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High and rising economic costs of biological invasions worldwide

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24 **Summary**

25 Biological invasions are responsible, in addition to significant biodiversity declines, for enormous
26 economic losses to society as well as monetary expenditures for their management^{1,2}. The *InvaCost*
27 database has allowed for the first time a reliable, comprehensive, standardized, and easily updatable
28 synthesis of the monetary impacts of invasions worldwide³. Here, we found that total reported costs of
29 invasions reached a minimum of \$1.288 trillion (2017 US dollars) over the last few decades (1970-
30 2017), with an annual average cost of \$26.8 billion. Moreover, we estimate that the annual average
31 cost could reach \$162.7 billion in 2017. These costs remain massively underestimated and do not show
32 any sign of slowing down with a consistent three-fold increase per decade. Our synthesis reveals that
33 documented costs are both widely distributed and with strong gaps at regional and taxonomic scales,
34 with damage costs being an order of magnitude higher than management expenditures. Research
35 approaches for documenting costs of biological invasions need to be further improved. Nonetheless,
36 our findings are a compelling call for the implementation of consistent management actions and
37 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 biodiversity⁴, ecosystem functioning and services⁵,
40 human health⁶ and welfare⁷, as well as on the economy⁸. 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-makers¹¹. A
44 clear and standardized overview of the economic costs of invasions should contribute to (i) optimizing
45 current and future cost-effective management strategies¹² and (ii) strengthen awareness and
46 communication to a wide and diverse audience¹³. This would help to move the issue of invasions
47 higher on international policy agendas for sustainable development¹⁴.

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 management¹⁵. There are few global
51 attempts of cost assessments¹⁶, which all suffer recognized flaws¹⁵ 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* database³. 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; $\sim 57\%$) 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⁻¹)
97 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 worldwide²⁰. 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 invasions²⁰; 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 invasions²¹; and the awareness and reporting of economic impacts of invasions have concomitantly
146 grown over time²² (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 literature³, logistical and linguistic constraints which impair the discovery of all non-
153 English sources²³, the subjective terminology in invasion science²⁴ 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 invasions²⁶ 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 invaders²⁹), 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 responses³¹. 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 undetected³². 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 contentious³.

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 available³ as well as the inherent intricacies associated with their
183 relevant analyses require strong caution when investigating and interpreting them¹⁹. 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 distributed¹⁹. 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 methodologies⁸. 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 basis³). 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 scarce³⁷. 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 economies⁴¹. 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 introductions⁴³. 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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343 package. BioRxiv (2020). doi: <https://doi.org/10.1101/2020.12.10.419432>

344

345

346 **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/>).

385 **TABLES**

386 **Table 1** | Recommendations for relevant reporting of economic data associated with biological
 387 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 <i>observed</i> or <i>potential</i> implementation of the costs, and their distribution between <i>damage</i> and <i>management</i> 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

388

389 **Methods**

390 **Dataset and processing steps**

391 We used the *InvaCost* database that compiles and describes the monetary costs associated with
392 invasive alien species globally³. For each entry, we considered the cost estimates standardized to 2017
393 US dollars (\$) based on exchange rates provided by the World Bank (see column *Raw cost estimate*
394 *2017 USD exchange rate*), because this allowed us to consider almost all cost data entered in the
395 database. Note obvious duplicate cost estimates (*i.e.*, same cost figures from [non-]identical sources)
396 were removed when building the database, while acknowledging that some overlaps can still occur³
397 (see also Supplementary Discussion 1). To ensure a realistic, robust and conservative synthesis, we
398 filtered out some cost data from the database to keep only those expected to have actually occurred.
399 Therefore, we first applied filters to exclude unrealistic or potential costs. To do this, we successively
400 excluded estimates corresponding to *potential* costs (*Implementation* column; $n = 539$) and then those
401 derived from studies deemed of *low* reliability (*Method reliability* column; $n = 531$). Second, we
402 removed cost entries that did not have a known *start year* to avoid considering these dubious costs for
403 a period of one year ($n =$ see ‘Duration time of cost estimates’ below). Thus, from an initial pool of
404 2419 cost estimates in the original database, we kept a final total of 1319 cost estimates deemed to be
405 the most robust in the final dataset (Supplementary Data 1). From there, although a few undetectable
406 and redundant estimates might still occur, the costs derived from our robust subset still represent
407 conservative estimates.

