

Global economic costs of invasive plants

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Abstract

Biological invasions impose substantial ecological and socio-economic burdens, yet the global economic impacts of invasive plants remain incompletely quantified. Here, we provide the first comprehensive global synthesis of reported monetary costs associated with invasive plants using the *InvaCost* database. After data validation and filtering for highly reliable, observed estimates, we identified a total of US\$361.8 billion in documented costs between 1960 and 2022, representing a conservative baseline of invasive plant impacts at global level. Costs were unevenly distributed across taxa and regions, with a small number of species and families accounting for the vast majority of costs, and with North America accounting for 61% of reported impacts. Terrestrial environments and the agricultural sector bore the greatest economic burden. The cost of damage was over three times the amount spent on management; preventive investments were negligible. Annual costs increased markedly from the 1990s onward, exceeding US\$50 billion in some years. Cumulative annual damage costs followed a sigmoidal trajectory, indicating rapid escalation over recent decades and suggesting substantial future economic pressures if historical cost-accumulation patterns continue. Socio-economic context and size of countries were key predictors of reported costs, highlighting strong reporting and capacity biases. Despite the magnitude of documented impacts, plant invasion costs remain severely underestimated due to taxonomic, geographic and sectoral data gaps. Our synthesis reveals the scale, distribution and increasing burden of invasive plant costs globally, underscoring the urgent need for improved reporting, proactive prevention and more effective management to limit future economic losses.

Introduction

Biological invasions are among the greatest threats to biodiversity worldwide¹. Following establishment, many non-native species spread and become invasive (*sensu*²), potentially causing substantial ecological and societal impacts^{3,4}, including growing economic burden⁵. Plants are the most numerous and among the best studied taxa of invasive species worldwide and continue accumulating globally^{6,7}. Invasive plants are well known to cause severe ecological impacts⁸, but there is growing recognition of their impacts on human health and economies^{5,9}.

The open-access database *InvaCost*, compiling reported monetary costs associated with invasive species^{5,10}, has increased visibility around the economic dimensions of biological invasions. *InvaCost* constitutes the most comprehensive tool currently available for synthesising invasion costs, enabling comparisons across geographic regions, economic sectors, introduction pathways, and taxa, among others¹¹. To date, reported invasion costs are in the order of US\$ trillions and continue to rise rapidly¹², although their real number is likely several orders higher¹³. While global monetary costs of invasive trees and aquatic plants have been estimated using *InvaCost*^{14,15}, these groups represent only a minor subset of invasive plant taxa, and no comprehensive global synthesis has yet been conducted for invasive plants as a whole.

Whereas invasive plants have been considered to be less impactful compared to invasive animals¹⁶ and often operate through different impact mechanisms^{17,18,19,20}, economic impacts could provide a quantitative measure for such a comparison. Other major knowledge gaps are the lack of a comprehensive global assessment of plant invasion costs across habitats, given the prevailing biases in existing data²¹, and the absence of evidence on whether the drivers of invasion costs identified across taxa—such as country invasibility, area suitability, and management and reporting effort^{13,22,23,24}—also apply to plants.

Moreover, understanding how these costs accumulate through time can help inform future cost trajectories, especially for damage costs, which are more closely linked to invasion dynamics and less influenced by management decisions than management expenditures. Recent studies across diverse taxa show that cumulative invasion impacts often follow sigmoidal curves, with slow initial increases, rapid growth phases, and subsequent deceleration, consistent with ecological evidence of invasion lags and non-linear impact dynamics^{25,26}. Similar cumulative approaches have been applied to invasive species damage costs^{21,27,28}, demonstrating how these patterns can inform projections of future costs and identify windows for management intervention²⁸, while distinguishing genuine slowdowns from artefacts of under-reporting or observation lags^{5,10,21,29}. Cost accumulation is also likely influenced by species' residence time, as longer-established species can increase impacts through population growth and spread²⁶, while older invasions may become less reported due, for example, to reduced management feasibility. Although multiple non-linear relationships have been observed between residence time and the economic costs of invasive species, most are sigmoidal and differ between damage and management costs^{13,26,27}. However, no study explicitly addressed these relationships for invasive plants, yet.

Here, we synthesize the global monetary costs of invasive plants using the *InvaCost* database. Specifically, we assess (i) the taxonomic and geographic distribution of costs, (ii) the most affected environments and economic sectors, (iii) the country-specific drivers of reported costs, (iv) the temporal trends in reported costs, (v) the long-term accumulation and trajectory of damage costs, and (vi) the relationship between monetary costs and species' residence time. Rather than providing a definitive global cost estimate, we aim to establish a conservative baseline, summarize the current state of knowledge, and highlight key data gaps relevant for future research and more effective policy and management responses

Results

Cost description

The *highly reliable observed* costs amounted to US\$167.2 billion, resulting in US\$361.8 billion between 1960 and 2022 after database expansion (Fig. 1).

Most cost entries (61%; US\$221.1 billion) were attributed to specific taxa (including spp.), while the remaining 39% (US\$140.7 billion) were classified as “Diverse” (13.1% of the 12,708 entries). The 15-costliest families (out of the 93 present in the database) accounted for 61% of total costs (US\$221.5 billion), while the “Diverse” category represented the remaining 39% (US\$140.3 billion). Costs were dominated by Tamaricaceae, primarily driven by *Tamarix* spp., followed by Cactaceae and Asteraceae (Fig. 2). Similarly, despite 407 taxa being present in the database, 15 alone accounted for 99% (US\$358.3 billion) of total costs. Among these, *Tamarix* spp. alone contributed approximately US\$148.3 billion, far exceeding all other taxa (Fig. 2). *Opuntia* spp., *Ambrosia artemisiifolia*, *Euphorbia esula*, and *Pontederia crassipes* were associated with multi-billion US\$ costs (Fig. 2).

Costs were unevenly distributed geographically, with several countries (especially in Africa and Asia) not represented in *InvaCost* (Fig. 3). North America alone accounted for most costs (US\$265.0 billion), followed by Oceania (including Pacific islands; US\$63.8 billion), while all remaining regions each accounted for less than US\$12 billion. Costs were US\$11.4 billion in Europe, US\$8.5 billion in Africa, US\$7.8 billion in Central and South America, and US\$5.4 billion in Asia. Costs attributed to multiple geographic regions were minimal (approximately US\$1 million). Costs were highly concentrated, with the 10-costliest countries representing 97% (US\$351.8 billion) of total costs. The USA alone accounted for US\$252.3 billion, followed by Australia (US\$60.9 billion) and Canada (US\$12.1 billion). Damage costs were higher than management costs in most countries, except for a few (e.g., Brasil, India, Japan; Fig. 3a). The global pattern of costs per country reflected the number of invasive plant species from *GloNAF* and the research effort (Fig. 3b), as well as socio-economic context, with higher costs in higher-prosperity countries (Fig. 3c).

