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High and rising economic costs of biological invasions worldwide

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Biological invasions are responsible for substantial biodiversity declines as well as high economic losses to society and monetary expenditures associated with the management of these invasions[1,2]. The InvaCost database has enabled the generation of a reliable, comprehensive, standardized and easily updatable synthesis of the monetary costs of biological invasions worldwide[3]. Here we found that the total reported costs of invasions reached a minimum of US$1.288 trillion (2017 US dollars) over the past few decades (1970–2017), with an annual mean cost of US$26.8 billion. Moreover, we estimate that the annual mean cost could reach US$162.7 billion in 2017. These costs remain strongly underestimated and do not show any sign of slowing down, exhibiting a consistent threefold increase per decade. We show that the documented costs are widely distributed and have strong gaps at regional and taxonomic scales, with damage costs being an order of magnitude higher than management expenditures. Research approaches that document the costs of biological invasions need to be further improved. Nonetheless, our findings call for the implementation of consistent management actions and international policy agreements that aim to reduce the burden of invasive alien species.

Invasive alien species—species that have successfully been introduced, established and spread beyond their native range—can have profound, negative effects on biodiversity[4], ecosystem functioning and services[5], human health[6] and welfare[7], and 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 remains limited, mostly because the effects of biological invasions are undervalued by the general public, stakeholders and decision-makers[11]. A clear and standardized overview of the economic costs of invasions should contribute to optimizing current and future cost-effective management strategies[12], and strengthen the awareness of and include communication to a wide and diverse audience[13]. This would help to move the issue of invasions higher up the agenda for international policies of 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 to assess the costs of biological invasions[16] and all previous analyses are affected by recognized flaws[15]. Furthermore, the majority of assessments are restricted to particular taxa[8], sectors[17] or areas[15]. As biological invasions are an increasingly planet-wide issue, a worldwide reliable economic impact assessment is needed to quantify more precisely the patterns and trends of associated costs[18,19]. We have now addressed this need with an analysis of the most comprehensive database in which the documented economic costs of biological invasions are compiled: the InvaCost database[3]. This database covers most taxonomic groups, activity sectors and geographical regions worldwide. Here, we provide robust estimates of the large economic costs of invasions reported worldwide, the trends of these costs reported over time and their distribution among regions, taxa and cost types. We also highlight recommendations for future reporting of economic data in invasion science. Finally, we discuss the research and policy implications from the analysis of the economic facet of biological invasions.

Global costs of invasions

We used two complementary approaches to assess the global costs of invasions reported over time from the most robust subset (n = 1,319 cost estimates; around 57%) of the original database (detailed procedures and the rationale for limiting biases are provided in the Methods). First, we assessed these cost estimates directly using the costs 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 US$1.288 trillion (2017 US dollars) between 1970 and 2017. Over this period, invasions resulted in a mean cost of US$26.8 billion per year (Fig. 1 and Supplementary Table 1). This mean annual cost steadily increased over time and reached US$83.3 billion

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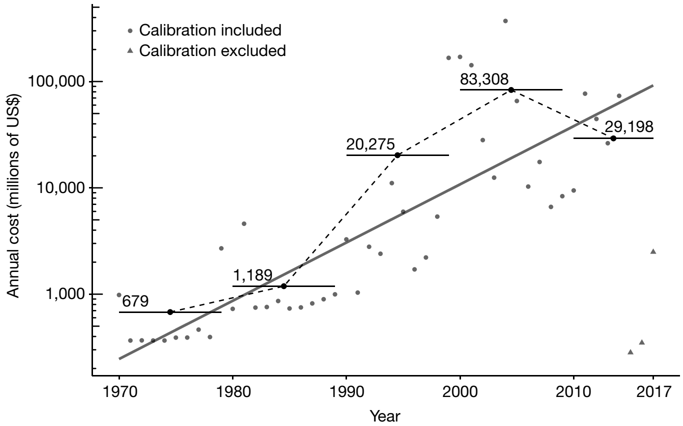

Fig. 1 | Temporal trend of global invasion costs (in millions of 2017 US dollars) between 1970 and 2017. The solid line represents the temporal dynamics of costs based on a linear regression (see Extended Data Fig. 2 and Supplementary Methods 1 for details). The dashed line connects the mean annual costs for each decade (see Methods, 'Approach based on available estimates' for details). The horizontal bars indicate the total time span over which decadal mean costs were calculated. The last three years (displayed as triangles) were not included in the model calibration; they are data-deficient and probably contribute to the artefactual decrease in global costs during the past decade (Supplementary Methods 1). We considered 1,319 cost estimates from the original database after successive processing steps (see Supplementary Data 1).

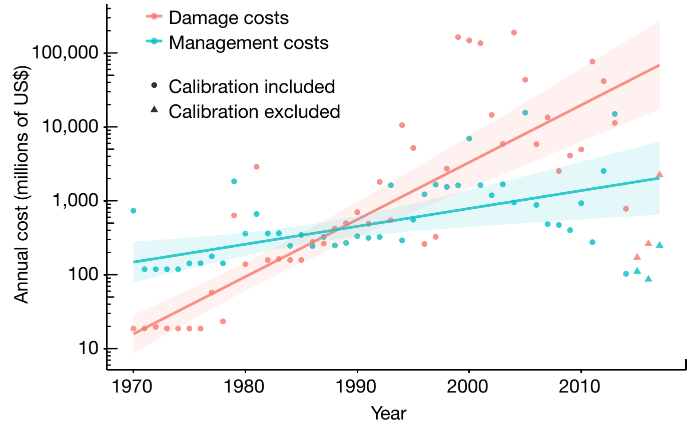

Fig. 2 | Temporal trends of global damage and management costs (in millions of 2017 US dollars) based on both mean annual costs for each decade and model prediction between 1970 and 2017. Damage comprises economic losses due to direct and/or indirect impacts of invaders, such as yield loss, illness, land alteration, infrastructure damage or income reduction. Management includes 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. Details of the categorization of the cost entries (damage or management) are available in Supplementary Methods 2. Regression lines were obtained by robust regression to minimize the effect of outliers (Supplementary Methods 1). Note that the error bands represent the 95% confidence intervals. The last three years (displayed as triangles) were not included in the model calibration. We considered 1,287 cost estimates ($n = 402$ estimates for damage costs; $n = 878$ estimates for management costs) from the original database (see Supplementary Data 1).

between 2000 and 2009, but decreased to US$29.2 billion between 2010 and 2017 (Fig. 1 and Supplementary Table 1). This apparent decrease for 2010–2017 is probably an artefact arising from a lack of cost estimates for this period given the multi-year delay between the occurrence and reporting in the literature (Extended Data Fig. 1). An overall increase in the reporting rate for costs in the literature could 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' and Supplementary Methods 1). Globally, our models confirmed that the costs have continuously increased each year since 1970, at a rate of more than threefold per decade, and that such an increase is expected for the latest decade as well (that is, the period of 2010–2017) (Extended Data Fig. 2 and Supplementary Table 2). These estimates therefore confirmed that the apparent decline observed in the past few years with the previous approach was probably due to the paucity of reported data over the recent past rather than an actual downward trend in costs (Supplementary Methods 1). We therefore estimate that the global mean cost of invasions ranges between US$1.0 and US$3.1 billion annually in 1990, between US$5.6 and $32.6 billion in 2000, and between US$18.3 and US$38.1 billion in 2010. Ultimately, we predict that the mean annual cost of invasions reached the range of US$46.8 billion to US$162.7 billion in 2017. We also found large and increasing interannual 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 mean) (Extended Data Fig. 2 and Supplementary Methods 1). Overall, we observed similar patterns of cost increase when scrutinizing these global costs according to the types of cost, or at the taxonomic and geographical levels (Figs. 2–4, Extended Data Figs. 3–5 and Supplementary Methods 1).

