descriptors in this database include a categorisation of the type of cost incurred, distinguishing primarily between damage (i.e. resource degradation or loss) and management (i.e. expenditures to prevent, control or eradicate IAS); as well as the type and stage of management investment (i.e. pre-invasion, post-invasion, funding/knowledge). National and international studies based on these data have consistently shown that management expenditures represent only a small fraction of the costs of IAS damage (e.g. Bradshaw et al., 2021; Haubrock et al., 2021a; Heringer et al., 2021; Kirichenko et al., 2021; Kourantidou et al., 2021; Cuthbert et al., 2022b). At the same time, overall damage costs have increased at a higher rate than management expenditures (Diagne et al., 2021a), suggesting that the way in which management investments are undertaken deserves careful consideration across time, space and taxonomic groups. The fundamental fact that damage costs are rising rapidly indicates that better management is needed to reduce future impacts. Nevertheless, no studies have placed global management spending in the context of damage costs using the latest version of the InvaCost database or considering different management types. Such a quantification could provide compelling evidence that management is warranted if management spending is substantially lower than incurred damage costs, and is accordingly not implemented at the sole benefit of agencies involved (Leung et al., 2002; Cuthbert et al., 2020).

Here, we use this InvaCost database to identify patterns and trends, research biases, and knowledge gaps surrounding management expenditures against biological invasions worldwide. Our aims were to (*i*) quantify management costs relative to IAS damage costs, (*ii*) characterise management expenditures for IAS at different spatial, taxonomic, environmental and temporal scales, (*iii*) model ecological and socio-economic determinants of damage costs and management spending, as well as potential savings should management have been more timely, and (*iv*) identify avenues for further efficient spending and research on IAS management.

2. Materials and methods

2.1. Data collection and processing

We used cost data collected from studies across the globe and presented in the latest version of the InvaCost database at the time of writing (version 4.0; 13,123 cost entries; Diagne et al., 2020b; Angulo et al., 2021a; doi:

https://doi.org/10.6084/m9.figshare.12668570). All costs were adjusted for inflation through the Consumer Price Index (https://data.worldbank.org/indicator/FP.CPI.TOTL?end=2017&start=1960) and are reported in 2017-value United States (US) dollars (hereafter, $; Diagne et al., 2020b) in order to be comparable across space and over time.

As cost estimates in InvaCost are made under different temporal scales, we annualised the data based on the difference between the "Probable_starting_year_adjusted" and "Probable_starting_year_adjusted" (i.e. the approximate starting and ending years of the cost; see doi: https://doi.org/10.6084/m9.figshare.12668570 for description) columns using the *expandYearlyCosts* function of the 'invacost' package in R (v4.0.2) (R Core Team, 2020; Leroy et al., 2021). Each expanded entry thus corresponded to a single year for which costs were available following this expansion process, i.e. costs spanning multiple years were divided among those same years (e.g. a single cost entry of $20 million between 1991 and 2000 in the original database was transformed to ten cost entries of $2 million annually across those ten years). Following expansion, we considered only costs that impacted years between 1960 and 2020, respectively reflecting the first year appropriate exchange rates could be determined and the last year costs were searched for.

We then performed several filtering steps to this dataset so that we obtained the most robust subset (hereafter called "filtered dataset"), considering the nature of the cost and quality of the source material. First, we filtered the database to include "observed" costs only (thus excluding "potential" costs), since we were interested in definitively realised costs over time rather than those that had been extrapolated or predicted to potentially occur either in space or time. Second, we retained only costs classified as "highly reliable" (thus excluding "low reliability" costs), meaning that we used exclusively those that were either published in peer-reviewed journals and official reports or, if they were found in grey literature, that had adequately supported, replicable analyses and justified assumptions. Third, we filtered out "mixed" cost types (n = 560 unexpanded entries) to keep only costs that were clearly determined to be either "management" or "damage" costs (in order to place management costs into a wider context as a proportion of IAS damages). Last, we removed entries for which the management type was unspecified (for management costs only; n = 124 unexpanded entries) or where the temporal duration of the cost was unclear (i.e. missing "Probable_starting_year_adjusted" and/or "Probable_ending_year_adjusted", because the cost could not be expanded over time in those cases). Unless specified, all results are provided for the filtered dataset, but results using unfiltered data (i.e. including "low reliability" and "potential" costs) are presented initially. Our final, filtered datasets are provided as Supplementary Material 1 — detailed information on all descriptive variables can be found in an on-line repository (doi: https://doi.org/10.6084/m9.figshare.12668570, "Descriptors 4.0.xlsx").

2.2. Categorisation of management expenditures

We followed the classification provided in the InvaCost database regarding management expenditures. Each cost entry was therefore classified under one of the following four categories that broadly represent different types of management actions (full list in Supplementary Material 2):

1. *Pre-invasion management*: proactive monetary investments for preventing alien species invasions to or within an area. Includes, among others: quarantine or border inspection and risk analyses (e.g. assessments of the risk of invasion, potential impact of invasion, etc.);
2. *Post-invasion management*: reactive expenditure for managing already introduced or established populations of IAS (including eradication, containment, control, etc.);
3. *Knowledge funding*: money allocated to all actions and operations that could be of interest across all steps of management at pre- and post-invasion stages (including administration, communication, education, research, etc.);
4. *Mixed*: when costs include at least two of the above categories.

2.3. Distribution and analyses of management expenditures

We used a range of descriptors (see Diagne et al., 2020b and doi:https://doi.org/10.6084/m9.figshare.12668570 for details on these descriptors) from our filtered dataset, described earlier, to examine the monetary investments in management actions in relation to:

(1) the geographic regions [*Africa*, *Antarctic-Subantarctic*, *Asia*, *Europe*, *North America* (including *Central America*), *Oceania* (including *Pacific Islands*) or *South America*], official countries and spatial scales (*global*, *intercontinental*, *continental*, *regional*, *country*, *site* or *unit*);
(2) broad taxonomic groupings [*vertebrates*, *invertebrates*, *plants*, *others* (i.e. fungi, chromists or pathogens), or *diverse/unspecified*] and individual species (i.e. excluding multiple or unspecified species); and.
(3) environment type(s) of the IAS causing impact (*aquatic*, *semi-aquatic*, *terrestrial* or *diverse/unspecified*).

We compared the total cumulative and mean annual costs of damage and management costs, as well as the different management categories defined above, and how they evolved over time. This was done using the *summarizeCosts* function of the 'invacost' R package (Leroy et al., 2021), thereby determining the decadal and absolute annual average expenditures for (*i*) total management, (*ii*) total damage, (*iii*) pre-invasion management, (*iv*) post-invasion management and (*v*) knowledge funding.