Most costs were due to terrestrial plant species (US\$266 billion), followed by aquatic (US\$6.8 billion), and semi-aquatic species (US\$1.5 billion). As a result, costs were mainly in terrestrial environments (US\$311.8 billion across 10,816 entries; Fig. 4). Costs attributed to the “Diverse” environment category totalled US\$41.6 billion, while aquatic and semi-aquatic environments contributed much smaller shares (US\$7.7 billion and US\$613.9 million, respectively). Across economic sectors (Fig. 4; see Diagne et al. 2020 for detailed information), costs were highest in agriculture (US\$130.6 billion), followed by authorities–stakeholders (US\$25.9 billion) and the environment (US\$1.6 billion). Other sectors, including public and social welfare, health, forestry, and fisheries, accounted for smaller proportions of total costs. Damage costs predominated (US\$255.7 billion), compared with management costs (US\$67.7 billion), and costs classified as “Diverse” (US\$38.4 billion; Fig. 4). Most management costs were associated with post-invasion actions such as control or eradication (US\$39.3 billion), whereas pre-invasion actions (e.g., prevention; US\$1.6 million) and knowledge or funding-related activities (e.g., research; US\$146.3 million) represented much smaller proportions.

Country-specific predictors

The GAM (adjusted $R^2 = 0.79$; Appendix 1 in the Supplementary Information) showed no spatial autocorrelation (Moran's $I = 0.12$, $p = 0.089$). Country size was a strong positive predictor ($p < 0.001$),

while the Prosperity Rank showed a significant ($p = 0.02$) negative relationship with costs (Fig. 3c). Among the other predictors, only the number of studies displayed a positive albeit marginally significant ($p = 0.09$) effect, while countries' ecological diversity and GDP were not significant predictors.

Temporal trends of annualized costs

The average annual cost over the entire period amounted to US\$5.75 billion, with a peak during 2005–2010 (US\$24.93 billion). The temporal trend showed a steady increase over the last ~ 60 years, with a decrease in reported data in the last years (Fig. 5A). Costs remained relatively constant for the first few decades, with values below US\$1 billion, then increased substantially in the early 1990s, reaching over US\$50 billion in some years (2005 and 2009). This pattern was consistent across all geographic regions, although North America and Oceania reported relatively high (and stable) costs much earlier, from 1960s to 1990s (Fig. 5B). The slightly lower costs in the last few years were likely due to fewer entries, reflecting the time-lag between cost occurrence and reporting³⁰. The temporal trends of damage costs closely paralleled those of total costs, both at the global (Fig. 5C) and continental scales (Fig. 5D). In contrast, management costs showed an earlier increase at both the global (Fig. 5E) and continental scales (Fig. 5F), but remained considerably lower than damage cost trends.

Damage cost accumulation

Damage costs up to 2018 amounted to US\$255.73 billion, increasing to US\$289.97 billion after inclusion of the damage component from mixed cost entries. The Gompertz model closely reproduced the observed cumulative damage cost trajectory (Fig. 6), with high explanatory power (adjusted $R^2 = 0.98$). The model estimated the inflection in 2018 ($\approx$ US\$319 billion), indicating sustained intensification of costs throughout the 2000s and late 2010s. The long-term cumulative cost burden was estimated at $K \approx$ US\$867 billion, with 90% of the model-estimated asymptote ($\approx$ US\$781 billion) reached in 2067. Although the curve extends beyond the observed period, the trajectory should be interpreted as a model-based extrapolation under continuation of historical cost-accumulation patterns, rather than a precise forecast.

Residence time

The effect of residence time on costs varied among continents and cost types (Appendix 2 in the Supplementary Information). The number of records was a strong positive predictor ($p < 0.001$), and species and country explained a substantial proportion of the variation ($p < 0.001$ for both). Continent did not predict costs after accounting for residence time, number of records, and random effects (all $p > 0.12$). However, continent-specific smooths indicated significant relationships between residence time and costs in some regions. Costs declined with increasing residence time in Africa ($p = 0.002$) and Europe ($p = 0.039$). No significant relationships were detected in other continents (all $p > 0.23$), despite some variation in predicted trajectories.

Management costs were substantially lower than damage costs across residence times (Appendix 2 in the Supplementary Information). Although the interaction between residence time and costs did not differ significantly between damage and management costs (both $p > 0.23$), management costs tended to decline with increasing residence time, whereas damage costs remained comparatively stable.

Discussion

This is the first global picture of invasive plants' economic burden, and it is likely much underestimated by our conservative approach. Despite plant records comprising 47% of *InvaCost*, our global cost estimation represents only 8% of biological invasions' total costs, being half of those incurred by terrestrial invertebrates but almost four times higher than vertebrates (Appendix 3 in the Supplementary Information). Although this result might be due to different *InvaCost* versions and data filtering, it is important to note that in the dataset 17% of total costs in *InvaCost* (Appendix 3 in the Supplementary Information) derive from multiple taxa, from which it is not possible to extract plant-only costs, suggesting that real costs for plants might be underrepresented. Indeed, plants seem to actually be the costliest taxon after filling data gaps¹³. Invasive plant costs corroborate a global picture, where economic impacts are dominated by a few hyper-costly taxa²⁴. Tamarisks (*Tamarix* spp.) alone had even higher costs than some hyper-costly species such as invasive mosquitoes, while the prickly pear *Opuntia* spp. had costs comparable to the black rat, and ragweed *Ambrosia artemisiifolia* had higher costs than the domestic cat (Appendix 3 in the Supplementary Information).

Plant costs were associated with 407 taxa (of which 76 at genus level), a number similar to the total number of invasive plant species according to *GISD*³¹, but only ~ 40% of invasive plant taxa with recorded impacts according to *GIDIAS*³², and only ~ 11% of the plant species that are considered invasive somewhere and < 3% of the naturalized non-native plant species worldwide according to *GloNAF*⁷ (Appendix 4 in the Supplementary Information). This suggests that our results could be massively underestimated. Interestingly, only three of the 15-costliest species were reported as the most-widespread worldwide in *GloNAF*: *P. crassipes*, *C. arvense*, and *C. solstitialis*³³, underlining that invasion extent may be a poor predictor of impact, with costs being contingent on the activity sectors specific to the invaded area, as well as the propensities of local researchers and stakeholders to report impacts. The limited diversity of species with reported impacts in at least part of their invaded range suggests a substantial underestimation here. Moreover, at the global scale, filling spatial gaps in *InvaCost* evidenced that costs might be several orders greater than reported, with vascular plants among the most underestimated taxa¹³.

Most (~ 99%) costs were attributed to angiosperms, with gymnosperms underrepresented in the database (six species only). Moreover, ~ 82% of costs were attributed to woody species, suggesting a potential bias due to their higher management costs. The most frequent introduction pathway (following CBD categories³⁴) for species accounting for ~ 85% of the total costs was escape from confinement,

and in particular, introduction for ornamental purposes or horticulture, followed by intentional release in nature for erosion control or dune stabilization.

Costs were strongly unevenly geographically distributed, with many countries not reporting any costs, especially in Africa and Asia. A general lack of cost data from these regions has already been underlined^{22,35,36}, and may stem from other languages of cost reporting, limited investment in invasion impact assessments, and uneven scientific capacity^{37,38}. Consequently, some economic impacts may remain undocumented or inaccessible, especially in biodiversity-rich regions with limited reporting infrastructure or where invasion impacts are considered secondary to other environmental or economic concerns. On the other hand, this uneven distribution reflects both the global distribution of invasive plants and the longer tradition in the study and stronger management policies of invasive species of other geographic regions (North America, Europe, Oceania³⁹).