Regarding the types of cost, we considered either 'damage' (economic losses due to the direct and/or indirect effects of invading species) or 'management' (economic resources allocated to actions dedicated to avoid or limit the negative effects of invasions) (Supplementary Methods 2). We found that the costs from damage by invading species (total cumulative cost of US$892.2 billion; annual mean of US$18.6 billion per year) were about 13 times higher than the expenditures for managing invasions (US$66.3 billion; US$1.4 billion per year) for 1970–2017 (Fig. 2 and Extended Data Fig. 3)—this is despite fewer estimates for damage costs (Supplementary Table 1). Furthermore, damage costs (an around sixfold increase every ten years) increased at a much faster rate than management costs (a less than twofold increase every ten years) (Fig. 2 and 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 that US$591 billion from the total estimates could unambiguously be assigned to a single taxonomic group (Supplementary Table 1). Within this subset, invasive invertebrates seemed to be the costliest, with a cumulative cost of US$416 billion and a mean annual cost of US$8.7 billion from 1970 to 2017, which is estimated to increase up to US$23.8 billion per year in 2017 (Fig. 3). This essentially occurs owing to a predominance of reported costs for insects (around 90% of the total cost). Vertebrates had the second-highest financial impact, with a cumulative cost of US$166 billion and a mean annual cost of US$3.5 billion for 1970–2017. We estimated that this mean cost decreased to US$1.3 billion per year in 2017, mostly because the higher mean cost for 1970–2017 is driven by a limited number of years with high costs—which is not necessarily due to the scarcity of cost data during the past decade (Fig. 3 and Extended Data Fig. 4). Most (around 88%) of the total calculated costs were from mammals. Plants had the third cumulative cost (US$8.9 billion) for the same period, but this is probably due to a data deficiency in the current database for this group ($n = 221$ cost estimates compared with $n = 469$ and 526 for invertebrates and vertebrates, respectively) rather than an actual pattern of cost distribution (Supplementary Table 1 and Supplementary Discussion 1). The observed increase in the temporal

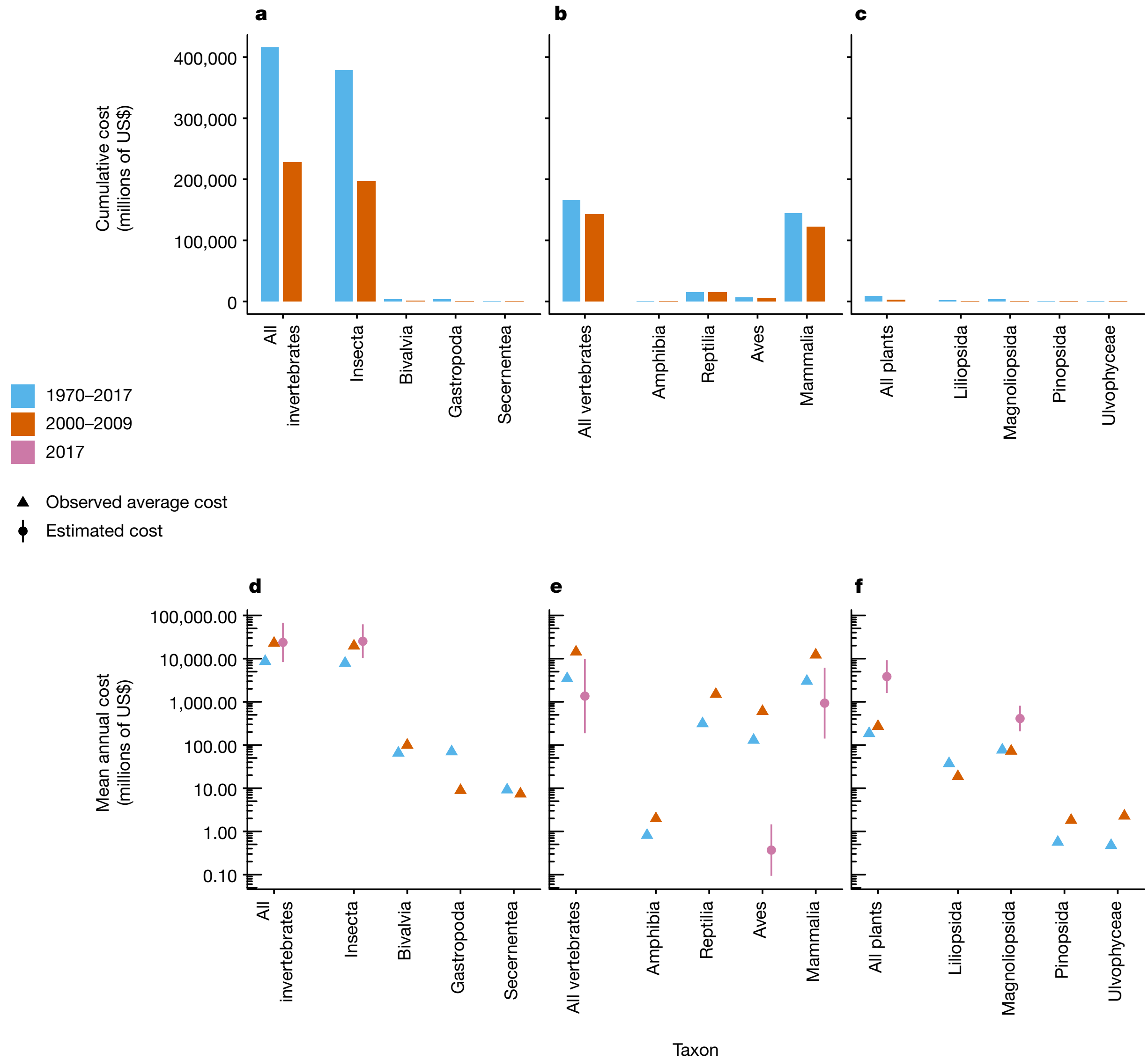

Fig. 3 | Cumulative and mean annual costs observed in the database and predicted by linear regression. a–**f**, Cumulative costs over time for 1970–2017 and 2000–2009 (**a**–**c**) and the mean annual costs (**d**–**f**) as observed in the database (1970–2017 and 2000–2009) and as predicted by linear regression over time for 2017 for taxa with enough data (that is, more than 30 years of data). **a**, **d**, Invertebrates. **b**, **e**, Vertebrates. **c**, **f**, Plants. Costs are expressed in millions of 2017 US dollars. Cost values include only estimates that could be derived for one of the three major taxonomic groups (invertebrates, plants and vertebrates). 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 more limited for plants. The mean annual costs for 1970–2017 and 2000–2009 are represented without error bars for two reasons as described previously[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. **d**–**f**, Data are mean (triangles) or estimated costs ± 95% confidence intervals (circles and error bars).

dynamics could support this assertion (Extended Data Fig. 4 and Supplementary Methods 1).

At the geographical level, economic estimates that can be unambiguously attributed to a single region accounted for a total cumulative cost of US$959 billion for 1970–2017 (Supplementary Table 1). The distribution of these costs was highly skewed towards North America (around 57% of the total cost) (Fig. 4) with a mean reported cost of US$11.0 billion per year for 1970–2017. Costs for the other regions ranged from US$120 million per year to US$5.6 billion per year (Supplementary Table 1).

