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High and rising economic costs of biological invasions worldwide

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Summary

Biological invasions are responsible, in addition to significant biodiversity declines, for enormous economic losses to society as well as monetary expenditures for their management[1,2]. The *InvaCost* database has allowed for the first time a reliable, comprehensive, standardized, and easily updatable synthesis of the monetary impacts of invasions worldwide[3]. Here, we found that total reported costs of invasions reached a minimum of $1.288 trillion (2017 US dollars) over the last few decades (1970-2017), with an annual average cost of $26.8 billion. Moreover, we estimate that the annual average cost could reach $162.7 billion in 2017. These costs remain massively underestimated and do not show any sign of slowing down with a consistent three-fold increase per decade. Our synthesis reveals that documented costs are both widely distributed and with strong gaps at regional and taxonomic scales, with damage costs being an order of magnitude higher than management expenditures. Research approaches for documenting costs of biological invasions need to be further improved. Nonetheless, our findings are a compelling call for the implementation of consistent management actions and international policy agreements aiming to reduce invasive alien species burden.

Invasive alien species — species successfully introduced, established and spread beyond their native range — can have profound, negative impacts on biodiversity[4], ecosystem functioning and services[5], human health[6] and welfare[7], as well as on the economy[8]. In addition, biological invasions are increasingly exacerbated by globalization and climate change[9,10]. The worldwide implementation of efficient, coordinated control and mitigation strategies remain limited, mostly due to the impacts of biological invasions being undervalued by the general public, stakeholders and decision-makers[11]. A clear and standardized overview of the economic costs of invasions should contribute to (*i*) optimizing current and future cost-effective management strategies[12] and (*ii*) strengthen awareness and communication to a wide and diverse audience[13]. This would help to move the issue of invasions higher on international policy agendas for sustainable development[14].

Invasive alien species are responsible for substantial losses of goods, services and production capacity (such as reduced crop yield, damaged infrastructure and altered use values of ecosystem services)[8], and economic resources are spent each year for their management[15]. There are few global attempts of cost assessments[16], which all suffer recognized flaws[15] and the majority of assessments are restricted to particular taxa [e.g.,8], sectors [e.g.17] or areas[e.g.,15]. As biological invasions are an increasingly planetary issue, a worldwide reliable economic impact assessment is needed to quantify more precisely patterns and trends of associated costs[18,19]. We have now addressed this need with an analysis of the most comprehensive database compiling the documented economic costs of biological invasions — the *InvaCost* database[3]. This database covers most taxonomic groups, activity sectors, and geographical regions worldwide. Here, we provide (*i*) robust estimates of the large economic costs of invasions reported worldwide, (*ii*) the trends of these costs reported over time and their distribution among regions, taxa and cost types, and (*iii*) original recommendations for future reporting of economic data in invasion science. Finally, we discuss the research and policy implications from this pioneering analysis of the economic facet of invasions.

Results

We used two complementary approaches to assess the global costs of invasions reported over time from the most robust subset (n = 1319 cost estimates; ~ 57%) of the original database (see *Methods* for detailed procedures and rationale for limiting biases). First, we assessed these cost estimates directly using the cost from the database (see *Methods*, *Approach based on available estimates*). We found that the minimum reported cost of biological invasions to human societies reached a total of $1.288 trillion (2017 US dollars) between 1970 and 2017. Over this period, invasions resulted in an average of $26.8 billion per year (Fig. 1). This average annual cost steadily increased over time and reached $83.3 billion between 2000 and 2009, but declined to $29.2 billion between 2010 and 2017 (Fig. 1; Supplementary Table 1). This apparent decrease for 2010–2017 is most likely an artefact arising from a lack of cost estimates given the multi-year delay between occurrence and reporting in the literature. An overall rise in the reporting rate for costs in the literature might also contribute partially to the observed increase in costs.

We therefore addressed these issues by modelling the temporal trends of costs over the same period (see *Methods*, *Modelling-based approach*; Supplementary Methods 1). Globally, our models confirmed that costs have continuously increased each year since 1970, at a rate of more than three-fold per decade and that such an increase is expected for the latest decade as well (i.e., 2010–2017) (Extended Data Fig. 1; Extended Data Fig. 2; Supplementary Table 2). Hence, this confirmed that the apparent decline observed in the last few years with the previous approach was likely due to the paucity of reported data over the recent past rather than an actual downward trend in costs (Supplementary Methods 1). We therefore estimated that the global average cost of invasions ranged between $1.0 and $3.1 billion annually in 1990, between $5.6 and $32.6 billion in 2000, and between $18.3 and $38.1 billion in 2010. Ultimately, we predicted that the average annual cost of invasions reached the range of $46.8 billion to $162.7 billion in 2017. We also found large and increasing, inter-annual variation in the cost estimates (illustrated by the different trends between the 0.1 and 0.9 cost quantiles), with few high-cost years and most years exhibiting below-average economic costs (illustrated by the lower rate of increase predicted for the median cost than for the average) (Extended Data Fig. 2; Supplementary Methods 1). Overall, we observed similar patterns of cost increase when scrutinizing these global costs regarding the *types of costs*, or at the *taxonomic* and *geographic* levels (Figs. 2-4; Extended Data Figs. 3-4; Supplementary Methods 1).

Regarding the *types of costs*, we considered either ‘damage’ (economic losses due to direct and/or indirect impacts of invaders) or ‘management’ (economic resources allocated to actions dedicated to avoid or limit negative impacts of invasions) (Supplementary Methods 2). We found that costs from invader damage (total cumulative cost of $892.2 billion; annual average of $18.6 billion year^{-1}) were about thirteen times higher than expenditures for managing invasions ($66.3 billion; $1.4 billion year^{-1}) for 1970–2017 (Fig. 2; Extended Data Fig. 3) — this is despite fewer cost estimates (Supplementary Table 1). Furthermore, damage costs (~ six-fold increase every 10 years) increased at a much faster rate than management costs (< two-fold increase every 10 years) (Fig. 2; Extended Data Fig. 3).

