High and rising economic costs of biological invasions worldwide

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1   **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.

38   Invasive alien species — species successfully introduced, established and spread beyond their native

39   range — can have profound, negative impacts on biodiversity[4], ecosystem functioning and services[5],

40   human health[6] and welfare[7], as well as on the economy[8]. In addition, biological invasions are

41   increasingly exacerbated by globalization and climate change[9,10]. The worldwide implementation of

42   efficient, coordinated control and mitigation strategies remain limited, mostly due to the impacts of

43   biological invasions being undervalued by the general public, stakeholders and decision-makers[11]. A

44   clear and standardized overview of the economic costs of invasions should contribute to (*i*) optimizing

45   current and future cost-effective management strategies[12] and (*ii*) strengthen awareness and

46   communication to a wide and diverse audience[13]. This would help to move the issue of invasions

47   higher on international policy agendas for sustainable development[14].

48   Invasive alien species are responsible for substantial losses of goods, services and production

49   capacity (such as reduced crop yield, damaged infrastructure and altered use values of ecosystem

50   services)[8], and economic resources are spent each year for their management[15]. There are few global

51   attempts of cost assessments[16], which all suffer recognized flaws[15] and the majority of assessments are

52   restricted to particular taxa [e.g.,8], sectors [e.g.17] or areas[e.g.,15]. As biological invasions are an increasingly

53   planetary issue, a worldwide reliable economic impact assessment is needed to quantify more

54   precisely patterns and trends of associated costs[18,19]. We have now addressed this need with an analysis

55   of the most comprehensive database compiling the documented economic costs of biological invasions

56   — the *InvaCost* database[3]. This database covers most taxonomic groups, activity sectors, and

57   geographical regions worldwide. Here, we provide (*i*) robust estimates of the large economic costs of

58   invasions reported worldwide, (*ii*) the trends of these costs reported over time and their distribution

59   among regions, taxa and cost types, and (*iii*) original recommendations for future reporting of

60   economic data in invasion science. Finally, we discuss the research and policy implications from this

61   pioneering analysis of the economic facet of invasions.

62   **Results**

63 We used two complementary approaches to assess the global costs of invasions reported over time

64 from the most robust subset (*n* = 1319 cost estimates; ~ 57%) of the original database (see *Methods* for

65   detailed procedures and rationale for limiting biases). First, we assessed these cost estimates directly

66   using the cost from the database (see *Methods*, *Approach based on available estimates*). We found that

67   the minimum reported cost of biological invasions to human societies reached a total of $1.288 trillion

68   (2017 US dollars) between 1970 and 2017. Over this period, invasions resulted in an average of $26.8

69   billion per year (Fig. 1). This average annual cost steadily increased over time and reached $83.3

70   billion between 2000 and 2009, but declined to $29.2 billion between 2010 and 2017 (Fig. 1;

71   Supplementary Table 1). This apparent decrease for 2010–2017 is most likely an artefact arising from

72   a lack of cost estimates given the multi-year delay between occurrence and reporting in the literature.

73   An overall rise in the reporting rate for costs in the literature might also contribute partially to the

74   observed increase in costs.

75   We therefore addressed these issues by modelling the temporal trends of costs over the same period

76   (see *Methods*, *Modelling-based approach*; Supplementary Methods 1). Globally, our models

77   confirmed that costs have continuously increased each year since 1970, at a rate of more than three-

78   fold per decade and that such an increase is expected for the latest decade as well (i.e., 2010–2017)

79   (Extended Data Fig. 1; Extended Data Fig. 2; Supplementary Table 2). Hence, this confirmed that the

80   apparent decline observed in the last few years with the previous approach was likely due to the

81   paucity of reported data over the recent past rather than an actual downward trend in costs

82   (Supplementary Methods 1). We therefore estimated that the global average cost of invasions ranged

83   between $1.0 and $3.1 billion annually in 1990, between $5.6 and $32.6 billion in 2000, and between

84   $18.3 and $38.1 billion in 2010. Ultimately, we predicted that the average annual cost of invasions

85   reached the range of $46.8 billion to $162.7 billion in 2017. We also found large and increasing, inter-

86   annual variation in the cost estimates (illustrated by the different trends between the 0.1 and 0.9 cost

87   quantiles), with few high-cost years and most years exhibiting below-average economic costs

88   (illustrated by the lower rate of increase predicted for the median cost than for the average) (Extended

89   Data Fig. 2; Supplementary Methods 1). Overall, we observed similar patterns of cost increase when

90   scrutinizing these global costs regarding the *types of costs*, or at the *taxonomic* and *geographic* levels

91   (Figs. 2-4; Extended Data Figs. 3-4; Supplementary Methods 1).

92   Regarding the *types of costs*, we considered either 'damage' (economic losses due to direct and/or

93   indirect impacts of invaders) or 'management' (economic resources allocated to actions dedicated to

94   avoid or limit negative impacts of invasions) (Supplementary Methods 2). We found that costs from

95   invader damage (total cumulative cost of $892.2 billion; annual average of $18.6 billion year^{-1}) were

96   about thirteen times higher than expenditures for managing invasions ($66.3 billion; $1.4 billion year^{-}

97   ^{1}) for 1970–2017 (Fig. 2; Extended Data Fig. 3) — this is despite fewer cost estimates (Supplementary

98   Table 1). Furthermore, damage costs (~ six-fold increase every 10 years) increased at a much faster

99   rate than management costs (< two-fold increase every 10 years) (Fig. 2; Extended Data Fig. 3).