Although some of the costliest species are aquatic plants, most costs occurred in terrestrial environments. This could also reflect a bias in cost reporting, with terrestrial environments being of greater interest for human societies, and with more readily-quantified impacts, while also reflecting aquatic environments' lower accessibility. Nonetheless, most (~ 98%) invasive plant species in *InvaCost* are terrestrial, so this difference could simply reflect their different habitat. However, given the challenges in early detection and control, and the ecological sensitivity of aquatic systems, the economic impacts of aquatic invasive plants are likely even more underestimated. The most impacted sector was agriculture, as has been found for trees¹⁴, likely due to interference with crop production. Indeed, primary sectors, and especially agriculture, are the most impacted by biological invasions overall⁴⁰.

Damage costs were > 3 times higher than management costs, and within management costs, post-invasion costs were disproportionately higher than pre-invasion costs, which include prevention actions. This differs from studies on other taxa, reporting damages exceeding management spending by approximately one order of magnitude⁴¹, suggesting higher damage costs for invasive animals or a more effective management of plant invasions. At the same time, we highlight a much lower investment in proactive strategies than necessary, eventually leading to higher costs due to inaction^{41,42}, despite prevention costs are less easily-quantifiable, and often lost in government accounts⁴³. Among management, knowledge/funding received very little investment, highlighting the research underlying practical management actions is often under-funded.

Countries with larger areas and higher socio-economic conditions bore higher costs, which is a general pattern for invasive species' costs^{10,35}. This does not imply that invasive plants are less burdensome in less prosperous regions, but rather reflects greater research capacity, monitoring efforts, management investment, reporting infrastructure and response capacities in wealthier countries^{44,38}, and is in line with the high damage:management cost ratio that we found for some less prosperous countries.

The increasing temporal trend in invasive plants' costs reflects a common pattern for invasive species^{5,23}. The cumulative global damage costs showed a rapid escalation over recent decades, consistent with global increases in trade, propagule pressure, climate-driven range shifts, and landscape disturbance^{6,45}. The eventual slowing in the accumulation rate does not necessarily indicate genuine ecological saturation, and may rather reflect lags in cost detection and reporting^{10,28,42}. Moreover, the fitted curve does not fully account for new invasions, data gaps, or changes in management strategy that could occur over time. Apparent plateaux must therefore be interpreted cautiously. Nevertheless, the magnitude and trajectory of the fitted curve suggest that economic burdens from invasive plants are likely to continue increasing, reflecting long-term ecological processes such as continued global spread, climate-mediated expansion, and compounding impacts on ecosystems, biodiversity, and agricultural productivity⁴⁶. The modelled cost-trajectory should therefore be interpreted as a conditional representation of cumulative damage costs accumulation if historical patterns (e.g. new invasions establishment, management actions) persist, rather than as a precise prediction of future costs.

The dynamics of ecological and economic impacts of invasive species can vary substantially across regions and taxa^{5,47}. Thus, an inconsistent global relationship between species residence time and total costs suggests that economic impacts are not simply driven by time since establishment. Across all continents excepting Africa, costs remained stable with time, implying that any changes are a reflection of other factors, such as cost type. This contrasts with the strong positive relationship between invasive species' costs and residence time found in some countries⁴⁸, also suggesting a role of the spatial scale of investigation. The pronounced negative relationship in Africa may indicate that damages are greatest shortly after establishment, rapid response as a management tool, or reduced reporting intensity. However, disaggregating cost types at the global scale evidenced that management costs declined with residence time, which could reflect increased efficiency, or conversely, reduced perceived feasibility or willingness to manage longstanding invasions⁴⁹, whereas damage costs showed a weak positive trend, suggesting that invasive species' detrimental effect remains high even as management effort changes. These patterns may also be influenced by temporal lags, as species can remain long undetected or underreported before impacts are fully realised, recorded, and decisions made.

Conclusion

Invasive plants have cost a highly-conservative underestimation of hundreds of billions US\$ in economic impact worldwide, with damages expected to continue rising in future. Our study is not an exhaustive, complete assessment of invasive plants' economic costs (Appendix 5 in the Supplementary Information). Indeed, most economic impacts of biological invasions remain unquantified due to well-known biases^{11,13,50}. However, as the first study comprehensively assessing invasive plants' costs globally, it paves the way for more refined cost estimations and signal priority knowledge gaps and existing biases to stimulate research and data collection in areas and sectors lacking such data.

Materials and Methods

The InvaCost database

We quantified the monetary costs associated with invasive plants using the most recent version of the *InvaCost* database (v4.1; <https://doi.org/10.6084/m9.figshare.12668570>, accessed on 30th December 2025), a global repository of reported monetary costs caused by invasive species. *InvaCost* compiles cost data from peer-reviewed and grey literature through systematic searches and expert contributions^{10,37}, and currently contains 13,553 individual cost records. Each record is catalogued using a structured set of descriptors that capture taxonomic identity, geographic location, impacted sector, cost typology, temporal coverage, and data reliability, among others¹⁰. Following the original database protocol, all costs are standardised to a common currency and reference year (2017 US\$) to account for inflation and exchange-rate variation, with currency conversions available from 1960 onwards based on official exchange-rate data¹⁰.

InvaCost is a dynamic database, with entries regularly added or refined as new information becomes available. As a result, analyses based on any given version may change as additional cost data are reported or existing records are updated¹¹. Earlier versions (i.e., v1.0) of *InvaCost* contained substantially fewer plant-related cost entries than other taxonomic groups⁵¹, whereas the latest version (v4.1) incorporates a marked increase of plant cost entries, from 381 in v1.0 to 6,388 in v4.1. Moreover, for the purposes of this study, we added 157 new plant costs entries derived from reports and articles opportunistically identified and not yet included in *InvaCost* but relevant for assessing plant-related costs.

Data checking and filtering

All entries of the database were first cross-checked against their source documents to ensure accuracy and minimize overlap, and removed records with duplicated costs (e.g., same species, same site, same year), erroneous kingdom attribution, or missing cost information. Where possible, entries were split to extract more detailed information (e.g., species identity or cost type), improving taxonomic and cost-specific resolution. This initial screening process resulted in 38 entries being removed and 12 additional entries included (in addition to the 157 new plant costs entries).

We subsequently removed entries lacking identifiable starting or ending years, for the period over which costs were incurred, and those without a monetized value reported in the column "Cost_estimate_per_year_2017_USD_exchange_rate". The dataset was then restricted to entries assigned to the kingdom *Plantae*. Records attributed to multiple kingdoms (i.e., *Animalia/Plantae* or *Bacteria/Plantae*) were excluded because plant-specific costs could not be reliably separated, resulting in 6,357 entries (47% of all *InvaCost* records). Eventual taxonomic inconsistencies were corrected referring to Plants of the World Online⁵². We further filtered the data to include only *observed* costs with a *high reliability* of method, defined as costs derived from official reports, peer-reviewed articles, or studies using reproducible estimation methods, based on the 'Implementation' and 'Method_reliability' columns.