At the *taxonomic* level, we considered the three major groups for which we had substantial information in the final dataset: plants, invertebrates and vertebrates. We calculated $591 billion from estimates unambiguously assigned to a single taxonomic group (Supplementary Table 1). Within this subset, invasive invertebrates appeared the costliest, with a cumulative cost of $416 billion and an average annual cost of $8.7 billion from 1970–2017, estimated to increase up to $23.8 billion year^{-1} in 2017 (Fig. 3). This essentially occurs due to a predominance of reported costs from insects (~ 90% of the total cost). Vertebrates had the second-highest financial impact, with a cumulative cost of $166 billion and an average annual cost of $3.5 billion for 1970–2017. We estimated this average cost to decrease at $1.3 billion year^{-1} in 2017, mostly because the higher average cost for 1970–2017 is driven by a limited number of years with high costs — and not necessarily due to the scarcity of cost data during the last decade (Fig. 3; Extended Data Fig. 4). Most (~ 88%) of the total amount calculated was from mammals. Plants had the third cumulative cost ($8.9 billion) for the same period, but this likely due to data deficiency in the current database for this group (n = 221 cost estimates *versus* n = 469 and 526 for invertebrates and vertebrates, respectively) rather than an actual pattern of cost distribution (Supplementary Table 1; Supplementary discussion 1). The observed increase in the temporal dynamics could support such assertion (Extended Data Fig. 4; Supplementary Methods 1).

At the *geographic* level, economic estimates that can be unambiguously attributed to a single region accounted for a total cumulative of $959 billion for 1970–2017 (Supplementary Table 1). The distribution of these costs was highly skewed towards North America (Fig. 4; ~ 57% of the total cost) with an average reported cost of \$11.0 billion year^{-1} for 1970–2017. Costs for the other regions ranged from \$120 million year^{-1} to \$5.6 billion year^{-1} (Supplementary Table 1).

Discussion

Large and increasing cost estimates. Invasions are clearly economically costly to human societies, with a minimum of \$1.288 trillion in losses and expenses accumulated between 1970 and 2017 and a trebling of the average annual cost every 10 years. We predicted this amount to reach between \$18 billion and \$38 billion in 2010 and exceed US\$47 billion to 163 billion in 2017 worldwide. Considering the different timeframes and inflation, the annual amounts we estimated in the early 2000s (\$6 billion to \$33 billion in 2000) seem lower than the earlier estimate inferred by Pimentel et al.[16]. This discrepancy is mostly explained by our conservative approach based on (*i*) keeping only the most robust data from the original database (~57% of our dataset), (*ii*) relying on scientific and official materials reporting cost estimates rather than hypothetical calculations of the costs of the impacts, and (*iii*) considering the most realistic assumptions on the temporal dynamics of invasion impacts worldwide. Considering a less-stringent approach to our data selection would have led to a global amount 33 times higher for 2017 (\$5.405 trillion; Extended Data Fig. 6). Nevertheless, our conservative, annual global estimates still represent a huge economic burden. As an illustration, this average annual cost largely exceeds the gross domestic product (GDP) of 50 out of 54 countries on the African continent in 2017 (data.worldbank.org); it is also more than twenty times higher than the total funds available in 2016–2017 for the World Health Organization (open.who.int) and the United Nations (un.org) combined. Moreover, we found that costs roughly doubled every six years, a pattern mimicking the continuous increase in the number of alien species worldwide[20]. Assuming a similar continuing trend would place the global average costs of invasions in the alarming order of trillions of dollars annually over the coming decade. This temporal trend can potentially be explained by a combination of three factors: the ongoing intensification of global trade and transport creates many more opportunities for invasions[20]; the growing ‘land take’ of the planet surface (e.g. expansion of agriculture and infrastructures) makes our societies increasingly sensitive to impacts from these invasions[21]; and the awareness and reporting of economic impacts of invasions have concomitantly grown over time[22] (Extended Data Fig. 7).

Underestimated global costs. More alarmingly, these costs are still largely underestimated. First, we relied on a conservative approach based on the most robust portion of the original dataset (see *Methods*). Hence, our analyses revealed a substantial inter-annual variability in the costs over time. This pattern likely arose from insufficient data for many years during the targeted period. Second, the corpus of available reported costs is inherently restricted by an unknown proportion of relevant but inaccessible grey literature[3], logistical and linguistic constraints which impair the discovery of all non-English sources[23], the subjective terminology in invasion science[24] and the lack of reporting consistency (e.g. salaried positions are rarely included)[25] which hamper consistent data collation. For instance, considering emerging pathogens (currently underrepresented in the original database) in the framework of biological invasions[26] would greatly increase our estimated costs. In that way, increasing relevant assessment of sanitary impacts associated with alien invaders[e.g.27,28] (e.g., including indirect costs on tourism or productivity) offer new opportunities. Third, the data available are geographically and taxonomically uneven (79% of the recorded data belong to high-income regions from North America, Oceania and Europe; and 76% are linked to animal taxa, while plants are recognized as a major group of invaders[29]), meaning that impacts might be further undervalued for many areas and taxa. As a likely consequence, cost amounts were highest for insects and mammals confirming nevertheless that both taxonomic groups include some of the most pervasive and harmful invasive species worldwide[8,30]. Similarly, North America was by far the region with the highest reported amounts, illustrating that high-income areas are more prone to report invasion impacts while simultaneously having better financial capacity to invest in management responses[31]. The influence of local economic priorities, practical limitations and cultural and historical specificities on research agendas might also partially explain these geographical discrepancies. These patterns might also only reflect a trend broadly described in invasion science as a bias in research effort rather than an actual distribution of data[29,31]. Fourth, an undetermined — but probably large — proportion of total invasion costs is simply ignored due to many invasion impacts remaining undetected[32]. Hence, invasion costs can remain hidden and/or underestimated over time simply because (*i*) the moment of introduction, (*ii*) the date at which an invasion starts to be costly and (*iii*) the shape of the cost dynamics when they start are generally all unknown or unreported. Lastly, the monetary valuation of particular 'costs' such as losses of non-market values, indirect impacts, or impacts on some ecosystem services is rarely straightforward[33,34]. The very principle of monetary valuation of nature is often associated with philosophical or ethical debates[35,36]. These types of monetary losses are therefore underrepresented and underreported in the body of documented costs and their relevance within the global cost of invasions remains contentious[3].

Caveats and directions for further research. Our study should serve as an empirical basis for substantial and iterative improvements of research on this topic. Indeed, the intrinsic complexity and heterogeneity of the cost information available[3] as well as the inherent intricacies associated with their relevant analyses require strong caution when investigating and interpreting them[19]. First, while we clearly demonstrate that the costs have been rising steadily over time, this finding obviously relies only on costs documented in the literature. However, it currently remains impossible to disentangle rising costs from increasing publishing and reporting rates. Therefore, we are referring to reported costs and not to exhaustive ones. Regardless of whether our increased reported costs reflect more increasing costs or increasing reports, the final amounts robustly show staggering amounts. Second, while we show that the costs we report are not evenly distributed regionally and among taxa, discussing specific patterns further, or drawing conclusions based on the cost distribution highlighted, would be too speculative. This is because *(i)* the costs we assessed represent only a limited fraction of the full cost (see above) and *(ii)* specific data processing and awareness are required for depicting how reported costs are actually distributed[19]. Third, while we ensured robust data pre-processing prior to analysis, the quality and reproducibility of reporting studies remain intrinsically variable. Such variability inevitably leads to uncertainties associated with some cost estimates derived from questionable methodologies[8]. Therefore, the cost figures we report should be considered in terms of relative orders of magnitude rather than precise cost estimates.