2.4. Statistical modelling

We built two models to examine the predictiveness of biosecurity investment for the total management or damage cost incurred by a nation in a given decade (n = 7 decades 1960–2020; n = 102 countries; n = 198 [country + decade] pairs). To do this, we first summed our cost data within each decade and within each country, employing the 'countrycode' R package (Arel-Bundock et al., 2018) to ensure consistent country naming by converting all InvaCost country records to ISO3C codes. In both models, we included several other factors hypothesised to influence economic impacts of biological invasion (Haubrock et al., 2021a, 2021b; Kourantidou et al., 2021), including the Gross Domestic Product (GDP) and human population of each country in 2014 (from the World Bank, adapted from Sardain et al., 2019), as well as total volume of imports in metric tonnes (BACI CEPII 2021; http://www.cepii.fr/cepii/en/bdd_modele/presentation.asp?id=37), either using the annual average from 2015 to 2019 or a historical annual average from 1995 to 1999 (given our data were grouped by decade and that historical trade can be more predictive of present day invasion risk due to invasion lags; see Latombe et al., 2021). We also included a measure of the total invader burden in a country from the sTwist first record database (Seebens et al., 2017), calculated as the cumulative number of species first records up to that decade. Models were formulated as generalised additive models (GAM) using the R package 'mgcv' (Wood, 2011) in order to include temporal terms as thin plate smoothers. This allowed us to detrend our cost data with respect to time and to explore potential non-monotonic relationships between cost and lags in management. In addition to the decade term, we also calculated the mean time difference between a particular decade and each IAS' first management cost record within each country. This allowed us to get a measure of mean time since first management onset across countries and decades, and to see whether this time-since-management term was predictive of total management or damage costs in each country and decade. Within the GAM, we employed the 'select' method to avoid the overparameterisation of our smoother terms. This method uses a cross-validation approach to penalise overfitted smoother terms (using the *GCV.Cp* method). All non-smoothed variables were $\log_e$-transformed prior to analysis to meet model assumptions as determined by GAM model-checking results. Overall, two full models were built with (*i*) total damage costs and (*ii*) total management costs as response variables per decade and country, according to the aforementioned 12 predictor variables [i.e. damage cost (for management model only), pre-invasion management spending, post-invasion management spending (for damage model only), knowledge funding, number of unique cost references, current trade imports, historical trade imports, population size, GDP, species richness, first invasion records, decade, and time since first management record]. Models were checked for high concurvity (the GAM equivalent of multicollinearity; Wood, 2011) and when predictor variables were highly correlated ($r > 0.8$), the predictor with the greatest correlation with the response variable was retained. All code and derived data are available at github.com/emmajhudgins/biosecurity_invacost.

In addition to the two main GAM models, we examined trends in the degree of proactive (i.e. pre-invasion) and reactive (i.e. post-invasion) management across IAS, countries, and time by fitting a linear model of management delay to each IAS-country pair reported in each decade. For instance, if an IAS had its first recorded damage cost in Canada in 1985 and its first recorded management cost in Canada in 1992, we obtained a minimum management delay of 7 years for that species in Canada that was associated with the year 1985. Any entry without management spending to date was assigned 2020 as the year of management, although we note that this is necessarily an underestimate of the true delay.

2.5. Cost of inaction

We set out to quantify the additional cost incurred due to delayed management action (i.e. the cost of inaction) on a global scale using the filtered dataset. We applied the cost model developed by Ahmed et al. (2021), which predicts the temporal dynamics of potential damage and inaction costs by fitting cost curves to damage and management cost data (Supplementary Material 3). Globally aggregated damage costs were reported on an annual basis from 1960 to 2020, with a maximum reported cost value of $216.6 billion in 2004. Management costs were also reported yearly over the same time period, with a maximum cost of $7.4 billion in 2002. To make predictions of the cost of inaction across all delay scenarios, we used the total damage and management costs per year in the filtered data. Cost curves were fitted using the non-linear regression tool 'lsqcurvefit' from MATLAB (Supplementary Material 3), where estimated model parameters included the intrinsic cost growth rate, cost carrying capacity, management efficiency and the initial cost at the time of first detection (Supplementary Material 3, Ahmed et al., 2021).

3. Results

3.1. Geographic distribution

Considering the unfiltered dataset (i.e. including low reliability and potential costs), expenditure for managing invasions has totalled $307.9 billion between 1960 and 2020 worldwide, based on 20,758 expanded cost entries from the InvaCost database (hereafter, n); a value that sums to only 6% of the total recorded damages incurred from IAS worldwide ($5118.6 billion, $n = 10{,}494$) (Supplementary Material 4). Total management costs were greatest in North America ($92.9 billion) and Oceania ($92.0 billion), then Asia ($48.9 billion), with the remainder each contributing under $30 billion. Considering total costs, all regions, except Antarctic-Subantarctic (damage cost = $0.9 million; management cost = $6.1 million; represented mainly by French Southern and Antarctic Lands, and South Georgia), spent less on management than was incurred in damages, ranging from 3-times less in Oceania to 92-times less in South America (Supplementary Material 4).

Considering the total management cost of $307.9 billion, just 5% ($15.0 billion, $n = 725$) has been spent on pre-invasion management, which is approximately 18-times less than that spent on post-invasion management ($263.5 billion, $n = 16{,}530$). Investments in knowledge funding reached $16.3 billion ($n = 1573$) and the remainder comprised mixed management types ($13.0 billion, $n = 1930$) (Supplementary Material 4). All regions (except Antarctic-Subantarctic: pre-invasion = $1.0 million; post-invasion = $0.8 million) invested less in pre-invasion management than post-invasion management, ranging from over 7000-times less in Africa to 4-times less in North America (Supplementary Material 4). For the sake of conservativeness and robustness, the remainder of the analyses (i.e. those in the remainder of the Results) is based on highly reliable, observed costs only (see Materials and methods).

The filtered dataset (i.e. excluding low reliability and potential costs) revealed qualitatively similar patterns. Management spending totalled $95.3 billion (n = 15,864), which is only 8% of the total incurred from damages ($1130.6 billion, $n = 4872$) (Fig. 1a). Total management costs were greatest in North America ($51.6 billion, i.e. 54%) and Oceania ($28.7 billion, i.e. 30%), with remaining regions spending under $5 billion. Across all regions except Antarctic-Subantarctic (damage cost = $0.9 million; management cost = $6.1 million), damage costs were substantially higher than management costs, ranging from 3-times higher in Africa to 77-times higher in Asia (Fig. 1a).

Within this filtered management spending of $95.3 billion, the investment in pre-invasion management is low ($2.8 billion, $n = 579$), with approximately 25-times less invested than in post-invasion management and with considerably fewer database entries ($72.7 billion, $n = 12{,}439$). In turn, $15.6 billion ($n = 1143$) has been invested in knowledge funding actions, with the remaining costs mixed in type ($4.2 billion, $n = 1703$) (Fig. 1b). Within management spending, all regions (except Antarctic-Subantarctic: pre-invasion = $1.0 million; post-invasion = $0.8 million) invested less in pre-invasion management than in post-invasion