408 **Database descriptors**

409 We considered three descriptors from the dataset to decipher how cost estimates are distributed over
410 regions, taxa and types of costs. For the spatial distribution, we used information from the *geographic*
411 *regions* column. For the taxonomic distribution, we combined information from *kingdom*, *phylum* and
412 *class* columns to group the economically harmful invaders recorded among *plants*, *invertebrates* and
413 *vertebrates*. For the type of cost, we used the information from the *type of cost* column to classify the
414 cost estimates among *damage* (economic losses due to direct and/or indirect impacts of invaders, such
415 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 package⁴⁴.

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 worldwide⁹, 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

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 2015² 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 package⁴⁴.

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

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502 and standardised all data. CD, BL and ACV processed the final database. BL and CD implemented the
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504 from all contributing authors. All authors read and approved the final manuscript.

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507 www.nature.com/reprints. Readers are welcome to comment on the online version of the paper.
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510 saclay.fr).

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.

521 **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).*

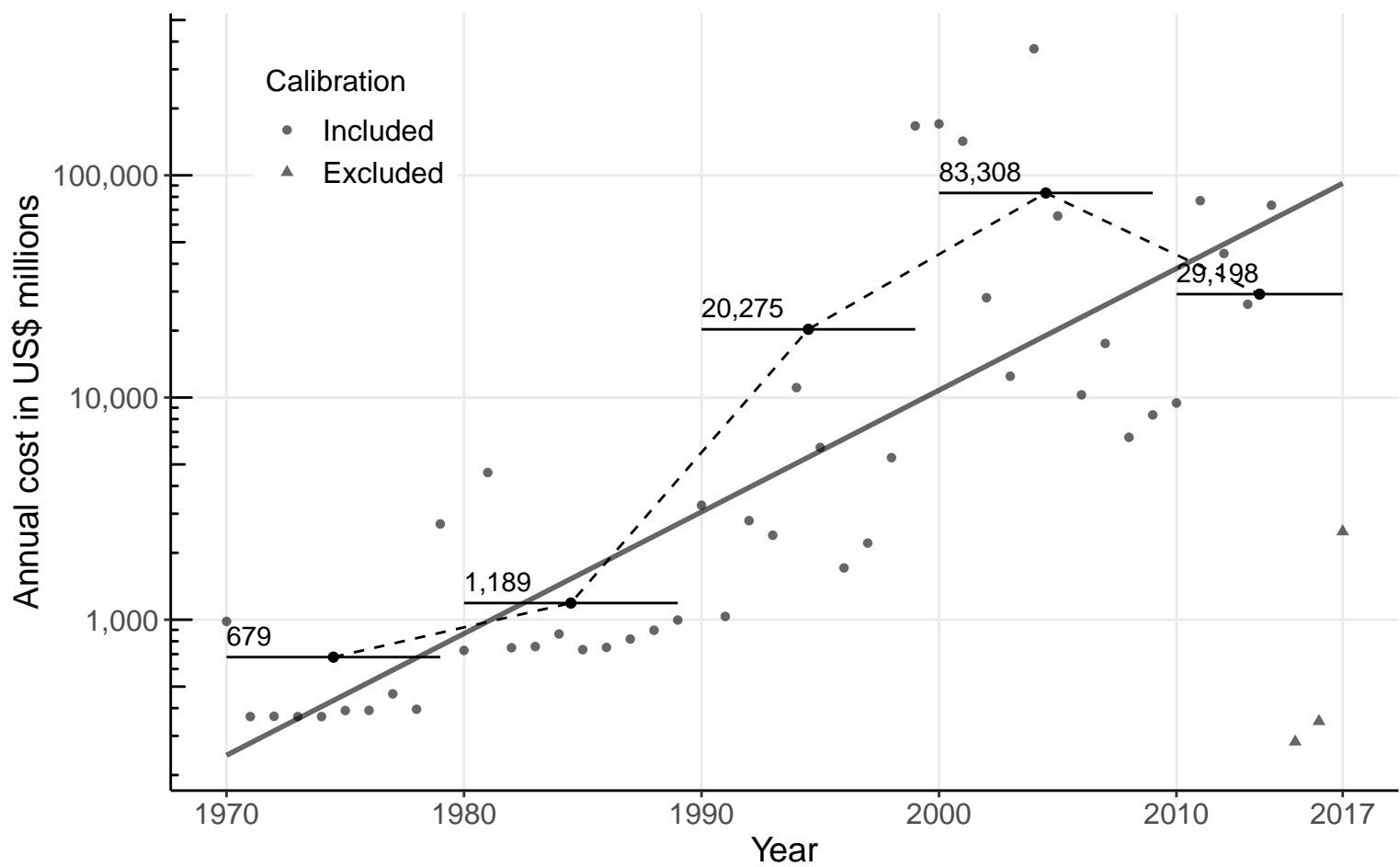
543 **Figure 4** | Temporal trend (1970–2017) of global costs (in 2017 USD millions) following taxonomic
544 group [plants (A), invertebrates (B), vertebrates (C)] and each class within for which data were
545 sufficient to allow our modelling approach. Given that some subsets for taxonomic groups were 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 log₁₀-transformed cost estimates (from the ‘Cost estimate per year 2017*
549 *USD exchange rate’ column in the database).*