100   At the *taxonomic* level, we considered the three major groups for which we had substantial

101   information in the final dataset: plants, invertebrates and vertebrates. We calculated $591 billion from

102   estimates unambiguously assigned to a single taxonomic group (Supplementary Table 1). Within this

103   subset, invasive invertebrates appeared the costliest, with a cumulative cost of $416 billion and an

104   average annual cost of $8.7 billion from 1970–2017, estimated to increase up to $23.8 billion year^{-1} in

105   2017 (Fig. 3). This essentially occurs due to a predominance of reported costs from insects (~ 90% of

106   the total cost). Vertebrates had the second-highest financial impact, with a cumulative cost of $166

107   billion and an average annual cost of $3.5 billion for 1970–2017. We estimated this average cost to

108   decrease at $1.3 billion year^{-1} in 2017, mostly because the higher average cost for 1970–2017 is driven

109   by a limited number of years with high costs — and not necessarily due to the scarcity of cost data

110   during the last decade (Fig. 3; Extended Data Fig. 4). Most (~ 88%) of the total amount calculated was

111   from mammals. Plants had the third cumulative cost ($8.9 billion) for the same period, but this likely

112   due to data deficiency in the current database for this group (*n* = 221 cost estimates *versus n* = 469 and

113   526 for invertebrates and vertebrates, respectively) rather than an actual pattern of cost distribution

114   (Supplementary Table 1; Supplementary discussion 1). The observed increase in the temporal

115   dynamics could support such assertion (Extended Data Fig. 4; Supplementary Methods 1).

116   At the *geographic* level, economic estimates that can be unambiguously attributed to a single

117   region accounted for a total cumulative of $959 billion for 1970–2017 (Supplementary Table 1). The

118   distribution of these costs was highly skewed towards North America (Fig. 4; ~ 57% of the total cost)

119   with an average reported cost of \$11.0 billion year^{-1} for 1970–2017. Costs for the other regions ranged

120   from \$120 million year^{-1} to \$5.6 billion year^{-1} (Supplementary Table 1).

121   **Discussion**

122   *Large and increasing cost estimates.* Invasions are clearly economically costly to human societies,

123   with a minimum of \$1.288 trillion in losses and expenses accumulated between 1970 and 2017 and a

124   trebling of the average annual cost every 10 years. We predicted this amount to reach between \$18

125   billion and \$38 billion in 2010 and exceed US\$47 billion to 163 billion in 2017 worldwide.

126   Considering the different timeframes and inflation, the annual amounts we estimated in the early

127   2000s (\$6 billion to \$33 billion in 2000) seem lower than the earlier estimate inferred by Pimentel et

128   al.[16]. This discrepancy is mostly explained by our conservative approach based on (*i*) keeping only the

129   most robust data from the original database (~57% of our dataset), (*ii*) relying on scientific and official

130   materials reporting cost estimates rather than hypothetical calculations of the costs of the impacts, and

131   (*iii*) considering the most realistic assumptions on the temporal dynamics of invasion impacts

132   worldwide. Considering a less-stringent approach to our data selection would have led to a global

133   amount 33 times higher for 2017 (\$5.405 trillion; Extended Data Fig. 6). Nevertheless, our

134   conservative, annual global estimates still represent a huge economic burden. As an illustration, this

135   average annual cost largely exceeds the gross domestic product (GDP) of 50 out of 54 countries on the

136   African continent in 2017 (data.worldbank.org); it is also more than twenty times higher than the total

137   funds available in 2016–2017 for the World Health Organization (open.who.int) and the United

138   Nations (un.org) combined. Moreover, we found that costs roughly doubled every six years, a pattern

139   mimicking the continuous increase in the number of alien species worldwide[20]. Assuming a similar

140   continuing trend would place the global average costs of invasions in the alarming order of trillions of

141   dollars annually over the coming decade. This temporal trend can potentially be explained by a

142   combination of three factors: the ongoing intensification of global trade and transport creates many

143   more opportunities for invasions[20]; the growing 'land take' of the planet surface (e.g. expansion of

144   agriculture and infrastructures) makes our societies increasingly sensitive to impacts from these

145   invasions[21]; and the awareness and reporting of economic impacts of invasions have concomitantly

146   grown over time[22] (Extended Data Fig. 7).

147   *Underestimated global costs.* More alarmingly, these costs are still largely underestimated. First, we

148   relied on a conservative approach based on the most robust portion of the original dataset (see

149   *Methods*). Hence, our analyses revealed a substantial inter-annual variability in the costs over time.

150   This pattern likely arose from insufficient data for many years during the targeted period. Second, the

151   corpus of available reported costs is inherently restricted by an unknown proportion of relevant but

152   inaccessible grey literature[3], logistical and linguistic constraints which impair the discovery of all non-

153   English sources[23], the subjective terminology in invasion science[24] and the lack of reporting

154   consistency (e.g. salaried positions are rarely included)[25] which hamper consistent data collation. For

155   instance, considering emerging pathogens (currently underrepresented in the original database) in the

156   framework of biological invasions[26] would greatly increase our estimated costs. In that way, increasing

157   relevant assessment of sanitary impacts associated with alien invaders[e.g.27,28] (e.g., including indirect

158   costs on tourism or productivity) offer new opportunities. Third, the data available are geographically

159   and taxonomically uneven (79% of the recorded data belong to high-income regions from North

160   America, Oceania and Europe; and 76% are linked to animal taxa, while plants are recognized as a

161   major group of invaders[29]), meaning that impacts might be further undervalued for many areas and

162   taxa. As a likely consequence, cost amounts were highest for insects and mammals confirming

163   nevertheless that both taxonomic groups include some of the most pervasive and harmful invasive

164   species worldwide[8,30]. Similarly, North America was by far the region with the highest reported

165   amounts, illustrating that high-income areas are more prone to report invasion impacts while

166   simultaneously having better financial capacity to invest in management responses[31]. The influence of

167   local economic priorities, practical limitations and cultural and historical specificities on research

168   agendas might also partially explain these geographical discrepancies. These patterns might also only

169   reflect a trend broadly described in invasion science as a bias in research effort rather than an actual

170   distribution of data[29,31]. Fourth, an undetermined — but probably large — proportion of total invasion

171   costs is simply ignored due to many invasion impacts remaining undetected[32]. Hence, invasion costs

172 can remain hidden and/or underestimated over time simply because (*i*) the moment of introduction, (*ii*)

173 the date at which an invasion starts to be costly and (*iii*) the shape of the cost dynamics when they start

174 are generally all unknown or unreported. Lastly, the monetary valuation of particular 'costs' such as

175 losses of non-market values, indirect impacts, or impacts on some ecosystem services is rarely

176 straightforward[33,34]. The very principle of monetary valuation of nature is often associated with

177 philosophical or ethical debates[35,36]. These types of monetary losses are therefore underrepresented and

178 underreported in the body of documented costs and their relevance within the global cost of invasions

179 remains contentious[3].