Large and increasing cost estimates

Invasions are clearly economically costly to human societies, with a minimum of US$1.288 trillion in losses and expenses accumulated between 1970 and 2017 and a trebling of the mean annual cost every 10 years. We predicted that this amount reaches between US$18 billion and US$38 billion in 2010 and exceeds US$47 billion to US$163 billion in 2017 worldwide. Considering the different time frames and inflation, the annual amounts that we estimated in the early 2000s (US$6 billion to US$33 billion in 2000) seem lower than the estimate previously inferred elsewhere[16]. This discrepancy is mostly explained by our conservative approach based on (1) keeping only the most robust data from the original database (around 57% of our dataset); (2) relying on scientific and official materials that report cost estimates rather than hypothetical calculations of the costs of the impacts; and (3) 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 that was 33 times higher for 2017 (US$5.405 trillion) (Extended Data Fig. 6). Nevertheless, our conservative, annual global estimates still represent a huge economic burden. As

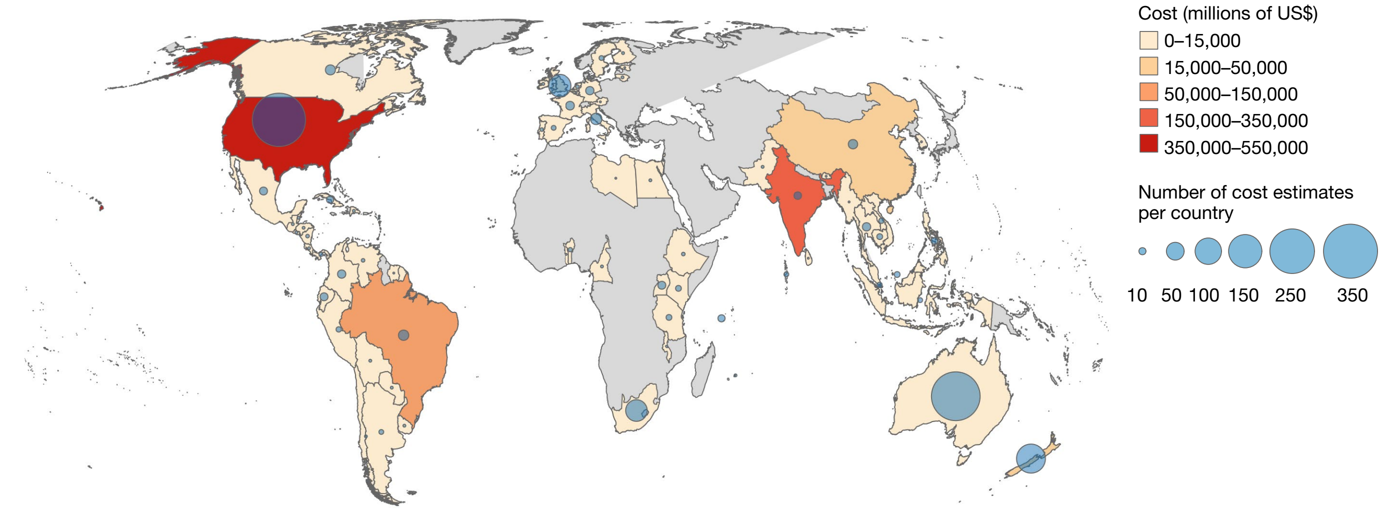

Fig. 4 | Geographical distribution of the cost estimates (in millions of 2017 US dollars) available in the most robust subset of the original database for the period of 1970–2017. We included only estimates that could be derived for a single geographical region (Africa, Asia, Central America, Europa, North America, Oceania and the Pacific Islands, and South America) or country.

an illustration, this mean annual cost largely exceeds the gross domestic product of 50 out of 54 countries on the African continent in 2017 (data.worldbank.org) and it is also more than 20 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 6 years, a pattern that mimics the continuous increase in the number of alien species worldwide[20]. Assuming a similar continuing trend would place the global mean costs of invasions in the 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 (for example, 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

Importantly, 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 interannual variability in the costs over time. This pattern probably 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 that impair the discovery of all non-English sources[23], the subjective terminology in invasion science[24] and the lack of reporting consistency (for example, salaried positions are rarely included)[25] that 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 assessments of sanitary impacts associated with alien invading species[27,28] (for example, 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, even though plants are recognized as a major group of invaders[29]), meaning that impacts might be further undervalued for many areas and taxa. As a probable consequence, cost amounts were the highest for insects and mammals, which confirms 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 a better financial capacity to invest in management responses[31]. The influence

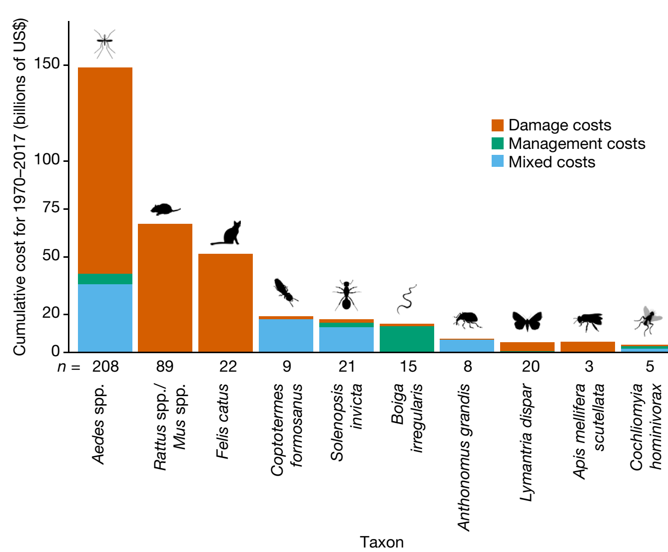

Fig. 5 | The 10 costliest taxa from the most robust subset of the original database for both cumulative damage and management costs (in billions of 2017 US dollars) between 1970 and 2017. Mixed costs are cost estimates for which the specific monetary contribution of damage and management costs could not be disentangled from the reporting studies. Each bar represents a species or a complex of species (when different species were often considered simultaneously to provide cost estimates). Numbers below the 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 animal silhouettes were obtained from an open source platform (http://phylopic.org/). The silhouette of *Coptotermes* was created by Melissa Broussard.

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 the analysis and facilitates the use of cost data in syntheses and meta-analyses.
Cost responsibility	Identify who pays for the incurred costs (for example, governments, stakeholders, activity sector, private companies and/or citizens) in the affected 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.	Enables 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 impacts 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) for which the cost was estimated.	Enables the 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 in which multiple species are involved.
Temporal extent	Indicate the precise start and end year(s) as well as the duration (which identifies cases for which 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.

of local economic priorities, practical limitations and cultural and historical specificities on research agendas might also partially explain these geographical discrepancies. These patterns could also reflect only 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 because many invasion impacts remain undetected[32]. Thus, invasion costs can remain hidden and/or underestimated over time simply because (1) the moment of introduction; (2) the date at which an invasion starts to be costly; and (3) the shape of the cost dynamics when they started are generally all unknown or unreported. Last, 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, although 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, they robustly show staggering amounts. Second, although we show that the costs that 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 the costs that we assessed represent only a limited fraction of the full cost (see ‘Underestimated global costs’ section) and specific data processing and awareness are required for depicting how reported costs are actually distributed[19]. Third, although we ensured robust data pre-processing before 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 that we report should be considered in terms of relative orders of magnitude rather than precise cost estimates.