This choice represented a deliberately conservative approach for cost quantification. This filtering resulted in a final dataset of 5,459 highly reliable, observed cost entries for invasive plants.

To account for the temporal structure of costs, we expanded this dataset using the *expandYearlyCosts* function from the *invacost* package⁵³ in R version 4.3⁵⁴. This procedure distributes multi-year cost estimates into annual values based on the interval between the ‘Probable_starting_year_adjusted’ and ‘Probable_ending_year_adjusted’ columns¹⁰). For instance, a cost reported as US\$10 million over the period 2001–2010 is evenly distributed across that interval (i.e., US\$1 million per year), allowing all costs to be analyzed on a comparable annual basis. After expansion, the dataset covered the period 1960–2022 and comprised 12,708 annualised cost entries spanning 63 years. All subsequent analyses were conducted using this final dataset.

Data analysis

Cost description

The total costs of invasive plants were classified according to a series of cost descriptors (i.e., columns of the *InvaCost* database; Appendix 6 in the Supplementary Information). For the taxonomic description, the species and family responsible for the cost were considered. For the geographic description, the macrogeographic location (i.e., continent) and the country in which the cost was incurred were considered by summing cost data. The geographic distribution of costs was mapped together with other variables, namely the research effort proxied by the number of entries, the number of invasive plant species per country from the Global Naturalized Alien Flora (*GloNAF*⁷), and the Legatum Prosperity Index 2023⁵⁵ which ranks countries according to major socio-economic aspects such as safety, health, education, and economic quality. Maps were produced using the R package *sf*⁵⁶ and the Mollweide projection, with colours based on the *scico* R package⁵⁷.

To compare how costs affected different recipient contexts, we quantified costs within each environment where the cost estimate occurred (i.e., terrestrial, aquatic, and semi-aquatic), economic sector (i.e., agriculture, fishery, forestry, authorities-stakeholders, environment, public and social welfare, and health), and cost type (i.e., damage/loss or management). Entries associated with *unknown* or more than one category for a given descriptor (e.g., costs linked to unknown or multiple species, or costs occurring in multiple countries or environments that could not be assigned separately) were grouped into the category “Diverse”.

Country-specific predictors

To identify the main drivers of plant invasion costs at the country level, we used generalized additive models (GAMs) to model log-transformed total costs in function of a series of country-specific predictors: country size (or country surface area in km², log-transformed), Gross Domestic Product, Prosperity Rank⁵⁵ (higher ranks indicate lower-prosperity countries), the number of assessments

(studies or reports, as a proxy of research effort), and the Shannon diversity index of relative biome abundance (as a proxy of ecological diversity). This latter was retrieved for each country⁵⁸, while country size and GDP were retrieved from the *rnatuarearth* R package⁵⁹. Since human population size was highly correlated with other predictors, we did not include it as a predictor. GAMs were performed using the *mgcv* R package⁶⁰ using thin plate smoothers for all predictors except country size, and the gamma family error distribution. Spatial autocorrelation in the model residuals was evaluated by computing Moran's I statistic through the R package *spdep*⁶¹.

Temporal trends in annualized costs

To assess temporal trends in invasive plant costs, globally and by continent, we used the *summarizeCosts* function of the *invacost* R package with 5-year intervals from 1960 to 2022. This function summarizes cumulative costs over predefined periods and allocates them evenly to annual estimates corresponding to the years over which costs were incurred, without inflating cost values. This approach was applied to total costs, and then separately to management and damage costs.

Long-term damage cost accumulation

To analyse the long-term accumulation of damage costs, we included sole damage cost entries as well as the damage component from cost entries classified as 'mixed' (i.e., costs combining damage and management). Mixed costs were proportionally separated based on the global ratio of reported damage to management costs for each year, assuming that mixed entries follow a similar annual damage:management ratio as explicitly classified costs for that year. This proportional allocation represents a neutral assumption in the absence of detailed information, as excluding mixed entries or assigning them entirely to one cost type would distort cumulative damage estimates. It also reduces systematic bias in future cost projections, as damage costs would be underestimated if entries that partially represent damage impacts were excluded, because mixed cost entries often cannot be separated directly into damage and management components. Following this allocation, annualized damage costs were then aggregated by impact year to generate a global time series for analysis.

To characterize global plant damage cost dynamics, we fitted a Gompertz sigmoidal model to cumulative annual totals using constrained non-linear least-squares regression in MATLAB (v.R2016a). The Gompertz model was selected because cumulative invasion costs are expected to follow non-linear growth patterns consistent with lag phases and changing rates of accumulation observed in invasion dynamics^{26,28,30,42}, while allowing asymmetric accumulation around the inflection point. The fitted model was

$$C(t) = K \exp\{-\exp[-r(t - t_0)]\},$$

where $C(t)$ is cumulative damage cost at time t , and t is measured in years from 1960, K is the model-estimated long-term cumulative damage cost, r controls the steepness of cost escalation, and t_0 is the timing of maximum escalation, corresponding to the inflection point of the curve. We selected the

Gompertz model rather than the logistic model because it does not impose symmetry around the inflection point, and rather than the Richards model because it avoids an additional shape parameter that can increase practical parameter-identification issues when the upper part of the trajectory is not strongly constrained⁶². However, reported costs for the most recent years (2019–2022) are at least two orders of magnitude lower than typical annual values in preceding decades (cf. Figure 4c). This is most likely due to the reporting lag in *InvaCost*, rather than a genuine reduction in global damage costs¹⁰. Including these years would artificially flatten the cumulative curve and bias parameter estimates. Model fitting was therefore restricted to the period 1960–2018, ensuring that statistical inference was based on periods with more complete reporting.

Model parameters describing the estimated long-term cumulative damage cost (K), the rate of cost escalation (r), and the timing of maximum escalation (t_0) were estimated by minimizing the residual sum of squares. Model fit was assessed using Akaike's Information Criterion (AIC) and adjusted R^2 . From the fitted curve, we identified two salient points: the inflection point, marking the transition from increasingly rapid growth in cumulative damage costs to continued accumulation at a slower rate, and the point at which damages reach 90% of the model-estimated asymptote. Uncertainty in curve-fitting was quantified using 500 residual bootstrap replicates, from which a 95% bootstrap envelope was constructed for the fitted cumulative curve.

Residence time

To assess whether costs varied with the species residence time, we first calculated the number of years between a species' earliest digitized occurrence record in Global Biodiversity Information Facility (GBIF) and 2018. Occurrence records were retrieved for each species using the *rgbif* R package⁶³, with searches restricted to the focal country of cost. Species-country combinations with no *GBIF* occurrence records were excluded from the analysis.

The relationship between costs and residence time across continents and cost types (damage or management) were analysed with a GAM (with Gamma error distribution and log link function), using the *mgcv* R package⁶⁰. Residence time was included as a smooth term on the log scale, while continent and cost type were included as fixed effects with group-specific smooths to allow relationships to vary among regions and cost categories. The number of cost records was included as a log-transformed fixed effect to account for reporting effort, and species and country were included as random effects.