180 *Caveats and directions for further research*. Our study should serve as an empirical basis for

181 substantial and iterative improvements of research on this topic. Indeed, the intrinsic complexity and

182 heterogeneity of the cost information available[3] as well as the inherent intricacies associated with their

183 relevant analyses require strong caution when investigating and interpreting them[19]. First, while we

184 clearly demonstrate that the costs have been rising steadily over time, this finding obviously relies

185 only on costs documented in the literature. However, it currently remains impossible to disentangle

186 rising costs from increasing publishing and reporting rates. Therefore, we are referring to reported

187 costs and not to exhaustive ones. Regardless of whether our increased reported costs reflect more

188 increasing costs or increasing reports, the final amounts robustly show staggering amounts. Second,

189 while we show that the costs we report are not evenly distributed regionally and among taxa,

190 discussing specific patterns further, or drawing conclusions based on the cost distribution highlighted,

191 would be too speculative. This is because *(i)* the costs we assessed represent only a limited fraction of

192 the full cost (see above) and *(ii)* specific data processing and awareness are required for depicting how

193 reported costs are actually distributed[19]. Third, while we ensured robust data pre-processing prior to

194 analysis, the quality and reproducibility of reporting studies remain intrinsically variable. Such

195 variability inevitably leads to uncertainties associated with some cost estimates derived from

196 questionable methodologies[8]. Therefore, the cost figures we report should be considered in terms of

197 relative orders of magnitude rather than precise cost estimates.

198   We therefore advocate for (*i*) strengthening interdisciplinary cooperation among scientists and

199   concerned stakeholders to capture as much as possible the completeness, diversity and complexity of

200   invasion costs, (*ii*) increasing the number and spatial coverage of studies to achieve a more balanced

201   and complete picture of invasion costs globally, especially in low-income areas, and (*iii*) ensuring a

202   minimum standardization for acquiring and publishing economic data on invasions (the descriptive

203   fields implemented in the database provide a relevant basis[3]). The ten costliest taxa from our dataset

204   (Fig. 5) illustrate well this need for more accurate and complete cost information (Supplementary

205   Discussion 1). In this respect, we provide seven recommendations for an appropriate collection and

206   reporting of these costs data (Table 1).

207   *Societal and policy implications*. The reported economic damages caused by invaders were

208   approximately an order of magnitude higher than the money spent to manage them, and damage costs

209   increased twice as rapidly as management expenditures each decade. While this result might reveal

210   more cost-efficient management actions locally, the large increase of these damage costs globally

211   confirms that the actual implementation of international agreements by local authorities is still

212   scarce[37]. This strong discrepancy between these costs and the low societal awareness of invasions in

213   general is a problem. This calls for reassessing the emphasis placed on this major driver of global

214   change in international agendas as connecting research actions and societal perspectives is

215   increasingly needed. The prioritization of policy and management actions could benefit from linking

216   cost information to other data repositories measuring different aspects of invasion impacts worldwide,

217   such as the Global Register of Introduced and Invasive Species (GRIIS)[38] and the Socio-Economic

218   Impact Classification of Alien Species (SEICAT)[22]. In addition to remaining a main priority of

219   multilateral environmental agreements such as the Convention on Biological Diversity

220   (CBD/COP/DEC/XIII/13; cbd.int/meetings/COP-13), managing invasions must be reinforced as a

221   priority for national governments. In particular, invaders costs could be significantly reduced with

222   timely investments in preventive measures (such as risk assessment, pro-active surveillance and early

223   detection) and cost-effective control campaigns (such as biological control)[39,40]. More evidence-based

224   and integrated management actions should be set up for each specific invasion context as some

225 invaders might also have neutral or positive outcomes for local ecosystems and economies[41]. The

226 transboundary nature of invasions reinforces the need for concerted international governance with

227 transboundary legal instruments and balance management expenditures at a regional scale[37,41]. Low-

228 income regions have limited capacity to act against invasions and often have few historical

229 invasions[31,42], thus international cooperation should concentrate on preventing further invasions in

230 these areas. More generally, biological invasions should become a major decision factor in most

231 transnational projects. One of the most contemporary and emblematic examples is the ambitious *Belt*

232 *and Road Initiative* that will open avenues along its way for new species introductions[43]. The

233 unintended impacts — including costs — that will be likely generated for all implicated countries

234 ought to be accounted for in the estimated net income of this commercial initiative. Hence, our work

235 concretely supports the inclusion of economic costs as a complementary quantitative indicator of

236 invasion impacts.

237   In conclusion, invasions generate a massive but still undervalued economic burden to our societies.

238 Our findings illustrate that these reported costs (*i*) have significantly increased over the last few

239 decades, (*ii*) show no sign of slowing down, (*iii*) deserve more and better organized research, and (*iv*)

240 stress the need of evidence-based and cost-effective management actions. Most worrisome is that these

241 economic losses are only part of the full aggregate of impacts incurred from invasive alien species.

242 Indeed, the ecological and health impacts of invasions are at least as significant, yet often

243 incalculable[4,6]. Finally, our work highlights once again the critical need of more global investments in

244 research as well as policy development and implementation to minimize the impact of invasions

245 worldwide.

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344

345

FIGURE LEGENDS

347 **Figure 1 |** Temporal trend of global invasion costs (in 2017 USD millions) between 1970 and 2017.

348 The solid line represents the temporal dynamics of costs based on a linear regression (see Extended Data Fig. 2

349 and Supplementary Methods 1 for details). The dashed line connects the average annual costs for each decade,

350 while the horizontal dotted line indicates the average annual cost for the entire period (see Methods, *approach*

351 *based on available estimates* for details). The last three years (displayed as triangles) were not included in the

352 model calibration; they are data-deficient and likely contribute to the artefactual decrease in global costs during

353 the last decade (Supplementary Methods 1). We considered 1319 cost estimates from the original database

354 following successive processing steps.