We therefore advocate for (1) strengthening of interdisciplinary cooperation among scientists and concerned stakeholders to capture the completeness, diversity and complexity of invasion costs as much as possible; (2) increasing the number and spatial coverage of studies to achieve a more balanced and complete picture of invasion costs globally, especially in low-income regions; and (3) 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 10 costliest taxa from our dataset (Fig. 5) illustrate this need for more accurate and complete cost information (Supplementary Discussion 1). In this respect, we provide seven recommendations for the 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. Although this result may reveal more cost-efficient management actions locally, the large increase in 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 that measure different aspects of invasion impacts worldwide, such as the Global Register of Introduced and Invasive Species[38] and the Socio-Economic Impact Classification of Alien Taxa[22]. In addition to remaining a main priority of multilateral environmental agreements such as the Convention on Biological Diversity (cbd.int/meetings/COP-13), the management of invasions must be reinforced as a priority for national governments. In particular, the costs of invading species could be considerably reduced with timely investments in preventive measures (such as risk assessment, proactive 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 invading species could also have neutral or positive outcomes for local ecosystems and economies[41]. The transboundary nature of invasions reinforces the need for (1) concerted international governance with cross-border legal instruments; and (2) balanced management expenditures at a regional scale[37,41]. Low-income regions have a 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 the introduction of new species[43]. The unintended effects—including costs—that are likely to be generated for all implicated countries ought to be accounted for in the estimated net income of this commercial initiative. Therefore, our work concretely supports the inclusion of economic costs as a complementary quantitative indicator of the effects of biological invasions.

In conclusion, invasions generate a high but still undervalued economic burden to our societies. Our findings illustrate that these reported costs (1) have markedly increased over the past few decades; (2) show no sign of slowing down; (3) require more and better organized research; and (4) stress the need of evidence-based and cost-effective management actions. Of particular note is the fact that these economic losses are only part of the full aggregate of effects that are incurred from invasive alien species. Indeed, the ecological and health impacts of invasions are at least as important, but are often incalculable[4,6]. Finally, our work highlights once again the critical need for more global investment in research as well as policy development and implementation to minimize the effect of invasions worldwide.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-021-03405-6.

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Methods

Dataset and processing steps

We used the InvaCost database, in which the monetary costs that are associated with invasive alien species globally are compiled and described[3]. For each entry, we considered the cost estimates standardized to 2017 US dollars based on exchange rates provided by the World Bank ('Raw cost estimate 2017 USD exchange rate' column of Supplementary Data 1), because this allowed us to consider almost all of the cost data entered in the database. Obvious duplicate cost estimates (that is, same cost figures from (non-)identical sources) were removed when building the database, although some overlaps can still occur[3] (Supplementary Discussion 1). To ensure a realistic, robust and conservative synthesis, we filtered out some cost data from the database to keep only those data that are 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 of Supplementary Data 1; $n = 539$) 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 numbers are provided in the 'Duration time of cost estimates' section). Thus, from an initial pool of 2,419 cost estimates in the original database, we kept a final total of 1,319 cost estimates that were deemed to be the most robust in the final dataset (Supplementary Data 1). 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 cost. For the spatial distribution, we used information from the 'Geographical regions' column of Supplementary Data 1. For the taxonomic distribution, we combined information from the columns describing the kingdom, phylum and class to group the economically harmful invaders that have been recorded among plants, invertebrates and vertebrates. For the type of cost, we used the information from the 'Type of cost' column of Supplementary Data 1 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 or eradication) costs (Supplementary Methods 2). For specific analyses on cost distribution, we ignored the estimates that could not be unambiguously assigned to any one category of the targeted descriptors.

Duration time of cost estimates

Deriving the mean annual cost of invasions over time requires knowing the years over which the effects occurred, but this information was not readily available for 720 out of 1,338 entries in the database (that is, 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 on the basis of the available information (based on the duration of the effects indicated by the authors of previous studies) or the 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 the present). 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, for which 1970 is the first year for which InvaCost has robust and sufficient economic data, and 2017 is the last year of the standardized data collection.

Estimating global cost patterns

Because the raw cost estimates standardized to 2017 US dollars ('Raw cost estimate 2017 USD exchange rate' column of Supplementary Data 1) encompass estimates with two different time ranges ('Period' or 'Year' in the 'Time range' column of Supplementary Data 1), they were expressed as annual costs ('Cost estimate per year 2017 USD exchange rate' column of Supplementary Data 1). To do this, we divided the raw costs provided for a period exceeding a year ('Period' in the 'Time range' column of Supplementary Data 1) by the duration time described above, although we did not transform the raw costs provided yearly or for a period up to one year ('Year' in the 'Time range' column of Supplementary Data 1). For estimating global cost patterns and trends over time, we used the two approaches described in the 'Approach based on available estimates' and 'Modelling-based approach' sections that are fully implemented in the 'invacost' R package[44].

Approach based on available estimates. We first depicted global cost patterns by calculating the mean annual cost for each decade since 1970 (intervals of 10 years, except for the last period (2010–2017), which is incomplete). For this, we summed all of the annual costs that occurred each year of a given decade and then divided them by the number of years. Second, we calculated the mean annual cost for the entire period (1970–2017). We present mean annual costs rather than median annual costs because we assume that the skewness of data is caused by the considerable incompleteness of economic data for most years. Therefore, we deemed that the mean annual cost is probably closer to the actual annual cost than the median.

Modelling-based approach. Nonetheless, although the first approach is important to depict the patterns that are 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 probably underestimates the mean 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 mean annual cost for the past 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 mean annual costs. To account for the time lag caused by the reporting of costs, we excluded the most-incomplete years (that is, years expected to have less than 25% of cost data; Supplementary Methods 1).

To model the temporal cost trend, we used an ensemble approach based on different linear and nonlinear techniques (details, procedures and appropriate literature are fully provided in the Supplementary Methods 1): an ordinary least-squares model, linear and quadratic regressions, robust linear and quadratic regressions, multiple adaptive regression splines, generalized additive models and quantile regressions. We accounted for temporal autocorrelation and heteroscedasticity with methods that were specific to each model (see Supplementary Methods 1 for details). We $\log_{10}$-transformed all of the annual costs before analysis. We had one a priori assumption for the probable shape of trends over time. Because of the exponential increase in the number of invasive species globally[20], we expected that the long-term temporal trend was either increasing or stabilizing, but not decreasing.

Therefore, we assumed that a model describing a decreasing trend in recent years (that is, 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 owing to data deficiencies.

Note that the economic valuation of costs of invasions is a highly challenging task (a review of these challenges has been published previously[2]). All of the cost estimates presented here represent ranges that should be therefore 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].

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this paper.

Data availability

The original InvaCost database[3] considered here is openly accessible at https://doi.org/10.6084/m9.figshare.12668570.v1 and provided as Supplementary Data 1.

Code availability

We carried out 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 has been described in detail previously[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.

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Author contributions F.C., C.D., B.L. and C.J.A.B. conceived and refined the initial project. C.D. designed the study strategy with inputs from B.L. and F.C. C.D., B.L., A.-C.V., I.J., J.-M.S., R.E.G., D.R. and F.C. collected and standardized all data. C.D., B.L. and A.-C.V. processed the final database. B.L. and C.D. implemented the analyses with inputs from A.C.V., R.E.G. and D.R. C.D. 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 interests.

