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Economic costs of invasive alien species in Mexico

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Abstract

Invasive alien species (IAS) are a leading driver of biodiversity loss worldwide, and have negative impacts on human societies. In most countries, available data on monetary costs of IAS are scarce, while being crucial for developing efficient management. In this study, we use available data collected from the first global assessment of economic costs of IAS (InvaCost) to quantify and describe the economic cost of invasions in Mexico. This description was made across a range of taxonomic, sectoral and temporal variables, and allowed us to identify knowledge gaps within these areas. Overall, costs of invasions in Mexico were estimated at US$ 5.33 billion (i.e., 10^9) ($MXN 100.84 billion) during the period from 1992 to 2019.

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Biological invasion costs were split relatively evenly between aquatic (US$ 1.16 billion; $MXN 21.95 billion) and terrestrial (US$ 1.17 billion; $MXN 22.14 billion) invaders, but semi-aquatic taxa dominated (US$ 2.99 billion; $MXN 56.57 billion), with costs from damages to resources four times higher than those from management of IAS (US$ 4.29 billion vs. US$ 1.04 billion; $MXN 81.17 billion vs $MXN 19.68 billion). The agriculture sector incurred the highest costs (US$ 1.01 billion; $MXN 19.1 billion), followed by fisheries (US$ 517.24 million; $MXN 9.79 billion), whilst most other costs simultaneously impacted mixed or unspecified sectors. When defined, costs to Mexican natural protected areas were mostly associated with management actions in terrestrial environments, and were incurred through official authorities via monitoring, control or eradication. On natural protected islands, mainly mammals were managed (i.e. rodents, cats and goats), to a total of US$ 3.99 million, while feral cows, fishes and plants were mostly managed in protected mainland areas, amounting to US$ 1.11 million in total. *Pterygoplichthys* sp. and *Eichhornia crassipes* caused the greatest reported costs in unprotected aquatic ecosystems in Mexico, and *Bemisia tabaci* to terrestrial systems. Although reported damages from invasions appeared to be fluctuating through time in Mexico, management spending has been increasing. These estimates, albeit conservative, underline the monetary pressure that invasions put on the Mexican economy, calling for urgent actions alongside comprehensive cost reporting in national states such as Mexico.

Abstract in Spanish

Costos económicos de las especies invasoras en México. Las especies invasoras implican una pérdida de biodiversidad a nivel mundial, y presentan impactos negativos en la sociedad humana. En la mayoría de los países, es escasa la información disponible sobre los costes monetarios de las especies invasoras, la cual es información crucial para el desarrollo de un manejo eficiente. En el presente estudio, se empleó información disponible recolectada de la primera evaluación global de los costes económicos de las especies invasoras (InvaCost), para cuantificar y describir los costes económicos de las invasiones en México. Se elaboró la descripción a través de diferentes categorías taxonómicas, descriptores sectoriales y temporales, lo que permitió identificar los vacíos de información en esas áreas. Los costes por invasiones en México en general, se estimaron en US$ 5.33 mil millones (i.e., 10^9) ($MXN 100.84 mil millones) durante el periodo de 1992 a 2019. Los costes de las invasiones biológicas se separaron en forma relativamente equitativa entre los invasores acuáticos (US$ 1.16 mil millones; $MXN 21.95 mil millones) y los invasores terrestres (US$ 1.17 mil millones; $MXN 22.14 mil millones), pero los taxa semiacuáticos dominaron (US$ 2.99 mil millones; $MXN 56.57 mil millones), con costes donde el daño a recursos fue cuatro veces más elevado que aquellos por el manejo de especies invasoras (US$ 4.29 mil millones vs US$ 1.04 mil millones; $MXN 81.17 mil millones vs $MXN 19.68 mil millones). El sector de la agricultura obtuvo los mayores costes (US$ 1.01 mil millones; $MXN 19.1 mil millones), seguido por la pesquería (US$ 517.24 millones; $MXN 9.79 mil millones), mientras que la mayoría de otros costes impactan simultáneamente en sectores mezclados o inespecíficos. Cuando se definieron, los costes en las áreas naturales protegidas mexicanas se relacionaron en mayor medida con acciones de manejo en ambientes terrestres y se llevaron a cabo por autoridades gubernamentales vía monitoreo, control o erradicación. En islas naturales protegidas principalmente se manejaron mamíferos (i.e. roedores, gatos y cabras), para un total de US$ 3.99 millones, mientras que las vacas ferales, peces y plantas se manejaron predominantemente en áreas continentales protegidas, alcanzando un total de US$ 1.11 millones. Se reportó que el pez diablo (*Pterygoplichthys* sp.) y el lirio acuático (*Eichhornia crassipes*) causaron los costes más elevados en ambientes acuáticos no protegidos en México, y la mosca blanca (aleuródidos) en sistemas terrestres. A pesar de que los daños reportados por invasiones aparentemente parecen fluctuar a través del tiempo en México, la inversión en manejo ha ido en incremento. Estas estimaciones, aunque conservadoras, señalan la presión monetaria que las invasiones ejercen sobre la economía mexicana, haciendo un llamado a las acciones urgentes en conjunto con informes integrales de los costes en estados nacionales como México.