355 **Figure 2 |** Temporal trends of global *damage* and *management* costs (in 2017 USD millions) based on

356 both average annual costs for each decade and model prediction between 1970 and 2017. *Damage*:

357 economic losses due to direct and/or indirect impacts of invaders, such as yield loss, illness, land alteration,

358 infrastructure damage or income reduction; *Management*: economic resources allocated to actions to avoid the

359 invasion or to deal with more or less established invaders such as prevention, control, research, long-term

360 management or eradication. Regression lines were obtained by robust regression to minimize the effect of

361 outliers (see Supplementary Methods 1). The last three years (displayed as triangles) were not included in the

362 model calibration. We considered 1287 cost estimates ($n = 402$ estimates for *damage* costs; $n = 878$ estimates for

363 *management* costs) from the original database.

364 **Figure 3 |** Cumulative costs over time for 1970–2017 and 2000–2009 (a, b, c); and the average annual

365 costs (d, e, f) as observed in the database (1970–2017 and 2000–2009) and as predicted by linear

366 regression over time for 2017 for taxa with enough data (i.e., > 30 years of data). Costs are expressed in

367 2017 USD millions. Cost values only include estimates that could be derived for one of the three major

368 taxonomic groups (invertebrates, plants, vertebrates), with all taxonomic classes grouped within represented in

369 boldface. We chose 2000–2009 as the decade for which we have the most complete data and the highest

370 economic impacts of invasive alien species, although data are clearly more limited for plants. The average annual

371 costs for 1970-2017 and 2000-2009 are represented without error bars for two reasons following Weissgerber et

372 al. (2015)[42]. First, there are insufficient data for error bars to be meaningful; second, the distribution of data is

373 skewed, with most years having a lower-than-average economic cost. CI: 95% confidence interval.

374   **Figure 4 |** Geographic distribution of the cost estimates (in 2017 USD millions) available in the most

375   robust subset of the original database over 1970–2017. We only included estimates that could be

376   derived for a single geographic region (Africa, Asia, Central America, Europa, North America,

377   Oceania-Pacific islands, South America) or country.

378   **Figure 5 |** The 10 costliest taxa from the most robust subset of the original database regarding both

379   cumulative damage and management costs (in 2017 USD millions) between 1970 and 2017. Each bar

380   represents a species or a complex of species (when different species were often considered simultaneously to

381   provide cost estimates). Numbers below bars indicate the number of cost estimates. This ranking illustrates the

382   limits of the available data and the need for more thorough and standardized cost reports (Supplementary

383   Discussion 1). All silhouette animals were freely downloaded from an open source platform

384   (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*

416   (economic resources allocated to actions to avoid the invasion, or to deal with more or less established

417   invaders such as prevention, control, research, long-term management, eradication) costs

418   (Supplementary Methods 2). For specific analyses on cost distribution, we ignored the estimates that

419   could not be unambiguously assigned to one or the other category of the targeted descriptors.

420   **Duration time of cost estimates**

421   Deriving the average annual cost of invasions over time requires knowing the years over which

422   impacts occurred, but this information was not readily available for 720 out of 1338 entries in the

423   database (i.e., cost data marked as *unspecified* in the *probable_starting_year* and/or

424   *probable_ending_year* columns). We filled the missing information on the duration of each cost

425   estimate with educated estimates based on the available information (based on duration of impacts

426   indicated by the authors), or publication year when no information was available in another set of two

427   columns created for the purpose of our analysis. We again opted for a conservative choice when

428   completing missing data. When no period of impact was specified, we counted only a single year for

429   costs repeated over several years, but for which we had no information on the exact duration (even

430   though the cost might have been repeated over many years, even up to present time). Therefore, the

431   number of years over which a cost likely occurred was the difference between the

432   *probable_starting_year* and the *probable_ending_year* columns (to which we add a 1 to avoid null

433   values for costs occurring only once). We thereafter chose to focus on the period 1970–2017, where

434   1970 is the first year from which *InvaCost* has robust and sufficient economic data, and 2017 is the

435   last year for the standardized data collection.

436   **Estimating global cost patterns**

437   Because the raw cost estimates standardized to 2017 US$ (*raw cost estimate 2017 USD exchange rate*

438   column) encompass estimates with two different time ranges ('period' or 'year' in the *Time range*

439   column), they were expressed as annual costs (*Cost estimate per year 2017 USD exchange rate*

440   column). To do this, we divided the raw costs provided for a period exceeding a year ('period' in the

441   *Time range* column) by the duration time described above, while we did not transform the raw costs

442   provided yearly or for a period up to one year ('year' in the *Time range* column). For estimating global

443   cost patterns and trends over time, we used two approaches described in the following two paragraphs

444   and fully implemented in the 'invacost' R package[44].

445   *Approach based on available estimates*. We first depicted global cost patterns by calculating the

446   average annual cost for each decade since 1970 (intervals of ten years, except for the last period 2010–

447   2017 that is incomplete). For this, we summed all the annual costs occurring each year of a given

448   decade and then divided them by the number of years. Second, we calculated the average annual cost

449   for the entire period (1970–2017). We presented average annual costs rather than median annual costs

450   because we assumed that the skewness of data is caused by the considerable incompleteness of

451   economic data for most years. Therefore, we deemed that the average annual cost is probably closer to

452   the actual annual cost than the median.

453   *Modelling-based approach*. Nonetheless, while the first approach is important to depict the patterns

454   obtained directly from the content of the database, it might not be sufficiently robust to infer the actual

455   cost patterns. Indeed, it does not take into account the dynamics of both invasions and their costs over

456   time. In addition to the increasing trend of invasions worldwide[9], a time lag of several years is likely to

457   exist between the actual occurrence of a cost and its reporting in the grey or scientific literature

458   (Supplementary Methods 1). Ignoring this time lag likely underestimates the average annual economic

459   cost of invasions, especially at the end of the time series because the most recent costs are probably

460   not yet reported or published. This discrepancy could explain why the average annual cost for the last

461   decade (2010-2017) appears lower, giving a biased summary of the actual trend of the costs over time.

462   Therefore, we modelled the long-term trend of costs over time to derive estimates of average annual

463   costs. To account for the time lag caused by the reporting of costs, we excluded the most incomplete

464   years (i.e., years expected to have < 25% of cost data; Supplementary methods 1).