Additional information
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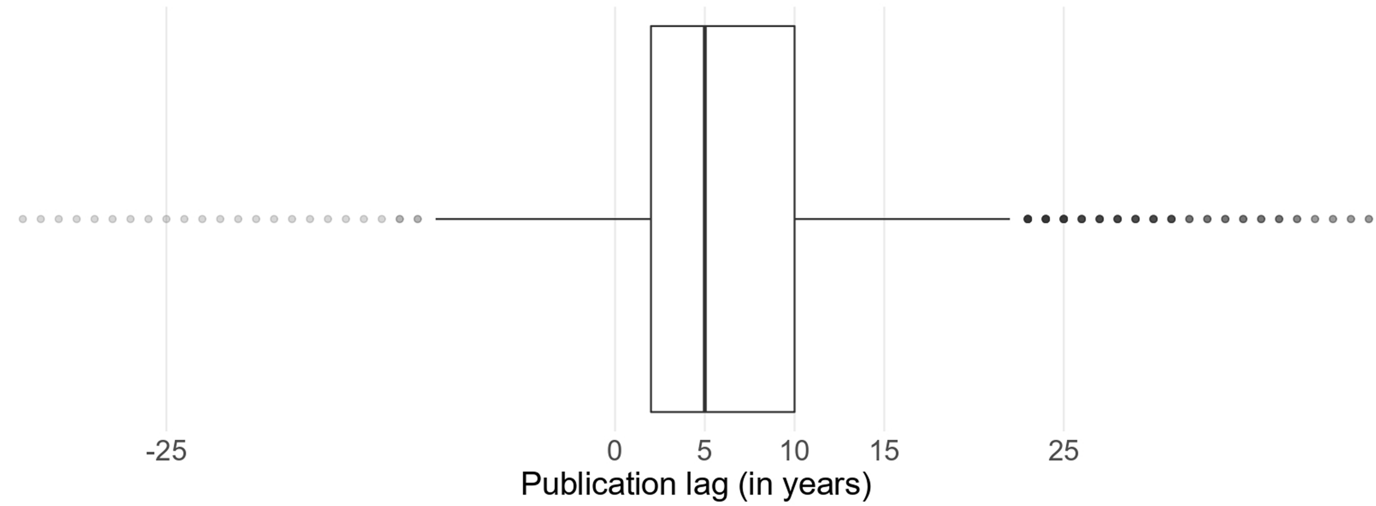
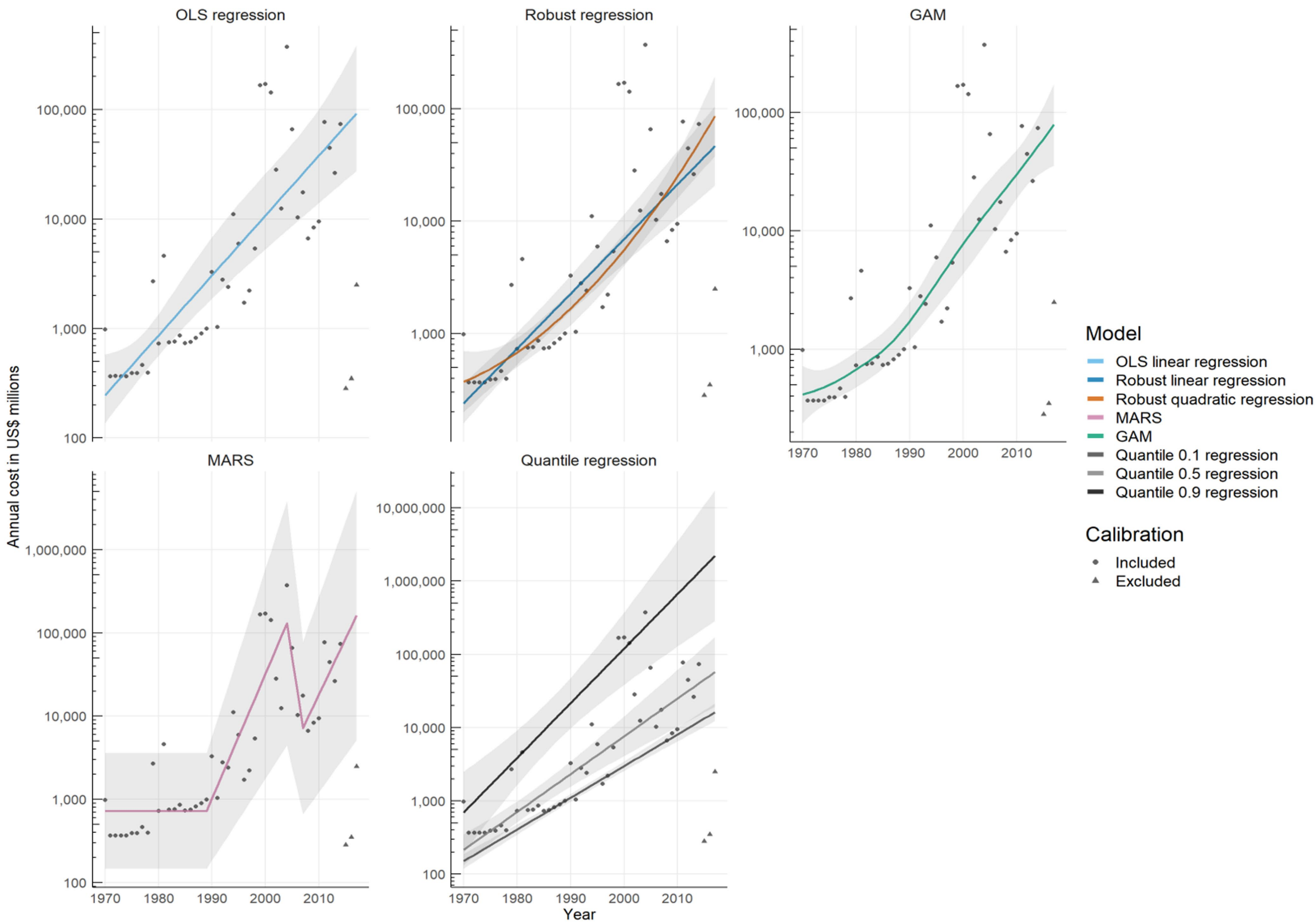
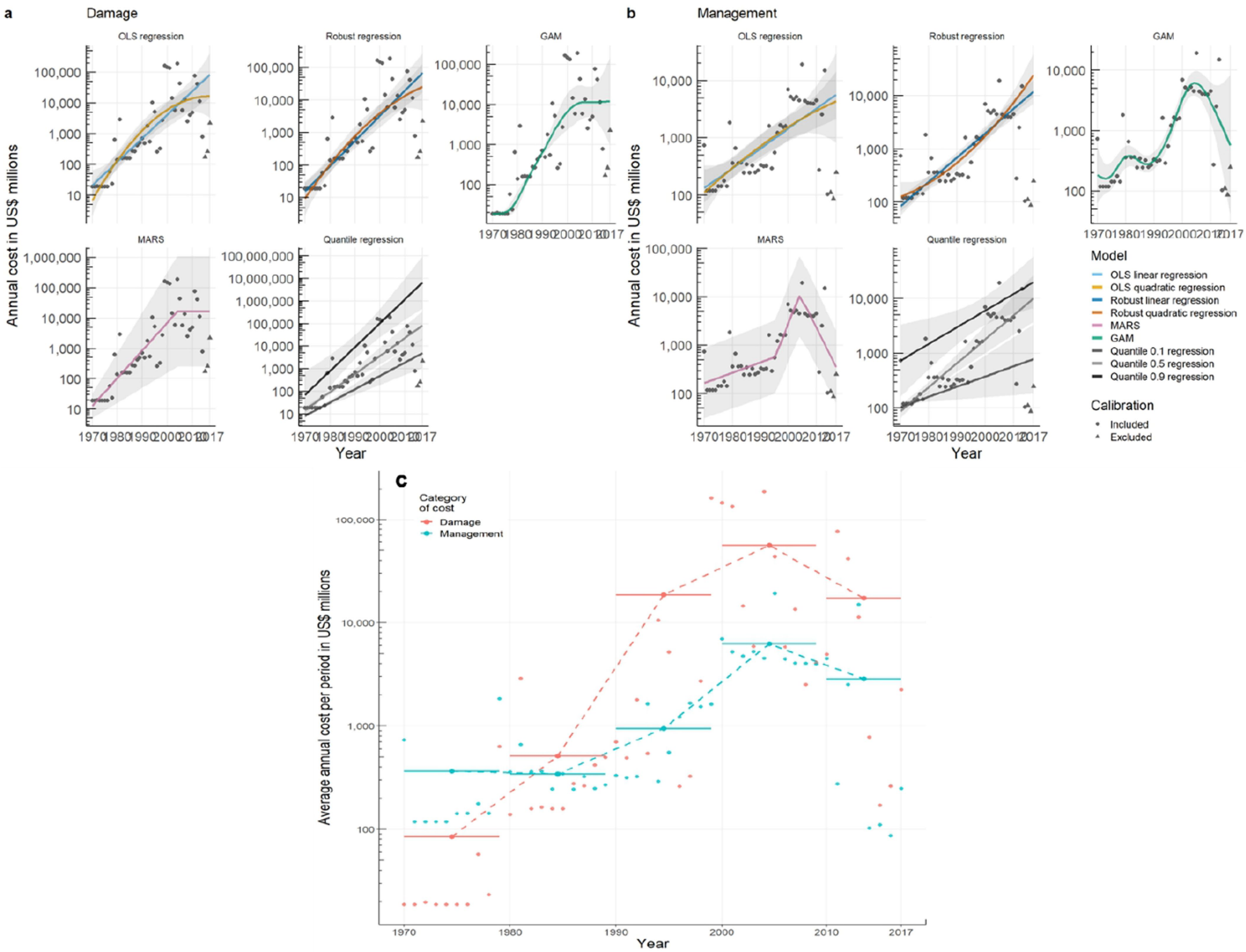
Correspondence and requests for materials should be addressed to C.D. or F.C.
Peer review information *Nature* thanks Thomas Kneib, Shana McDermott, Michael Springborn and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Peer reviewer reports are available.