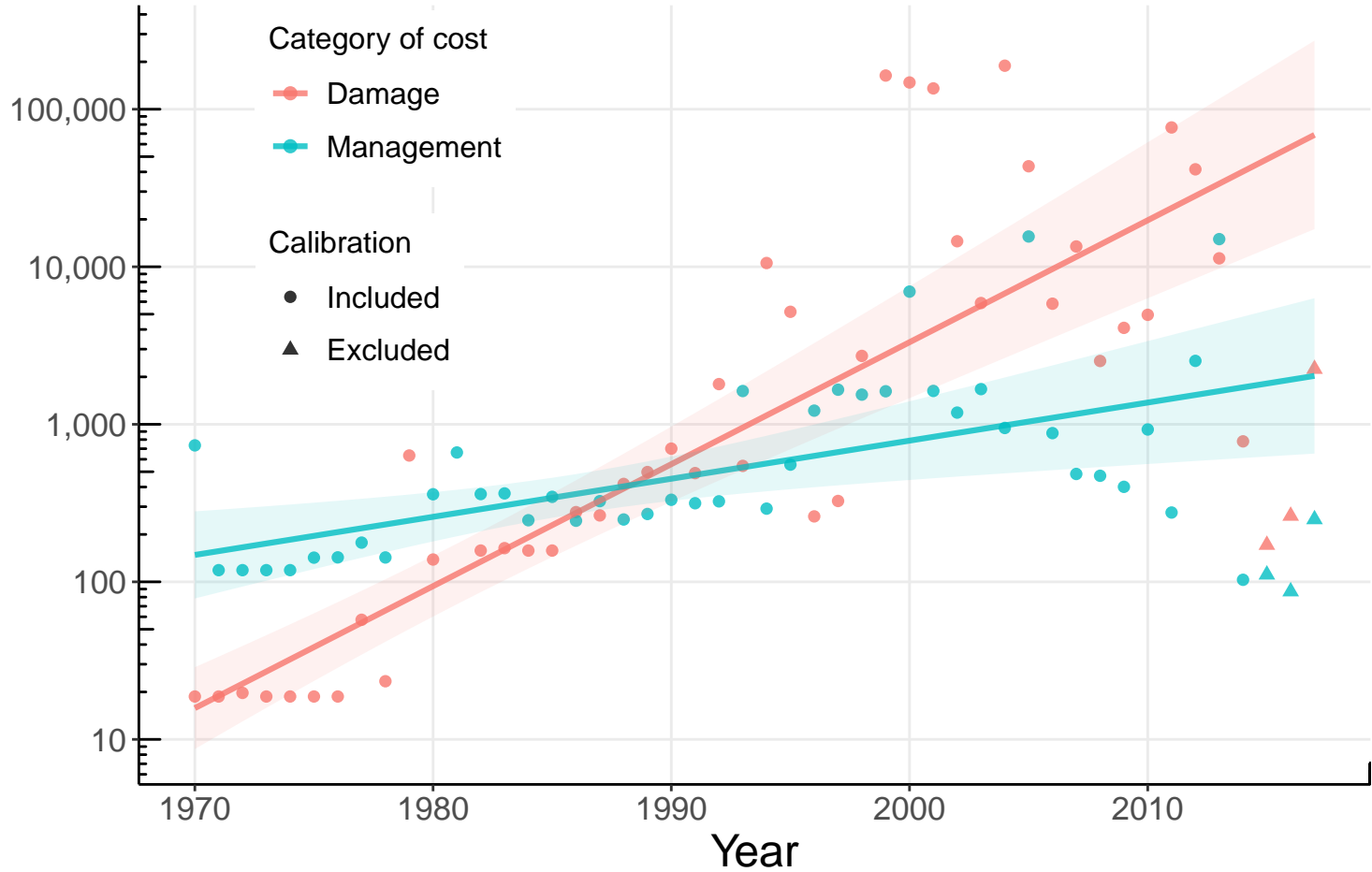
550 **Figure 5** | Temporal trends (1970–2017) based on the cumulative and average costs (in 2017 USD
551 millions) following the geographic regions (Africa, Asia, Central America, Europa, North America,
552 Oceania-Pacific islands, South America).