465   To model the temporal cost trend, we used an ensemble approach based on different linear and non-

466   linear techniques (details, procedures and appropriate literature are fully provided in the

467   Supplementary Methods 1): ordinary least-squares linear and quadratic regressions, robust linear and

468   quadratic regressions, multiple adaptive regression splines (MARS), generalized additive models

469   (GAM), and quantile regression. We accounted for temporal autocorrelation and heteroscedasticity

470   with methods specific to each model (see details in Supplementary Methods 1). We $\log_{10}$-transformed

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471   all the annual costs prior to analysis. We had one *a priori* assumption on the probable shape of trends

472   over time. Because of the exponential increase in the number of invasive species globally (Seebens et

473   al. 2017), we expected the long-term temporal trend to be either increasing or stabilizing, but not

474   decreasing. Hence, we assumed that a model describing a decreasing trend in recent years (i.e., for

475   years lower than the 75% completeness threshold) could indicate an effect of the lack of data for

476   recent years. We provided the entire range of model predictions for three decadal years as benchmarks

477   (1990, 2000 and 2010) as well as for 2017, which was the last year of our data collection. Note that

478   this approach was not designed for future extrapolation because there is no certainty that the

479   underlying explanatory factors of cost trends will be similar in the future. Moreover, we did not apply

480   this *Modelling-based approach* to geographical regions, because we could not adequately model

481   trends over time due to data deficiencies.

482   Note that the economic valuation of costs of invasions is a highly challenging task (see Jackson et al.

483   2015[2] for a critical review). All the cost estimates presented here represent ranges that should be

484   viewed in terms of relative orders of magnitude rather than exact figures. All analyses and figures

485   generated were made with the 'invacost' R package[44].

511 **Data availability**

512 The original dataset considered for our data processing is provided as a supplementary material

513 (Supplementary Data 1).

514 **Code availability**

515 We did all data processing and analyses with the 'invacost' R package (available on the

516 Comprehensive R Archive Network at https://cran.r-project.org/package=invacost). The analytical

517 framework is described in details in Leroy et al. (2020)[44]. A step-by-step tutorial for this framework is

518 also available at https://www.github.com/Farewe/invacost. The code used to generate the graphs and

519 analyses for this paper is available at

520 http://borisleroy.com/invacost/global_invasion_costs_scripts.html.

EXTENDED DATA

522 **Figure 1 |** Box-and-whisker plot of the lag between cost occurrence and year of publication, based on

523 the most robust subset of the database (see 'Dataset and processing steps' in the *Methods* section). The

524 few occurrences of publications before economic impacts corresponded to planned budgets over

525 specific periods expanding beyond the publication year

526 **Figure 2 |** Temporal trend (1970–2017) of global invasion costs (in 2017 USD millions) predicted

527 based on different modelling techniques (see 'Model' legends). OLS: ordinary least-squares; GAM:

528 generalized additive model; linear regression, quadratic regression, MARS: multiple adaptive regression splines.

529 *The linear trend over time is considered the best way to estimate the average annual cost of invasions over time*

530 *(see Supplementary Methods 1 for details). Results are those obtained when considering models calibrated with*

531 *at least 25% data completeness (calibration interval 1970–2015). We log$_{10}$-transformed cost estimates (from the*

532 *'Cost estimate per year 2017 USD exchange rate' column in the database).*

533 **Figure 3 |** Temporal trend (1970–2017) of global costs (in 2017 USD millions) following the type of

534 costs (*damage*: economic losses due to direct and/or indirect impacts of invaders; *management*:

535 economic resources allocated to actions to avoid or limit invasion impacts). a: predicted trend for

536 damage costs (see 'Model' legends); b: predicted trend for management costs (see 'Model' legends); c:

537 observed trends for both damage and management costs. OLS: ordinary least-squares; GAM: generalized

538 additive model; linear regression, quadratic regression, MARS: multiple adaptive regression splines. *Results are*

539 *those obtained when considering models calibrated with at least 25% data completeness (calibration interval*

540 *1970–2015). We log$_{10}$-transformed cost estimates (from the 'Cost estimate per year 2017 USD exchange rate'*

541 *column in the original database). We log$_{10}$-transformed cost estimates (from the 'Cost estimate per year 2017*