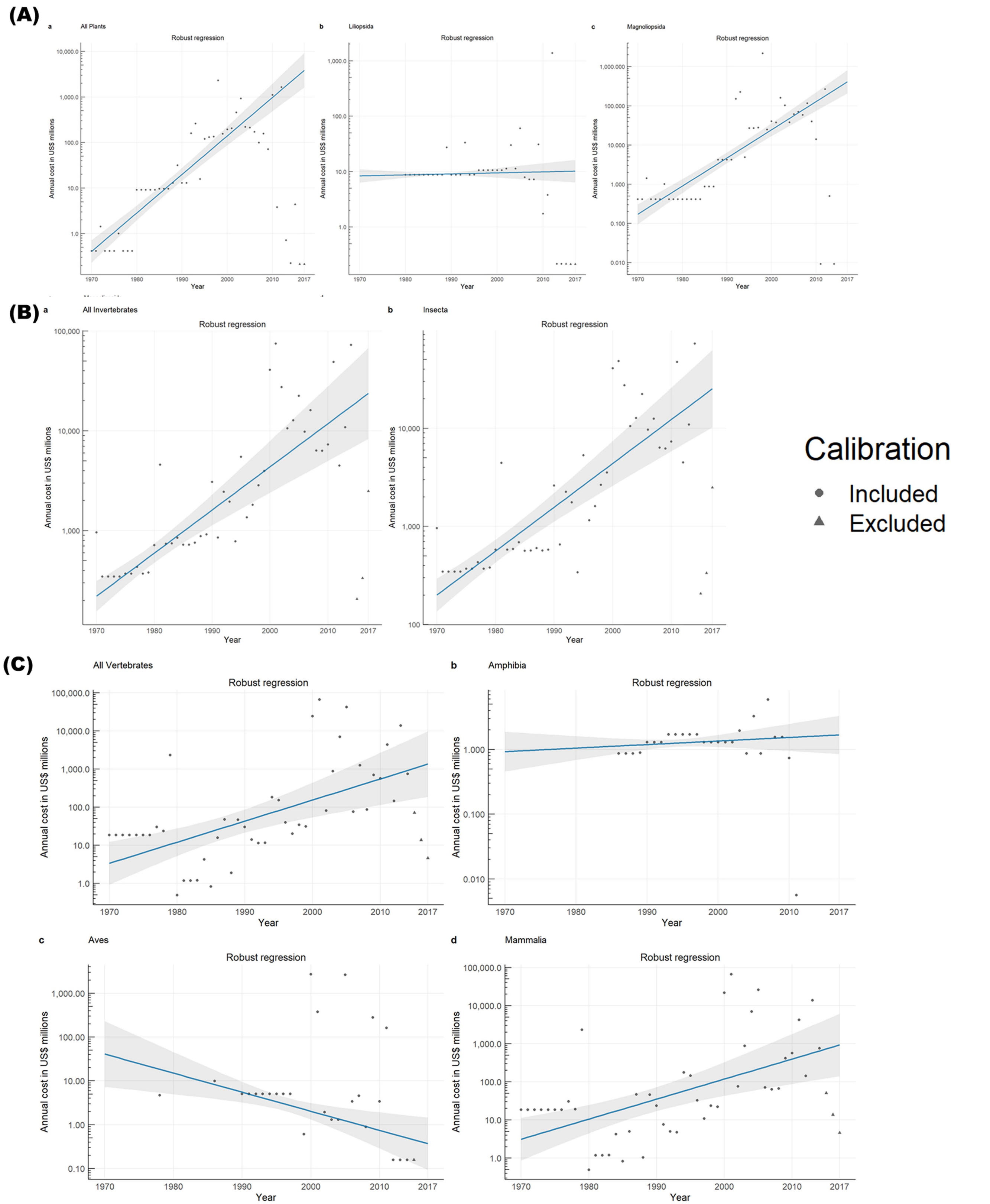
Extended Data Fig. 1 | The lag between cost occurrence and year of publication based on the most robust subset of the database. Further information is included in the Methods, 'Dataset and processing steps' section. The box-and-whisker plot shows the median of the distribution (centre), box boundaries corresponding to the first and third quartiles and whiskers that extend to up to 1.5× the interquartile range. The few occurrences of publications before economic impacts corresponded to planned budgets over specific periods expanding beyond the publication year.