We therefore advocate for (*i*) strengthening interdisciplinary cooperation among scientists and concerned stakeholders to capture as much as possible the completeness, diversity and complexity of invasion costs, (*ii*) increasing the number and spatial coverage of studies to achieve a more balanced and complete picture of invasion costs globally, especially in low-income areas, and (*iii*) ensuring a minimum standardization for acquiring and publishing economic data on invasions (the descriptive fields implemented in the database provide a relevant basis[3]). The ten costliest taxa from our dataset (Fig. 5) illustrate well this need for more accurate and complete cost information (Supplementary Discussion 1). In this respect, we provide seven recommendations for an appropriate collection and reporting of these costs data (Table 1).

Societal and policy implications. The reported economic damages caused by invaders were approximately an order of magnitude higher than the money spent to manage them, and damage costs increased twice as rapidly as management expenditures each decade. While this result might reveal more cost-efficient management actions locally, the large increase of these damage costs globally confirms that the actual implementation of international agreements by local authorities is still scarce[37]. This strong discrepancy between these costs and the low societal awareness of invasions in general is a problem. This calls for reassessing the emphasis placed on this major driver of global change in international agendas as connecting research actions and societal perspectives is increasingly needed. The prioritization of policy and management actions could benefit from linking cost information to other data repositories measuring different aspects of invasion impacts worldwide, such as the Global Register of Introduced and Invasive Species (GRIIS)[38] and the Socio-Economic Impact Classification of Alien Species (SEICAT)[22]. In addition to remaining a main priority of multilateral environmental agreements such as the Convention on Biological Diversity (CBD/COP/DEC/XIII/13; cbd.int/meetings/COP-13), managing invasions must be reinforced as a priority for national governments. In particular, invaders costs could be significantly reduced with timely investments in preventive measures (such as risk assessment, pro-active surveillance and early detection) and cost-effective control campaigns (such as biological control)[39,40]. More evidence-based and integrated management actions should be set up for each specific invasion context as some invaders might also have neutral or positive outcomes for local ecosystems and economies[41]. The transboundary nature of invasions reinforces the need for concerted international governance with transboundary legal instruments and balance management expenditures at a regional scale[37,41]. Low-income regions have limited capacity to act against invasions and often have few historical invasions[31,42], thus international cooperation should concentrate on preventing further invasions in these areas. More generally, biological invasions should become a major decision factor in most transnational projects. One of the most contemporary and emblematic examples is the ambitious *Belt and Road Initiative* that will open avenues along its way for new species introductions[43]. The unintended impacts — including costs — that will be likely generated for all implicated countries ought to be accounted for in the estimated net income of this commercial initiative. Hence, our work concretely supports the inclusion of economic costs as a complementary quantitative indicator of invasion impacts.

In conclusion, invasions generate a massive but still undervalued economic burden to our societies. Our findings illustrate that these reported costs (*i*) have significantly increased over the last few decades, (*ii*) show no sign of slowing down, (*iii*) deserve more and better organized research, and (*iv*) stress the need of evidence-based and cost-effective management actions. Most worrisome is that these economic losses are only part of the full aggregate of impacts incurred from invasive alien species. Indeed, the ecological and health impacts of invasions are at least as significant, yet often incalculable[4,6]. Finally, our work highlights once again the critical need of more global investments in research as well as policy development and implementation to minimize the impact of invasions worldwide.

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FIGURE LEGENDS

Figure 1 | Temporal trend of global invasion costs (in 2017 USD millions) between 1970 and 2017. The solid line represents the temporal dynamics of costs based on a linear regression (see Extended Data Fig. 2 and Supplementary Methods 1 for details). The dashed line connects the average annual costs for each decade, while the horizontal dotted line indicates the average annual cost for the entire period (see Methods, *approach based on available estimates* for details). The last three years (displayed as triangles) were not included in the model calibration; they are data-deficient and likely contribute to the artefactual decrease in global costs during the last decade (Supplementary Methods 1). We considered 1319 cost estimates from the original database following successive processing steps.

Figure 2 | Temporal trends of global *damage* and *management* costs (in 2017 USD millions) based on both average annual costs for each decade and model prediction between 1970 and 2017. *Damage*: economic losses due to direct and/or indirect impacts of invaders, such as yield loss, illness, land alteration, infrastructure damage or income reduction; *Management*: economic resources allocated to actions to avoid the invasion or to deal with more or less established invaders such as prevention, control, research, long-term management or eradication. Regression lines were obtained by robust regression to minimize the effect of outliers (see Supplementary Methods 1). The last three years (displayed as triangles) were not included in the model calibration. We considered 1287 cost estimates (n = 402 estimates for *damage* costs; n = 878 estimates for *management* costs) from the original database.

Figure 3 | Cumulative costs over time for 1970–2017 and 2000–2009 (a, b, c); and the average annual costs (d, e, f) as observed in the database (1970–2017 and 2000–2009) and as predicted by linear regression over time for 2017 for taxa with enough data (i.e., > 30 years of data). Costs are expressed in 2017 USD millions. Cost values only include estimates that could be derived for one of the three major taxonomic groups (invertebrates, plants, vertebrates), with all taxonomic classes grouped within represented in boldface. We chose 2000–2009 as the decade for which we have the most complete data and the highest economic impacts of invasive alien species, although data are clearly more limited for plants. The average annual costs for 1970-2017 and 2000-2009 are represented without error bars for two reasons following Weissgerber et al. (2015)[42]. First, there are insufficient data for error bars to be meaningful; second, the distribution of data is skewed, with most years having a lower-than-average economic cost. CI: 95% confidence interval.

Figure 4 | Geographic distribution of the cost estimates (in 2017 USD millions) available in the most robust subset of the original database over 1970–2017. We only included estimates that could be derived for a single geographic region (Africa, Asia, Central America, Europa, North America, Oceania-Pacific islands, South America) or country.

Figure 5 | The 10 costliest taxa from the most robust subset of the original database regarding both cumulative damage and management costs (in 2017 USD millions) between 1970 and 2017. Each bar represents a species or a complex of species (when different species were often considered simultaneously to provide cost estimates). Numbers below bars indicate the number of cost estimates. This ranking illustrates the limits of the available data and the need for more thorough and standardized cost reports (Supplementary Discussion 1). All silhouette animals were freely downloaded from an open source platform (http://phylopic.org/).