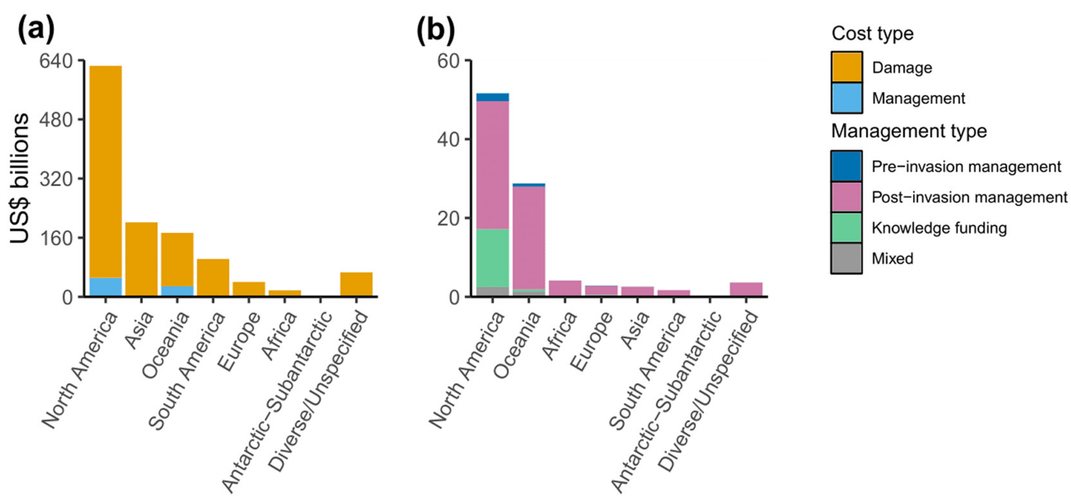

Fig. 1. Distribution of (a) total damage and total management costs and (b) management cost types across geographic regions, considering filtered (i.e. highly reliable, observed) costs in 2017 US$. The "Diverse/Unspecified" category encompasses cost estimates that could not be assigned to a single geographic region. Note different scalings on the y-axes and region ordering on the x-axes between subplots.

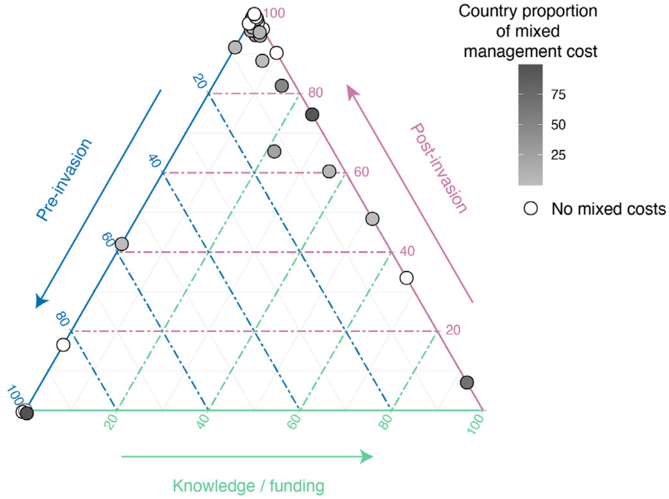

Fig. 2. Matrix of country-scale management spending for biological invasions considering proportional shares of pre-invasion management, post-invasion management and knowledge funding (and mixed cost types as a fill gradient). Note that only costs pertaining to individual countries (n = 83) were shown and points represent individual countries. The coloured dash-dotted lines illustrate zonations from each respective axis, such that each point sums to 100% across the three axes. Specific information for each country node is provided in Supplementary Material 5.

management, from over 1400-times less in Africa to 16-times less in North America (Fig. 1b).

Only 83 countries, out of the 204 included in InvaCost, documented some form of management costs, with almost all (n = 79) including post-invasion management (Fig. 2). Just 24 countries reported costs specifically associated with pre-invasion management, and 22 for knowledge funding. Accordingly, proportional management spending was highly clustered among countries towards post-invasion investment (Fig. 2; Supplementary Material 5).

Most pre-invasion management spending (70%) was recorded as invested at the country-scale, followed by site-specific scales (27%), and with relatively little expenditure reported at spatial scales larger than single countries (<1%). Post-invasion management was reported at similar levels proportionally: country-scale (67%), site-specific scales (24%), and 9% at international levels. However, knowledge funding spending was mostly expended at site-specific scales (87%), with more limited national (11%) and international (1%) spending. Any remaining cost estimates were provided at a diverse range of spatial units (e.g. square kilometres, hectares, etc.).

3.2. Taxonomic and environmental distribution

Although the largest shares of management costs were spent on diverse/unspecified taxonomic groups (42%, i.e. \$39.9 billion, n = 1763), the majority of taxonomically-defined costs were spent on invertebrates (58%, \$32.1 billion, n = 2764), then plants (27%, \$14.8 billion, n = 8912) and vertebrates (12%, \$6.7 billion, n = 2314) (Fig. 3a), followed by "Other" taxa, i.e. fungi, chromists and pathogens (3%, \$1.8 billion, n = 105). For all of these defined taxonomic groups, post-invasion management dominated over pre-invasion management (invertebrates: \$28.5 billion vs. \$0.2 billion; plants: \$14.5 billion vs. \$0.2 million; vertebrates: \$5.9 billion vs. \$0.6 billion; other: \$1.3 billion vs. \$0.1 billion); however, the largest share (68%) of taxonomically-defined pre-invasion management was spent on vertebrates overall.

Regarding habitat, the vast majority of overall management spending was on terrestrial species (69%, i.e. \$66.1 billion, n = 12,002), followed by semi-aquatic (\$6.7 billion, n = 1336) and aquatic (\$2.0 billion, n = 1521) taxa; the remainder was diverse/unspecified. When considering only pre-invasion management, terrestrial species were still highest in investment (\$840.4 million), but there was also a relatively large proportional share of investments on aquatic IAS (\$624.2 million) (Fig. 3b).

For costs that could be attributed to individual species, nine of the top ten species targeted with pre-invasion management were animals, and one was a chromist (Fig. 4), comprising four insects, three mammals, two reptiles and one alga. Similarly, post-invasion investments exclusively comprised animals in the top ten list (Fig. 4), with eight insects, one mammal and one bird. Just two of the costliest species for pre-invasion management, both insects (*Solenopsis invicta* and *Ceratitis capitata*), also appeared among the costliest for post-invasion management (Fig. 4). Interestingly, none of the species with the highest pre-invasion investment were among the top ten costliest invaders in terms of damages.

3.3. Temporal trends

Total global management spending has increased by two orders of magnitude since 1960, peaking at \$4.2 billion per year between 2010 and 2020, and with an annual average of \$1.6 billion since 1960. Global damage costs,

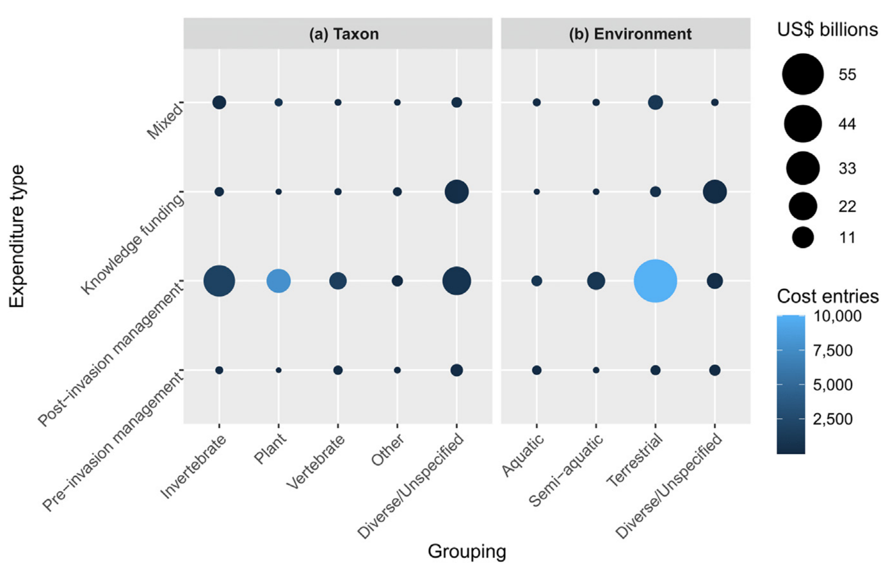

Fig. 3. Total management spending among expenditure types according to (a) taxonomic groups and (b) environment types in 2017 US\$. Note that "Other" taxa include fungi, chromists and pathogens. The colour ramp corresponds to expanded entry numbers.