Declarations

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Figures

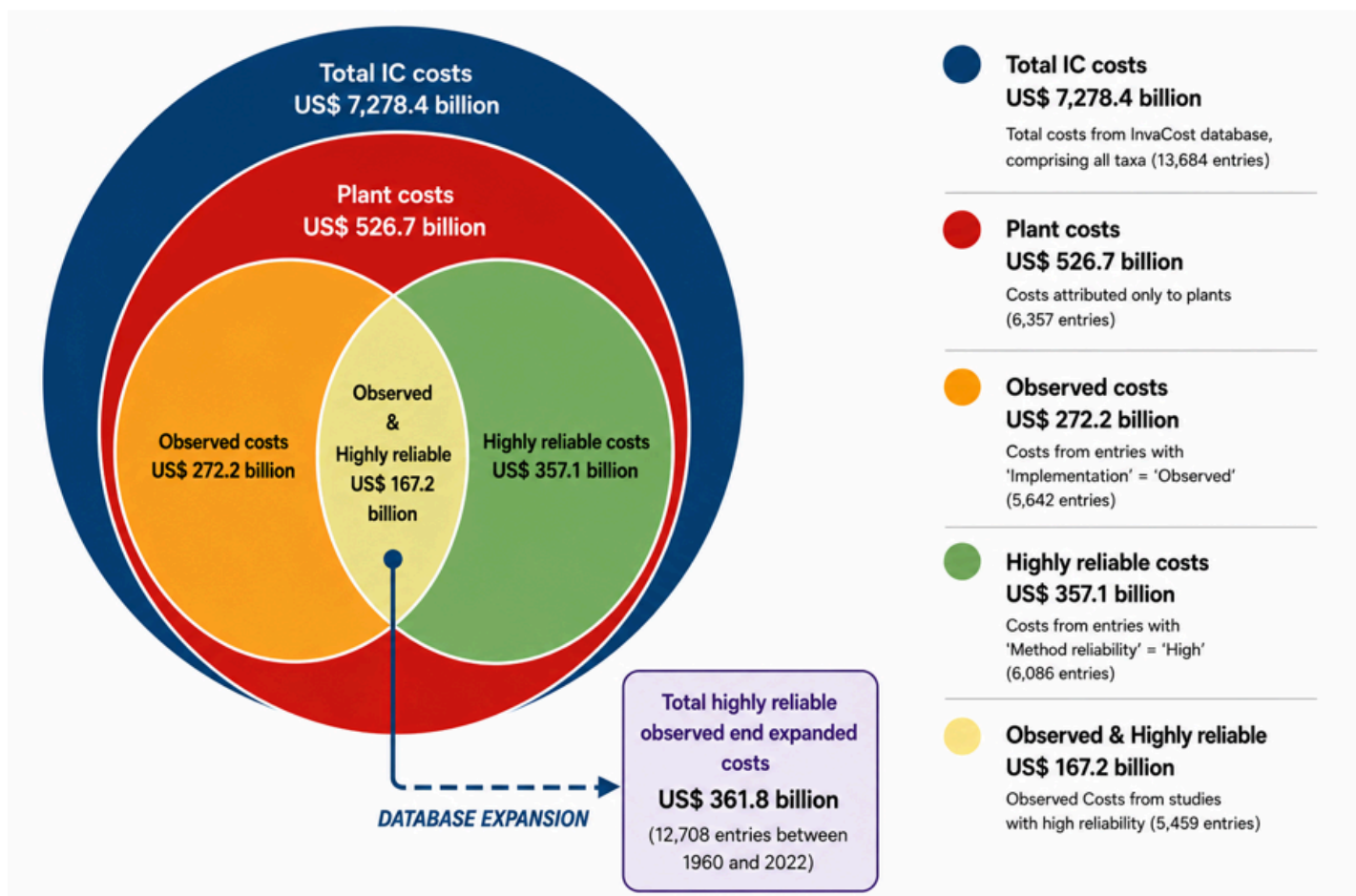


Figure 1

Structure of invasive plant costs in the *InvaCost* database. Total plant costs (US\$526.7 billion) are partitioned according to implementation type (observed costs), method reliability (highly reliable costs), and their overlap (observed and highly reliable costs). Database expansion of the observed and highly reliable subset resulted in total highly reliable observed and expanded costs of US\$361.8 billion between 1960 and 2022, which form the basis of subsequent analyses.

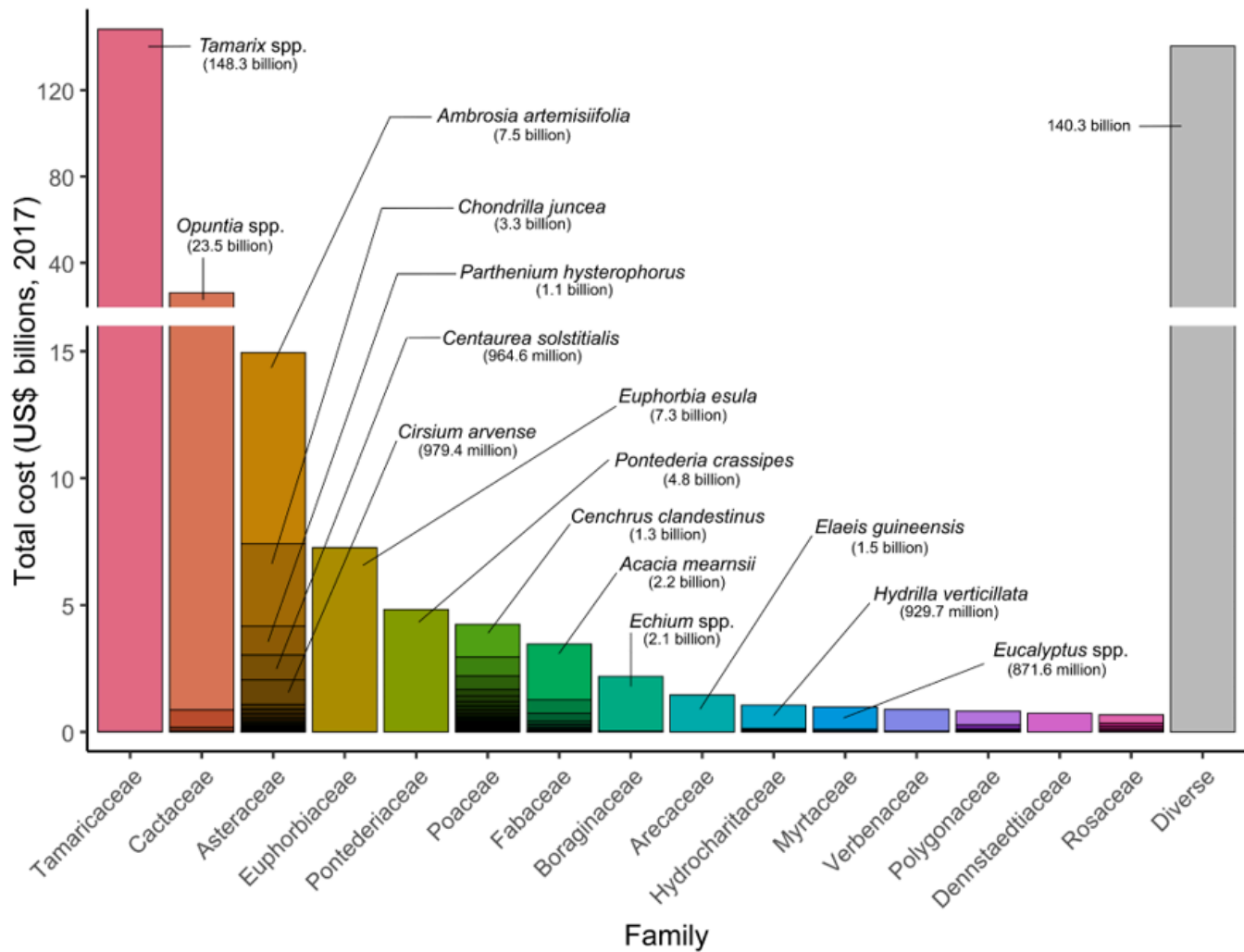


Figure 2

Cumulative global costs of the 15-costliest invasive plant families and taxa between 1960 and 2022, standardized to 2017 US\$. Note that the y-axis is broken for visualisation purposes.

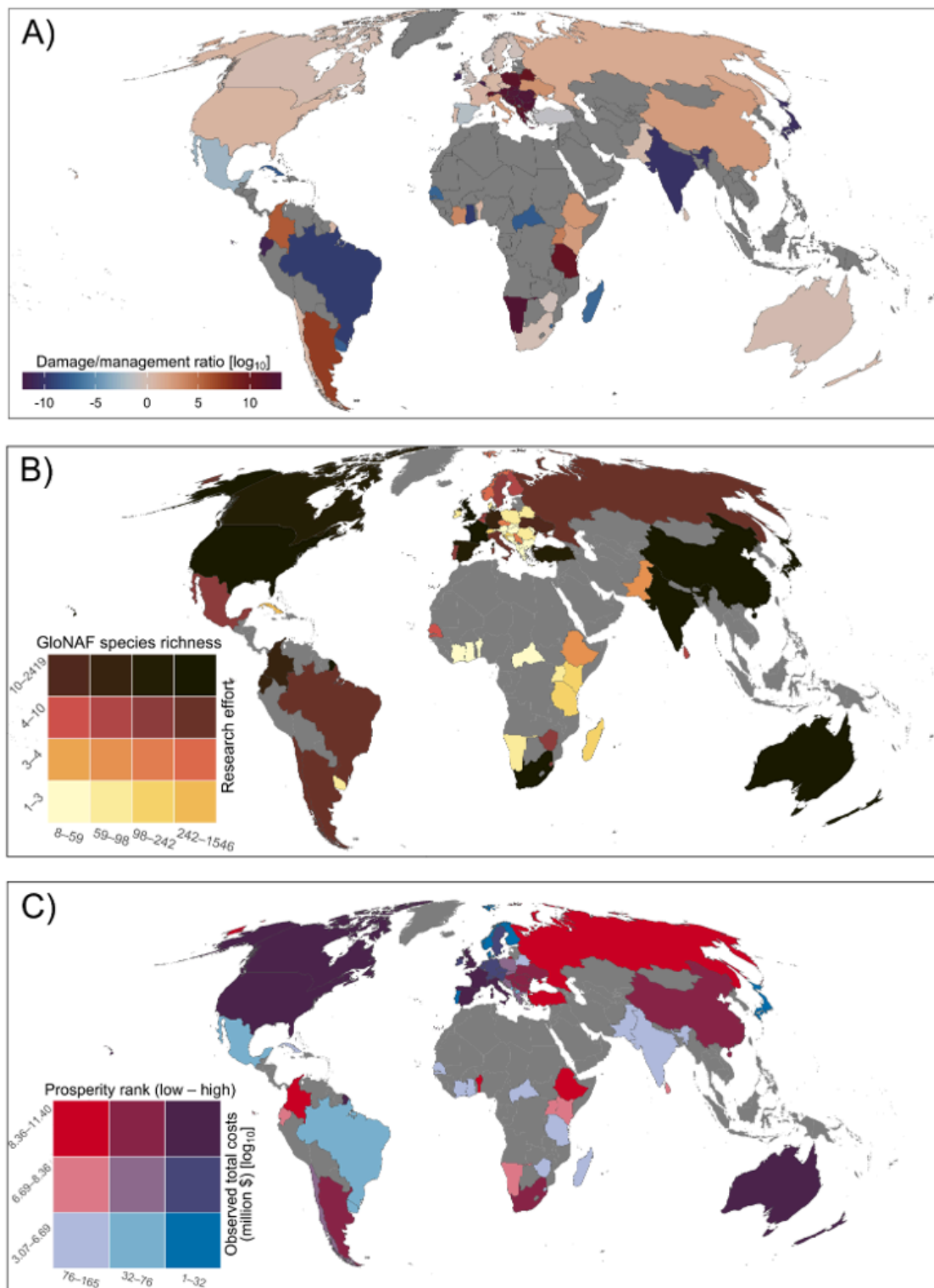


Figure 3

Geographical distribution of the costs of invasive plants (in 2017 US\$ million) between 1960 and 2022. a) Proportion ($\log_{10}$ -ratio) of damage vs management costs. b) Bivariate choropleth map showing the number of invasive species per country (retrieved from *GloNAF*) and the research effort (the number of cost entries in *InvaCost*). c) Bivariate choropleth map showing the joint distribution of observed costs ($\log_{10}$ -transformed, million US\$) and prosperity. Countries are classified into terciles based on cost and

prosperity, with colours representing their combined position in the bivariate space. Grey countries indicate missing data for one or both variables. The map is displayed in an equal-area Mollweide projection.

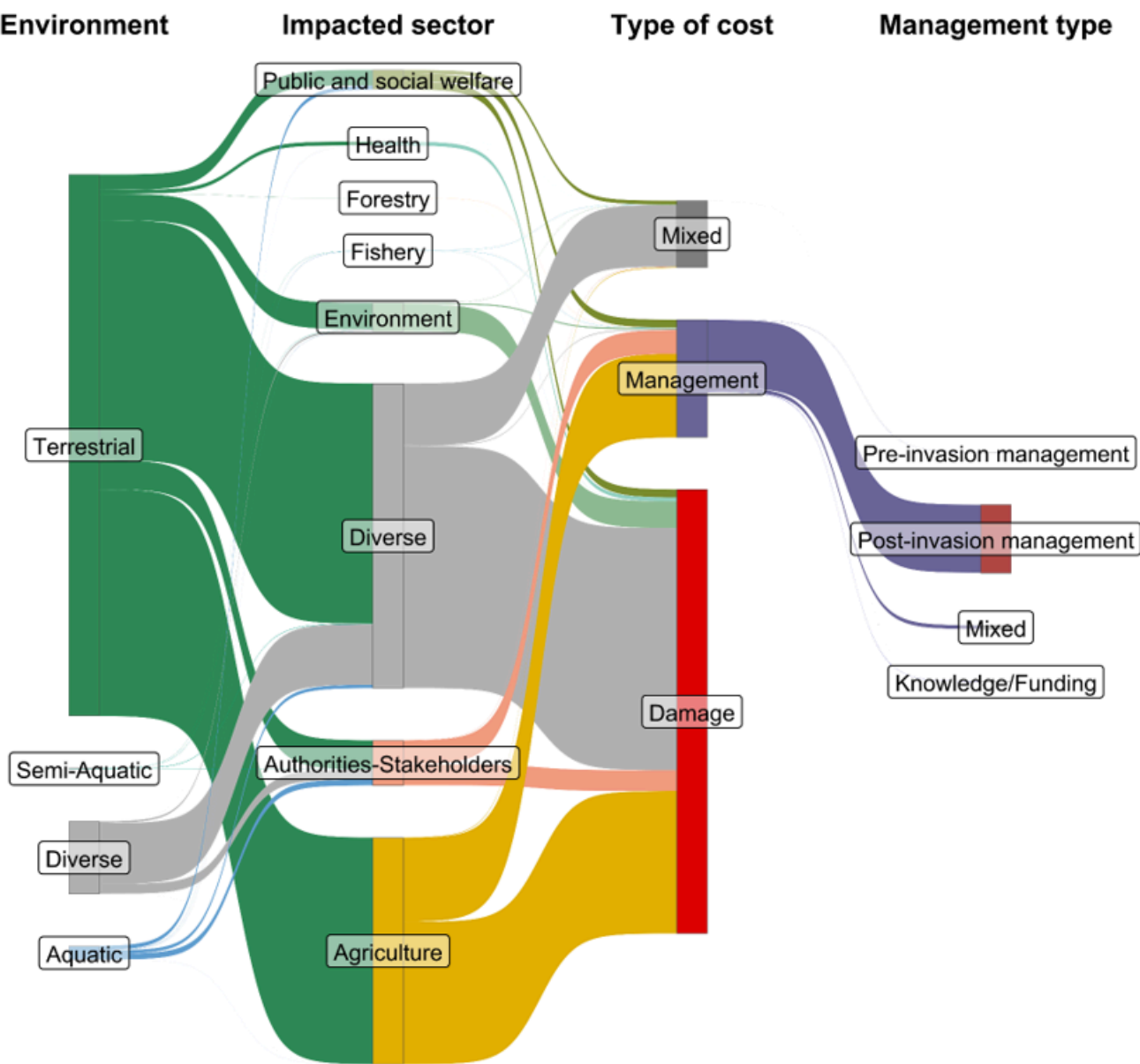


Figure 4

Distribution of reported invasive plant total costs (in 2017 US\$) between 1960 and 2022 across impacted environments, sectors and cost types, with management costs further subdivided by management type.

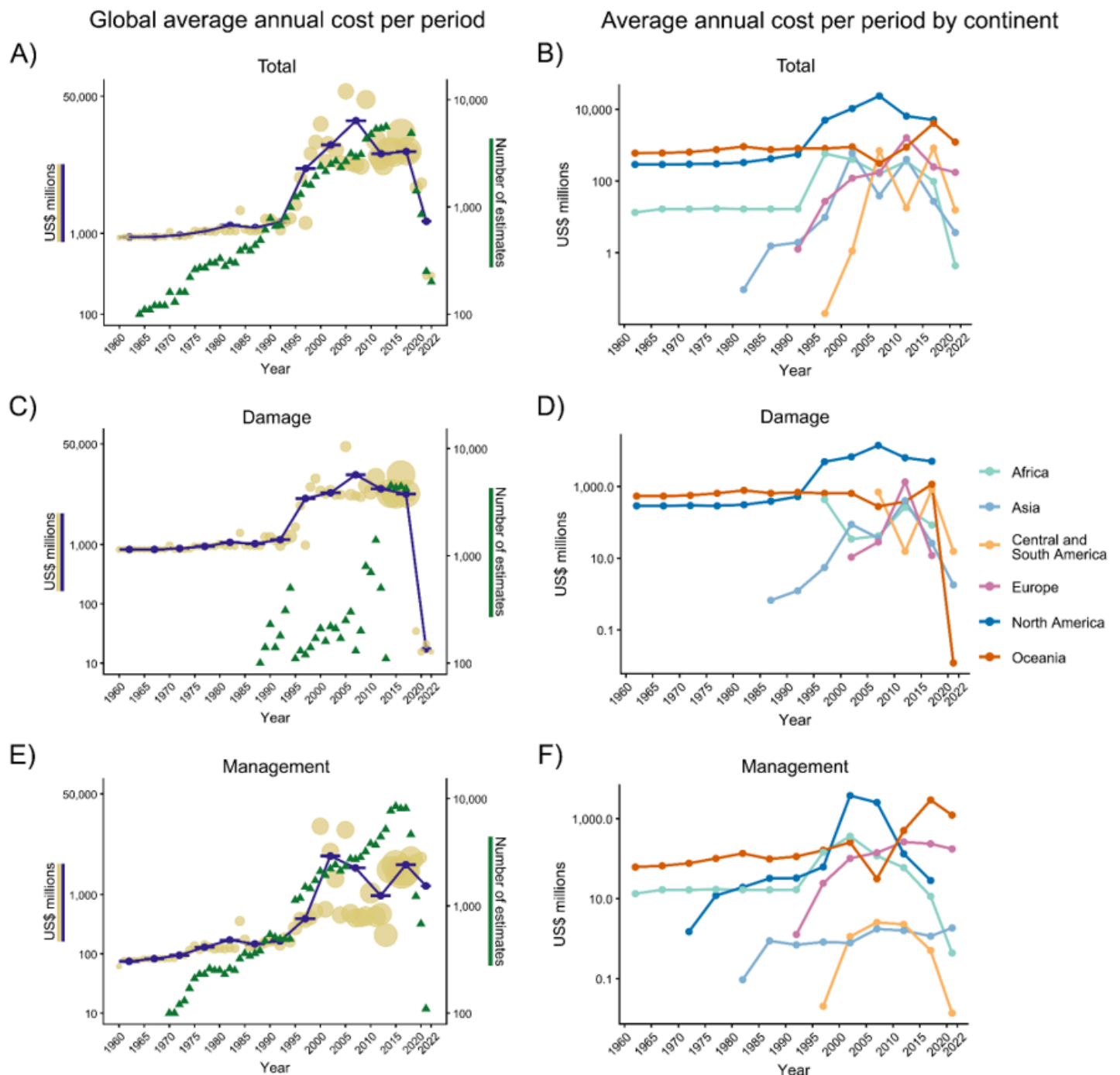


Figure 5

Temporal trends in reported costs (in 2017 US\$) of invasive plants over 5-year averages, including total costs (A, B), damage costs (C, D), and management costs (E, F). Panels on the left column (A, C, E) show global trends, where green triangles indicate the number of cost entries, gold circles represent annual cost estimates (with symbol size proportional to the number of studies), and blue dots indicate the mean cost for each 5-year period. Panels on the right column (B, D, F) show trends by continent. Y axes are log scaled.