TABLES

Table 1 | Recommendations for relevant reporting of economic data associated with biological invasions.

Type of information	Recommendations	Applicability
cost reproducibility	provide sources for directly reported economic costs and indicate all potential steps applied to derive economic costs	enables reproducibility of analysis, facilitates use of cost data in syntheses and meta-analyses
cost responsibility	identify who pays for the incurred costs (e.g., governments, stakeholders, activity sector, private companies, citizens) in the impacted area	identifies the breakdown of costs for each category of impact
monetary estimate	provide the currency (and for multi-country currencies, such as dollars, provide also the country) and the year of the cost estimation	allows appropriate cost conversion and standardization for comparing transboundary trends and drawing broad interpretations
implementation and type	characterize the *observed* or *potential* implementation of the costs, and their distribution between *damage* and *management* expenditures	evaluates the real and specific impact of invaders as well as the cost-effectiveness of dedicated actions
spatial coverage	give the exact location and the geographical boundaries (at the finest scale possible) where the cost was estimated	allows relevant spatial extrapolation of cost data at different scales for forecasting
taxonomy of invaders	identify which individual species are associated with the monetary impacts	estimates the specific contribution to the total cost in cases of multiple species involved
temporal extent	indicate the precise start and end year(s) as well as the duration (which identifies cases where a cost estimate is provided for a one-year period straddling two calendar years) over which the cost estimates occur	tracks the temporal dynamics of damage and management costs to identify whether, how and why the trajectory of costs changes

Methods

Dataset and processing steps

We used the *InvaCost* database that compiles and describes the monetary costs associated with invasive alien species globally[3]. For each entry, we considered the cost estimates standardized to 2017 US dollars ($) based on exchange rates provided by the World Bank (see column *Raw cost estimate 2017 USD exchange rate*), because this allowed us to consider almost all cost data entered in the database. Note obvious duplicate cost estimates (*i.e.*, same cost figures from [non-]identical sources) were removed when building the database, while acknowledging that some overlaps can still occur[3] (see also Supplementary Discussion 1). To ensure a realistic, robust and conservative synthesis, we filtered out some cost data from the database to keep only those expected to have actually occurred. Therefore, we first applied filters to exclude unrealistic or potential costs. To do this, we successively excluded estimates corresponding to *potential* costs (*Implementation* column; n = 539) and then those derived from studies deemed of *low* reliability (*Method reliability* column; n = 531). Second, we removed cost entries that did not have a known *start year* to avoid considering these dubious costs for a period of one year (n = see 'Duration time of cost estimates' below). Thus, from an initial pool of 2419 cost estimates in the original database, we kept a final total of 1319 cost estimates deemed to be the most robust in the final dataset (Supplementary Data 1). From there, although a few undetectable and redundant estimates might still occur, the costs derived from our robust subset still represent conservative estimates.

Database descriptors

We considered three descriptors from the dataset to decipher how cost estimates are distributed over regions, taxa and types of costs. For the spatial distribution, we used information from the *geographic regions* column. For the taxonomic distribution, we combined information from *kingdom*, *phylum* and *class* columns to group the economically harmful invaders recorded among *plants*, *invertebrates* and *vertebrates*. For the type of cost, we used the information from the *type of cost* column to classify the cost estimates among *damage* (economic losses due to direct and/or indirect impacts of invaders, such as yield loss, health injury, land alteration, infrastructure damage, or income reduction) or *management* (economic resources allocated to actions to avoid the invasion, or to deal with more or less established invaders such as prevention, control, research, long-term management, eradication) costs (Supplementary Methods 2). For specific analyses on cost distribution, we ignored the estimates that could not be unambiguously assigned to one or the other category of the targeted descriptors.

Duration time of cost estimates

Deriving the average annual cost of invasions over time requires knowing the years over which impacts occurred, but this information was not readily available for 720 out of 1338 entries in the database (i.e., cost data marked as *unspecified* in the *probable_starting_year* and/or *probable_ending_year* columns). We filled the missing information on the duration of each cost estimate with educated estimates based on the available information (based on duration of impacts indicated by the authors), or publication year when no information was available in another set of two columns created for the purpose of our analysis. We again opted for a conservative choice when completing missing data. When no period of impact was specified, we counted only a single year for costs repeated over several years, but for which we had no information on the exact duration (even though the cost might have been repeated over many years, even up to present time). Therefore, the number of years over which a cost likely occurred was the difference between the *probable_starting_year* and the *probable_ending_year* columns (to which we add a 1 to avoid null values for costs occurring only once). We thereafter chose to focus on the period 1970–2017, where 1970 is the first year from which *InvaCost* has robust and sufficient economic data, and 2017 is the last year for the standardized data collection.

Estimating global cost patterns

Because the raw cost estimates standardized to 2017 US$ (*raw cost estimate 2017 USD exchange rate* column) encompass estimates with two different time ranges (‘period’ or ‘year’ in the *Time range* column), they were expressed as annual costs (*Cost estimate per year 2017 USD exchange rate* column). To do this, we divided the raw costs provided for a period exceeding a year (‘period’ in the *Time range* column) by the duration time described above, while we did not transform the raw costs provided yearly or for a period up to one year (‘year’ in the *Time range* column). For estimating global cost patterns and trends over time, we used two approaches described in the following two paragraphs and fully implemented in the 'invacost' R package[44].

Approach based on available estimates. We first depicted global cost patterns by calculating the average annual cost for each decade since 1970 (intervals of ten years, except for the last period 2010–2017 that is incomplete). For this, we summed all the annual costs occurring each year of a given decade and then divided them by the number of years. Second, we calculated the average annual cost for the entire period (1970–2017). We presented average annual costs rather than median annual costs because we assumed that the skewness of data is caused by the considerable incompleteness of economic data for most years. Therefore, we deemed that the average annual cost is probably closer to the actual annual cost than the median.

Modelling-based approach. Nonetheless, while the first approach is important to depict the patterns obtained directly from the content of the database, it might not be sufficiently robust to infer the actual cost patterns. Indeed, it does not take into account the dynamics of both invasions and their costs over time. In addition to the increasing trend of invasions worldwide[9], a time lag of several years is likely to exist between the actual occurrence of a cost and its reporting in the grey or scientific literature (Supplementary Methods 1). Ignoring this time lag likely underestimates the average annual economic cost of invasions, especially at the end of the time series because the most recent costs are probably not yet reported or published. This discrepancy could explain why the average annual cost for the last decade (2010-2017) appears lower, giving a biased summary of the actual trend of the costs over time. Therefore, we modelled the long-term trend of costs over time to derive estimates of average annual costs. To account for the time lag caused by the reporting of costs, we excluded the most incomplete years (i.e., years expected to have < 25% of cost data; Supplementary methods 1).