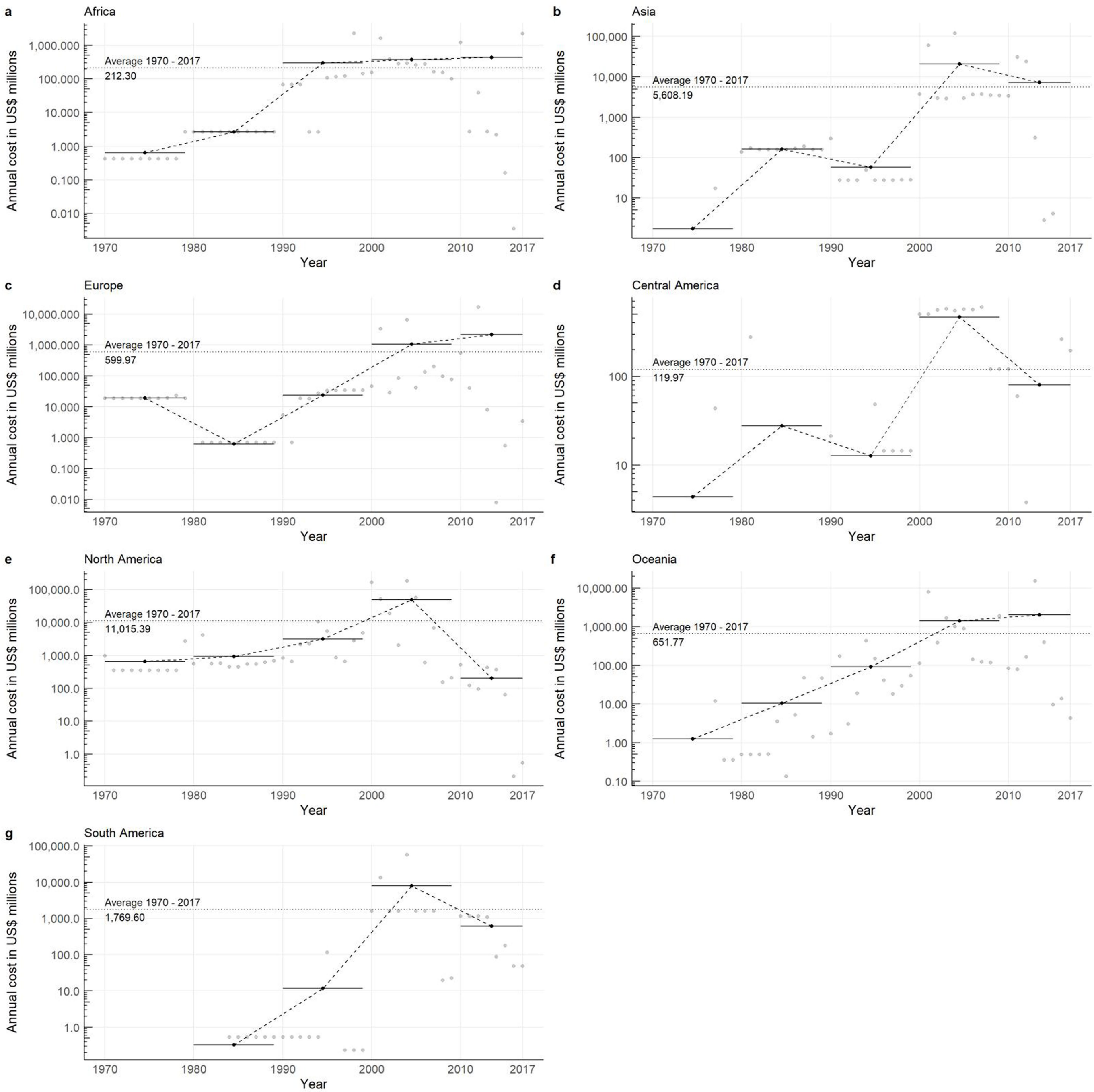
Extended Data Fig. 2 | Temporal trend (1970–2017) of global invasion costs (in millions of 2017 US dollars) predicted based on different modelling techniques. OLS, ordinary least-squares model; GAM, generalized additive model; MARS, multiple adaptive regression splines. The linear trend over time is considered the best way to estimate the mean 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 of Supplementary Data 1).



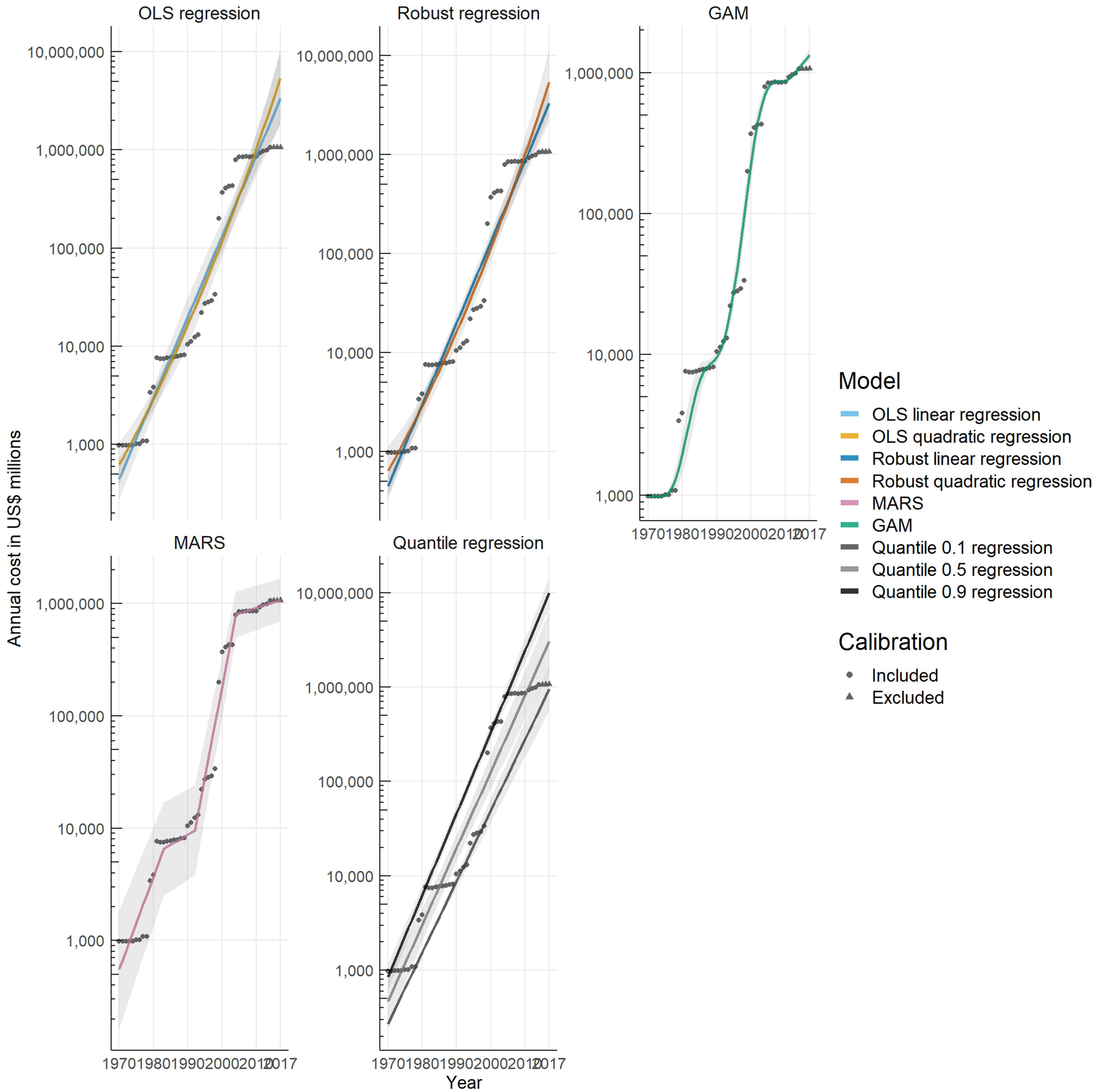
Extended Data Fig. 3 | Temporal trend (1970–2017) of global costs (in millions of 2017 US dollars) according to the type of cost. The type of cost included damage (economic losses due to direct and/or indirect impacts of invaders) and management (economic resources allocated to actions to avoid or limit invasion impacts). **a**, Predicted trend for damage costs. **b**, Predicted trend for management costs. **c**, Observed trends for both damage and management costs. The horizontal bars indicate the total time span over which decadal mean costs were calculated. Results were obtained when considering models calibrated with at least 25% data completeness (calibration interval, 1970–2015). Note that the error bands (**a**, **b**) represent the 95% confidence intervals for all models except MARS, for which they represent 95% prediction intervals (as confidence intervals cannot be estimated using MARS). We $\log_{10}$-transformed cost estimates (from the 'Cost estimate per year 2017 USD exchange rate' column of Supplementary Data 1).