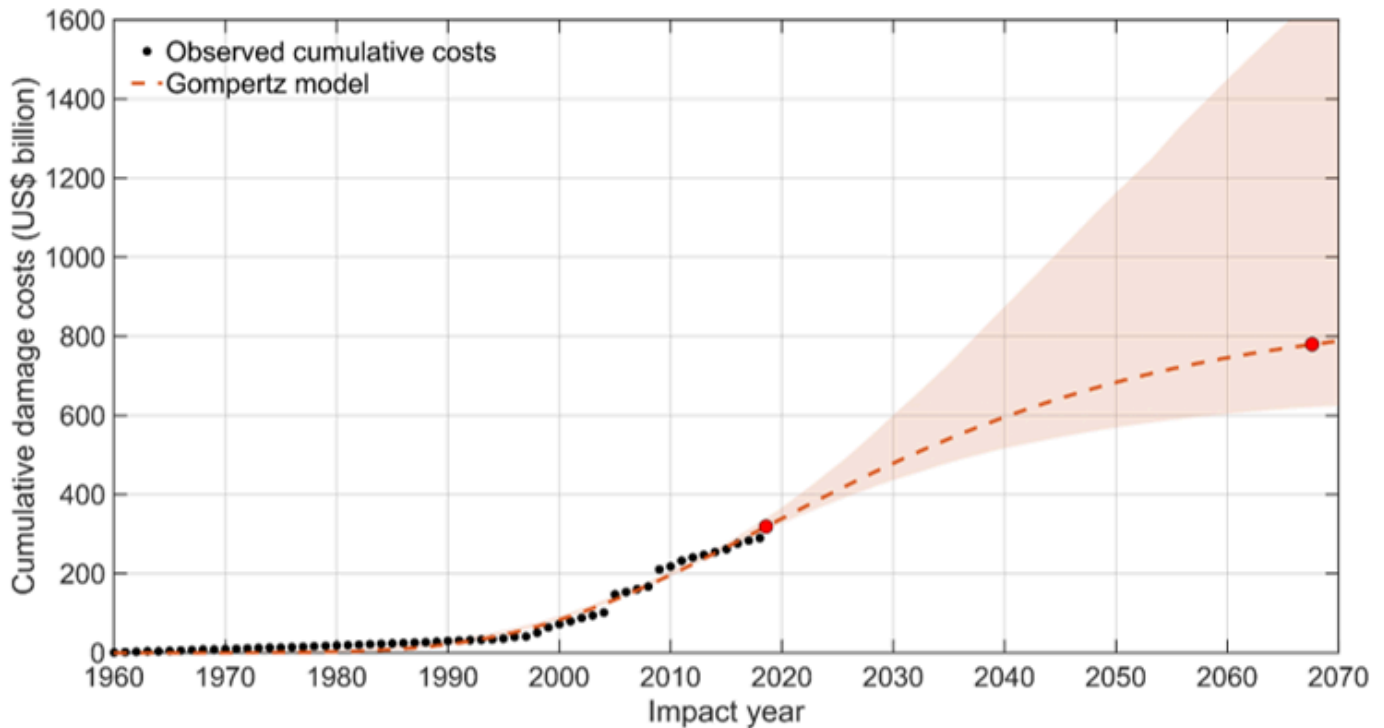


Figure 6

Observed and modelled cumulative global damage costs of invasive plants (1960–2018). Black points show observed cumulative damage costs (2017 US\$). The dashed curve shows the fitted Gompertz model, with the shaded region indicating the 95% bootstrap envelope (500 residual bootstrap replicates). The Gompertz model ($AIC = 303.45$; adjusted $R^2 = 0.980$) estimated a projected long-term cumulative cost of $K \approx \text{US\$}867$ billion, with an inflection point in 2018 ($\approx \text{US\$}319$ billion) and the point at which cumulative costs reach 90% of K occurring around 2067 ($\approx \text{US\$} 781$ billion). Red circles indicate the model-derived inflection point and 90% K point. The curve is shown beyond 2018 to illustrate the potential long-term trajectory of cumulative damage costs under continuation of the historical cost-accumulation process. This extrapolation should not be interpreted as a precise forecast, but rather as a conditional model-based scenario beyond the empirically observed period.

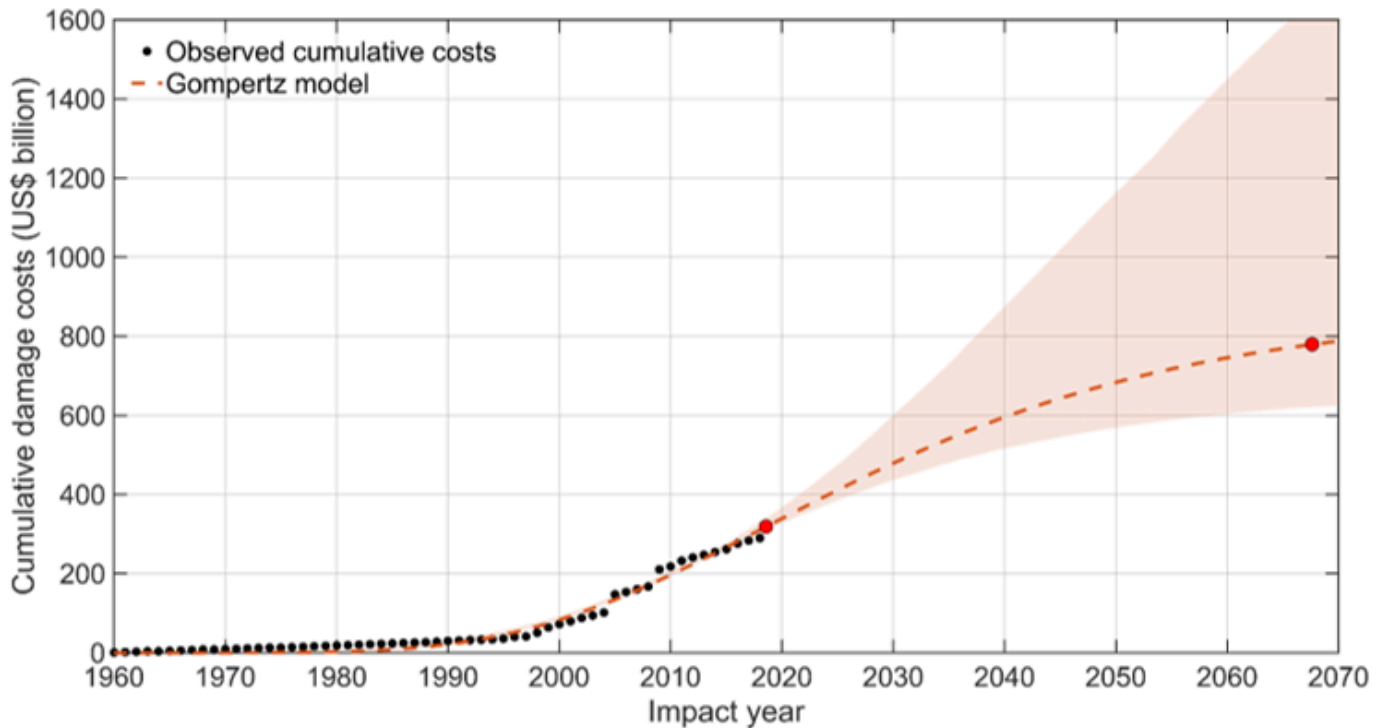


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