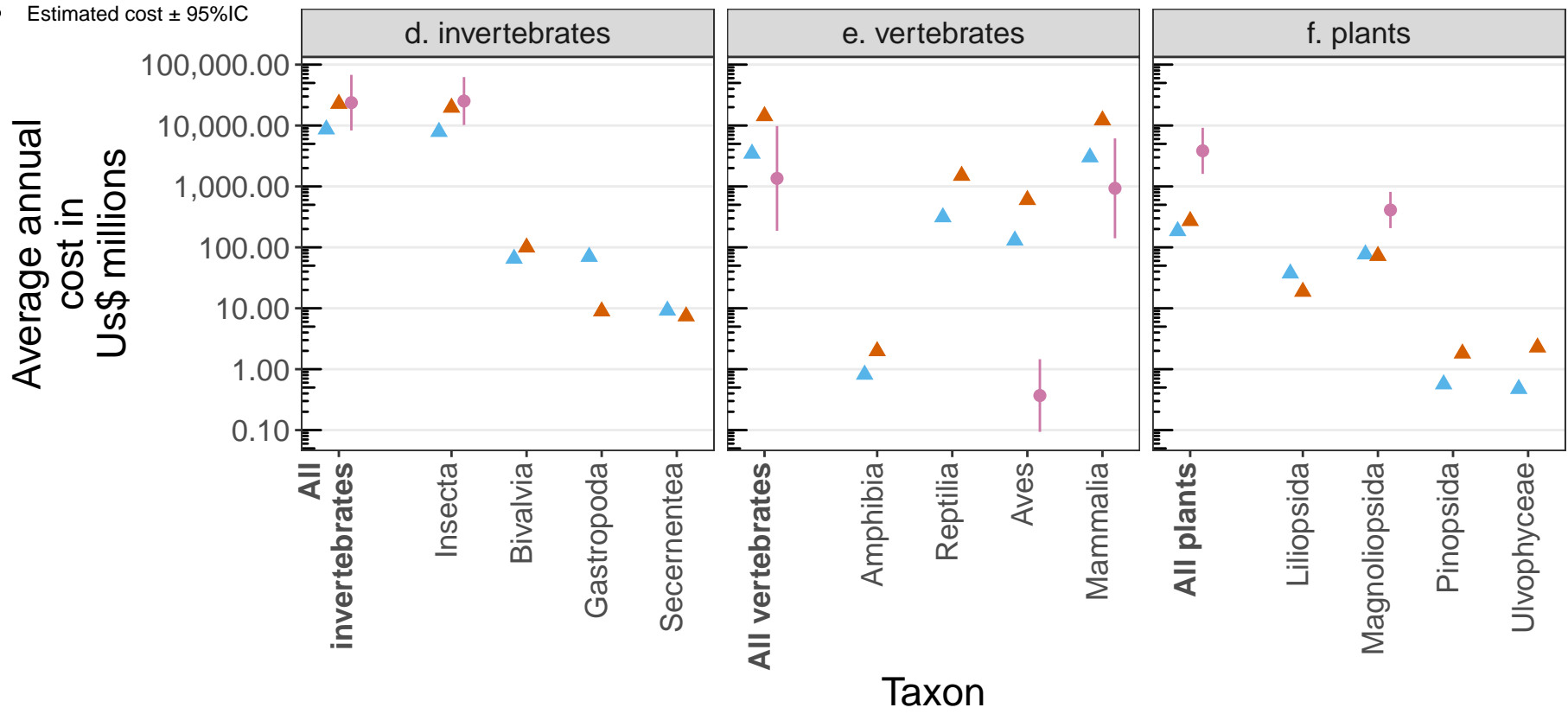
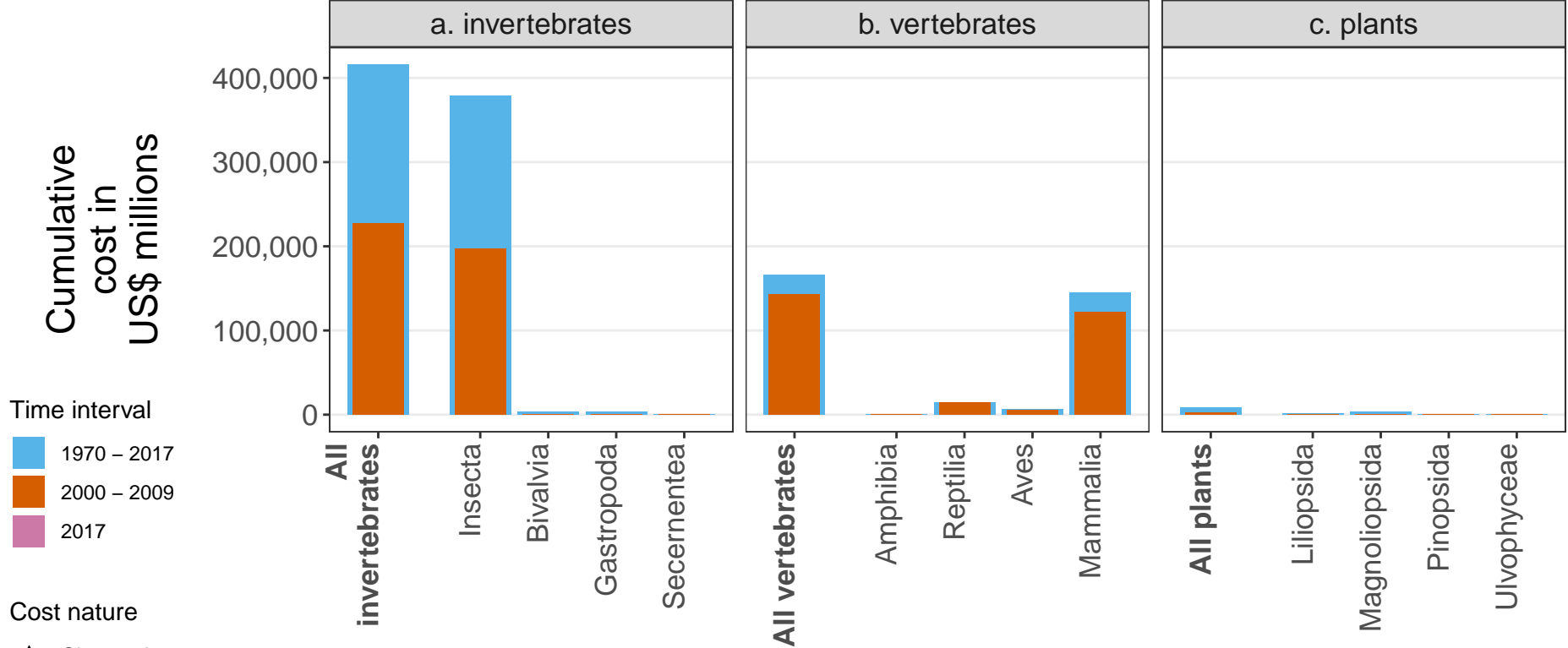
553 **Figure 6** | Temporal trend (1970–2017) of global invasion costs (in 2017 USD millions) predicted
554 based on different modelling techniques (see ‘Model’ legends). OLS: ordinary least-squares; GAM:
555 generalized additive model; linear regression, quadratic regression, MARS: multiple adaptive 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 log₁₀-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.*