Abstract in Fench

Coûts économiques des espèces exotiques envahissantes au Mexique. Les espèces invasives constituent l'un des principaux facteurs de perte de biodiversité dans le monde, et ont de nombreuses répercussions négatives sur les activités humaines. Dans la plupart des pays, les données relatives aux coûts monétaires induits par la présence d'espèces invasives sont rares, bien que ces informations soient cruciales dans l'optique du déploiement d'actions de gestion efficaces. Dans cette étude, nous avons analysé les données issues de la première base de données mondiale centralisant les coûts économiques générés par les espèces invasives (InvaCost) pour quantifier et décrire le coût monétaire de la présence de ces espèces au Mexique. Cette description s'appuie sur un éventail de descripteurs, incluant différents taxons, et secteurs d'activités sur une large période. Cette étude nous a également permis d'identifier les manques de connaissances des impacts économiques générés par les espèces invasives. En cumulé, le coût des invasions biologiques au Mexique s'élève à 5,33 milliards de dollars américains (100,84 milliards de dollars MXN) au cours de la période 1992–2019. Le coût des invasions biologiques se répartit de façon égale entre les espèces invasives aquatiques (1,16 milliard de dollars US; 21,95 milliards de dollars MXN) et terrestres (1,17 milliard de dollars US; 22,14 milliards de dollars MXN). Néanmoins, les taxons semi-aquatiques excèdent largement ces valeurs (2,99 milliards de dollars US; 56,57 milliards de dollars MXN). Les coûts résultant des dommages sont quant à eux quatre fois supérieurs à ceux liés à la gestion des espèces invasives (4,29 milliards de dollars américains contre 1,04 milliard de dollars américains; 81,17 milliards de dollars MXN contre 19,68 milliards de dollars MXN). Le secteur agricole a subi les coûts les plus élevés (1,01 milliard de dollars US; 19,1 milliards de MXN), suivi de la pêche (517,24 millions de dollars US; 9,79 milliards de MXN), tandis que la plupart des autres coûts ont eu des répercussions sur différents secteurs, et sur des secteurs non renseignés dans les données sources. Lorsqu'ils ont été définis, les coûts pour les aires naturelles protégées du Mexique étaient principalement associés aux mesures de gestion des milieux terrestres, et ont été engagés par les autorités par des actions de surveillance, de contrôle ou d'éradication des espèces invasives. Sur les îles bénéficiant d'un statut de protection, la gestion des mammifères envahissants (c.-à-d. rongeurs, chats et chèvres) a induit un coût total de 3,99 millions de dollars ; les vaches sauvages, les poissons et les plantes ont été principalement gérés dans des zones continentales protégées, et ont conduit à une dépense totale de 1,11 million de dollars. Le pléco (poisson, *Pterygoplichthys* sp.) et la jacinthe d'eau (plante, *Eichhornia crassipes*) ont entraîné les coûts les plus élevés dans les écosystèmes aquatiques non protégés au Mexique, et les aleurodes dans les systèmes terrestres. Bien que les dommages signalés à la suite d'invasions semblent fluctuer au fil du temps au Mexique, les dépenses liées à la gestion des espèces invasives ont quant à elles augmenté. Ces estimations, bien que prudentes, soulignent l'impact financier important que les invasions exercent sur l'économie mexicaine, appelant à des mesures urgentes de gestion parallèlement à la publication de rapports détaillant les coûts induits par les espèces invasives.

Keywords

Damages, InvaCost, islands, management, monetary impact, non-native species, North America, protected areas

Introduction

Biological invasions have become a major international concern and pervasive driver of global change, causing ecological, social and economic issues in impacted countries (Hulme et al. 2009; Early et al. 2016; Seebens et al. 2017, 2020). Invasive alien species (IAS), translocated through human-mediated vectors, have been identified as one main driver of global biodiversity loss (Malcolm and Markham 2000; Stigall 2010; Bellard et al. 2016). The magnitude of ecological impacts driven by IAS has received increasing attention across taxonomic groups and habitat types (e.g., Didham et al. 2005; Courchamp et al. 2017; Cuthbert et al. 2019; Haubrock et al. 2019; Mofu et al. 2019). However, relatively few studies have synthesised monetary impacts of biological invasions at national scales (Pimentel et al. 2000, 2005; Hoffmann and Broadhurst 2016). As a result, investments in safeguarding ecosystems from IAS have remained lackluster, given that knowledge of their economic costs at national levels is essential. Indeed, this is the main scale at which legislation is implemented and management responses are funded (Eiswerth and Johnson 2002).

Economic costs from IAS can arise through a large variety of impacts, including damages directly or indirectly caused by invaders on environments, resources or infrastructures (e.g. Shwiff et al. 2010), to different types of expenditures dedicated to preventing, controlling or eradicating invasions (e.g. Hoffmann and Broadhurst 2016). Invasive alien species can also negatively affect opportunities for income generation by compromising the supply of natural resources for e.g. aquaculture and agriculture, and can lead to severe health issues by vectoring pathogens (Shackleton et al. 2007; Medlock et al. 2012; Selck et al. 2014). Quantifications of economic costs associated with IAS have been limited to a few taxa globally (insects: Bradshaw et al. 2016), or certain geographic areas (USA: Pimentel et al. 2000, 2005; Europe: Kettunen et al. 2009; Australia: Hoffmann and Broadhurst 2016). However, some previous large-scale studies concerning biological invasion costs have been criticised for an overreliance on the upscaling of small-scale estimates, with limited method reproducibility that, in turn, detracts from monetary estimate reliability (Hoffmann and Broadhurst 2016; Cuthbert et al. 2020). As such, more resolute, comprehensive and harmonised cost reporting is crucial for enabling efficient decision-making at governmental levels for invasions (Dana et al. 2014; McConnachie et al. 2016; Hiatt et al. 2019; Diagne et al. 2020a).

Mexico is a major national economy within Latin America; with a surface area of 1,947,156 km^2 and being located in a transition zone between the Nearctic and Neotropic, it features a mostly arid and tropical climate, and has one of the most diverse biotas among temperate zones (Mastretta-Yanes et al. 2015). Due to geological and climatic changes during the Pliocene-Pleistocene and Neogene, respectively, it is one of the most biodiverse ecoregions (Salzmann et al. 2011). Mexico has undertaken substantial environmental actions in terms of, for example, protected area designations (2% increase; update on global statistics from Protected Planet Report 2016). Consequently, 182 natural protected areas have been designated to date (Armendáriz-Villegas et al. 2015), and 12 protected areas belong to islands in Mexico, such as the National Parks of Archipiélago Espíritu Santo, Archipiélago de Revillagigedo Biosphere Reserve, and Isla Guadalupe Biosphere Reserve (CONABIO 2020). The protected areas possess great biological diversity and a high degree of endemism, and islands in particular harbour a high diversity of birds, mammals and reptiles (Aguirre-Muñoz et al. 2011). Hence, the Mexican flora and fauna contribute a considerable degree to global biodiversity, making conservation efforts and impacts of IAS particularly important (Rico-