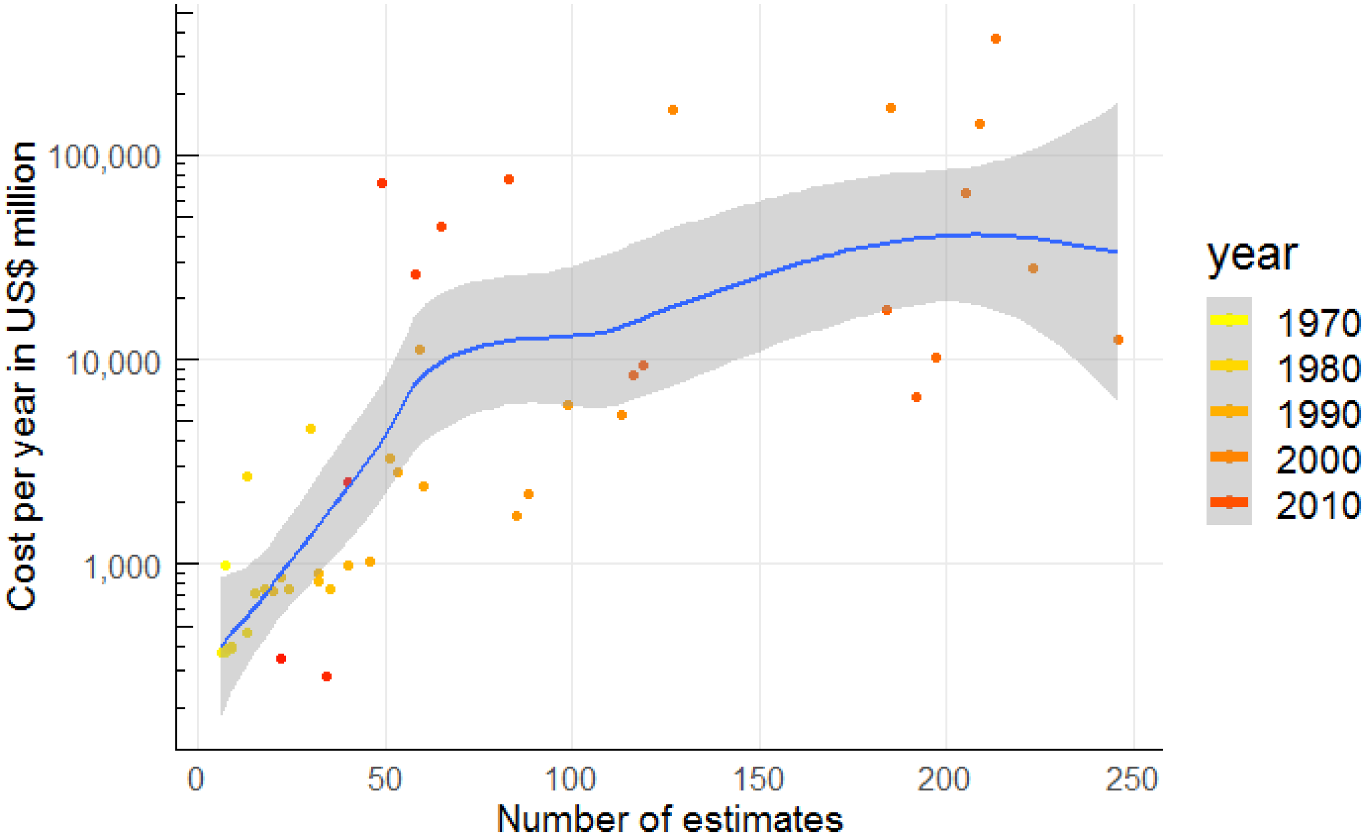
Extended Data Fig. 4 | Temporal trend (1970–2017) in global costs (in millions of 2017 US dollars) for the taxonomic groups plants, invertebrates and vertebrates. A, All plants (**Aa**) and classes for which sufficient data were available (Liliopsida (**Ab**) and Magnoliopsida (**Ac**)). **B**, All invertebrates (**Ba**) and classes for which sufficient data were available (Insecta (**Bb**)). **C**, All vertebrates (**Ca**) and classes for which sufficient data were available (Amphibia (**Cb**), Aves (**Cc**) and Mammalia (**Cd**)). Given that some subsets of the taxonomic groups were also heavily affected by outliers, we also decided to focus exclusively on robust regressions (see Supplementary Methods 1 for details). Note that the error bands represent the 95% confidence intervals for all models except MARS, for which they represent 95% prediction intervals (as confidence intervals cannot be estimated using MARS). 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 of Supplementary Data 1).



Extended Data Fig. 5 | Temporal trends (1970–2017) based on the cumulative and mean costs (in millions of 2017 US dollars) in different geographical regions. Geographical regions include Africa, Asia, Central America, Europa, North America, Oceania and the Pacific Islands, and South America. The horizontal bars indicate the total time span over which the decadal mean costs were calculated.



Extended Data Fig. 6 | Temporal trend (1970–2017) of global invasion costs (in millions of 2017 US dollars) predicted based on different modelling techniques. The linear trend over time is considered the best way to estimate the mean annual cost of invasions over time (see Supplementary Methods 1 for details). Note that the error bands represent the 95% confidence intervals for all models except MARS, for which they represent 95% prediction intervals (as confidence intervals cannot be estimated using MARS). 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 of Supplementary Data 1). 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.



Extended Data Fig. 7 | Relationship between annual cost and number of estimates. The blue line represents the average trend fitted with locally estimated scatterplot smoothing. The surrounding bands represent the 95% confidence interval (Supplementary Methods 1).

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Reporting Summary

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☐	☒	The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
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☐	☒	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☐	☒	A description of all covariates tested
☐	☐	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
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☐	☒	For null hypothesis testing, the test statistic (e.g. F, t, r) with confidence intervals, effect sizes, degrees of freedom and P value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's d, Pearson's r), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No software was used to collect the data which are openly available in a data repository (available here: https://doi.org/10.6084/m9.figshare.12668570.v1) and describe in a published paper (see here: https://www.nature.com/articles/s41597-020-00586-z)
Data analysis	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

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Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:
- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

The original InvaCost database considered here is openly accessible at https://doi.org/10.6084/m9.figshare.12668570.v1 and provided here as a supplementary material (Supplementary Data 1).

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Synthesis and analysis of the global economic costs of biological invasions
Research sample	Cost information recorded in the InvaCost database (openly accessible on figShare website)
Sampling strategy	We used the InvaCost database that compiles and describes the monetary costs associated with invasive alien species globally3. 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 occur3 (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.
Data collection	InvaCost has been generated following a systematic, standardised methodology to collect information from scientific articles, grey literature, stakeholders and expert elicitation. Each source was checked for relevance and the cost information was collated and standardised to a common and up-to-date currency in the database (i.e. 2017 US dollars). Each cost entry was depicted by a range of descriptive fields pertaining to the original source (e.g. title, authors and publication year of the reporting document), spatial extent (e.g. location and spatial scale), temporal coverage (e.g. time range and period of estimation), estimation methodology (e.g. method reliability and acquisition method) and the cost figure (e.g. type of cost and impacted sector). All methodological procedures and details for data search (e.g. literature review), collation (e.g. cost standardization), validation (e.g. method repeatability) and improvement (i.e. corrections and inputs) are published elsewhere (Diagne et al. 2020; available at https://www.nature.com/articles/s41597-020-00586-z).
Timing and spatial scale	Cost data from 1970 (first year with enough cost information) to 2017 (last year of data collection in the original version of the database used)
Data exclusions	Data were not considered if they referred to potential (i.e., not actually observed) and/or low reliability (i.e., based on unclear methodology) costs. All these exclusion criteria were pre-established.
Reproducibility	To ensure the full reproducibility of our analyses, we have repeated twice each of them and made freely accessible all R codes used as well as graphs and results generated at http://borisleroy.com/invacost/global_invasion_costs_scripts.html
Randomization	No relevant for our study which focused on cost data recorded in a public database
Blinding	Data collation in InvaCost was ensured through a double-blind review process (see complete description in Diagne et al. 2020; available at https://www.nature.com/articles/s41597-020-00586-z).

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Human research participants
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging