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The economic costs of biological invasions in Brazil: a first assessment

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Abstract

Biological invasions are one of the leading causes of global environmental change and their impacts can affect biodiversity, ecosystem services, human health and the economy. Yet, the understanding on the impacts of invasive alien species is still limited and mostly related to alien species outbreaks and losses in agricultural yield, followed by the understanding of the ecological impacts on natural systems. Notably, the economic impacts of biological invasions have rarely been quantified. Brazil has at least 1214 known alien species from which 460 are recognized as invasive alien species. Still, there are no comprehensive estimates of the cost of their impact and management. Here, we aimed at filling this gap by providing a comprehensive estimate of the economic cost of biological invasions in Brazil. In order to quantify these costs for species, ecosystems and human well-being we used the InvaCost database which is the first global compilation of the economic costs of biological invasions. We found that Brazil reportedly spent a minimum of USD 105.53 billions over 35 years (1984–2019), with an average spent of USD 3.02 (± 9.8) billions per year. Furthermore, USD 104.33 billion were due to damages and losses caused by invaders, whereas only USD 1.19 billion were invested in their management (prevention, control or eradication). We also found that recorded costs were unevenly distributed across ecosystems, and socio-economic sectors, and were rarely evaluated and published. We found that the economic costs with losses and damages were substantially greater than those used for prevention, control or eradication of IAS. Since our data show costs reported in Brazil for only 16 invasive alien species, our estimates are likely a conservative minimum of the actual economic costs of biological invasions in Brazil. Taken together, they indicate that invasive alien species are an important cause of economic losses and that Brazil has mostly opted for paying for the damage incurred by biological invasions rather than investing in preventing them from happening.

Abstract in Portuguese

Os impactos resultantes da introdução de espécies exóticas e invasoras (t.c.p. invasão biológica) é um dos principais fatores associados as mudanças ambientais em escala global, cujos impactos afetam direta e indiretamente a biodiversidade, os serviços ecossistêmicos, o bem estar e a saúde humana, e a economia. Contudo, muito do conhecimento sobre os impactos das espécies exóticas e invasoras ainda é limitado aos prejuízos observados em áreas de cultivo e plantações, negligenciando o impacto de surtos de espécies exóticas em sistemas ecológicos e naturais. Somado a isso, é notável o desconhecimento dos impactos econômicos da invasão biológica que são raramente quantificados e reportados. No Brasil estima-se a ocorrência de ao menos 1214 espécies exóticas estabelecidas das quais 460 são reconhecidas como espécies invasoras. Ainda assim, as estimativas dos custos relacionados aos respectivos impactos por prejuízos e por manejo de espécies exóticas e invasoras são desconhecidos. Neste estudo, pretendemos contribuir para preencher esta lacuna sumarizando os custos econômicos da invasão biológica para o Brasil. Para quantificar os custos econômicos da invasão biológica usamos informações em nível de espécie, ecossistemas, bem estar e saúde humana, e setores socio-econômicos disponíveis no primeiro levantamento de dados global para custos econômicos da invasão biológica, InvaCost. Encontramos que os custos reportados para o Brasil apresentam valor mínimo de USD 105,3 bilhões ao longo dos últimos 35 anos (1984–2019), com custo médio de USD 3,02 (± 9,8) bilhões ao ano. Detectamos que USD 104,33 bilhões estão relacionados a prejuízos (danos e perdas) causados por espécies invasoras, enquanto USD 1,9 bilhões foram investidos em ações preventivas como o de manejo, controle ou erradicação de espécies. Além disso, nossos resultados apontam para uma significativa disparidade dos custos econômicos entre os diferentes setores analisados (ecológicos, sociais e econômicos) reforçando a escassez de dados econômicos reportados e ou disponíveis para análise. Com os dados disponiveis observamos que os custos econômicos dos prejuízos (perdas e danos) foram mais representativos do que os custos de prevenção, controle e erradicação de espécies exóticas e invasoras. Uma vez que nossos dados de custo disponíveis para o Brasil estão associados apenas à presença de 16 espécies invasoras, certamente nossos resultados representam uma estimativa conservadora que reflete o valor mínimo esperado para os custos atuais dos impactos econômicos referente a presença de espécies exótico invasoras para o Brasil. Em conjunto, providenciamos a primeira análise de custos econômicos baseado em evidências que indicam que o custo com espécies exótico invasoras no país está associado à reversão dos prejuízos acometidos pela invasão biológica ao invés do incentivo em investimento para a prevenção de danos. Portanto, concluímos que espécies exótico invasoras são uma importante fonte do prejuízo econômico ao país.

Keywords

Biological invasions, economic cost, economic damage, Invasive species impact, InvaCost database, invasive alien species, Invasion management

Introduction

The pervasive impacts of invasive alien species (IAS hereafter) are complex and multifaceted, since IAS are responsible for substantial damages in social, ecological, and human health worldwide (Strayer 2012; Jones 2017; Bradley et al. 2019; Crystal-Ornelas and Lockwood 2020a). Among the wide range of impacts imposed by IAS are changes in native species composition (Vilà et al. 2011; but see Crystal-Ornellas and Lockwood 2020b), the decline in biodiversity (Bellard et al. 2016; Doherty et al. 2016), disturbance in ecosystem services and environmental functioning (Ricciardi et al. 2013), spreading diseases that affect human well-being (Shepard et al. 2011; Shackleton et al. 2019; Nuñez et al. 2020) and destruction of croplands (Paini et al. 2016). However, public awareness of the impacts associated with IAS seems to be insufficient to support effective management efforts in prevention, control, and eradication. Thus, mitigation of biological invasions remains a challenge. For instance, although the ecological impacts of IAS have been more thoroughly scrutinized (Blackburn et al. 2014; Gallardo et al. 2016; Crystal-Ornelas and Lockwood 2020b), there is a scarcity of information on economic costs imposed by IAS. Because economic costs are distributed over the market and non-market sectors (Bradshaw et al. 2016), understanding the type and the magnitude of economic costs associated with IAS are key for environmental management and for raising public awareness. Therefore, knowing IAS impacts becomes more relevant in the current context where many more species are expected to be introduced and become invasive worldwide (Seebens et al. 2017; Seebens et al. 2020).

Despite the growing knowledge in IAS distribution patterns and drivers (e.g., Dawson et al. 2017), estimating the impact of IAS remains a challenge owing to the temporal and spatial scales in which they occur, and the potential myriad of indirect effects that some IAS can have on ecological and human systems (Shackleton et al. 2019). With the recent development of standardized ecological (Blackburn et al. 2014, IUCN 2020) and socio-economic assessments (Bacher et al. 2018) of IAS impacts, it is increasingly clear that high-quality and comprehensive information is still lacking for most taxa, systems and regions. Yet, these data are necessary for researchers, managers and policy makers to develop and implement effective management programs towards IAS.

The economic cost of biological invasions tends to incur even when the ecological or human health impacts decrease. Indeed, managing invasions to reduce their ecological impact also produces an economic impact by consuming monetary and human resources. However, different sectors of activity differ in their required costs for managing IAS. In Brazil, IAS can rapidly damage crops fields and directly impact a wide range of commodities imposing billions of Reais (R$) in cost distributed over damage repair, species invasion mitigation, and prevention strategies (Oliveira et al. 2013; Oliveira et al. 2014; Pozebon et al. 2020). Furthermore, in tropical regions, IAS impact can be more severe and threat human well-being substantially by spreading multiple zoonotic diseases (i.e., dengue, chikungunya, and zika virus spread by species of the genus *Aedes*), consequently causing severe economic impact associated with human care (Teichi et al. 2017). Finally, IAS spread diseases into Forestry plantations (Schnell e Schühli et al. 2016) and imposes severe costs with IAS management and eradication in conservation areas (Guimarães et al. 2017). Therefore, partitioning of the economic impact of IAS over multiple activity sectors is central for understanding and planning effective impact reduction.

Despite the comprehensive impacts generated by IAS, the economic costs of biological invasions are rarely assessed (Diagne et al. 2020; Heringer et al. 2021 for the costs in Latin America) and effective management and policy decisions for the best possible resource allocation remains doubtful in most cases. Knowledge of the economic effects of IAS in a region can help inform management and policy decisions as well as raise public awareness regarding the implications of biological invasions on people's lives. Globally, the economic impact of biological invasions was estimated to reach at least USD 1.288 trillion between 1970 and 2017 (Diagne et al. 2021) owing to impacts associated with biodiversity loss, spread and cause of human diseases, damage to goods and infrastructure, and increased costs of travel and international trade. For Central and South Americas, when applying the same criteria used here, the known economic impact of invasive alien species has recently been estimated at USD 146.5 billion (see Heringer et al. 2021). In South America, Brazil is one of the world's rising economies (Shukla et al. 2018) that hosts two global biodiversity hotspots covering 17.25% of the hotspots surface area worldwide (Myers et al. 2000; Mittermeier et al. 2011). However, its biodiversity, ecological structure and ecosystem services (Pauchard et al. 2018) have been severely impacted by the damage imposed by human activities (Soares-Filho et al. 2014; Venter et al. 2016) which in turn raise opportunities for new IAS impacts. For Brazil, even though studies have shown the widespread presence and negative impacts of many invasive alien species (e.g., Zenni and Ziller 2011; Fontoura et al. 2013; da Rosa et al. 2017), the only general estimation for the economic impact of invasive alien species for the country was made 20 years ago based solely on the estimated impacts of rats and human diseases (Pimentel et al. 2001). Therefore, there is a knowledge gap regarding the costs with IAS in Brazil.

Here, we investigated the economic costs associated with the presence of IAS in Brazil. For the purpose of this study, invasive alien species are any non-native species that generate economic impact on ecological, societal or environmental sectors of activity. Using studies that report the economic impact of alien species we evaluated the reported expenses based on IAS identities, intervention classes and costs in environmental and societal sectors. Furthermore, by using InvaCost, a global dataset of the economic costs of invasive species (Diagne et al. 2020), we estimated the total cost of biological invasions in Brazil, as well as the distribution of these costs over the different economic sectors and type of costs. Finally, we tested whether the economic costs associated with the presence of IAS reflect preventive actions for managing or enduring damages and losses caused by IAS.

Method

The species list used in this study was obtained from the InvaCost database (Diagne et al. 2020). InvaCost is a global database (N = 9,823 entries) constructed from a systematic review in peer-reviewed articles, official reports and grey material that considers as IAS any non-native species that results in economic impact on the ecological, societal or environmental sector of activity (for details see Diagne et. al 2020 and Angulo et al. 2021). The resulting database is the most comprehensive, harmonized and robust global-scale data compilation and description of economic cost estimates associated with IAS reported in the existing literature (Diagne et al. 2020; https://doi.org/10.6084/m9.figshare.12668570). To compile these data, the Web of Science, Google Scholar, and Google search engines were used with standardized search strings (for details see Diagne et al. 2020). Additionally, institutions, researchers and managers were contacted in order to find all possible references. For Brazil, both English and Portuguese literature were used (Angulo et al. 2021).

From the InvaCost database, we selected all entries referring to Brazil (N = 54) by using the 'Official country' column of the dataset and used the 'expandYearlyCosts' function of the R package invacost (Leroy et al. 2020) to expand the dataset. This function expands the annual cost to the period of time higher than one year. Thus, each estimate cost corresponds to an annual cost, which was repeated as many times as the number of years over which the cost occurred. Then, the total reported cost entries after data 'expansion' (N = 173) was used in further analysis. However, owing to the small number of resulting cost information (N= 173 for 16 species), we did not remove the data classified as having low reliability (N = 55) and as potential implementation (N = 11), contrary to other studies using the InvaCost database which did not include these data (e.g., Heringer et al. 2021). The variable reliability refers to the accessibility of cost based on the availability of the information (i.e., low for not fully accessible information) and implementation indicates if the costs were incurred (i.e., observed) or expected, for example through modelling or extrapolation (i.e., potential). Therefore, these metrics represent the confidence attributed to the observed costs (Suppl. material 1: Table S1). Importantly, all cost data were converted to 2017 US Dollars (USD).

To estimate the total economic cost of IAS, we summed up all annual costs considering the ecological and societal sectors of activity for which information was available (i.e., without considering management or damage repair as distinct classes). The former is represented by the costs directly linked with species information on terrestrial, aquatic or both terrestrial and aquatic ecosystems (i.e., there is no marine species in the Brazil dataset). For the societal costs we used the market sector and the type of cost classes of reported economic costs. The market sector is a categorical variable that links the economic costs in the following six business classes: agriculture, stakeholders or decision makers, environment, forestry, health, and public and social welfare (for definition of each market sector see Table 1). Similarly, the type of cost classes directly links the economic costs with the following seven categories: control, damage repair, damage loss, eradication, medical care, prevention and research (for definition of each type of cost see Table 2).

In order to evaluate if the economic costs differed between costs used to repairing damage from costs used to IAS management, we used the impact year and the costs associated to create a new variable derived from the type of costs, here named of intervention group ("Type_2" in InvaCost database). The latter is a categorical variable where the seven types of cost classes explained above were reorganized into the

Table 1. Description of market sectors impacted by IAS in Brazil. Descriptions follow the classification used in the InvaCost database (Diagne et al. 2020).

Market sector	Description
Agriculture	Food and other useful products produced by human activities (i.e., plant resources, crop growing, livestock breeding, land management).
Stakeholders or decision makers	Governmental services or official organizations that allocate efforts and resources for the management, control, and eradication of IAS.
Environment	Impacts impose by IAS on natural resources, ecological processes or ecosystem services.
Forestry	Impacts impose by IAS on forest-based activities and services (i.e., timber production, industries).
Health	Directly or indirectly impact imposed by IAS that negatively affect human well-being or and the sanitary state of people (i.e., vector control, medical care and other derived damage on human productivity).
Public and social welfare	Directly or indirectly impact imposed by IAS on activities, goods or services that contribute to the human well-being and safety in our societies, including local infrastructures (e.g. electric system), quality of life (e.g. income, recreational activities), personal goods (e.g. private properties, lands), public services (e.g. transports, water regulation), and market activities (e.g. tourism, trade).

Table 2. Description of Type of Cost imposed by IAS in Brazil.

Type of cost	Description
Control	Costs used to control IAS population.
Damage repair	Costs used to repair the damages associated with IAS on local infrastructures or other human activity that affect the quality of life, personal goods, public services and market activities.
Damage loss	Costs used to repair the losses associated with IAS on food and other useful products produced by human activities.
Eradication	Costs used on activities that act on IAS mitigation aimed towards complete removal of IAS (e.g., authorized hunting).
Medical care	Costs used to medical care and other human well-being treatment (e.g., treatment of vector borne diseases).
Prevention	Costs used in surveillance, monitoring and other activities that help to prevents the trade, transport and/or introduction of alien species.
Research	Costs on theoretical (e.g., academic research on IAS), applied (e.g., evidence-based decisions plans) and technological (e.g., technological tools) knowledge that support strategies to reduce, control or mitigate the impacts imposed by IAS.

following group of intervention: damage, management, and mixed (Suppl. material 2: Table S2). This predictor indicates the type of intervention that caused the following expending: 1) damage – for costs related to the losses and repairs of damages associated with invasive species; 2) management – for costs related to the management of invasive alien species and other costs not included in damage repair; and 3) mixed – for costs related to the expenses reported without differentiation between damage and management. Then, using the intervention group variable, we fit an ANOVA comparing the three groups of costs with post-hoc Tukey contrast by least-squares means from *emmeans* package and tested the residual normality by Shapiro-Wilk.

Results

We found reports of economic costs for 16 IAS (Table 3). Together, the reported costs accumulate to USD 105.53 billion, or ca. R$ 349.3 billion, representing an average annual cost of USD 3.02 (± 9.8) billion (Fig. 1). From the total, USD 28.3 billion were based on cost entries with low reliability or expected costs and USD 76.8 billion

Table 3. Profile table of invasive alien species. Species: indicates species name. Impact descriptor: A brief overview of the available information of the impacts imposed by each of 16 invasive alien species.

Species	Impact descriptor
Aedes spp.	Is the vector of the most important mosquito-borne disease that impacts human health in the world (Gould et al. 2017). In Brazil, it is responsible for the spread of at least three different arboviruses (i.e., Dengue, Zika and Chikungunha) that threaten human well-being (Marcondes et al. 2016) costing millions of reais with insecticides, larvicides and medical care (Teich et al. 2017).
Artocarpus heterophyllus	Is associated with the Brazilian Atlantic forest (i.e., the most fragmented biomes of the country, see Ribeiro et al. 2009). In Brazil, *A. heterophyllus* occurs closer to human settlements as a fruit tree and ornamental species (Zenni and Ziller 2011) where it usually dominates species biomass and reduce small mammal composition (Boni et al. 2009; Abreu and Rodrigues 2010; Fabricante et al. 2012; Mello et al. 2015).
Bemisia tabaci	Is one of the most economically detrimental invasive alien species that damage a wide variety of horticultural, ornamental, and field crops worldwide (De Barro et al. 2011). In Brazil, its occurrence is associated with ornamental plants (de Moraes et al. 2017), and its economic costs with insecticides production, biological control plans, and virus diseases in field crops (Navas-Castillo et al. 2011; Gilbertson et al. 2015; Cavalcante et al. 2015; Inoue-Nagata et al. 2016).
Brachiaria eminii	Is one of the ecologically impactful invasive alien species that belongs to the group of invasive grasses (Zenni and Ziller 2011). Its costs are associated with fire disturbance (Ribeiro et al. 2000; Gorgone-Barbosa et al. 2016), cattle poisoning (Riet-Correa et al. 2011), competitive exclusion by allelopathic compounds (Barbosa et al. 2008; Damasceno et al. 2018) and reduction of floristic and native species diversity (Durigan et al. 2007; Almeida-Neto et al. 2010).
Cinara spp.	Initially recorded in Brazil in 1996, the species specifically affect the pine plantations productivity which are composed by *Pinus taeda* and *Pinus elliottii* species (Penteado et al. 2000). The economic costs are associated with the Forestry sectors that manage biological control programs and technology development (Schnell e Schühli et al. 2016).
Cydia pomonella	Is one of the most economically detrimental apple pests in the world (Beers et al. 2009; Jiang et al. 2018), and its damage can cause complete crop losses. In Brazil, its economic costs are associated with the development of species eradication planning (PNEPC) that costs US$ 398,000 annually (Kovaleski and Mumford 2007; Kovaleski et al. 2015). Since 2014 the species is considered eradicated (Kovaleski et al. 2015).
Drosophila suzukii	Reported by the first time in 2013 in Brazil's southern provinces (Deprá et al. 2014), its impact is poorly known. However, because of the several economic impacts on fruits growers in North America (Goodhue et al. 2011; Walsh et al. 2011), predictive models indicate wide economic impact in the Brazil's Southern region suggesting fig and pear crops as the main impacted host species (Benito et al. 2016).
Eragrostis plana	The species impacts more than one million hectares in Brazil's southern grasslands (Medeiros and Focht 2007). Its spread imposes impact by outcompeting with native species (Ferreira et al. 2008). Its costs are associated with the development of new technologies in order to mitigate and prevent species spreading as well as the low yield in feeding animals (Zenni and Ziller 2011; Baggio et al. 2018).
Helicoverpa armigera/*Tuta absoluta*	Are economically impactful invasive alien species that damage a wide variety of field crops worldwide including tomatoes. In Brazil, its economic impact is associated with crop damages (Czepak et al. 2013) and the development of advanced genetic modification technologies in order to improve the crop resistance to its respective pest (Thomazoni et al. 2013; Silva et al. 2016).
Limnoperna fortunei	Is one of the economically impactful invasive alien species that damage ecological, economical and human wellbeing worldwide (Boltovskoy 2015). Is responsible for impact the hydropower generation (Darrigran et al. 2007), water quality (Darrigran and Damborenea 2011), structure and function of the ecosystem (Boltovskoy and Correa 2015) and damage man-made structures (Boltovskoy 2015). In Brazil, its economic costs are distributed over multiple ecological and social activities sectors.
Panicum maximum	This is an invasive alien species that belongs to the group of invasive grasses. Its ecological impact is associated with the overconsumption of soil nitrogen (Leite et al. 2019) and slowing ecological succession (Montoani and Torezan 2016). Its economic costs are associated with herbicide and fertilization chemical production.
Pinus spp.	The species are one of the most common alien species used in forest plantations and management. In Brazil, its ecological and economic impacts are associated with negative effects in the native community (Brewer et al. 2018), water consumption and quality (Mello et al. 2018), citizen engagements in order to design effective species management (Dechoum et al. 2019), impacts on phytosanitary diseases (Schnell e Schühli et al. 2016), and changes in ecosystem services, functions, soil composition and nutrient cycling (Valduga et al. 2016).
Rhinella marina	Impacts and costs with this species are associated with biodiversity damage and eradication control. However, information of its impact in Brazil seems to be scarce (Forti et al. 2017).
Salvator merianae	Invasive in the Fernando de Noronha archipelago the species is considered a threat to the native community species by hosting, transporting, and spreading parasites to new regions (Ramalho et al. 2009). Further, effective management of the species is a challenge which incurs in economic costs associated with conservation plans design and in its absence the species can harm the livelihood of the local population by spreading zoonotic diseases (Abrahão 2019).

Table 3. Continued.

Species	Impact descriptor
Sirex noctilio	Is one of the most relevant threats to plantation forestry in South America and its impact is mainly associated with disease outbreaks in both natural and planted forests resulting in high levels of tree mortality (Corley et al. 2019). In Brazil, its presence is associated with *Pinus* spp. plantations which is composed by *Pinus taeda* and *Pinus elliotti* species (Iede et al. 2016) which the economic cost of species is estimated in USD 9 million annually over 4 hundred thousands of tree hectare (Schnell e Schühli et al. 2016).
Sus scrofa	Is one of the largest and most widespread invasive alien species in Brazil and it is responsible for several damages in vegetation surface, herbivory, rooting, soil overturning and crop fields damage (Hegel and Marini 2013; Pedrosa et al. 2015). Its economic costs are associated with species eradication control programs and crops damage.

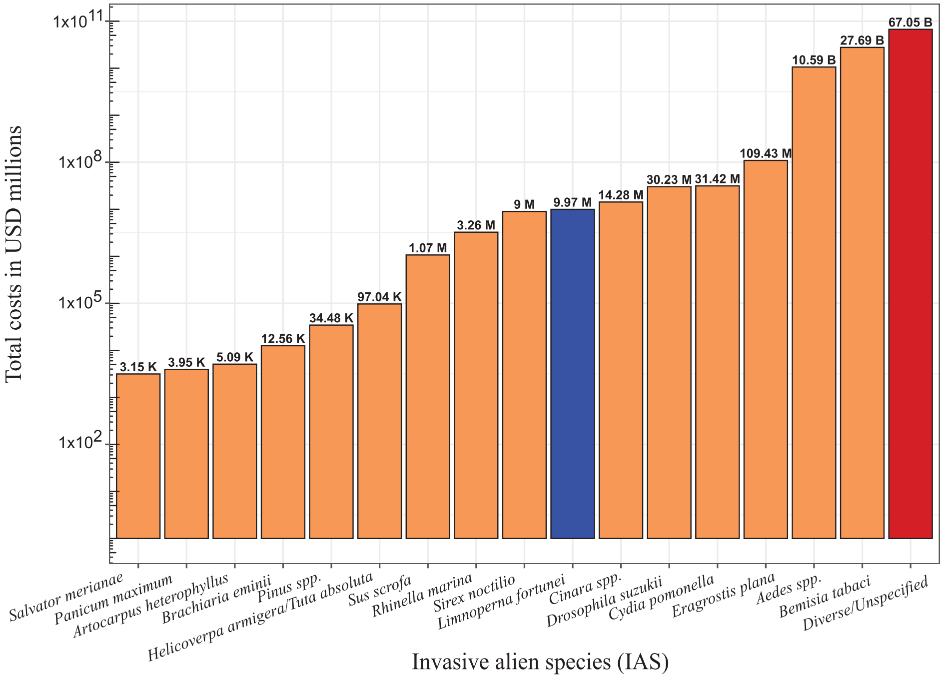

Figure 1. Economic costs incurred by the 16 invasive alien species in Brazil. Numbers above the bars indicate the abbreviated cost in thousand (K), millions (M) and Billions (B) of US dollars. Orange indicates costs assigned to the terrestrial ecosystem. Blue (i.e., *Limnoperna fortunei*) indicates costs assigned to the aquatic ecosystem. Red (in Diverse/unspecified) indicates costs assigned to both terrestrial and aquatic ecosystems.

were based on high-reliability and incurred costs. The reported economic costs among species ranged from USD 3.15 thousand (*S. merianae,* Fig. 1) to USD 27.68 billion (*B. tabaci,* Fig. 1). The five costliest invasive alien species together had a cumulated reported cost of USD 38.44 billion and were distributed within the damage intervention group (Fig. 2, ANOVA; $F = 7.123$; $p = 0.046$). Two of the top five costliest species occurred within the management intervention group. None of the top five species occurred within the mixed intervention group (Fig. 2).

In respect to ecosystem type, 52.4% of the costs (USD 55.28 billion) were distributed across both aquatic and terrestrial ecosystems. The costs reported exclusively for terrestrial ecosystems totaled USD 50.24 billion and had *Aedes* spp. as the costliest

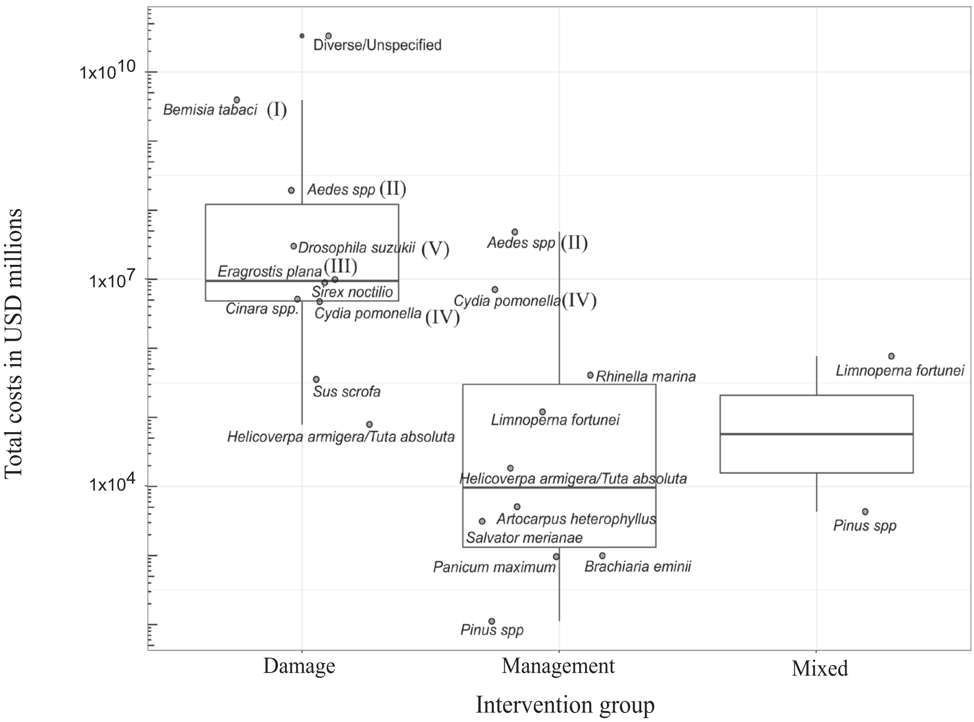

Figure 2. Invasive alien species economic impact associated with type of cost. The post hoc Tukey test for the differences shown statistically significance between damage and management type of cost (Estimate = 2.895 ± 0.78, t value = 3.692, p-value = 0.003). The differences between Damage to Mixed (Estimate = 2.608 ± 1.35, t value = 1.921, p-value = 0.102) and Management to Mixed (Estimate = -0.2864 ± 1.35, t value = -0.211, p-value = 0.835) were not statistically significant. Filled circles indicate species within each type of cost group. The costliest species are pointed out by roman numbers according to the top five costly species rank.

species. The costs reported exclusively for aquatic ecosystems totaled USD 9.97 million and were only due to expenses caused by *L. fortunei*. Considering both terrestrial and aquatic ecosystems, the class Insecta was over-represented, followed by Bivalvia and Liliopsida. The species *Aedes* spp., *L. fortunei, B. eminii* and *E. plana* were the costliest species in Brazil (Figure 3). Surprisingly, there were no costs reported for marine ecosystems.

The economic costs reported as damage contributed with 98.9% of the available cost information and was estimated at USD 104.33 billion, whereas management contributed with 1.13% of the total, reportedly costing USD 1.19 billion. Mixed costs represented less than 1%, at USD 7.7 million (see Suppl. material 3: Table S3). When partitioning the economic costs into classes of market sectors we observed that mixed sectors contributed 61.8% of the total cost, corresponding to USD 65.2 billion. Apart from mixed sectors, agriculture was the most impacted sector with an economic cost estimated at USD 39.61 billion, followed by health with USD 665.85 million and authorities-stakeholders with USD 24.37 million. The remaining impacted sectors

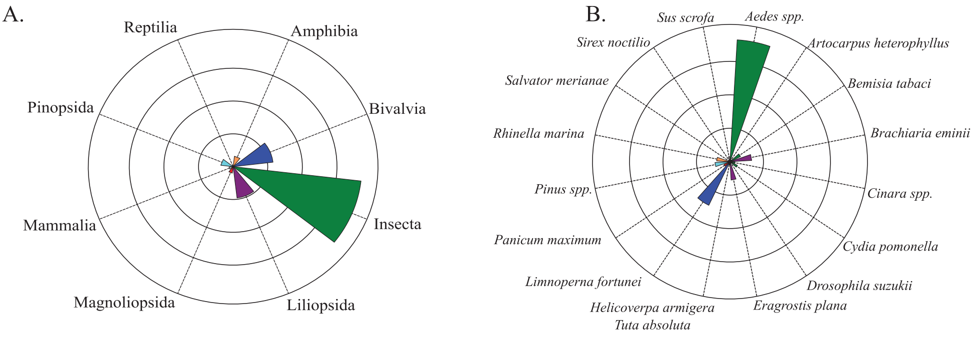

Figure 3. Radar plot showing the frequency of invasive taxonomic classes **(A)** and invasive alien species **(B)** distributed across different ecosystem types. Overrepresented species were: *Aedes* spp. (N = 73), *Limnoperna fortunei* (N = 29), *Brachiaria eminii* (N = 13) and *Eragrostis plana* (N = 11). Species with intermediate representativeness were *Pinus* spp. (N = 9), *Rhinella marina* (N = 8), *Bemisia tabaci* (N=7) and *Cydia pomonella* (N=5). The remaining species were underrepresented (N < 5). The overrepresented taxonomic classes were Insecta (N =93), Bivalvia (N=29) and Liliopsida (N=24), whereas the remaining ones were underrepresented (N <10).

were forestry with a cost of USD 14.28 million, public and social welfare with USD 9.97 million and environment with USD 59.24 thousand (Figure 4). The reported cost of each species by sector varies from USD 96.65 thousands for *B. eminii* in the environment sector to USD 3.96 billion incurred by *B. tabaci* in the agriculture sector (Suppl. material 4: Table S4). Representativeness of species on economic impact over the market sectors indicates that agriculture and environment were impacted by more species than the remaining market sectors, six species each one (see Fig. 6A). Agriculture suffered the highest economic impact caused by *B. tabaci, C. pomonela, E. plana* and *D. suzukii,* followed by the forestry sector, which was impacted by *Cinara* spp. and *S. noctilio,* and the health sector which was impacted by *Aedes* spp.

Regarding the type of intervention, damage losses contributed 89.9% of the available cost estimation at USD 94.91 billion, followed by medical care with USD 9.29 billion and species control with USD 1.19 billion (Fig. 5, see Suppl. material 3: Table S3). The remaining types of costs were indirect costs (USD 126.16 million reported), damage repair (USD 7.67 million), research (USD 3.91 million), prevention (USD 864.24 thousand) and eradication (USD 411.61 thousand) (Figure 5). The cost of each species by activity sectors varied from USD 96.65 thousand by *B. eminii* in the control to USD 3.96 billion incurred by *B. tabaci* in the damage-loss (Suppl. material 5: Table S5). Representativeness of species on economic impact over the type of costs indicated that control had nine species associated with economic impact. The highest impact was caused by *Aedes* spp. and *C. pomonella*. Similarly, damage-loss was reported for eight species, of which two species (*S. scrofa* and *H. armigera*) had the lowest cost reported (see Fig. 6B). Conversely, six species had considerably high impact in the damage-loss, with *B. tabaci* as costliest species. Finally, costs associated with medical care were reported exclusively for *Aedes* spp. (Fig. 6B).

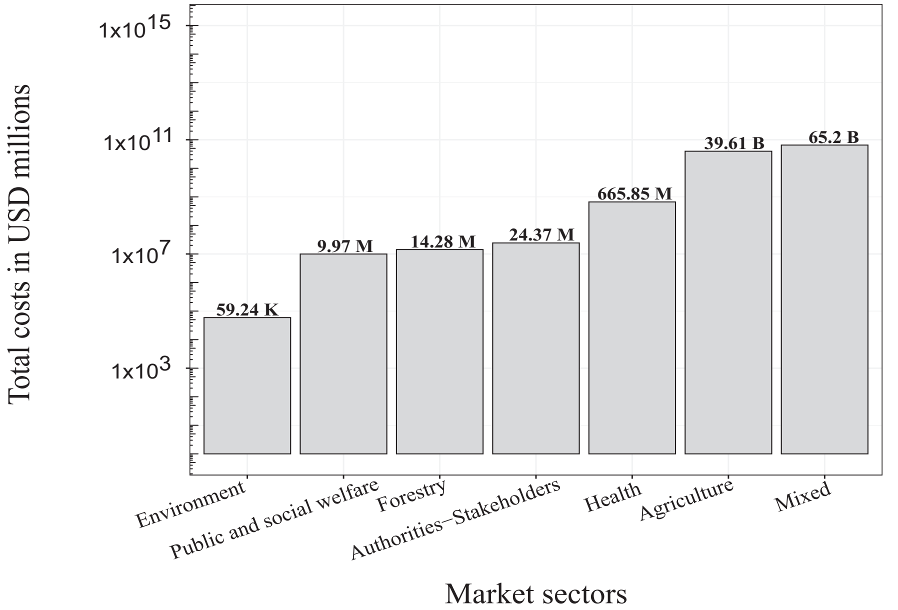

Figure 4. Economical costs with invasive alien species partitioned over seven market sectors. Numbers above the bars indicate the abbreviated cost in thousand (K), millions (M) and Billions (B) in 2017 US dollars over a time span of 35 years.

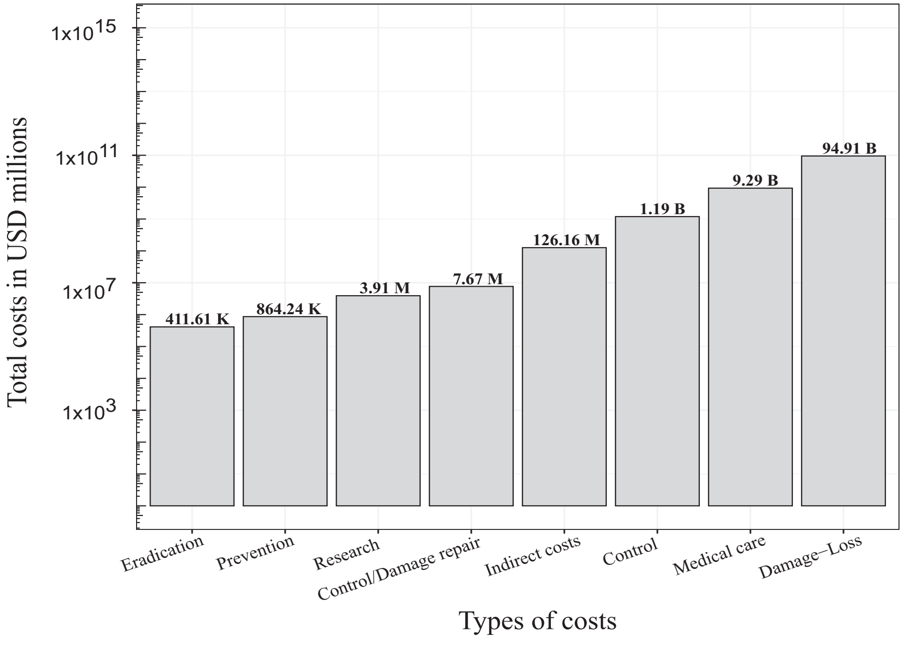

Figure 5. Economical costs with invasive alien species partitioned over eight types of costs. Numbers above the bars indicate the abbreviated cost in thousand (K), millions (M) and Billions (B) in 2017 US dollars over a time span of 35 years.

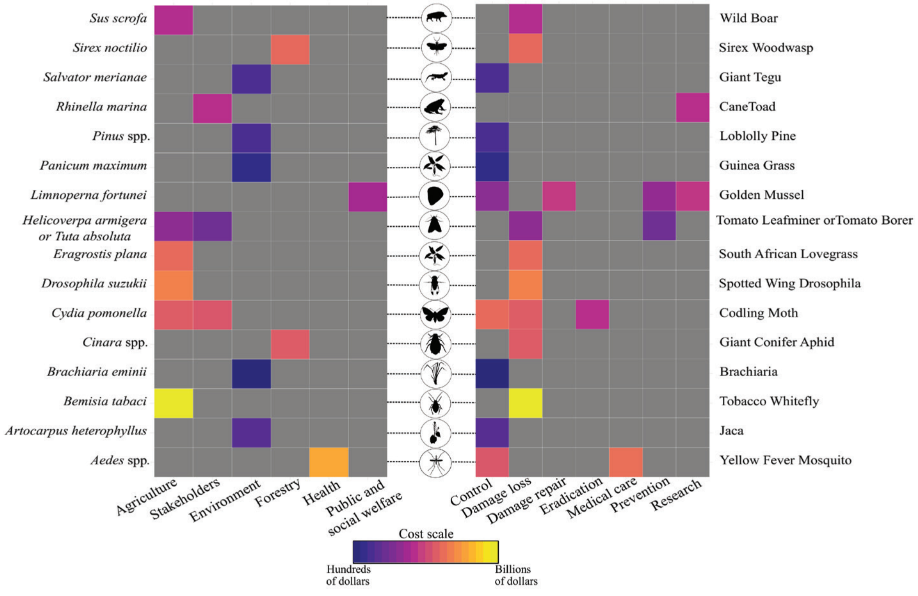

Figure 6. Heat map depicting the economic costs associated with species, market sectors and cost type. Each block indicates the cost incurred by each species over a specific market sector (in left) and cost type (in right). Gray blocks are associations with no available cost information and colorful blocks indicate the intensity of the economic cost incurred by each species. Low cost intensity (i.e. hundreds and thousands of dollars) are represented by blue to purple color transitions and high cost intensity (i.e. billions of dollars) are represented by orange to yellow color transitions. The remaining colors represent intermediate cost intensity (i.e., millions of dollars). Each row of the heatmap corresponds to one species and the species name and its vernacular name are depicted in the left and right margins of the heatmap respectively. Each column of the heat map corresponds to an impacted market sector and the type of cost required to overcome invasive species impact. The circles in the middle depicts a visual representation of invasive organisms. All silhouettes were freely obtained from www.phylopic.org.

Discussion

Here, we have provided the first detailed assessment of the economic costs of biological invasions in Brazil since the study of Pimentel et al. (2001). The relevance of the information provided here lies in incorporating detailed information of the estimated economic impact of invasive alien species, their impact on natural ecosystems, and multiple relevant economic sectors in Brazil. The present study represents a substantial improvement in the knowledge of IAS impacts, environmental and social perception and differ from previous studies that provide economic costs with no indication of the invasive status of the species (Oliveira et al. 2013; Oliveira et al 2014; Teich et al. 2017). Considering that we found economic costs for only 16 species from at least 460 known alien species classified as invasive in Brazil (Ziller et al. 2020), we caution that the USD 105.53 billion figure is a conservative minimum estimate of the actual economic impact. Still, the estimated costs with invasive alien species corresponded to 0.26% of the sum of Brazil's Gross Domestic Product from 1984 to 2019.

The quantification and reporting of economic costs of biological invasions were not a common practice in Brazil. Also, part of the available reports lack in accuracy, as there were 55 entries (*ca*. 31%) classified as low reliability. For instance, despite the high relevance of freshwater ecosystems in Brazil and the harmful effects of invasive alien species in aquatic environments (Pelicice et al. 2013), there were economic costs estimated for only one aquatic invasive alien species – the Golden mussel (*L. fortunei*) which impacts hydropower plant systems (de Campos et al. 2014). In addition, there were no costs associated with invasive alien species in marine ecosystems despite the fact that prevention, surveillance, and eradication of invasive species in marine ecosystems are officially one of the 10 goals established by the ministry of the environment as a strategy to conserve and mitigate the negative effects of invasive species in marine ecosystems. For example, the invasive lionfish *Pterois volitans* and orange cup coral *Tubastraea coccinea* are considered in Brazil's biodiversity plan for protecting coral reefs environments (PAN/Corais). Lionfish is an aggressive predatory IAS that impacts ecosystem functioning and threatens human well-being with human poisoning (Carlos-Júnior et al. 2015; Haddad Jr et al. 2015; Bumbeer et al. 2018). Orange cup corals (a species of sun coral) impact ecosystem dynamics and structure of native reef communities (Miranda et al. 2018; Silva et al. 2019). However, despite the intense efforts to understand the impacts of these invasive alien species, information on economic costs has not been formally gathered or published. In fact, the tendency of skewed evidence on environmental and conservation practices towards terrestrial ecosystems have previously been reported (Overbeck et al. 2015; Azevedo-Santos et al. 2019), including in the context of invasion costs (Cuthbert et al. 2021). Therefore, the actual costs of biological invasions in Brazil are probably much greater than the reported costs presented in this study.

Considering terrestrial ecosystems, we observed high costs by invasive insects (Fig. 3). Invasive alien insects are globally recognized as the main cause of agriculture (Bradshaw et al. 2016; Paini et al. 2016) and forestry damages (Aukema et al. 2011). Similarly, in Brazil insects (i.e., native and alien) are the main source of costs incurred in crop fields (Oliveira et al. 2013; Oliveira et al. 2014) and forestry plantations (Schnell e Schühli et al. 2016). Further, it is known that at least 24 insect species, four of which are present in this study, constitute the most important crop pests in Brazil since 1900, costing billions of dollars for the economy (Oliveira et al. 2013). The prevalence of invasive insects in the reported economic costs reflects the relevance of the agriculture and forestry sectors in the economic expenses associated with invasive species. Also, invasive alien insects (e.g., *Aedes* spp.) also affect public health by spreading vector-borne human diseases, increasing the economic impact perception (Taichi et al. 2017). Furthermore, and although it is well-known that mammals have high environmental impacts in Brazil (da Rosa et al. 2017), little is known about economic costs of invasive alien mammals.

The association between the agriculture sector and economic costs incurred by invasive alien species is not surprising (Oliveira et al. 2013; Oliveira et al. 2014). Indeed, agriculture represents one of the greatest portions of the Brazilian economy and has been responsible for 24.31% (± 4.06) of the country's Gross Domestic Product over the last 23 years on average (CEPEA). However, effective strategies to mitigate the impact of invasive alien species likely occur with the engagement of the private sectors' interests that support technological progress. For example, Kovaleski et al (2015) highlight that the eradication of the Codling moth only occurred due to the combined activity among multiple Brazilian apple private sector institutions. However, planning effective design seemed to be more feasible for species that impose a direct impact like invasive crop pests. For species with indirect impacts on the economy, such as environmental impacts, new challenges are imposed for planning effective design that require the engagement of multiple sectors.

Clear information on prevention strategies for invasive alien species and costs were missing and indicate the necessity for a country-level integrated database of invasive alien species, management programs and research, such as indicated in the Brazil's National Strategy for Invasive Alien Species – CONABIO Resolution 05/2019 – and its implementation plan (SBio/MMA Ordinance 3/2018; Resolution 05/2019). Indeed, 10 entries (USD 824.64 thousand) reported prevention as a type of cost in Brazil. Prevention strategies for IAS exist in Brazil but are currently limited and lack operational coordination (but see Brazil's National Strategy for Invasive Alien Species – CONABIO Resolution 05/2019). This supports the notion that in Brazil, as well as in Central and South America in general (Heringer et al. 2021), resource allocation for biological invasions focus on IAS with large observed impacts at later stages of invasion (i.e., *Aedes* spp. and *L. fortunei*). This represents a reactive approach that tends to be more expensive and less effective than preventing the alien species invasion and impacts (Wittenberg and Cock 2001; Leung et al. 2002).

In summary, here we have provided a first national estimate of the total economic cost of biological invasions in Brazil. The reported USD 105.53 billion of expenses in 35 years for 16 species is a conservative estimate of the total cost of biological invasions, as it only included direct and publicly available costs, which remain strikingly few. In addition to the clear biases in taxonomic groups, regions and activity sectors, some costs dissolved in broader actions, such as sanitary border control, ecosystem restoration efforts and environmental research were not estimated (Brancalion 2019). Costs of losses owing to biological invasions, such as ecosystem services degradation and yield reductions were also lacking from the literature. Brazil has at least 460 invasive alien species (Ziller et al. 2020) and hundreds more of naturalized species with invasive potential (Zenni 2015; da Rosa et al. 2017; Forti et al. 2017; Ziller et al. 2020; Bueno et al. 2021) and costs were reported for only 16 of them. Yet, Brazil is the country with the highest reported cost with invasive alien species in Latin America (Heringer et al. 2021; Rico-Sánchez et al. 2021; Crystal-Ornelas et al. 2021), and still the cost is unknown for most IAS. There is an urgent need for better reporting of both economic losses and costs imposed by IAS, as well as effective policy and management actions to reduce these costs.

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Supplementary material 1

Table S1. Observed costs for Brazil from the invacost database including the confidence attributed to the observed costs

Authors: José Ricardo Pires Adelino, Gustavo Heringer, Christophe Diagne, Franck Courchamp, Lucas Del Bianco Faria, Rafael Dudeque Zenni

Data type: cost

Explanation note: https://doi.org/10.6084/m9.figshare.12668570

Link: https://doi.org/10.3897/neobiota.67.59185.suppl1

Supplementary material 2

Table S2. Observed costs for Brazil from the invacost database organized into the following group of intervention: damage, management, and mixed

Authors: José Ricardo Pires Adelino, Gustavo Heringer, Christophe Diagne, Franck Courchamp, Lucas Del Bianco Faria, Rafael Dudeque Zenni

Data type: cost

Explanation note: https://doi.org/10.6084/m9.figshare.12668570

Link: https://doi.org/10.3897/neobiota.67.59185.suppl2

Supplementary material 3

Table S3. Observed mixed costs for Brazil from the invacost database

Authors: José Ricardo Pires Adelino, Gustavo Heringer, Christophe Diagne, Franck Courchamp, Lucas Del Bianco Faria, Rafael Dudeque Zenni

Data type: cost

Explanation note: https://doi.org/10.6084/m9.figshare.12668570

Link: https://doi.org/10.3897/neobiota.67.59185.suppl3

Supplementary material 4

Table S4

Authors: José Ricardo Pires Adelino, Gustavo Heringer, Christophe Diagne, Franck Courchamp, Lucas Del Bianco Faria, Rafael Dudeque Zenni

Data type: cost

Explanation note: All costs for Brazil present in the invacost database at the time of the analysis: https://doi.org/10.6084/m9.figshare.12668570

Link: https://doi.org/10.3897/neobiota.67.59185.suppl4

Supplementary material 5

Table S5

Authors: José Ricardo Pires Adelino, Gustavo Heringer, Christophe Diagne, Franck Courchamp, Lucas Del Bianco Faria, Rafael Dudeque Zenni

Data type: cost

Explanation note: Cost of species by activity sectors

Link: https://doi.org/10.3897/neobiota.67.59185.suppl5