To model the temporal cost trend, we used an ensemble approach based on different linear and non-linear techniques (details, procedures and appropriate literature are fully provided in the Supplementary Methods 1): ordinary least-squares linear and quadratic regressions, robust linear and quadratic regressions, multiple adaptive regression splines (MARS), generalized additive models (GAM), and quantile regression. We accounted for temporal autocorrelation and heteroscedasticity with methods specific to each model (see details in Supplementary Methods 1). We $\log_{10}$-transformed all the annual costs prior to analysis. We had one *a priori* assumption on the probable shape of trends over time. Because of the exponential increase in the number of invasive species globally (Seebens et al. 2017), we expected the long-term temporal trend to be either increasing or stabilizing, but not decreasing. Hence, we assumed that a model describing a decreasing trend in recent years (i.e., for years lower than the 75% completeness threshold) could indicate an effect of the lack of data for recent years. We provided the entire range of model predictions for three decadal years as benchmarks (1990, 2000 and 2010) as well as for 2017, which was the last year of our data collection. Note that this approach was not designed for future extrapolation because there is no certainty that the underlying explanatory factors of cost trends will be similar in the future. Moreover, we did not apply this *Modelling-based approach* to geographical regions, because we could not adequately model trends over time due to data deficiencies.

Note that the economic valuation of costs of invasions is a highly challenging task (see Jackson et al. 2015[2] for a critical review). All the cost estimates presented here represent ranges that should be viewed in terms of relative orders of magnitude rather than exact figures. All analyses and figures generated were made with the 'invacost' R package[44].

Supplementary Information. Supplementary information is linked to the online version of the paper at www.nature.com/nature.

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Author contributions. FC, CD, BL and CJAB conceived and refined the initial project. CD designed the study strategy with inputs from BL and FC. CD, BL, ACV, IJ, JMS, REG, DR and FC collected and standardised all data. CD, BL and ACV processed the final database. BL and CD implemented the analyses with inputs from ACV, REG and DR. CD wrote the first draft of the manuscript with reviews from all contributing authors. All authors read and approved the final manuscript.

Competing interests. The authors declare no competing financial interests.

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Data availability

The original dataset considered for our data processing is provided as a supplementary material (Supplementary Data 1).

Code availability

We did all data processing and analyses with the ‘invacost’ R package (available on the Comprehensive R Archive Network at https://cran.r-project.org/package=invacost). The analytical framework is described in details in Leroy et al. (2020)[44]. A step-by-step tutorial for this framework is also available at https://www.github.com/Farewe/invacost. The code used to generate the graphs and analyses for this paper is available at http://borisleroy.com/invacost/global_invasion_costs_scripts.html.

EXTENDED DATA

Figure 1 | Box-and-whisker plot of the lag between cost occurrence and year of publication, based on the most robust subset of the database (see 'Dataset and processing steps' in the *Methods* section). The few occurrences of publications before economic impacts corresponded to planned budgets over specific periods expanding beyond the publication year

Figure 2 | Temporal trend (1970–2017) of global invasion costs (in 2017 USD millions) predicted based on different modelling techniques (see 'Model' legends). OLS: ordinary least-squares; GAM: generalized additive model; linear regression, quadratic regression, MARS: multiple adaptive regression splines. *The linear trend over time is considered the best way to estimate the average annual cost of invasions over time (see Supplementary Methods 1 for details). Results are those obtained when considering models calibrated with at least 25% data completeness (calibration interval 1970–2015). We* log_{10}*-transformed cost estimates (from the 'Cost estimate per year 2017 USD exchange rate' column in the database).*

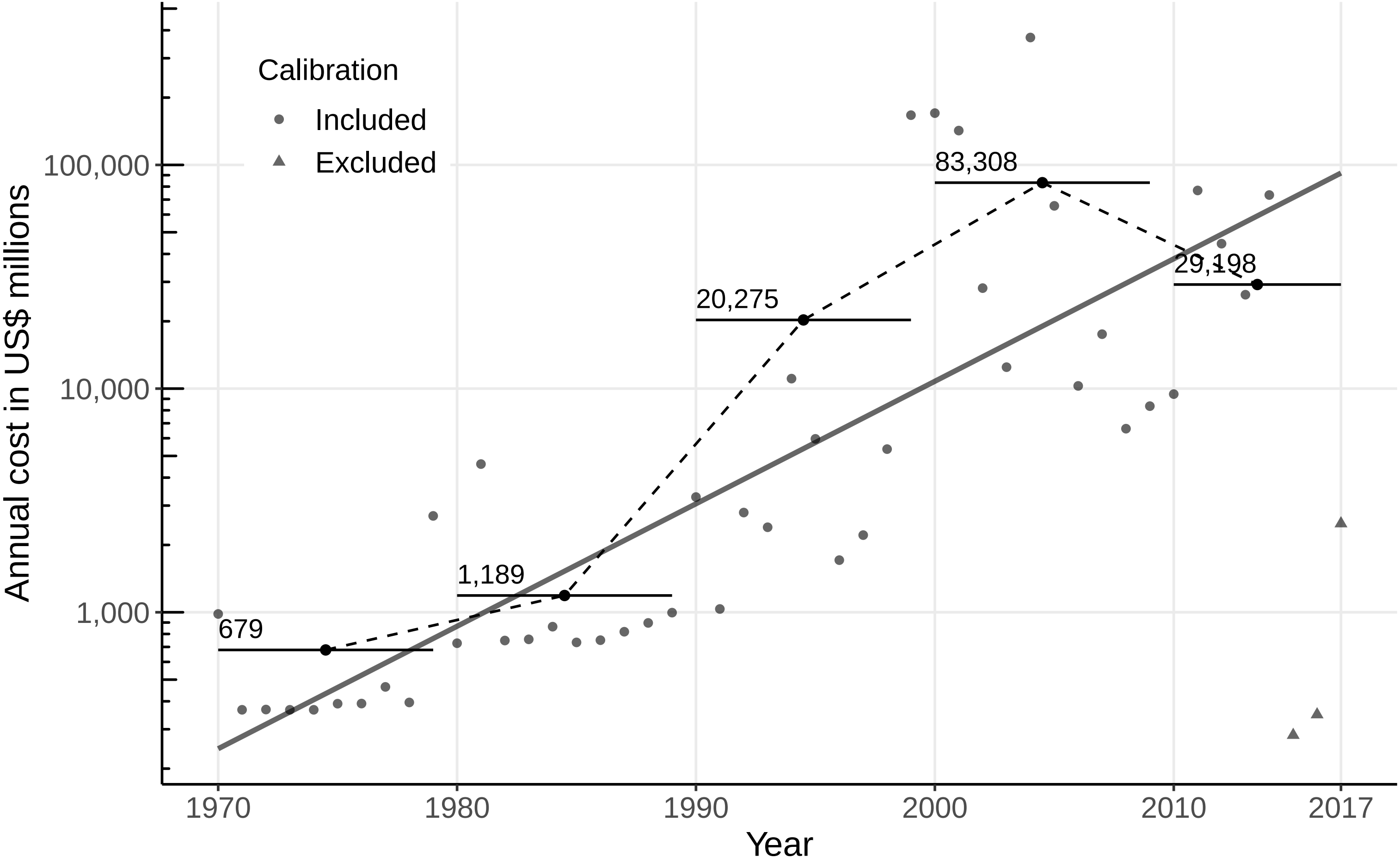
Figure 3 | Temporal trend (1970–2017) of global costs (in 2017 USD millions) following the type of costs (*damage*: economic losses due to direct and/or indirect impacts of invaders; *management*: economic resources allocated to actions to avoid or limit invasion impacts). a: predicted trend for damage costs (see 'Model' legends); b: predicted trend for management costs (see 'Model' legends); c: observed trends for both damage and management costs. OLS: ordinary least-squares; GAM: generalized additive model; linear regression, quadratic regression, MARS: multiple adaptive regression splines. *Results are those obtained when considering models calibrated with at least 25% data completeness (calibration interval 1970–2015). We* log_{10}*-transformed cost estimates (from the 'Cost estimate per year 2017 USD exchange rate' column in the original database). We* log_{10}*-transformed cost estimates (from the 'Cost estimate per year 2017 USD exchange rate' column in the database).*