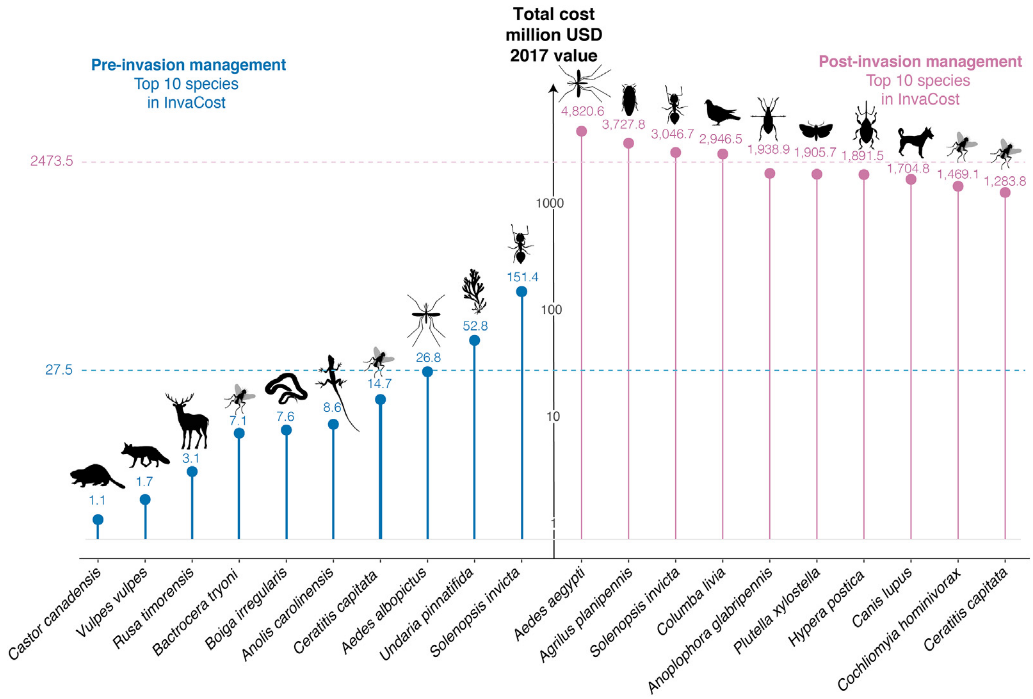

Fig. 4. Top 10 species incurring pre-invasion management and post-invasion management costs (in 2017 US$). Note that only species-specific entries were considered (i.e. not those unspecified or belonging to mixed groups) and the *y*-axis is on a $\log_{10}$ scale. Dashed lines correspond to the mean values from each group of ten species.

however, peaked at $78.2 billion in the 2000s, and were over ten-fold higher than management costs annually, averaging $18.5 billion per year since 1960 (Fig. 5a).

Pre-invasion management spending began to be reported much later than damage or post-invasion management (since the 1980s), and has increased through time with a peak of $162.1 million per year in the last decade, and an average of $46.6 million annually since 1960 (Fig. 5b). Post-invasion management has consistently been substantially higher than pre-invasion management (Fig. 5b), peaking at $2.8 billion per year in the 2000s, and averaging $1.2 billion annually since 1960. Knowledge funding investments have averaged $255.0 million per year since 1960, peaking in the most recent decade at $1.2 billion per year (Fig. 5b). The slight slowdowns or reductions in reported costs over recent years have likely resulted from delays in publication of invasion costs.

3.4. Statistical modelling

We found significant relationships between our response variables (damage and management costs) and some of the 12 tested predictors (Fig. 6; Supplementary Material 6). Due to high correlation with total human population ($r = 0.9$) and weaker predictive ability, GDP was removed from all models.

Considering total damages, (*i*) the amount of post-invasion management spending (estimate $= 1.2$, $t = 6.4$, $p < 0.001$) as well as (*ii*) the number of InvaCost references (i.e. unique cost sources) relating to damages reported (estimate $= 0.5$, $t = 5.2$, $p < 0.001$) were positively related to damage costs in a given country during a given decade (Supplementary Material 6). In addition, (*iii*) the effect of the total human population size on damage costs was significant and positive (estimate $= 0.1$, $t = 2.3$, $p = 0.02$) (Fig. 6).

Considering management spending, costs in a given country and decade were significantly positively related to (*i*) the amount of pre-invasion management spending in that country and decade (estimate $= 2.8$, $t = 8.6$, $p < 0.001$), (*ii*) the amount of damage cost in that country and decade (estimate $= 0.2$, $t = 7.0$, $p < 0.001$), as well as (*iii*) the number of InvaCost references relating to management costs reported in that country and decade (estimate $= 0.1$, $t = 2.9$, $p = 0.004$). In addition, (*iv*) the effect of the total human population size on total management costs was significant and negative (estimate $= -0.03$, $t = -2.6$, $p = 0.01$) (Fig. 6; Supplementary Material 6).

Damage costs have tended to increase and saturate across decades ($F = 1.7$, $p = 0.02$), whereas total management costs have decreased linearly across decades ($F = 0.9$, $p = 0.04$), notwithstanding time lags in cost reporting since cost incursion (Supplementary Material 6). Neither damage nor management costs were significantly related to the time-since-management variable. However, first management onset time was delayed at the global scale compared to the first damage cost onset per species (mean $= 10.7$ years). On the other hand, this delay has significantly decreased over time (estimate $= -0.8$, $t = -16.4$, $p < 0.001$, $R^2 = 0.43$) (Supplementary Material 3). All final models had reasonable levels of concurvity across all smooth terms (worst case concurvity < 0.6).

3.5. Cost of inaction

Through our model, we estimated that damage costs accumulated to $1291.4 billion from 1960 to 2020, whereas management costs amounted to only $158.0 billion. Assuming that these cost patterns reflected immediate management action for all species in all countries, management efficiency was constant over time, with a reduction of $53.5 in potential damage costs estimated for every $1 spent on management. If we instead assumed that all invasions were subject to our mean observed management delay time of 10.7 years, we estimated that this delay resulted in an additional global cost of $1247.2 billion relative to a scenario with immediate management. However, in the scenario where management was never introduced, the cost of inaction would have been approximately three-fold higher ($3423.6 billion; Supplementary Material 3) with damage costs potentially rising to $4873.0 billion. We also estimated that 95% of the cost of inaction was attained after a management delay time of approximately five decades, meaning that after delaying management by 50 years, the additional cost of waiting to manage does not increase much each year, highlighting the need for timely management of IAS (Supplementary Material 3).