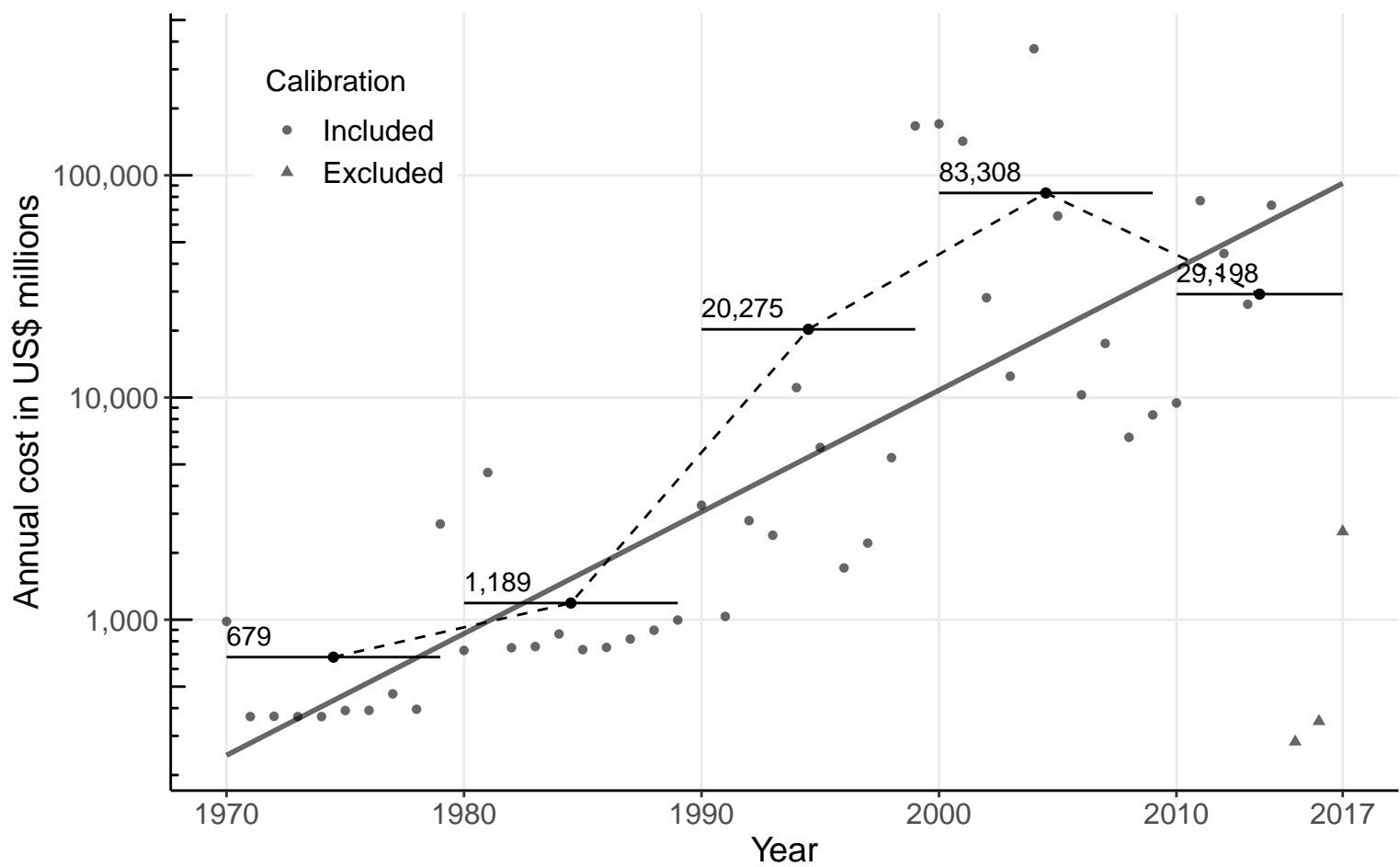542 *USD exchange rate' column in the database).*

543 **Figure 4 |** Temporal trend (1970–2017) of global costs (in 2017 USD millions) following taxonomic

544 group [plants (A), invertebrates (B), vertebrates (C)] and each class within for which data were

545 sufficient to allow our modelling approach. Given that some subsets for taxonomic groups were also heavily

546 affected by outliers, we also decided to focus exclusively on robust regressions *(see Supplementary Methods 1*

547 *for details). Results are those obtained when considering models calibrated with at least 25% data completeness*

548   *(calibration interval 1970–2015). We log$_{10}$-transformed cost estimates (from the 'Cost estimate per year 2017*

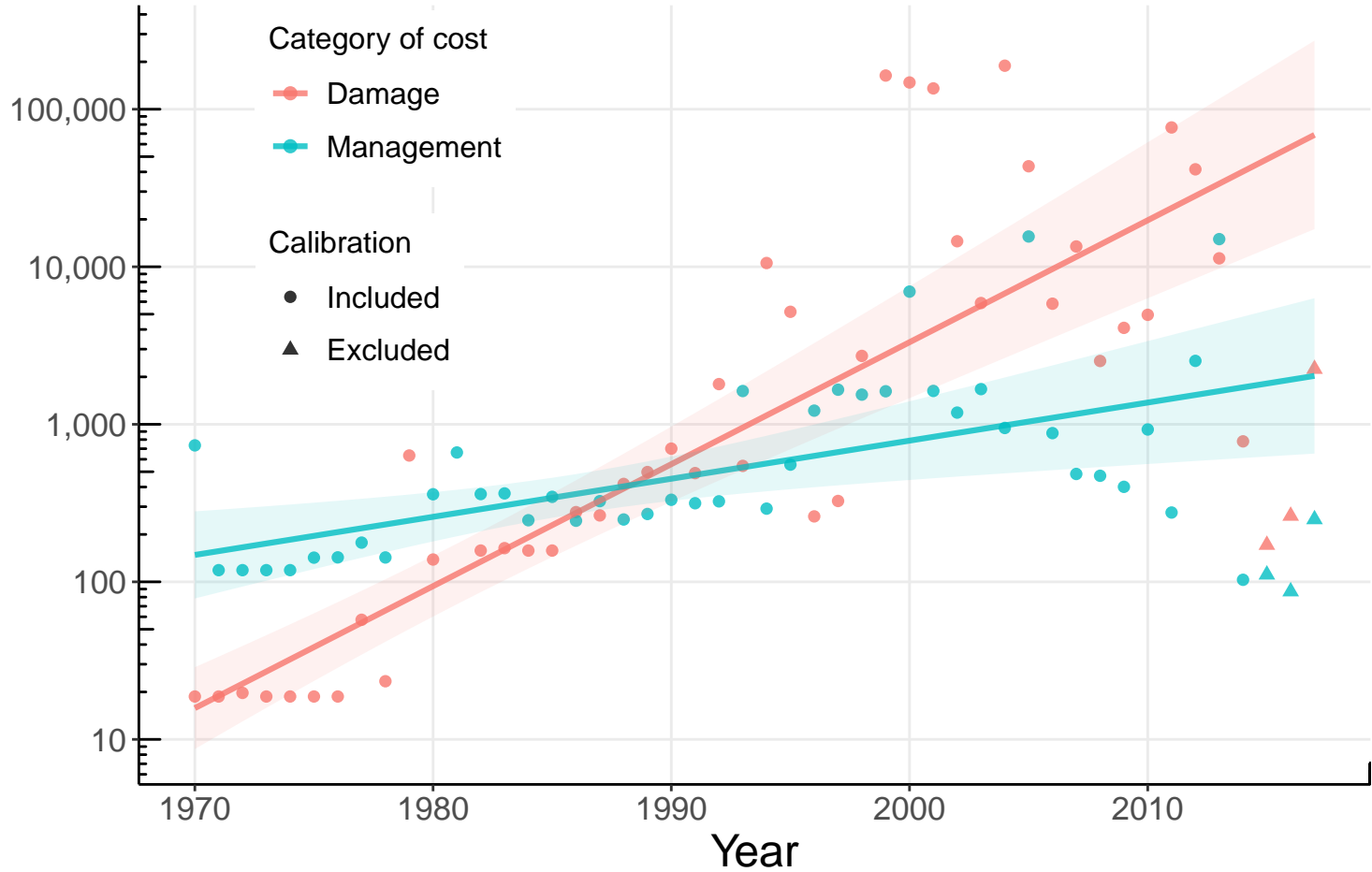549   *USD exchange rate' column in the database).*