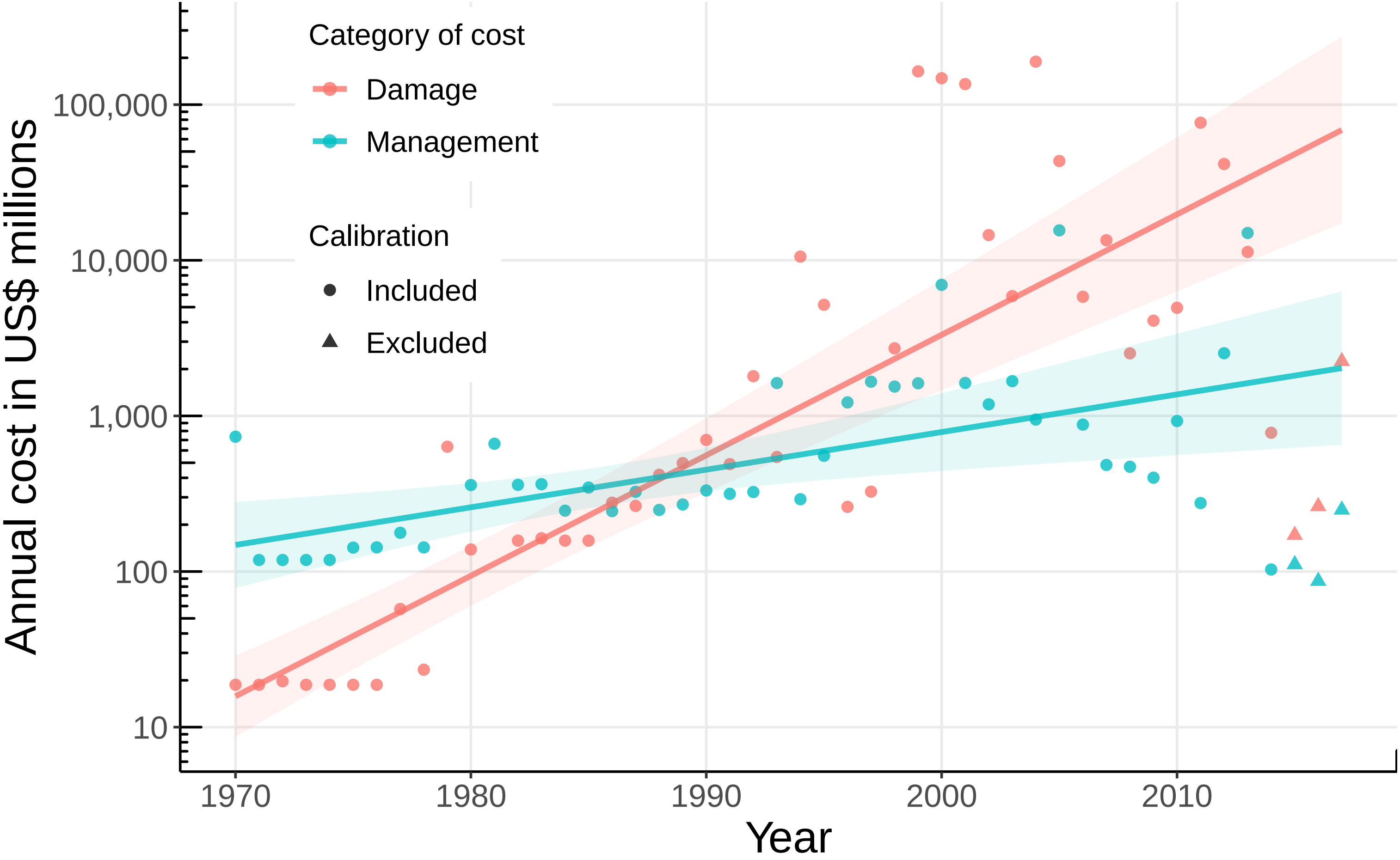
Figure 4 | Temporal trend (1970–2017) of global costs (in 2017 USD millions) following taxonomic group [plants (A), invertebrates (B), vertebrates (C)] and each class within for which data were sufficient to allow our modelling approach. Given that some subsets for taxonomic groups were also heavily affected by outliers, we also decided to focus exclusively on robust regressions *(see Supplementary Methods 1 for details). Results are those obtained when considering models calibrated with at least 25% data completeness* *(calibration interval 1970–2015). We log$_{10}$-transformed cost estimates (from the 'Cost estimate per year 2017 USD exchange rate' column in the database).*