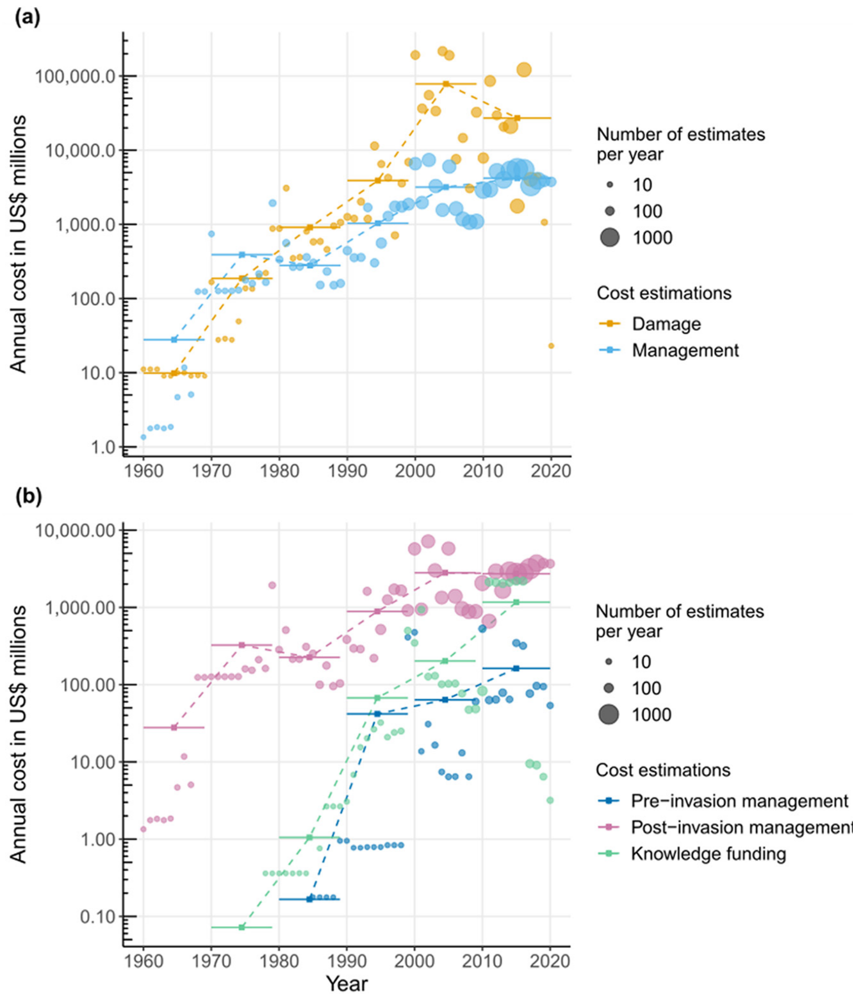

Fig. 5. Temporal trends in (a) total damage costs and total management costs, and (b) pre-invasion management, post-invasion management and knowledge funding investments. The solid horizontal bars represent decadal averages, and points show annual totals, scaled in size by expanded cost estimate numbers. Note that costs are shown in 2017 US$ millions and on a $\log_{10}$ scale.

4. Discussion

Management costs for IAS have totalled at least $95.3 billion worldwide in the last 60 years (1960–2020), and are potentially as high as $307.9 billion — at least one order of magnitude lower than damage costs over the same period ($1130.6 billion to $5118.6 billion). While these cost figures derived from the InvaCost database should not be perceived as exact totals (Diagne et al., 2021a), they represent the most up-to-date and exhaustive overview of management costs globally and allow us to investigate large-scale patterns. Our results reveal largely disparate, inadequate and rarely proactive management investments for addressing current and future IAS impacts. Consistent and marked differences in management typology were found, with proactive pre-invasion investments comprising a tiny fraction ($2.8 billion) of the filtered cost total — 25-times lower than reactive, post-invasion management. This trend was consistent among regions, with all regions (except offshore territories in the Antarctic-Subantarctic, where economic assets to be damaged are few) exhibiting substantially less management expenditures than observed damages, and always least in pre-invasion management. However, the magnitude of the difference between management types was greatest in Africa, Asia and South America, suggesting varying strategies or capacities to manage IAS or report costs. Geographical, taxonomical and environmental unevennesses were pervasive in management cost reporting, dominated by spending in North America and Oceania, and towards well-studied taxonomic groups such as insects, plants, birds and mammals (Pyšek et al., 2008). Models indicated that greater damages caused significantly higher total management spending through time, with current management delays having caused additional costs of $1247.2 billion at the global scale. Overall damage and management costs have been rising rapidly through time; a trend that is unlikely to abate in the future given the growing rates of biological invasions that could cause correspondingly higher economic impacts (Seebens et al., 2021).

4.1. Early-stage investments as the exception

Our results showed that damage costs not only largely outweigh management costs overall, but also that within management expenditures, proactive, pre-invasion management investments are much lower than reactive, post-invasion expenditures. Relatively low levels of proactive investment may be interpreted in two, potentially non-exclusive ways — depending on the success of these management actions. On the one hand, this result might reveal cost-efficient preventive actions so far, confirming that prevention is better and cheaper than 'cure' regarding biological invasions (Leung et al., 2002). This is further supported by management having three-times more expanded database entries than damage, but 12-times lower cost, indicating that management is generally cheaper than damage incurred. While this explanation remains broadly true (as efficient prevention measures mitigate further impacts from established invaders and their