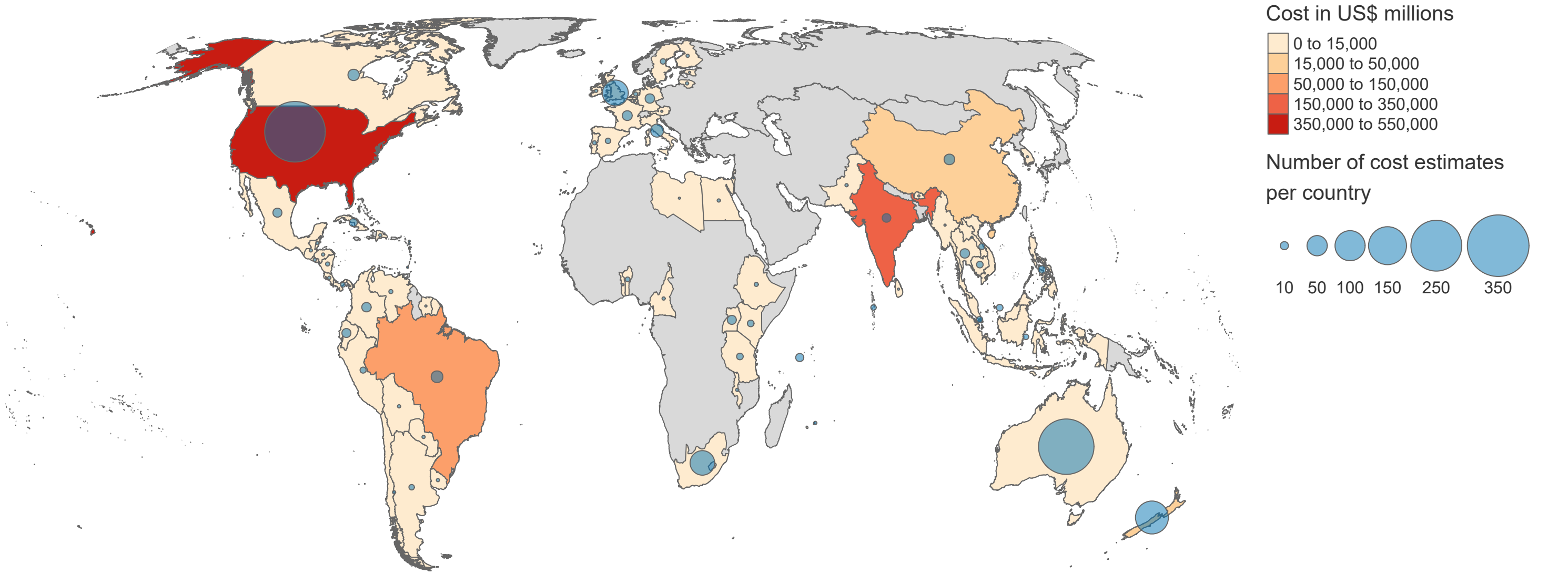
564 **Figure 7** | Relationship between annual cost and number of estimates. Blue line: average trend fitted
565 with locally estimated scatterplot smoothing.



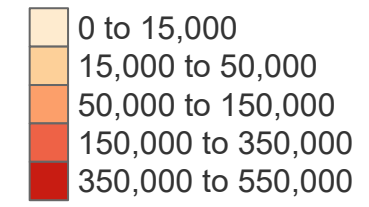
Annual cost in US\$ millions



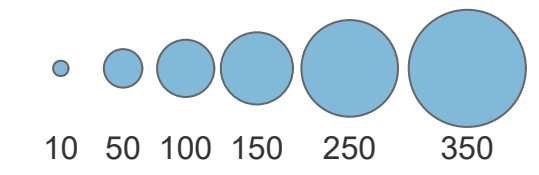




Cost in US\$ millions



Number of cost estimates per country



Cumulative cost for 1970-2017 in 2017 US\$ billions

Cost type
Damage
Management
Mixed