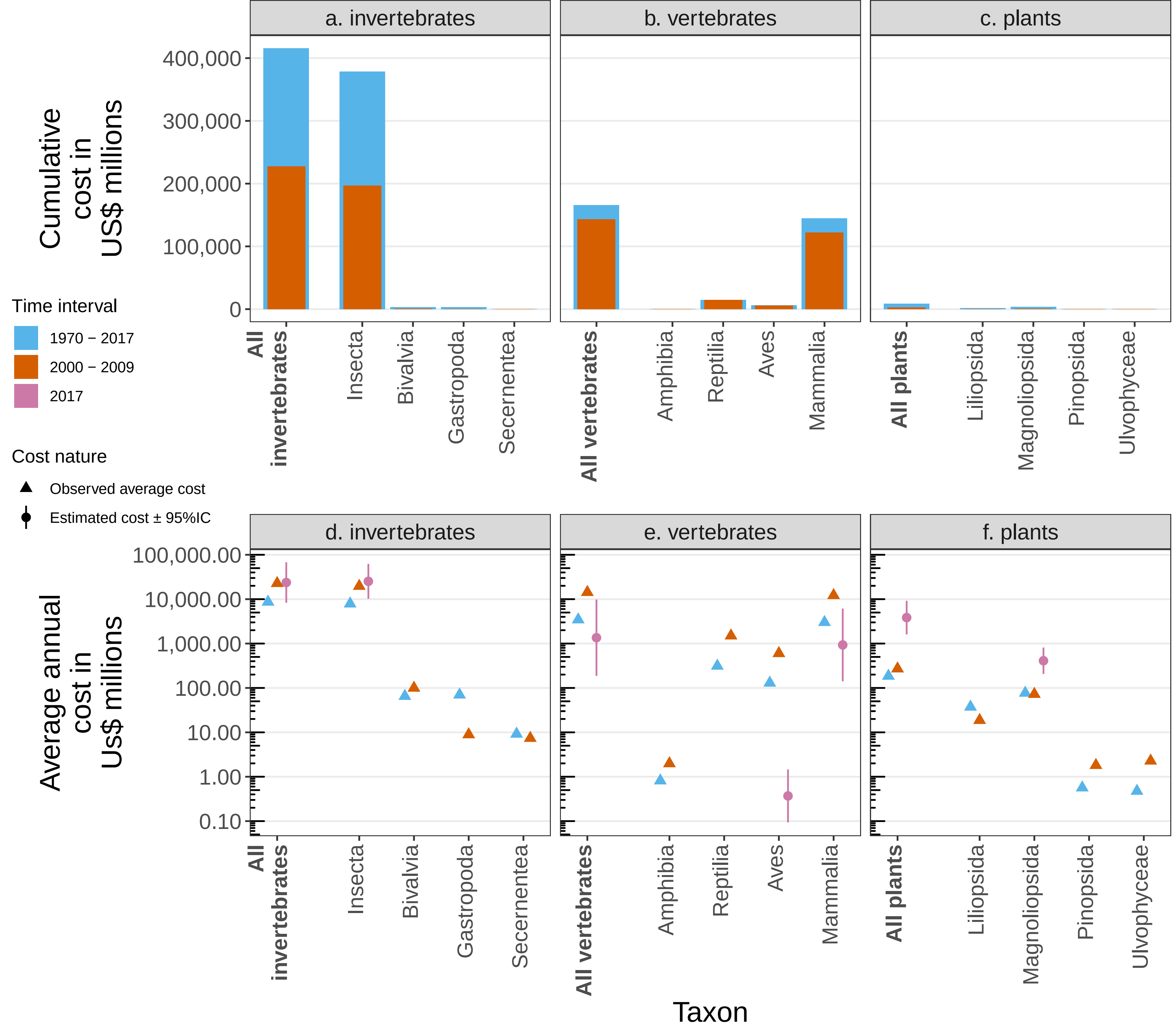
Figure 5 | Temporal trends (1970–2017) based on the cumulative and average costs (in 2017 USD millions) following the geographic regions (Africa, Asia, Central America, Europa, North America, Oceania-Pacific islands, South America).

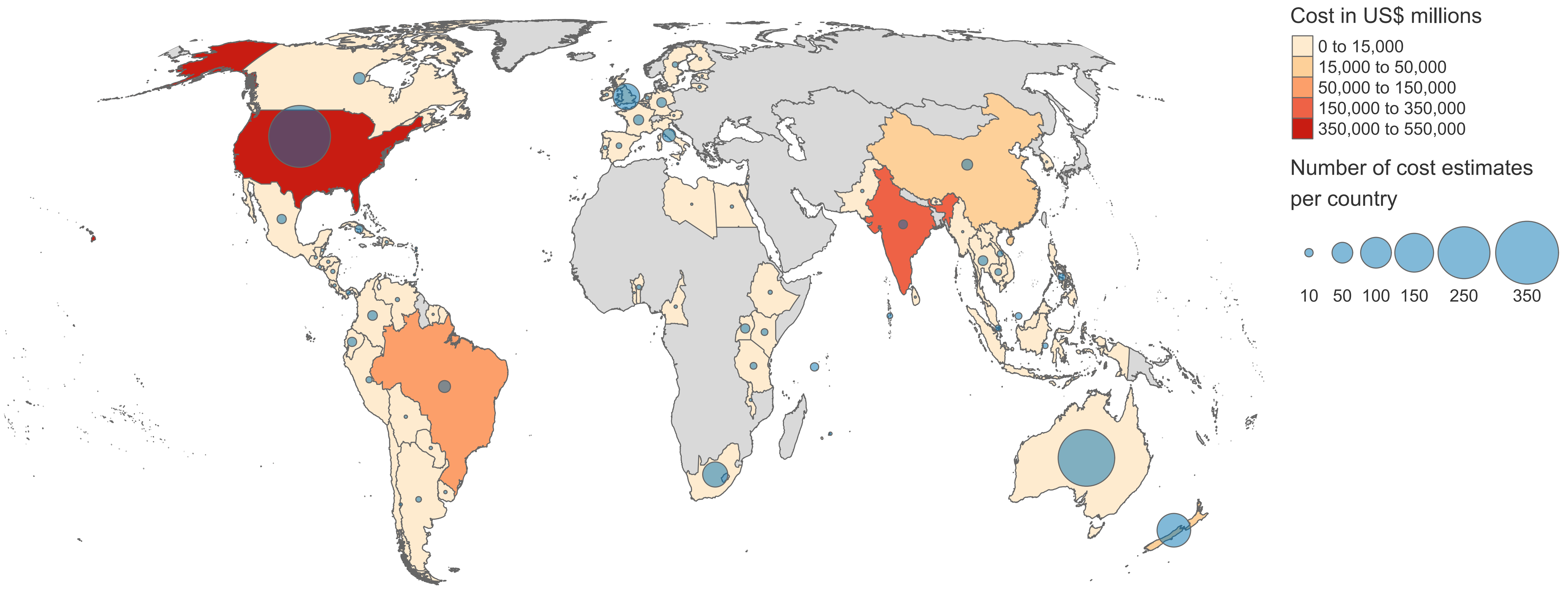
Figure 6 | Temporal trend (1970–2017) of global invasion costs (in 2017 USD millions) predicted based on different modelling techniques (see 'Model' legends). OLS: ordinary least-squares; GAM: generalized additive model; linear regression, quadratic regression, MARS: multiple adaptive regression splines. *The linear trend over time is considered the best way to estimate the average annual cost of invasions over time (see Supplementary Methods 1 for details). Results are those obtained when considering models calibrated with at least 25% data completeness (calibration interval 1970–2015). We log$_{10}$-transformed cost estimates (from the 'Cost estimate per year 2017 USD exchange rate' column in the database). We considered that the duration time of costs for which no period of impact was specified was higher than those considered in our conservative strategy when completing missing data on the temporal dynamics. For this purpose, we considered as occurring until 2017 every cost that could be repeated over several years, but for which we had no information on the exact duration.*