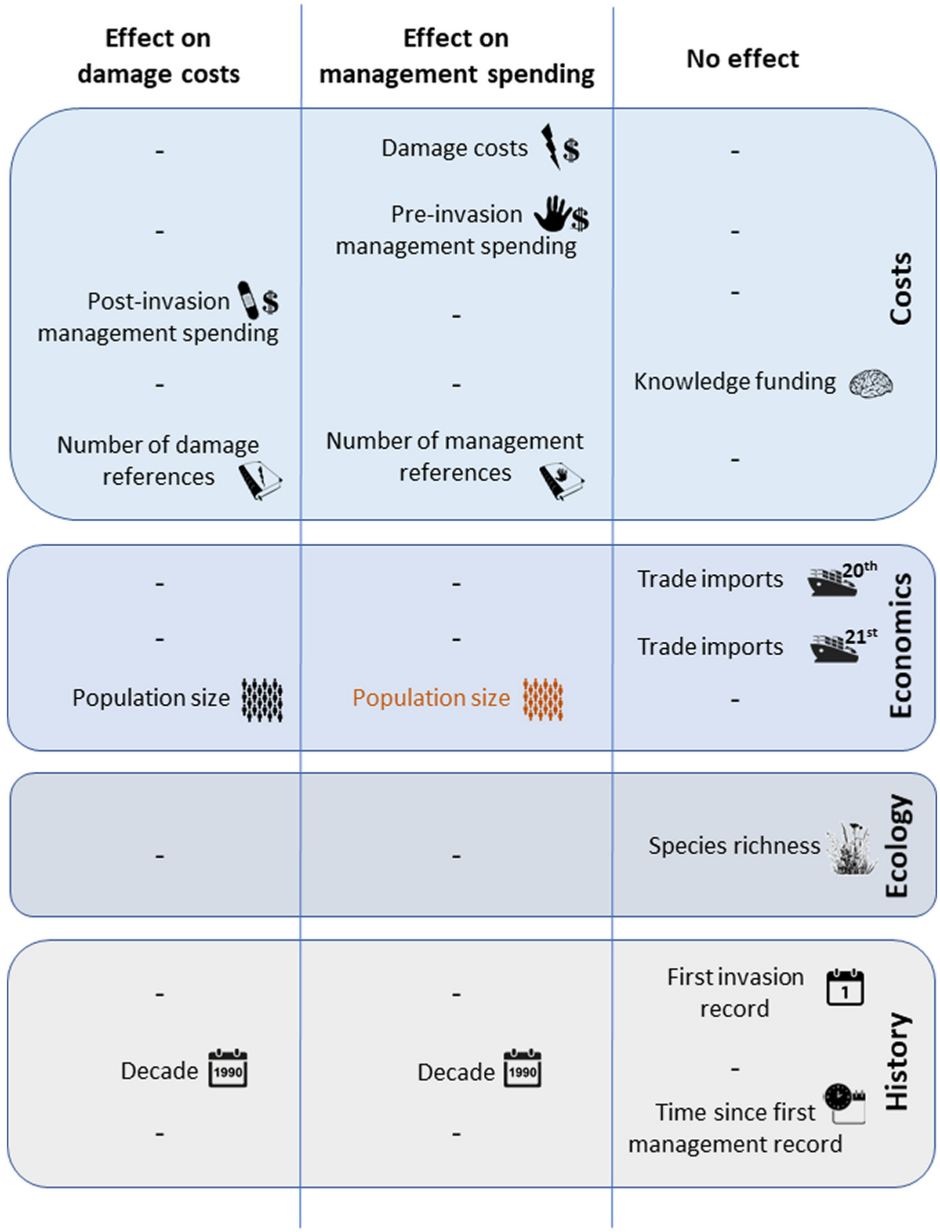

Fig. 6. Qualitative categorisation of significant ($p < 0.05$) effects considering total damage and total management costs per country and decade (no effects correspond to $p > 0.05$), grouped according to predictor type. Black text corresponds to a positive effect, and orange to a negative effect. All underlying coefficients are provided in Supplementary Material 6.

associated costs), it could not serve as a stand-alone reason for the low pre-invasion investment observed here, given the (*i*) known greater increase in damage costs compared to management spending, (*ii*) observed delays to management actions and (*iii*) ever-increasing ecological and health impacts of invaders globally (Pyšek et al., 2020). On the other hand, investments are typically most commonly made only when IAS-associated impacts become noticeable in colonised or otherwise protected areas, i.e. often when invaders are already well-established and their impacts are high and hard to minimise (Simberloff et al., 2013). Indeed, the average minimum management delay after reported damages was substantial (11 years), suggesting a sparsity of timely investment globally that has accrued substantial costs of inaction at the trillion-$ scale.

Examples of marked and sustained late-stage expenditures that would have benefited from earlier management interventions are legion (Supplementary Material 7). These examples have each borne substantial post-invasion costs, which could have been mitigated by effective prevention or rapid response measures (Ahmed et al., 2021). Conversely, there are examples of sound proactive management to minimise economic costs of invasions, as well as sanitary and ecological ones (Supplementary Material 7). Customs interceptions of insects in Australia, New Zealand and the US are a good illustration of efficient structures that would gain in being adopted elsewhere (McCullough et al., 2006; Turner et al., 2021). These services deal with large lists of potential invaders with only marginal costs for each additional species (Lougheed, 2007). As an example, interceptions as well as surveillance and early reaction protocols in New Zealand have allowed the identification and removal of several established colonies of red imported fire ants (*S. invicta*) over the last two decades (Ward, 2009). The first one, near Auckland airport, was managed for a cost of about 1.4 million NZ dollars, when if let to establish, its damage cost would have been at least 318 million per year (Convention on Biological Diversity, 2001). Invasions of this species now cost billions of dollars both in the US and in Australia (Angulo et al., 2021b). This proactive management of the red imported fire ant in New Zealand clearly illustrates how investing in pre-invasion management can save several hundreds to thousands of times the amount invested.

Aside from a few examples, the large discrepancy in expenditure across different stages of invasion is worrisome considering the budgetary constraints conservation managers face. Moreover, post-invasion management costs could arguably be added to the high costs of damages and losses as these impacts would have been avoided if their introduction/establishment had been successfully prevented. Concerningly, the cost differential between pre- and post-invasion management is often greatest in the Global South. In these regions, this trend could reflect the particularly limited budgets and hence capacity to manage proactively, with investments instead made reactively following impact detection. These trends and pre-post discrepancies held even when considering unfiltered (i.e. including low reliability and potential) costs. Nevertheless, there are some promising trends at the global scale, whereby pre-invasion investment and knowledge funding spending were increasing at a faster rate than post-invasion management between the 1980s and 1990s — albeit at a lower magnitude and unequally among regions — as well as reductions in management delays towards recent years.

Another pattern in our results is that at least two thirds of expenditures — particularly those at pre-invasion stages — were reported at the country scale or lower. Recent regulations and mandates have required countries to prevent, control and eradicate selected IAS and act collectively to achieve this, e.g. European Union Regulation 1143/2014 on IAS (EU, 2014); European and Mediterranean Plant Protection Organisation prioritisation for invasive alien plant species (Branquart et al., 2016). However, such cross-country initiatives are absent in many parts of the world. It has been well-demonstrated that biological invasions are a transboundary problem, and that concerted actions at regional scales improve efficiency and reduce overall expenditures (Faulkner et al., 2020). Therefore, not only should more be spent on biosecurity, but monetary resources need to be utilised strategically by considering broad-scale invasion pathways wherever possible (Turbelin et al., 2021). As the number of problematic IAS is positively correlated with the total number of established aliens (Ricciardi and Kipp, 2008), effective pre-invasion management will reduce the number of future problematic IAS, and therefore post-invasion management and damage costs (Early et al., 2016).

4.2. Imbalanced expenditures across management types

Stark geographic and taxonomic unevennesses were evidenced in the expenditure results of the present study. This is not particularly surprising as they largely reflect general biases in invasion research previously shown (Pyšek et al., 2008; Jeschke et al., 2012; Bellard and Jeschke, 2015). North America had by far the greatest pre-invasion management expenditure, and this might reflect relatively early efforts to report synthesised invasion costs in countries such as the US (Pimentel et al., 2000), which potentially promoted action in the following decades, during which proactive management has grown rapidly. Differences in damage and management expenditure data entries and costs among regions (e.g. North America vs. Africa) could additionally be linked to the different economic capacities of the countries, invasion histories, conservation priorities, levels of public awareness, socio-cultural differences and conflicting priorities, and differences in sectors affected, among other factors (Paini et al., 2016; Diagne et al., 2021a). They could also reflect language barriers, with the InvaCost database capturing costs in 'only' 22 languages, e.g. missing many African and Asian ones (Angulo et al., 2021a). In addition, it is worth noting that the significant difference in price levels between areas (e.g. labour costs for similar management actions are likely cheaper in most African countries when compared with those in Europe or North America) may contribute to discrepancies in reported costs among regions. Further monetary comparisons at the macroeconomic scale should require reliance on indicators such as the purchasing power parity, which are still prevented by very limited information for most countries and/or years from official sources such as the World Bank (Diagne et al., 2020b).

