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Fragmented yet high economic costs of biological invasions in India

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Globally, biological invasion rates show no signs of saturation (Seebens et al. 2017), and continued increases are even expected in the next three decades (Seebens et al. 2021). Biological invasions have eroded biogeographic realms (Capinha et al. 2015) and present a growing threat to ecosystems, with the potential to compromise their function, structure and service provision (Pyšek et al. 2020). Invasive alien species (IAS) have also been identified as major drivers of species extinction (Bellard et al. 2016), and they disrupt phylogenetic and functional diversities (Suarez and Tsutsui 2008; Ricciardi et al. 2013) and cause regime shifts in recipient environments (Brooks et al. 2004). Consequently, human-mediated introduction, establishment and spread of IAS have been considered defining elements of the Anthropocene (Pyšek et al. 2020; Ricciardi et al. in press). Notwithstanding biases at temporal, geographic and biological scales (Crystal-Ornelas and Lockwood 2020a), knowledge on the ecological impacts of IAS has accrued rapidly in recent decades (Kumschick et al. 2015; Crystal-Ornelas and Lockwood 2020b). Contrastingly, knowledge of socioeconomic effects has remained sparse, unstandardised and disparate across most scales until recently (Diagne et al. 2020a).

Where reported, economic impacts associated with IAS are burgeoning (e.g., Pimentel et al. 2001; Oreska and Aldridge 2011; Hoffman and Boradhurst 2016; Bradshaw et al. 2016). Although these earlier studies provided awareness and powerful incentives to increase expenditure on the management of IAS, they all focused on particular regions, habitat types and taxonomic groups. Overall, most countries have no comprehensive appraisals of the economic costs of IAS, precluding efficient allocation of resources to mitigate ecological and economic impacts (Lodge et al. 2016). Recently, however, the *InvaCost* database (Diagne et al. 2020b) was launched to tackle this critical knowledge gap and provide comparable means to assess costs of IAS. By systematically retrieving, collating and standardising reported economic costs of IAS, it provides the first global assessment of invasion monetary impacts (Diagne et al. 2021). With costs recorded against numerous environmental, typological, temporal and spatial descriptors, this database provides a critical step towards comprehensive assessments at continental (e.g., Africa, Diagne et al. *in press*; Asia, Liu et al. *in press*; Europe, Haubrock et al. *in press a*; North America, Crystal-Ornelas et al. *in press*; South America, Heringer et al. *in press*) and national scales, both for developed economies (e.g. USA, Fantle-Lepczyk et al., this special issue; Germany, Haubrock et al. *in press b*; the United Kingdom, Cuthbert et al. *in press*; New Zealand, Bodey et al. *in press*; or Japan, Watari et al. *in press*) and developing economies (e.g. Argentina, Duboscq-Carra et al. *in press*; Mexico, Rico-Sanchez et al. *in press*; or Ecuador, Ballesteros-Menja et al. *in press*).

India, a rapidly emerging developing economy which is categorised as mega-biodiverse and is home to four of the global biodiversity hotspots (Myers et al. 2000), has so far not benefited from such a national synthesis. Although several thousands of nonindigenous introduced species are reported from India (Sankaran et al. 2021), the most conservative estimates report 173 invasive plants (Reddy 2008; Botanical Survey of India) and 157 invasive animals (Government of India 2018). Pimentel et al. (2001) reported that the Indian economy suffers US\$ 116 billion per year as a result of IAS. However, almost all costs reported in this study were questionable. For example, agricultural loss costs incurred by invasive insects were estimated by taking into account the percentage of alien insect species in India, the percentage crop productivity loss due to insects, the total crop production and its value in India. Based on these values, they attributed an yearly monetary loss of US\$ 16.8 billion to agriculture by invasive insects. By missing robust, documented evidence for the monetary impacts due to IAS, gross overestimations of real costs are likely to arise from studies relying on potential costs.

In spite of the long-lasting ecological problems caused by IAS in India, the country lacks awareness of the enormity of associated economic costs, in turn preventing development of biosecurity protocols, pre- and post-invasion monitoring guidelines, effective eradication programmes and trained human resources to tackle this issue (Mungi

et al. 2019; Goyal et al. 2020). The most common examples of IAS in India include *Parthenium hysterophorus* gaining entry with imported wheat from the USA in the 1950s (Ahmad et al. 2019); the flagship mass social afforestation programmes undertaken by the government of India using the invasive *Leucaena leucocephala*; or the invasion of *Oreochromis mossambicus*, a fast-growing fish introduced as a source of income for disadvantaged fishing communities, but which is now replacing the native fish communities in Indian water bodies (Ganie et al. 2013).

While economic development and environmental conservation are often seen as two opposing sides of the development spectrum, quantifying the costs borne by a country due to invasions could be an effective way to attract the attention of policy-makers and motivate measures against IAS. Here, we provide an exploratory yet state-of-the-art analysis on the economic costs of IAS in India. Specifically, we aim to: (i) describe how IAS costs are distributed spatially, environmentally, sectorally, taxonomically, according to cost types and across introduction pathways; (ii) assess how IAS costs have changed over time, in particular in relation to type of costs (i.e. management vs damage); and (iii) assess how IAS costs of India and other countries vary according to population sizes, GDPs and economic development statuses.

Materials And Methods

Information on the economic cost of IAS in India was extracted from the *InvaCost* database (<https://doi.org/10.6084/m9.figshare.12668570.v3>; 9,823 entries using the latest version; Diagne et al. 2020b, c; Angulo et al. 2021). The data in *InvaCost* were collected via (i) literature searches using the ISI Web of Science, Google Scholar and the Google search and (ii) targeted searches through contacting experts and stakeholders to request additional cost information. *InvaCost* records costs whilst explicitly considering their source material, reliability (i.e. classification of cost estimates based on the type of publication and method of estimation; *low* vs. *high*) and implementation approach (i.e. *observed* vs *potential*). All the retrieved costs were standardized to 2017 USD for comparability. In order to obtain costs specific to India, we filtered costs based on the “Official_country” column of the database (see Online Resource 1), thereby excluding costs in other countries or at greater spatial scales (e.g. subcontinental or continental).

Costs in *InvaCost* are reported over different durations (e.g. several months, single years or several years), therefore, we standardised costs such that each cost entry corresponded to a single year. This was done using the *expandYearlyCosts* function of the ‘*invacost*’ R package (Leroy et al. 2021), thereby ‘expanding’ the data based on the difference between the “Probable starting year adjusted” and “Probable ending year adjusted” columns for each cost entry (see Online Resource 1). We removed cost entries that occurred outside of the 1960–2020 time range. We also removed cost entries for which the starting and/or the end year were not specified. This resulted in the omission of some highly prominent entries, such as Pimentel et al. (2001). However, we deemed these omissions necessary to annualise costs according to that year’s currency exchange rate and to produce reliable projections of temporal trends.

We describe the distribution of IAS costs by (i) spatial scale (i.e. national or restricted to a specific region of the country); (ii) environment of the IAS (i.e. terrestrial, aquatic or semi-aquatic; column “Environment_IAS”, see Online Resource 1); (iii) sector impacted (i.e. agriculture, authorities-stakeholders, environment, fishery, forestry, health and public and social welfare; column “Impacted_sector”, see Online Resource 1); (iv) taxonomic group (i.e. Kingdom, Class, Order, Family, Genus or Species; columns “Kingdom/Class/Order/Family/Genus/Species”, see Online Resource 1); and (v) across introduction pathways.

We evaluated the temporal trends of IAS costs (from 1960 to 2020) in relation to type of costs (i.e. management vs damage; column “Type_of_cost_merged”, see Online Resource 1). Damage expenditures included impact-related costs, such as infrastructure losses, health issues and reduction in ecosystem productivity, whereas management related costs included mitigation costs, such as prevention, control, eradication, research and long-term management of IAS. To conduct this analysis, we used the *summarizeCosts* function of the *invacost* package (Leroy et al. 2021) that produced the average annual cost at ten-year intervals, as well as annual totals and thus allows for the discernment of cost trajectories over time. Further, we used the *modelCosts* function of the same R package to statistically model the long-term trends in invasion costs, fitting ordinary least squares (linear/quadratic) and robust (linear/quadratic) regressions which is less sensitive to outliers, as well as multivariate adaptive regression splines, generalised additive models and quantile regressions. Multiple models were fit to discern generalities in trends over time, given the heteroskedasticity of econometric data. We employed the root mean square error (RMSE) to examine and compare the goodness of fit among models.

Finally, to examine how economic costs of IAS in India relate to other countries with reported economic costs included in *InvaCost* database (for details of countries considered here see Diagne et al. 2020c; data extracted from ‘*invacost*’ R package, Leroy et al. 2021) highly reliable, observed costs of all other countries in the *InvaCost* database ($n = 112$) were totalled (1960–2020) and compared in relation to total human population and GDP using data from worldometers (<https://www.worldometers.info/world-population/population-by-country/>) for population and The World Bank (<https://data.worldbank.org/indicator/NY.GDP.MKTP.CD>) for GDP (2019 value). We note that cost reporting for certain countries started later (or earlier) than 1960, but from 1960 allowed for robust exchange rate calculations. Economic development status (developed, transitioning, developing) of each country was obtained and characterised from the United Nations (2020). Two linear models were used to examine the relationship between \log_n -transformed total costs and (i) \log_n -transformed total population and (ii) \log_n -transformed GDP, with development status included as an interaction term in each two-way model, allowing to compare the economic cost of IAS in India with those of other countries.

Results

The average annual economic costs incurred by IAS to the Indian economy amounted to US\$ 182.6 billion (i.e. total costs) and US\$ 127.3 billion (i.e. when considering *Observed* and *High* reliability costs only) (Indian Rupees ₹ 11.9 trillion and 8.3 trillion, respectively) over the period 1960–2020. The total cost ($n = 300$ cost entries) includes *Potential* costs (US\$ 54.5 billion; $n = 152$ cost entries; 29.8% of costs) and *Low* reliability costs (US\$ 0.8 billion; $n = 52$; 0.5% of costs), which were excluded from the more conservative cost estimate that includes only *Observed* costs and *High* reliability costs ($n = 96$; 69.7%). In the subsequent sections, the analyses focused on this more conservative cost estimate to ensure the robustness of our conclusions.

Distribution of IAS costs

Geographical distribution

More than 99% of the economic costs were reported at the national level (US\$ 126.6 billion; $n = 53$; 99.4%) (Fig. 1). Despite scarce, regional costs revealed that US\$ 615 million were attributed to West India ($n = 19$; 87.5% of the regional costs), US\$ 64.2 million to South India ($n = 13$; 9.1% of the regional costs) and US\$ 23.9 million to North India ($n = 11$; 3.4% of the regional costs). No recorded costs were attributed to Central, Eastern, North-Eastern and Northern (claimed) India (Fig. 1). Considering all invasion-related costs of US\$ 127.3 billion, the cost of invasions in

India is equivalent to US\$ 38,727 per km² for the landmass of 3.287 million km², and *per capita* cost is equivalent to US\$ 92.2 per inhabitant for the population of 1.38 billion Indians (2020, Worldometer).

Environmental distribution

Among the environments invaded by IAS in India, only 8% of the total entries were from diverse or unspecified environments. However, they constituted 93% of the total economic costs (i.e. *Diverse/Unspecified*, US\$ 118 billion, n = 8). Species from semi-aquatic environments constituted only 6.7% of the total costs (US\$ 8.6 billion, n = 35). Aquatic and terrestrial species-related costs were one order of magnitude lower than semi-aquatic costs, and constituted less than 1% of total costs (aquatic, US\$ 509 million, n = 16; terrestrial, US\$ 207 million, n = 35). One out of the ten species in the dataset for which economic costs could be attributed occurred in semi-aquatic environments (e.g. *Aedes aegypti*), whereas the other nine species occurred in terrestrial environments. Economic costs could not be attributed to specific species for entries recorded under *Diverse/Unspecified* environments and aquatic environments.

Sectoral distribution and cost types

More than 99% of the costs affected multiple sectors, and were thus classified as the “*Mixed*” cost type (US\$ 126.8 billion, n = 48). These *Mixed* costs mostly comprised damage or loss related expenditures, affected diverse environments and were caused by diverse/unspecified species. Nearly all public and social welfare (US\$ 344 million, n = 14) and fisheries related costs (US\$ 165.4 million, n = 2) comprised damage-related expenditures, limited to aquatic environments and caused by diverse/unspecified species. All costs incurred by the agricultural sector (US\$ 39.9 million, n = 6) comprised damage-related expenditures, limited to terrestrial environments and exclusively caused by insects. The costs related to the authorities and stakeholders sector (i.e. governmental services and/or official organisations, US\$ 31.1 million, n = 21) were distributed between damage and management related expenditures, mostly limited to terrestrial environments, and caused by insects. The recorded costs related to forestry were negligible in comparison to other sectors (US\$ 363, n = 5). These costs were distributed between management and mixed (both damage and management) expenditures, costs were limited to terrestrial environments and solely caused by plants. The invasion costs related to the environment and health sectors were absent in uni-sectoral costs.

Taxonomic distribution

When economic costs could be attributed to a specific Kingdom, a substantial proportion was attributed to animals (US\$ 8.8 billion, n = 50; attributed to six species of insects). The majority of the animal-borne costs were attributed to Diptera (US\$ 8.6 billion, n = 35; all attributed to the yellow fever mosquito, *A. aegypti*), Hemiptera (US\$ 136 million, n = 6; attributed to the rugose spiraling whitefly, *Aleurodicus rugioperculatus* and to the papaya mealybug, *Paracoccus marginatus*), Lepidoptera (US\$ 38.4 million, n = 3; all attributed to the fall armyworm, *Spodoptera frugiperda*), Orthoptera (US\$ 27.5 million, n = 5; all attributed to the desert locust, *Schistocerca gregaria*), and Coleoptera (US\$ 3.8 million, n = 1; attributed to the coffee borer beetle, *Hypothenemus hampei*).

Plant costs were 3 orders of magnitudes lower than animal costs (US\$ 1.71 million, n = 22; attributed to four species of plants). The majority of costs were attributed to Poales (US\$ 0.99 million, n = 6; all attributed to the littleseed canarygrass, *Phalaris minor*), Asterales (US\$ 425, n = 11; attributed to the mile-a-minute vine, *Mikania micrantha* and to the carrot grass, *Parthenium hysterophorus*) and Lamiales (US\$ 321, n = 2; attributed to lantana, *Lantana camara*). Three entries, amounting to US\$ 0.72 million, were broadly attributed to invasive plants rather

than any specific IAS. Thus, all recorded species-specific costs could be attributed to six invasive insects and four invasive plant species. No costs were recorded specifically for fungi, bacteria, viruses and chromists. A very large part of the costs (93%) were attributed to either unspecified taxa or taxa that covered multiple kingdoms (i.e. *Diverse/Unspecified*; US\$ 118.5 billion; n = 24) (Fig. 2).

However, species-specific economic cost entries (n = 69) could only be attributed to six invasive animals and four invasive plants out of the 157 animal and 173 plant species that are conservatively reported to be invasive in India. This implies that only 4% of invasive animals and 2% of invasive plants in India have species-specific documented costs based on the taxonomic resolution of the reported data. Further, the species-specific cost entries belonged to only three taxonomic classes: Insecta (72%), Magnoliopsida (19%) and Liliopsida (9% of number of cost entries) (Fig. 2).

Species-wise cost allocations were highly skewed. Out of US\$ 8.8 billion species-specific costs, the yellow fever mosquito contributed 98% of the costs, followed by the papaya mealybug at 1.5% and the fall armyworm at 0.4%. These three species also contributed maximally to management-related costs, albeit in a different order, with the papaya mealybug contributing 66% of the costs, followed by the yellow fever mosquito at 29% and the fall armyworm at 4%. More than 99% of damage costs resulted from the yellow fever mosquito, followed by the fall armyworm (0.34%) and the desert locust (0.31%) (Fig. 3).

In terms of environments, all costs incurred from semi-aquatic taxa were caused by the yellow fever mosquito. Out of the nine species causing costs from the terrestrial environment, highest costs were attributed to insects, with the papaya mealybug contributing 66% of the costs, followed by the fall armyworm (18%), and the desert locust (13%). All incurred costs from aquatic taxa were attributed to *Diverse/Unspecified*, and as such the species-wise cost apportionment for aquatic environments was not possible (Fig. 3).

Introduction pathways

Nine of the ten IAS were introduced to India via human agency, while the only IAS which naturally expanded its range in South Asia and India was *S. gregaria*, as a result of the changing climate (Meynard et al. 2020). Seven IAS were introduced unintentionally as a result of unaided transport via trade or tourism, of which six arrived as contaminants of seeds and live material (i.e. *A. rugioperculatus*, *H. hampei*, *P. marginatus*, *P. hysterothorus*, *P. minor*, and *S. frugiperda*), whereas *A. aegypti* arrived via stowaway. The remaining two species were intentionally released in India during the British rule (*L. camara*, *M. micrantha*) (Table 1).

Table 1

IAS with reported costs in India, geographical origin, introduction pathways, reasons for introduction and year of the first record.

Species	US\$ billion	Continent/ Region of Origin	Pathway	Reason	First Record in India
Animals					
<i>Aedes aegypti</i>	8.62	Africa	Stowaway	Trade; Cargo ^a	Prior to 1963 ^b
<i>Paracoccus marginatus</i>	0.14	Central and North America	Contaminant	Trade; Live plant material ^c	2008 ^d
<i>Spodoptera frugiperda</i>	0.04	North, Central, and South America	Contaminant	Tourism/ Trade ^e	2018 ^f
<i>Schistocerca gregaria</i>	0.03	Africa, Asia (West)	Unaided	Natural range expansion ^g	Earliest record from 1812 ^h
<i>Hypothenemus hampei</i>	3.81 E-03	Africa	Contaminant	Trade; Plant material ⁱ	1990 ^j
<i>Aleurodicus rugioperculatus</i>	0.13 E-06	Central America	Contaminant	Trade; Live plant material ^k	2016 ^l
Plants					
<i>Phalaris minor</i>	0.99 E-03	Mediterranean region and North Africa	Contaminant	Trade; Plant material ^m	1970s ⁿ
<i>Lantana camara</i>	0.32 E-06	Central and South America	Release	Ornamental ^o	1809 ^o
<i>Mikania micrantha</i>	0.31 E-06	Central and South America	Release	Fodder/War ^p	1950s ^p
<i>Parthenium hysterophorus</i>	0.12 E-06	North, Central, and South America	Contaminant	Trade; Plant material ^o	1950s ^o
^a Tabachnick 1991; ^b Sarkar et al. 1964; ^c Finch et al. 2021; ^d Muniappan et al. 2008; ^e Early et al. 2018; ^f Sharanbasappa et al. 2018; ^g Meynard et al 2020; ^h Government of India 2013; ⁱ Johnson et al 2020; ^j Kumar et al. 1990; ^k Sreedhar et al. 2020; ^l Sundararaj and Selvaraj 2017; ^m Kaushik et al. 2005; ⁿ Booth et al. 2003; ^o Kohli et al. 2006; ^p Choudhury 1972					

Temporal trends

On average, damage expenditures amounted to US\$ 2.1 billion annually from 1960 to 2020, increasing from US\$ 0.6 million per year in the 1960s and escalating to US\$ 12.3 billion in the 2000s (Fig. 4). While management costs also increased, their reporting began three decades later than damage costs, averaging at US\$ 4.1 million overall to US\$ 13.2 million in 2010s. Management costs were always at least one order of magnitude below damages (Fig. 4). Considering models of the temporal trends in total costs, the amplitude of reported costs increased as the quantiles became more divergent. Thus, costs became more variable, making 2020 estimations of costs differ substantially among models (see Online Resource 2). This was partly due to model sensitivities to the lag time in reporting of costs (which also explains the decrease in the last decade).

Association with socioeconomic status

There was a significant positive relationship between economic cost and total human population across countries in *InvaCost* ($F(1,107) = 57.4, p < 0.001$), independent of economic development status as a two-way interaction ($F(2,107) = 1.4, p = 0.2$). Economic costs of IAS were also significantly positively related with GDP ($F(1,107) = 58.6, p < 0.001$), but not when the economic development was included as an interaction ($F(2,107) = 0.7, p = 0.5$). Accordingly, the strength of these population-cost and GDP-cost relationships were independent of economic development status.

Nonetheless, India had the second highest national total costs caused by IAS considering all countries in *InvaCost* (Fig. 5), only second to the USA, with costs generally low in relation to both population density and GDP. Indeed, given the strong correlation between economic costs and total population and GDP, costs of IAS in India are projected to have reached between US\$ 1.6 trillion (based on GDP) and US\$ 64.9 trillion (based on human population), predicated on the relationship considering all countries. The top five countries in *InvaCost* in terms of total economic costs include the USA, India, Australia, Brazil and China. In comparison to India, total invasion costs among these countries are generally underrepresented in terms of total population (with the exception of Australia) and GDP (Fig. 5).

Discussion

IAS cost the Indian economy at least US\$ 127.3 billion (Indian Rupees ₹ 8.3 trillion) from 1960 to 2020, with an average annual amount of US\$ 2.1 billion. If *low reliability* and *potential costs* were included in the aforementioned conservative cost estimates, the costs escalate to US\$ 182.6 billion (Indian Rupees ₹ 11.9 trillion), thus costing more than US\$ 3 billion annually over the last six decades. These cost estimates may appear to be insignificant as they constitute only 0.08% of India's GDP (i.e. US\$ 2.9 trillion; International Monetary Fund 2020). However, compared with the monetary allocation of the Indian fiscal environmental budget, the average annual economic cost estimates of IAS (US\$ 2.1 billion) was an order of magnitude higher than the 2021–2022 yearly allocated budget of the Government of India's Ministry of Environment, Forestry and Climate Change (i.e. Indian Rupees ₹ 28.7 billion or US\$ 0.4 billion) (Government of India 2021). In comparison to IAS costs incurred by other countries, India ranks as the second topmost country and incurs more costs as a result of IAS than the whole of continental Europe (US\$ 125.6 billion) (Haubrock et al. *in press a*) or Africa (US\$ 18.8 billion) (Diagne et al. *in press*).

Despite these burgeoning totals, there are multiple reasons which suggest these estimates could in fact be a small fraction of actual incurred invasion-related costs by the country. Firstly, in our knowledge, this study is the first

attempt of calculating invasion costs that are observed and highly reliable. It follows that more efforts to collect and curate data will lead to higher costs. Secondly, the methods were stringent and included several levels of filtering to achieve the most reliable costs for this study. Of the 300 cost entries derived from 73 unique cost-based references, we excluded 204 cost entries from 51 references from the final analysis, in order to keep only the most complete and reliable data. Thirdly, the data were geographically, taxonomically and sectorally fragmented, leading to likely underestimated costs (see details in the following sections). Fourthly, language barriers can cause gaps in information availability and this is likely the case for India - only two of the 73 unique references included non-English languages (both in Hindi). However, both non-English references were then excluded from the final analysis due to reliability issues. In a linguistically diverse country such as India, with 22 official regional languages, many cost entries, especially the regional and local costs, are possibly documented in regional languages and overlooked. Additionally, searching for costs was difficult because appropriate parallel regional language terms for 'invasive species' or 'biological invasions' do not exist. Accordingly, it has been shown that up to twice as many costs entries could be found in non-English sources in the *InvaCost* database (Angulo et al. 2021). Lastly, *InvaCost* only considers those cost entries which were directly attributable to IAS and could be monetised. IAS may impact native ecosystems in ways that are difficult to monetise, for example through declines in ecosystem services or native species populations. Alternatively, they may cause quantifiable, but indirect impacts, where attribution of species costs or invasion status may be secondary. The above-mentioned reasons suggest that the current cost projections reflect only a fraction of the actual costs and are thus grossly underestimated. An illustration of this is given by the global analysis of invasion costs relative to socio-economic indicators such as total human population and GDP. The costs of IAS in India are severely underestimated, by at least an order of magnitude – compared to what would be expected considering all other countries with invasion costs.

Distribution of IAS costs

Most cost entries lacked information accompanying costs, such as exact location and spatial scale, impacted environments, identification of the causal organism to species level, type of cost, and impacted sector. In most cases, the costs were attributed to the “diverse/unspecified” category, meaning that either the costs were calculated over multiple categories without the break-up amount per category, or more challengingly, these attributes were not specified. This lack of information makes it difficult to design action plans specific to regions, ecosystems, species, and sectors. For example, 99.5% of costs have been reported at the country level and not at the regional or provincial levels, making it challenging to design a management plan specific to the region. While these results add to our knowledge, these results need to be approached with caution. The fragmentary nature of cost distributions suggests that availability of more invasion-cost related information may lead to a change in the trends observed in this study.

Geographical distribution

Although the regional or local costs were only a fraction of the country-level costs, there were marked differences among the six administrative regions of India. All regional or local cost entries were reported from West, South and North Indian regions, without any costs associated with Central, East or North-East India. This biased geographic distribution of costs could be a result of the preliminary nature of this study, but there could be other reasons involved. Coincidentally, these three regions with attributable costs contribute to about 80% of India's GDP (2018-19 estimates; South India 29.9%, North India 27.2% and West India 22.2% of India's total Gross State Domestic Product). These three regions also share most inland and international trade (for example, West India contributes to

40%, and South India contributes about 30% of India's export of goods and services). Consequently, these regions may contain more IAS, and as a result, more cost entries are reported from these regions. Moreover, even if IAS are uniformly distributed across India, the availability of monetary resources at disposal to offset and record invasion costs may suffice to make these three regions more represented in the dataset.

Environmental distribution

Although terrestrial invaders are maximally represented in our data ($n = 37$), followed by those from semi-aquatic ($n = 35$) and aquatic environments ($n = 16$), the costs borne from taxa inhabiting terrestrial environments were half of those borne by aquatic taxa, and over over 40-fold less than semi-aquatic environments. This break-up of costs indicates that invasions by semi-aquatic and aquatic taxa have been causing more monetary burden to the economy, yet they are primarily understudied. However, importantly, the semi-aquatic costs were driven solely by a single species, yellow fever mosquito, reflecting the marked human healthcare costs associated with this taxon – which has aquatic juvenile stages – and corroborating previous studies (Bradshaw et al. 2016; Cuthbert et al. 2021). Nevertheless, the underrepresentation of aquatic and semi-aquatic ecosystems in studies on biological invasions is not unique to India, as these ecosystems are less represented in ecological literature than terrestrial ecosystems (Menge et al. 2009). More specifically, in the context of IAS, aquatic ecosystems, and in particular marine ones, might be underrepresented as well because these invasions might be less perceptible or costs are challenging to measure, thus, more likely to be predicted than observed (Oreska and Aldridge 2011; Cuthbert et al. 2021).

Sectoral distribution and cost types

More than 99% of costs affected multiple sectors and were therefore classified as “mixed costs”. For example, costs resulting from the yellow fever mosquito are borne by the health sector; however, they are also a burden on authorities and stakeholders. Even if the cost is reported to have impacted only one sector, delayed effects might impact other sectors. For example, *Eichornia* and many other exotic weeds have affected the fisheries sector but have also caused a steady decline in the tourism sector that relies on aquatic ecosystems. Thus, these mixed costs point to the multi-pronged nature of the impacts of biological invasions, possibly leading to a socioeconomic domino effect, especially in an emerging economy. Among uni-sectoral costs, maximum costs were attributed to anthropocentric sectors such as public and social welfare, fisheries, agriculture, and authorities and stakeholders. Sectors such as forestry and environment were either negligible in terms of amount and number of costs or completely absent from the records. This bias indicates selective reporting from anthropocentric sectors as well as difficulty in monetising costs in non-anthropocentric sectors such as forestry and the environment.

Taxonomic distribution

More than 95% of India's invasive animals and plants did not have a single documented cost. Similar patterns have been observed in invasion-related costs in the UK (Cuthbert et al. *in press*), Australia (Bradshaw et al. *in press*), Russia, (Kirichenko et al. *in press*), France (Renault et al. *in press*), Mexico (Rico-Sánchez et al. *in press*) or Argentina, (Duboscq-Carra et al. *in press*). Out of the 157 invasive animal species in India, 99 are reported from marine environments. Although the database has cost entries from marine environments, the species responsible for these costs were categorised as diverse or unspecified. Indeed, considering the entire database globally, marine species comprise only approximately 1% of total aquatic invasion costs (Cuthbert et al. 2021), indicating a paucity in reporting of their costs, or fewer human assets that are impacted in the marine realm. Further actions to tackle these costs becomes challenging because the IAS to be controlled are unknown. The 58 invasive animals found in India in terrestrial and freshwater ecosystems include 31 arthropod species, three molluscs, 19 fish species, one

reptile, two birds and two mammalian species (Government of India 2018). Except for arthropods (all belonging to class Insecta), none of the other taxa had any representation in *InvaCost*. The total absence of mammals from this estimate, when they are the second most costly order globally (Diagne et al. 2021), is striking in this regard. The representation was worse for Fungi and Chromista, as well as for viruses, since no cost entry was attributed to these entire Kingdoms. Only three of the 21 high concern invasive species (HiCIS) from India (Mungi et al. 2019) had cost entries in our dataset. If *low reliability* and *potential costs* were considered, three more species from HiCIS would be included, viz. *Achatina fulica*, *Eichhornia crassipes* and *Prosopis juliflora*. The remaining 15 HiCIS did not have a single cost entry in our dataset, despite probably high actual costs. More focused searches on HiCIS may reveal costs that could not be included in these analyses.

Introduction pathways

One of the considered species, *S. gregaria*, has been increasing its range in India due to climatic changes. We have nonetheless included it in this estimation because species expanding due to climate change are sometimes considered as IAS since climate change is humanmade (Hulme 2015; but also see Essl et al. 2019); yet, its exclusion would have changed neither our overall results nor our conclusions.

With increased foreign investment and decreased import tariffs, India's share in international trade has increased substantially. India is currently ranked 8th in the world in international trade imports. The impetus to international trade has not developed alongside international and national policy guidelines related to biological invasions. For example, policies of different international agencies may conflict with each other, such as those of the World Trade Organization (WTO) promoting an unrestricted movement of products and those of the Convention on Biological Diversity (CBD) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) promoting regulation of these movements (Hulme 2007, Hulme et al. 2018). Many of these policies also consider economic impacts in managed ecosystems such as agriculture, livestock and fisheries, but not economic impacts and biodiversity losses in natural ecosystems such as forests. Consequently, species that only affect natural ecosystems often do not come under the direct purview of many of these policies and may not be blacklisted (Hulme 2007).

Along with international trade, India also serves as a global hub for tourism, with an annual turnover of 17 million inbound foreign tourists and 26 million outbound Indian tourists (Government of India 2019). The inbound contaminants via trade and tourists are usually targeted via the international sanitary standards as a part of the border quarantine protocols. However, developing potentially invasive species lists and a 'whitelist' approach, wherein every contaminant or contaminate species is considered potentially dangerous unless proved safe via risk profiling, will be more effective than relying on 'blacklisted' species. Adopting a 'whitelisting' approach is more stringent and hence more effective in controlling potential invasions (Simberloff 2006; Hulme et al. 2018), and hence, are proposed to be implemented in trade-related movements of species (Bang and Courchamp 2021).

Temporal trends

Overall, costs have increased by five orders of magnitudes over the last six decades in India. The increase in the invasion costs over time could be a result of an increasing number of IAS entering, establishing and spreading in India, increased awareness about IAS, increased numbers of reports and studies on IAS and their costs, increased funds to allot to IAS, but inadequate legal and policy frameworks.

The break-up of costs revealed that the rate of increase in the damage-loss type of costs has been substantially higher than the management-related costs. Moreover, management costs have always been one-four orders of

magnitudes less than damage-loss costs, and this is quite telling of the problem related to IAS in India. It is well established that spending on pre-entry measures is more cost-effective than longer-term post-entry responses (Leung et al. 2002; Ahmed et al. this special issue), and thus preventative measures should be given priority. As newer species accumulate, existing species spread and "invasion debts" increase due to a delayed impact of IAS (Seebens et al. 2017), and increased world trade and climate change exacerbate biological invasions, their costs are also likely to further increase with time.

Association with socioeconomic status

A key finding emerging from our results is the significant positive association between invasion costs incurred by a country and its total population as well as its GDP. Anthropogenic impacts are known to affect biological invasions, with more populous and dense regions comprising higher numbers of IAS (Pyšek et al. 2010; Sharma et al. 2010). Furthermore, a high GDP and high volumes of international trade result in higher international imports and thus provides more opportunities for the introduction of IAS (Haubrock et al. *in press b*; Haubrock et al. *in press c*; Kouranditou et al. *in press*). India is currently ranked 8th in international imports and currently ranks in the top 4 countries on many national transport-related measures such as total road network, total rail network, total passengers carried via air transport annually, among other measures (<https://data.worldbank.org/indicator/IS.AIR.PSGR>). This inland transport network implies that once a non-native species gains entry, it may quickly spread to the distant corners of the country, leading to higher overall invasion costs.

Despite India being the second topmost country in the world regarding invasion costs, the invasion costs are less based on its total population and GDP relative to other countries. Indeed, relative to the global trend, costs in India from invasions are substantially underreported – by several orders of magnitude – with respect to GDP and human population. Considering the global regressions between costs, population and GDP, observed costs in India could have in fact reached between US\$ 1.6 and US\$ 65 trillion since 1960. Costs were particularly unrepresented considering the substantial total human population of India, which is a significant predictor of economic costs of IAS on the global scale. Other countries that reported the highest invasion costs, namely the USA, Brazil and China, also had underestimated costs relative to human population, as well as Australia in the case of GDP. India was most similar to China in terms of underreporting cost magnitudes relative to total human population – both having high population levels – but clustered with Australia and Brazil given similarities in GDP. Overall, this indicates that even for countries with a high total economic output and human population, costs of IAS tend to be severely underestimated, which is exemplified considering India.

Conclusion

Comparable to many other developing economies, India faces the conundrum of the simultaneous pursuit of economic development and environmental conservation. Although ecological impacts of biological invasions are increasingly recognised, the economic burdens they create is often challenging to comprehend, assess, quantify, and integrate in the national policy. The knowledge gaps in the reportage on economic costs are pervasive in India, as seen by the lack of geographical, environmental, sectoral and taxonomic specificity of costs. These gaps need to be addressed swiftly, primarily due to the escalating nature of IAS costs with time. India is the second topmost country regarding IAS costs, and even these costs are likely to be a gross underrepresentation of the actual costs based on our global analysis of 112 countries. In addition to the dire ecological impact of IAS, they are also an important hindrance on the economic development of this emerging country. Prioritizing IAS management will slow

the rate of new incursions and reduce the impacts of IAS, as opposed to prioritizing damage costs which will continue to escalate over time. To this end, it is crucial to build better national policies related to international trade, improve the existing border biosecurity and sanitary protocols, develop early-response programmes to contain IAS that have already gained entry, and foster agencies and human resource devoted to creating and disseminating knowledge on invasive alien species.

Declarations

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Conflicts of interest

The authors declare that they have no conflict of interests.

Availability of data and code

The data used for analyses are provided in the supplementary material (ESM_1). The scripts used for analyses are included in the 'invacost' package in R (<https://doi.org/10.1101/2020.12.10.419432>). Any further information can be obtained from request to the authors.

Author contributions:

A.B. and F.C. conceptualized research; F.C. provided funding acquisition; A.B., R.D.F, D.M., C.D. and A.K.B collected and curated data; A.B., R.N.C. and P.J.H conducted data analysis; R.N.C, P.J.H., D.M. and A.J.T. conducted data visualisation; A.B., R.N.C., P.J.H, R.D.F, and D.M. wrote the original draft; all authors reviewed and edited the final draft of the manuscript.

Ethics approval

Not relevant

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Figures

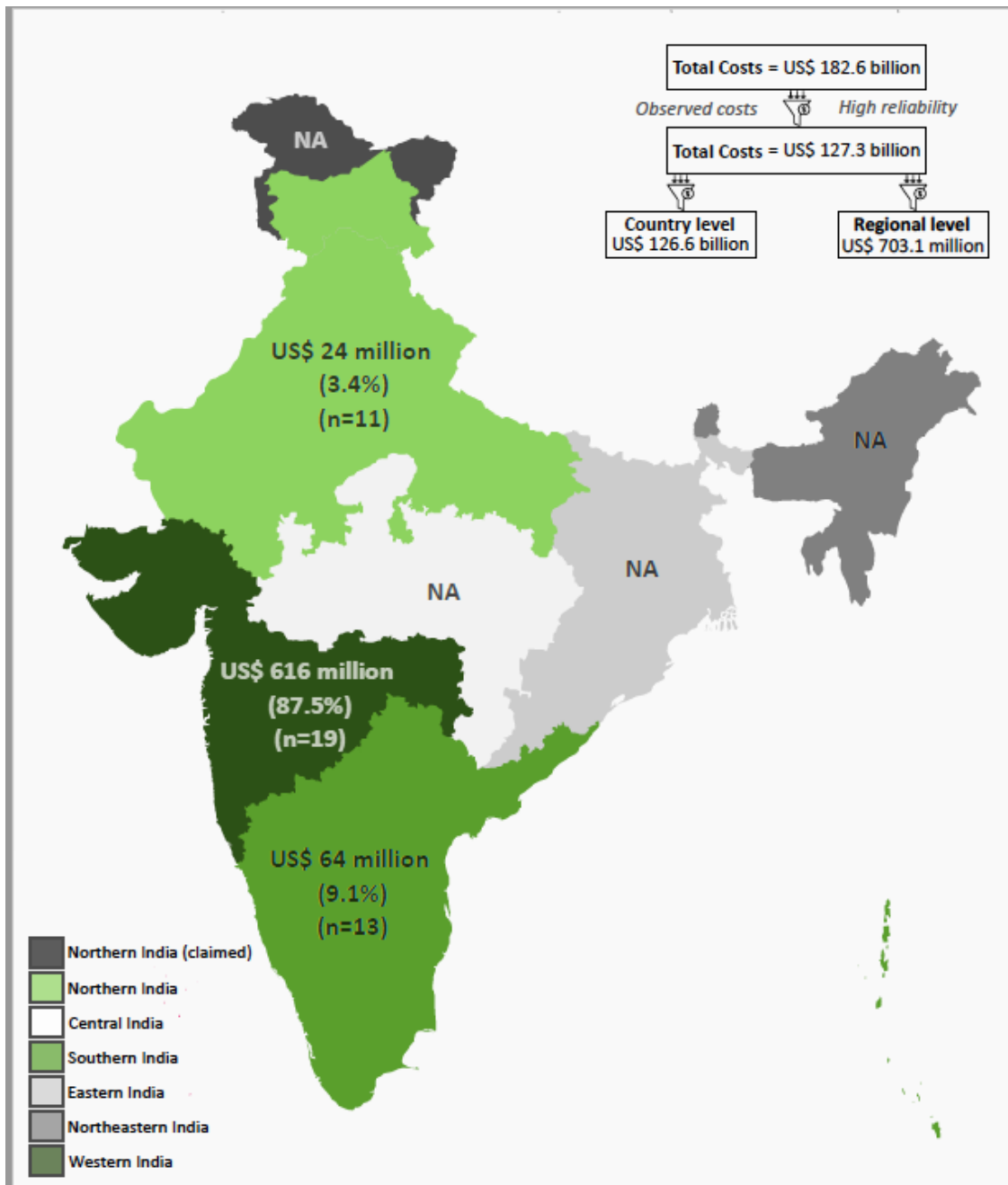


Figure 1

Regional distribution of biological invasion costs incurred in India. Note that the costs in brackets are percentages of regional costs. Four regions have no documented cost entries (i.e. designated as NA). However, this does not infer that 'Diverse/Unspecified' costs were not incurred across these regions. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

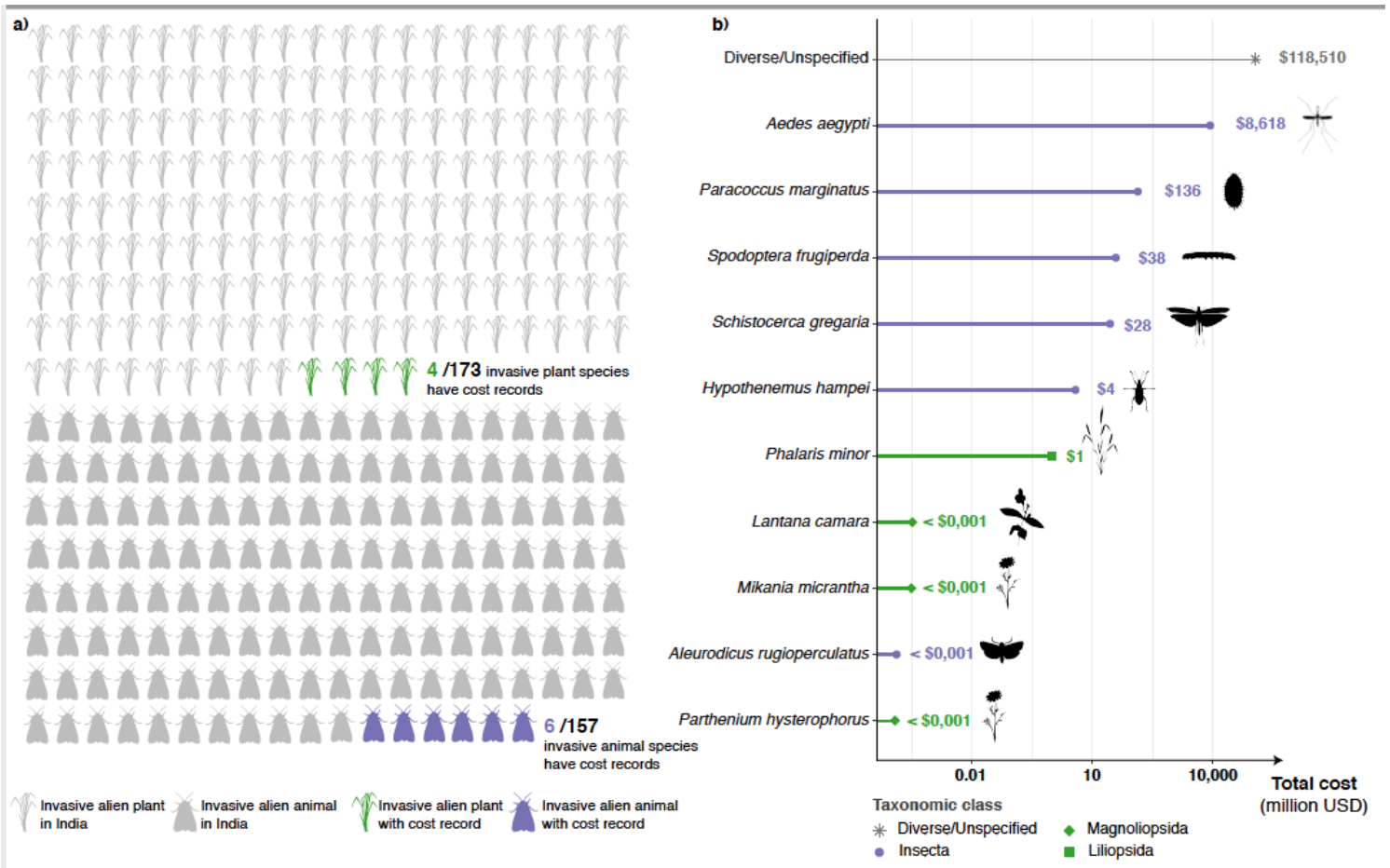


Figure 2

Cost distribution of IAS in India a) showing the number of specific plant (green) and animal (purple-blue) costs recorded in InvaCost against the total number of invasive alien plants and animals present in India (grey) and b) breakdown of cost by species from 1960 to 2020. Green bars represent plant costs and purple-blue bars represent animal costs. Costs are in million USD (2017 value)

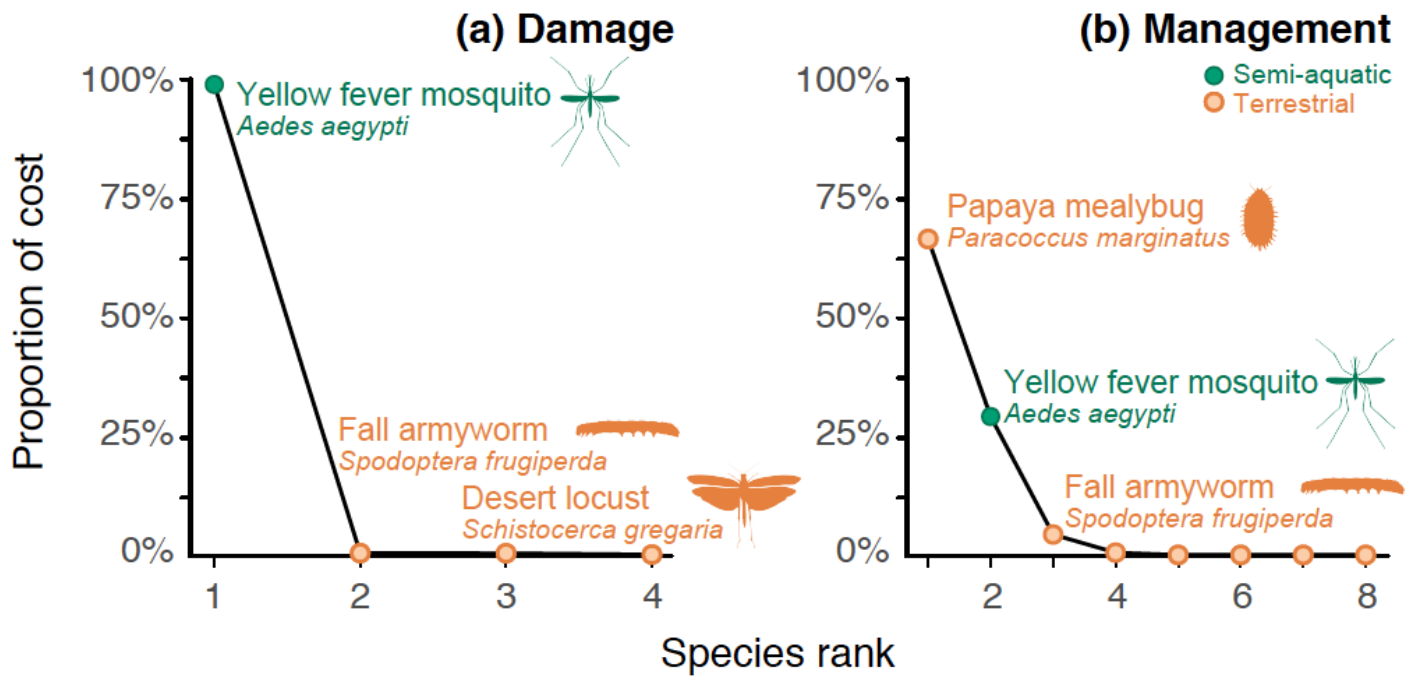


Figure 3

Whittaker plot showing the proportion of cost from IAS for (a) damage costs and (b) management costs. The proportion of cost is derived from the total cost (US\$ 8.8 billion) attributed to specific species over the period 1960-2020

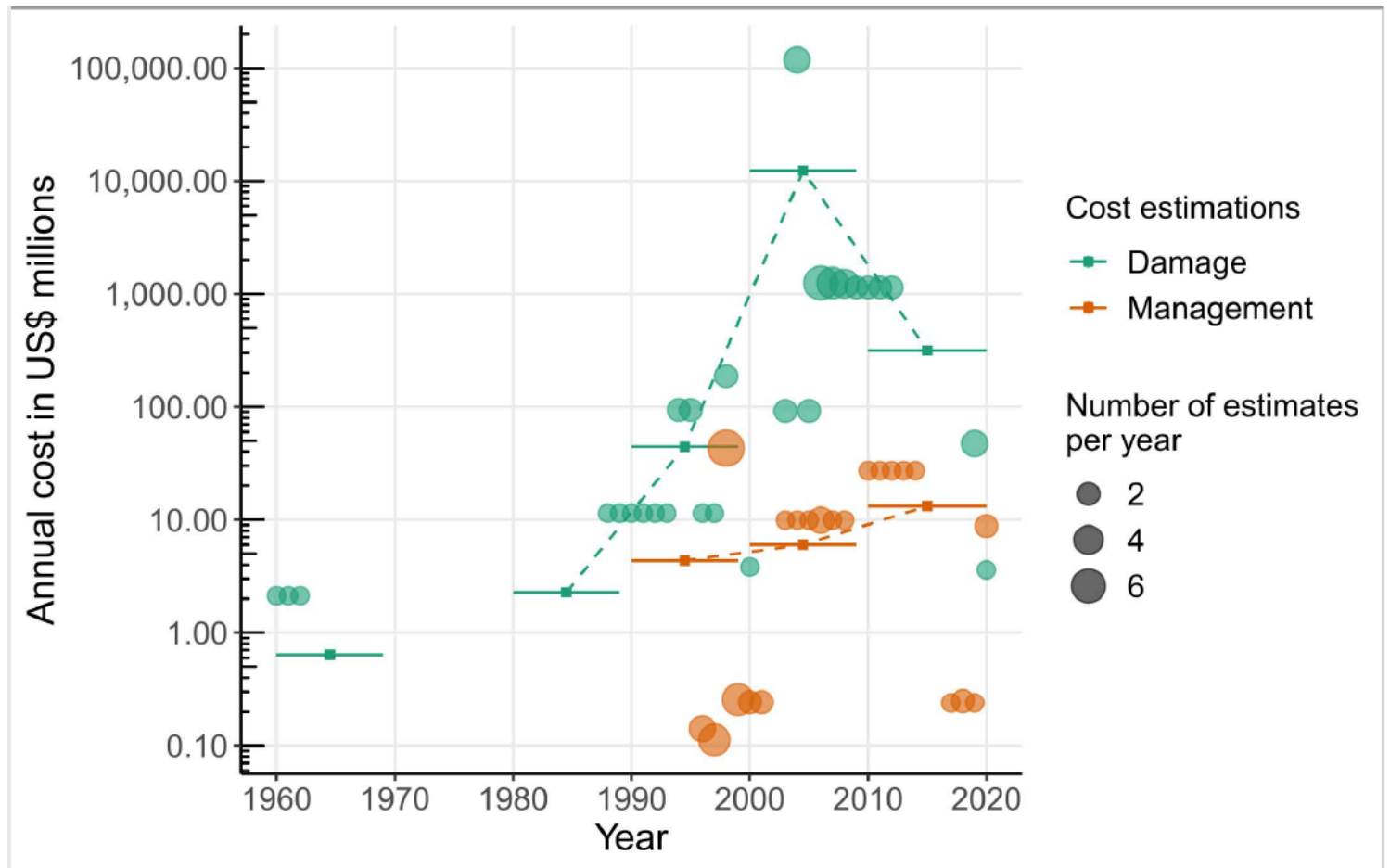


Figure 4

Temporal trends depicting damage and management costs of invasive alien species in India. Bars represent 10-year averages; points represent annual totals, with size scaled by numbers of cost entries per year; the dashed lines represent the trends between bars. No data were available for the decade of 1970-1980. Note that the y-axis is on a log₁₀ scale

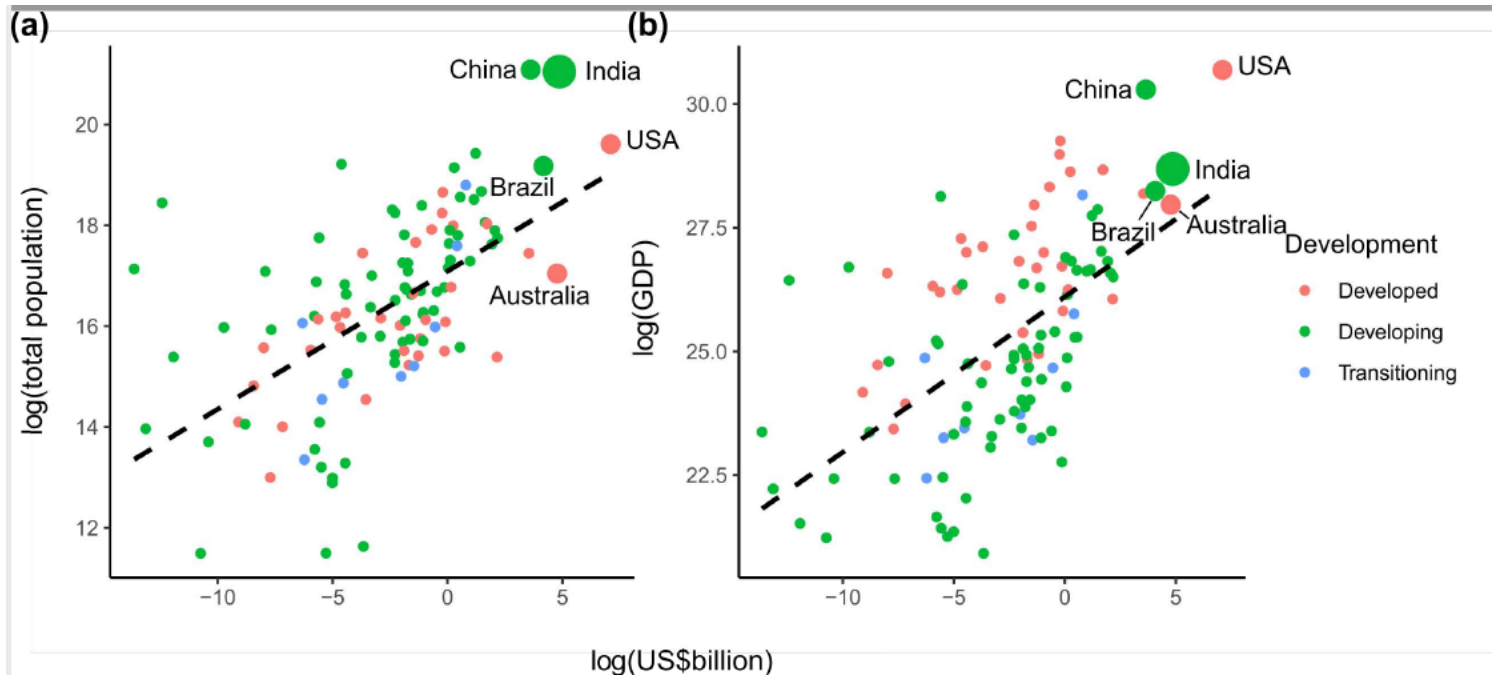


Figure 5

National economic total costs caused by IAS from 1960 to 2020 in relation to (a) total human population and (b) GDP. Note that both y-axes are on log_n scales. India, USA, China, Brazil and Australia are highlighted for comparison. Dashed lines correspond to linear regressions, irrespective of economic development status. Economic costs caused by IAS in all the countries considered here were extracted from the InvaCost database

Supplementary Files

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