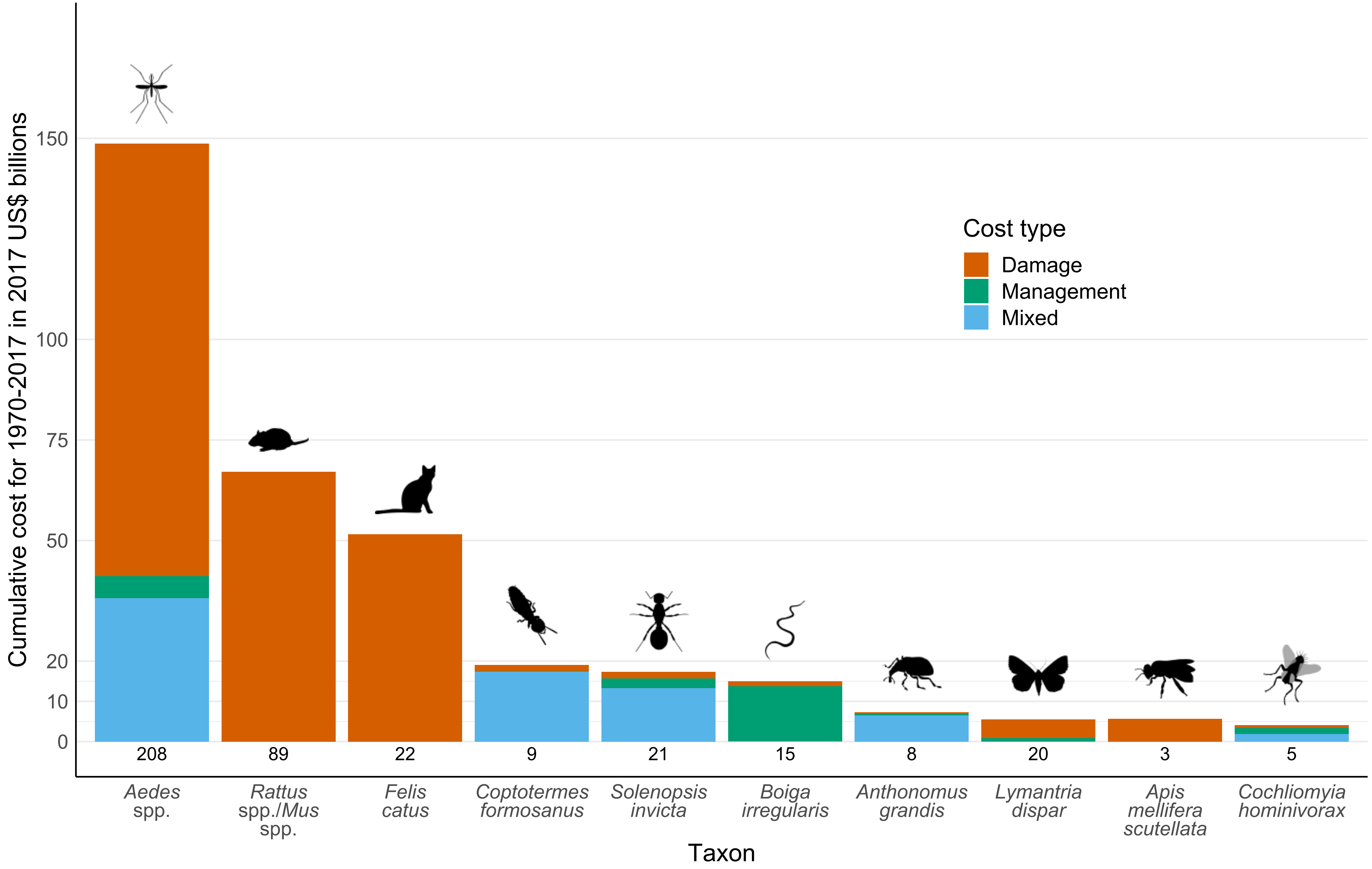
Figure 7 | Relationship between annual cost and number of estimates. Blue line: average trend fitted with locally estimated scatterplot smoothing.


Calibration
● Included
▲ Excluded
Annual cost in US$ millions
100,000
10,000
1,000
679
1,189
20,275
83,308
29,198
1970
1980
1990
2000
2010
2017
Year


Category of cost
Damage
Management
Calibration
Included
Excluded
Annual cost in US$ millions
100,000
10,000
1,000
100
10
1970
1980
1990
2000
2010
Year


a. invertebrates
b. vertebrates
c. plants
Cumulative cost in US$ millions
400,000
300,000
200,000
100,000
0
All invertebrates
Insecta
Bivalvia
Gastropoda
Secernentea
All vertebrates
Amphibia
Reptilia
Aves
Mammalia
All plants
Liliopsida
Magnoliopsida
Pinopsida
Ulvophyceae
Time interval
1970 – 2017
2000 – 2009
2017
Cost nature
Observed average cost
Estimated cost ± 95%IC
d. invertebrates
e. vertebrates
f. plants
Average annual cost in Us$ millions
100,000.00
10,000.00
1,000.00
100.00
10.00
1.00
0.10
Taxon


Cost in US$ millions
0 to 15,000
15,000 to 50,000
50,000 to 150,000
150,000 to 350,000
350,000 to 550,000
Number of cost estimates per country
10
50
100
150
250
350


Cost type
Damage
Management
Mixed
Cumulative cost for 1970-2017 in 2017 US$ billions
150
100
75
50
20
10
0
208
89
22
9
21
15
8
20
3
5
Aedes spp.
Rattus spp./*Mus* spp.
Felis catus
Coptotermes formosanus
Solenopsis invicta
Boiga irregularis
Anthonomus grandis
Lymantria dispar
Apis mellifera scutellata
Cochliomyia hominivorax
Taxon