At the taxonomic level, post-invasion management dominated for all taxa, but vertebrates received the highest reported pre-invasion spending. However, scrutinising the data at hand reveals that this was mainly due to a single surveillance programme for multiple invasive fish species in Mexico, with this single report driving the trend towards aquatic vertebrates with respect to pre-invasion spending (Diagne et al., 2020b; Rico-Sánchez et al., 2021; doi:https://doi.org/10.6084/m9.figshare.12668570). While further highlighting the value of non-English data sources (Angulo et al., 2021a), this Mexican fisheries example shows the patchy nature of the available reported spending data, resulting in costs for a single group of species in a specific place and time driving large-scale patterns and potentially obscuring true data gaps or trends. This case also highlights a likely substantial underestimation of the global management cost, when considering all taxonomic groups and geographic regions which are targeted by managers. Nevertheless, the fact that biosecurity investments are often recorded for multiple species in our data may reflect a 'broad-sweeping' approach that targets multiple aliens simultaneously. Such approaches could include taking pathway-level actions, such as indiscriminate airport checking and ballast water treatment (Lougheed, 2007; Lin et al., 2020), or area-level approaches (e.g. protected areas and islands; Rico-Sánchez et al., 2021). Regardless, most investments across all management types have been towards terrestrial IAS, likely the result of human assets and economic activities being predominantly terrestrial and certainly most visible in this realm (Menge et al., 2009), and this aligns with similar unevenness in cost reporting across biomes (Cuthbert et al., 2021).

Research efforts have also been biased towards structurally larger taxa, whereas the effects (and even biogeography) of smaller and less well-resolved taxa (e.g. fungi, chromists, bacteria) often remain unclear (Cuthbert et al., 2022a). This reflects a broader trend within invasion biology, whereby research effort is positively related to the size of study biota (i.e. "smalls rule"; Carlton, 2009). Relatedly, we found very few management costs directly attributable to taxonomic groups often comprising small species (e.g. fungi, chromists). Nevertheless, a large overall proportion of costs were for diverse or unspecified taxa (i.e. $39.9 billion at the phylum level), indicating poor reporting resolution that could hamper the directing of future management efforts. Where resolution in reporting reached the species level, our study showed management concentrated on animals, but that a different suite of taxa received a focus for pre-invasion as opposed to post-invasion management, or caused the greatest damage costs. This difference between targeted species may be an artefact of effective prevention, disparate reporting, different damages among regions, or it may indicate that societies are not sufficiently investing in spread-prevention of species already documented to be damaging invaders elsewhere (i.e. the precautionary principle; Simberloff et al., 2013).

4.3. Gaps and evidence-based recommendations

Our work allowed us to identify a number of knowledge gaps as well as avenues for further improvements, for both research and applied purposes (summarised in Table 1). Importantly, we are aware that the trends and patterns in InvaCost only reflect a sample of the true costs at the time of writing this paper. Our work should therefore be considered as a baseline that will need to be updated and improved as new cost information is both generated and collated in this living database. The suite of data available is highly uneven and changing rapidly, with temporal trends showing a significant increase in the number of cost-reporting documents available over time (Haubrock et al., 2022), paralleling increasing cost magnitudes and invasion rates (Seebens et al., 2017), and diversifying impacts. Particularly, as IAS can remain undetected for several decades before their impacts start becoming apparent (Essl et al., 2011), future invasions could implicate a new suite of geographic origins, activity sectors, taxonomic groups and habitats that require different management approaches than those applied today. Estimation and reporting of cost data should be substantially improved and homogenised in the future to further identify trends in economic impacts and direct management actions (Diagne et al., 2020a, 2021a). It is

Table 1
Issues and evidence-based recommendations pertaining to the reporting of management cost data from biological invasions.

Issues	Evidence-based recommendations
Cost data are biased/skewed towards particular regions, taxa, sectors and habitats	Increasing cost-based studies, funding and ensuring more balanced cost reporting for less-represented contexts[a]
Ambiguities, inconsistencies and subjectivities are found in the reporting literature	Adopting a unique, homogenised framework for estimating and reporting different management expenditures dedicated to invasions[b]
Cost information reported is often fragmentary, imprecise and not readily usable	Improving engagement in a joint paradigm for integrated, concerted and cross-sectoral management efforts (e.g. context-based policies) and reporting (e.g. breakdowns of observed costs reported across types and contexts)[c]
Outcomes (failure/success) of the reported management costs are imprecise or not available	Formalising a common repository for management actions to inform on cost effectiveness and guide further strategies[d]

[a] The InvaCost database has allowed the launch of several dozen projects to better inform on the economic costs of biological invasions worldwide and provides a 'living' platform for cost reporting (Diagne et al., 2020b).
[b] The framework proposed by Robertson et al. (2020) could serve as a sound basis for building such a framework.
[c] See Courchamp et al. (2017), Vaz et al. (2017) and Novoa et al. (2018) for proposed ways, avenues and benefits for concerted approaches in invasion science.
[d] Such an evidence-based approach has been adopted in other contexts to aid decision making (e.g. https://www.conservationevidence.com/).

also critical that a better balance of cost reporting is achieved across spatial, taxonomic and sectoral scales, given gaps in the available data (Table 1).

Our study allowed us to identify three additional, specific areas where further improvement will be instrumental. First, there are many ambiguities and subjectivities created by the definitions used for management terms in the literature. As an illustration, the terms "monitoring" and "control" are often used either at both early-stages (e.g. to reduce opportunities for introduction of invaders) or at late-stages (e.g. to check or reduce population abundances) of the invasion process. Relatedly, terminology used to report impacts from IAS may be inconsistent among fields. For example, agricultural and public health sectors frequently refer to "pest species" without specifically differentiating IAS, or even IAS from native species, within this terminology, despite increasingly large proportions of managed species being IAS. As a result, a large number of costs of IAS may be missed from the literature (e.g. the case of rodents, Diagne et al., 2021c). We therefore advocate for future work to adopt a consistent framework for estimating and reporting different management expenditures dedicated to invasions (see Robertson et al., 2020).

Second, while "mixed" management costs (an unattributable combination of pre- and post-invasion management, or mixed with knowledge funding) formed a significant proportion (11%) of the expanded cost entries in the filtered dataset, a number of cost entries ($n = 124$) were not retained due to their classification as "unspecified" (i.e. it was not possible to identify and classify any specific actions taken with respect to the stage at which they occurred). Moreover, costs that were mixed between "damage" and "management" were excluded entirely because it was not possible to reliably distinguish and split the expenditure reported into specific categories. Similarly, economic valuation approaches to invasions are not always complete, with expenditures such as labour costs being implicit or simply overlooked (Born et al., 2005), or other opportunity costs (i.e. the value of another use of the management resource) also often not included in monetary estimates. Indeed, the inclusion of labour costs can rapidly result in differences of orders of magnitude in cost estimations to single sectors (e.g. Diagne et al., 2021b vs. Eschen et al., 2021). This highlights that clearer and more comprehensive breakdowns of cost reporting across types and contexts would increase the value of such data instead of aggregated total expenditures. Moreover, the management of IAS can raise a number of conflicts, including those arising from opposing economic interests and insufficient communication among resource managers, policymakers, natural and social scientists, and the public (Andreu et al., 2009; Crowley et al., 2017; de Groot et al., 2020; Kourantidou et al., 2022). In economic systems where IAS impacts are not necessarily caused and incurred by the same actors, understanding the nature of past management investments provides important evidence to inform discussion across all stakeholders. For this purpose, cross-sectoral efforts within and among scientists, decision-makers and stakeholders are needed to gather more specific and detailed information, potentially helping to balance cost reporting unevenness (Courchamp et al., 2017; Vaz et al., 2017). In turn, such concerted efforts may facilitate the implementation of context-adapted policies and management measures at appropriate scales (Novoa et al., 2018).