550   **Figure 5 |** Temporal trends (1970–2017) based on the cumulative and average costs (in 2017 USD

551   millions) following the geographic regions (Africa, Asia, Central America, Europa, North America,

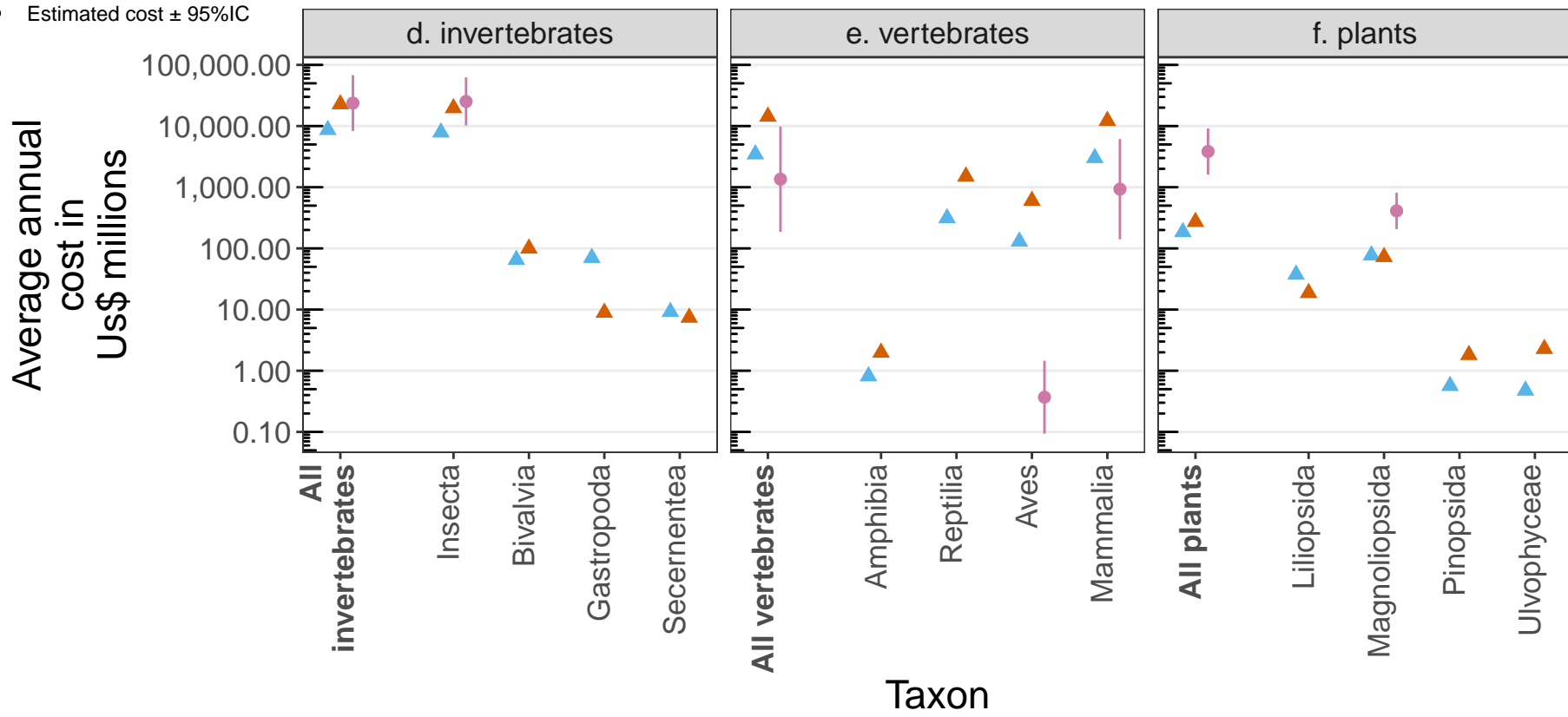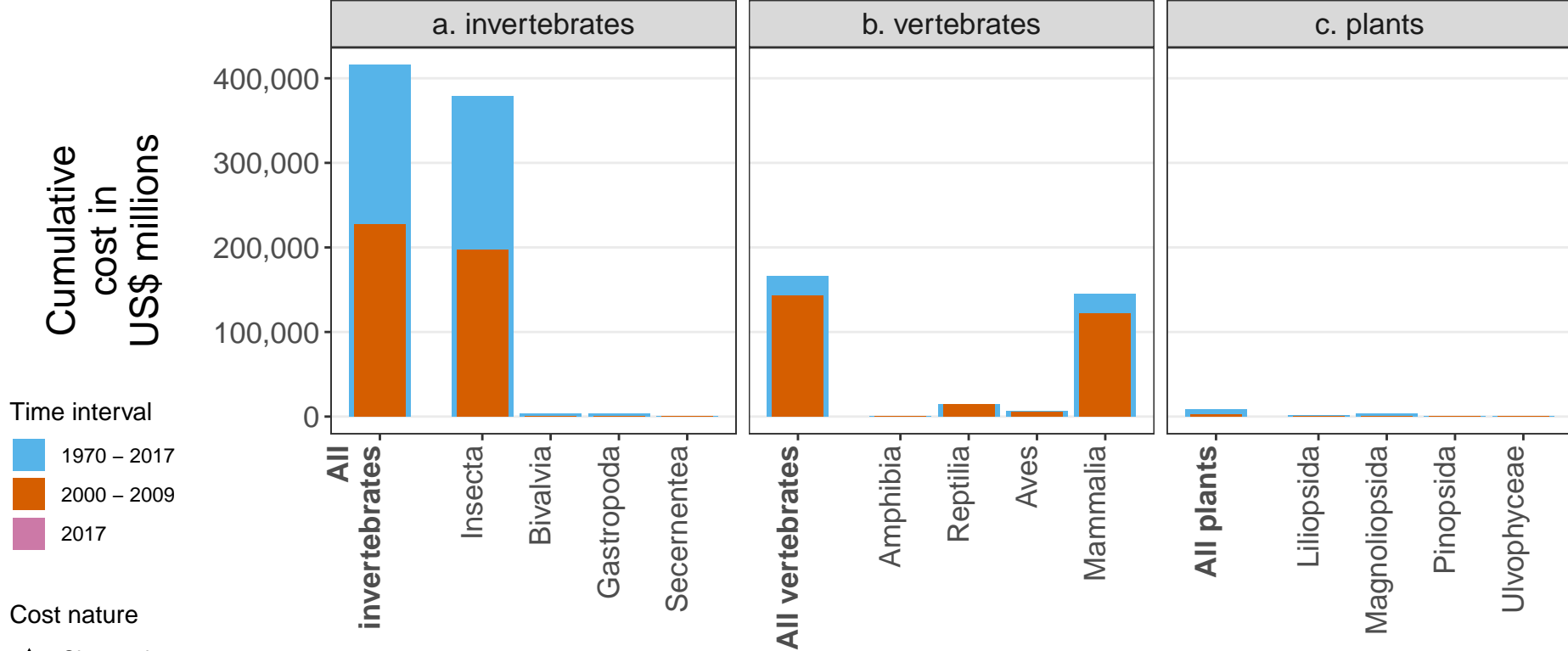552   Oceania-Pacific islands, South America).