Third, we do not have an adequate understanding of the outcomes (failure or success) of the reported management actions for which costs are currently reported. There is accordingly an urgent need to formalise an international repository for management actions (their costs and successfulness) to collate data and get a clearer picture of the ratio between investment and success. Doing so may guide further actions in other places where the same IAS is expected to invade and provide a concrete, quantitative incentive to invest in proactive management. In doing so, we can build not only an account of how much has been spent (i.e. management effort), but also where the spending has been most efficient. This can therefore potentially identify which taxa should be targeted using which approaches, as currently it is not possible for any species to determine management efficiencies.

4.4. Call for a biosecurity commitment

Total management spending was significantly positively related to damage costs, pre-invasion spending and numbers of references in the present study. The positive relationship between management spending and references reporting expenditure intuitively suggests that greater efforts to research and report costs result in higher observed costs. However, recent studies have shown that costs are rising at a faster rate than references which report them, indicating that rising costs are not only due to reporting dynamics (Haubrock et al., 2022). Therefore, damage costs and post-invasion spending are likely growing substantially faster than pre-invasion investment, independently from reporting efforts. Positive relationships among cost types also suggest countries that report high costs in one area are more likely to report high costs in another, perhaps simply due to better cost reporting capabilities. Further, there could be a species-level effect, where species with very high damages are likely to be managed intensely at all stages of the invasion, thus causing a positive relationship between management cost types and damage costs. These processes would each act to mask any negative relationship between pre-invasion management spending and total damage or total management costs.

Nevertheless, recent mathematical modelling approaches, based on the invasion process, have been developed to quantify the cost of inaction and motivate proactive management, incorporating management efficiency (Ahmed et al., 2021). However, this inaction model was fit assuming that global cost records reflected a system without management delays. If we instead simulate the impact of our mean global management delay across species and countries, the average management delay of 10.7 years was found to have caused an additional cost of $1247.2 billion compared to a scenario with immediate management. Although management costs were initially reported in the year 1960, this was for a relatively small number of species (4 from a total of 366 species and country combinations). Species and country-specific delay times are centrally distributed around the mean time delay of 10.7 years, and this provides a more accurate representation of the time of management introduction at the global level (Supplementary Material 3). Moreover, had management actions never occurred, inaction costs in excess of $3423.6 billion would have accrued to the present day. Although coarsely modelled at the global scale considering that management spending was pooled across species and countries that had significantly varied delay times (Supplementary Material 3), this very concretely illustrates the benefits of proactively managing biological invasions. Indeed, modest initial investments circumvented massive future costs — each $1 of management was estimated to reduce damages by $53.5 in this study. The fact that this model provides estimates of total expenditure ($1449.4 billion in realised damage plus management costs) that are commensurate with other global cost estimates imparts additional confidence in our parameterisation. For example, total reported costs of invasions were found to have reached a minimum of $1.3 trillion globally (Diagne et al., 2021a), and later with an improved estimate of $1.5 trillion considering additional non-English sources (Angulo et al., 2021a).

There is also a broader human nature and morality argument to IAS management, whereby it is difficult to motivate proactive investment given intrinsic inclinations to react where impact becomes apparent. In particular, it is difficult to convey a need to invest to decision-makers when impacts are seemingly absent in the short-term, incurred by other sectors or in different regions, and when other demands on limited funds may seem more pressing. In addition, efficient proactive management will prevent any impact, paradoxically removing concrete reasons for said management. Drawing parallels to motivations for climate action, IAS management represents another "perfect moral storm", whereby more emphasis should be placed on urging decision-makers to act collectively and proactively to solve a growing global and intergenerational problem (Gardiner, 2006).

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.153404.

CRediT authorship contribution statement

RNC: Conceptualisation, Methodology, Data curation, Formal analysis, Visualisation, Writing - original draft, Writing - review & editing.

CD: Conceptualisation, Methodology, Data curation, Formal analysis, Visualisation, Writing - original draft, Writing - review & editing.

EJH: Conceptualisation, Data curation, Formal analysis, Visualisation, Writing - review & editing.

AT: Conceptualisation, Data curation, Visualisation, Writing - review & editing.

DAA: Conceptualisation, Data curation, Formal analysis, Visualisation, Writing - review & editing.

CA: Conceptualisation, Data curation, Visualisation, Writing - review & editing.

TWB: Conceptualisation, Data curation, Writing - review & editing.

EB: Conceptualisation, Data curation, Writing - review & editing.

FE: Conceptualisation, Data curation, Writing - review & editing.

PJH: Conceptualisation, Data curation, Writing - review & editing.

REG: Conceptualisation, Data curation, Writing - review & editing.

NK: Conceptualisation, Data curation, Writing - review & editing.

MK: Conceptualisation, Data curation, Writing - review & editing.

AMK: Conceptualisation, Data curation, Writing - review & editing.

FC: Conceptualisation, Methodology, Data curation, Visualisation, Writing - review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank the French National Research Agency (ANR-14-CE02-0021) and the BNP-Paribas Foundation Climate Initiative for funding the InvaCost project and the work on InvaCost database development. The present work was conducted in the frame of InvaCost workshop carried in November 2019 (Paris, France) and funded by the AXA Research Fund Chair of Invasion Biology and is part of the AlienScenario project funded by BiodivERsA and Belmont-Forum call 2018 on biodiversity scenarios. RNC was funded through a Leverhulme Early Career Fellowship (ECF-2021-001) from the Leverhulme Trust and a Humboldt Postdoctoral Fellowship from the Alexander von Humboldt Foundation. DAA is funded by the Kuwait Foundation for the Advancement of Sciences (KFAS) (PR1914SM-01) and the Gulf University for Science and Technology (GUST) internal seed funds (187092 & 234597). CA was funded by the French National Centre for Scientific Research (CNRS). TWB acknowledges funding from the European Union's Horizon 2020 research and innovation programme Marie Skłodowska-Curie fellowship (Grant No. 747120). FE was funded through the 2017–2018 Belmont Forum and BiodivERsA joint call for research proposals, under the BiodivScen ERA-Net COFUND programme, and with the funding organisation Austrian Science Foundation FWF (grant I 4011-B32). NK is funded by the basic project of Sukachev Institute of Forest SB RAS, Russia (Project No. 0287-2021-0011; data mining) and the Russian Science Foundation (project No. 21-16-00050; data analysis).

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