553   **Figure 6 |** Temporal trend (1970–2017) of global invasion costs (in 2017 USD millions) predicted

554   based on different modelling techniques (see 'Model' legends). OLS: ordinary least-squares; GAM:

555   generalized additive model; linear regression, quadratic regression, MARS: multiple adaptive regression splines.

556   *The linear trend over time is considered the best way to estimate the average annual cost of invasions over time*

557   *(see Supplementary Methods 1 for details). Results are those obtained when considering models calibrated with*

558   *at least 25% data completeness (calibration interval 1970–2015). We log$_{10}$-transformed cost estimates (from the*

559   *'Cost estimate per year 2017 USD exchange rate' column in the database). We considered that the duration time*

560   *of costs for which no period of impact was specified was higher than those considered in our conservative*

561   *strategy when completing missing data on the temporal dynamics. For this purpose, we considered as occurring*

562   *until 2017 every cost that could be repeated over several years, but for which we had no information on the*
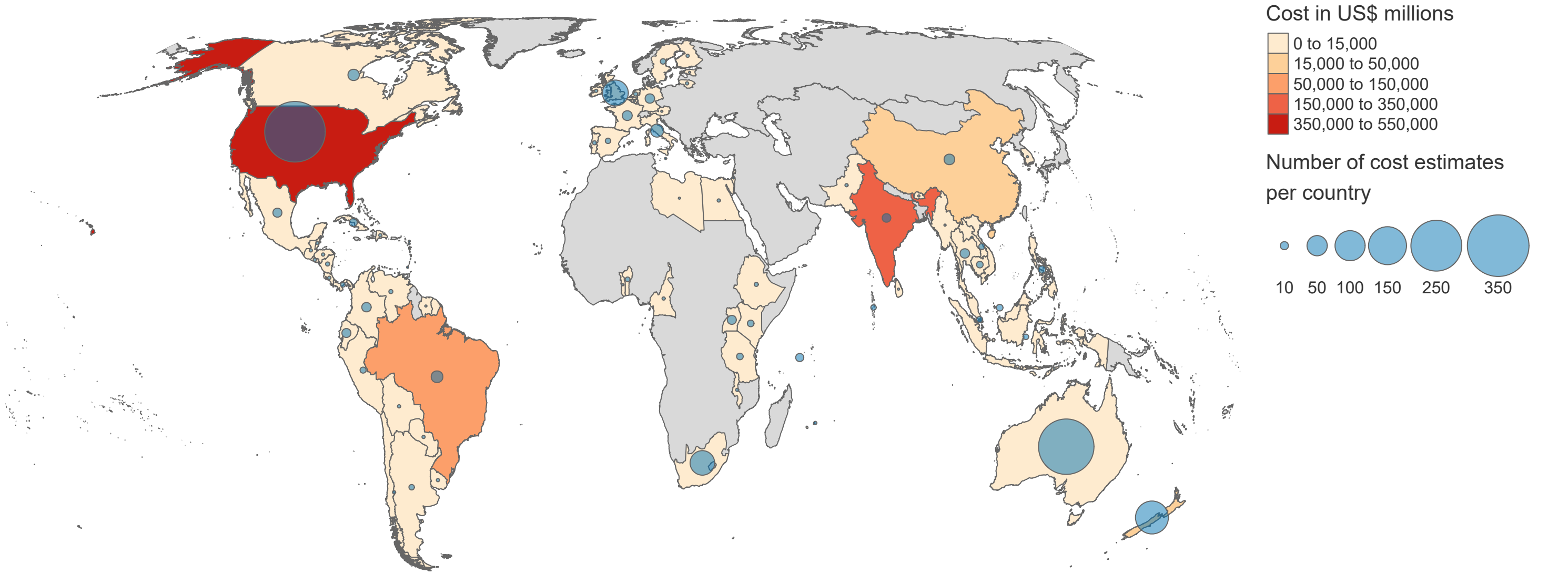
563   *exact duration.*

564   **Figure 7 |** Relationship between annual cost and number of estimates. Blue line: average trend fitted

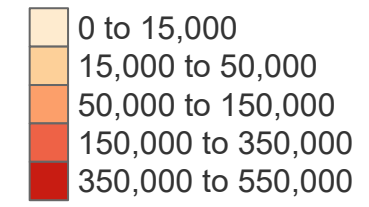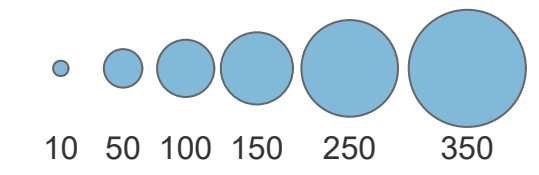565   with locally estimated scatterplot smoothing.