Sánchez et al. 2020). Protected areas have been identified as cornerstones of biodiversity conservation and are essential for maintaining ecosystem function, yet are increasingly at risk from biological invasions (Liu et al. 2020). However, appraisals of how invasion costs are structured in protected areas are lacking in Mexico, despite approximately 800 non-native species having been reported (350 of which are invasive) (Mifsut and Jiménez 2007). Prominent invasive species in Mexico include, among many others, several species classified among the IUCN list of "100 of the world's worst invasive alien species", such as the feral cat (*Felis catus*), the American bullfrog (*Lithobates catesbeianus*), the water hyacinth (*Eichhornia crassipes*), the red imported fire ant (*Solenopsis invicta*), the red-eared turtle (*Trachemys scripta*) and the black bass *Micropterus salmoides*. The listed "100 of the world's worst" IAS have been found to be more economically impactful than unlisted IAS on average (Cuthbert et al. 2021a). On Mexican islands, 20% of endemic mammals and 12% of endemic birds are now extinct because of introduced species (Aguirre-Muñoz et al. 2009). Marine and freshwater ecosystems are also much affected by IAS such as fish, lampreys, aquatic plants or snails.

For example, two lionfish species, *Pterois miles* and *P. volitans* are predators of fish and invertebrates in mangrove swamps and in reefs of the Gulf of Mexico, affecting some species of great economic importance (Mendoza and Koleff 2014). The introduction of bumblebees, such as *Bombus impatiens* from the USA or *B. terrestris* from Europe, North Africa, and Asia as pollinators of commercial crops has significantly affected native pollinators and plants (CANsEI 2010). As in several other countries, large-scale plantations of Eucalyptus (*Eucalyptus globulus*) were actively promoted in Mexico until this century, both to alter ecosystems and thereby reduce incidences of malaria and to boost the paper industry (Hinke 2000). It has since become one of the seven most damaging invasive plants in Mexico, the six others being *Ricinus communis*, *Pennisetum clandestinum*, *Eragrostis lehmanniana*, *Cenchrus ciliaris*, *Rhynchelytrum repens* and *Tamarix ramosissima* (Mifsut and Jiménez 2007). Notorious invasive birds in Mexico include the house sparrow *Passer domesticus*, the Monk Parakeet *Myiopsitta monachus* and the rock dove *Columba livia*, affecting native bird species, damaging buildings and reducing crop yields (Pineda-López et al. 2013).

In recent years, Mexico has also undertaken actions derived from a national strategy on IAS presented in the Global Environment Facility ("GEF invaders") (De Alba et al. 2017), which have highlighted the economic impact of invasions on agriculture, forestry and wildlife. Previous studies (Ramírez-Albores et al. 2019) compiled pioneering information about references on biological invasions in Mexico. The "GEF invaders" strategy has contributed to increasing the knowledge of economic costs over the period of 2014 to 2018 via a project managed by the National Commission for the Knowledge and Use of Biodiversity (CONABIO). Despite all these efforts, information regarding costs of IAS in Mexico has not yet been synthesised in a standardised manner, hampering management actions and appraisals of the costs and benefits of interventions (Aguirre Muñoz et al. 2009). In consequence, data on IAS costs in Mexico are unavailable for stakeholders or authorities to make relevant decisions; recent records or estimates of costs are missing entirely.

The InvaCost database (Diagne et al. 2020b) has recently been developed in a global effort to quantify known economic costs of biological invasions. InvaCost is an accessible, broad inventory of economic costs based on a large pool of both scientific and grey literature, as well as unpublished data gathered from international experts and local stakeholders. Monetary estimations of damages and expenditures associated with IAS are considered. The structure of this database enables detailed quantification of invasion costs across different taxonomic, spatial, temporal and environmental scales. Moreover, economic costs of IAS are linked to a set of descriptors indicating which activity, societal or market sectors were related to each cost estimate (socioeconomic sectors); or which type of costs was reported, ranging from the economic damages and losses incurred by the invasion (e.g., value of crop losses, damage repair) to different management actions against the invaders (e.g., prevention, control, eradication). Using data available from this database, we analysed the economic costs of invasions currently available in Mexico. For this purpose, we describe costs among taxa, environments, cost types, and socioeconomic sectors. We also explored reported costs from protected areas, both from mainland and island areas, owing to their contribution to the biodiversity of Mexico. To understand the full dimensions of invasion costs, we distinguished cost estimates on the basis of their implementation (i.e. predicted or empirically observed) and method reliability (i.e. reproducibility of the estimation methodology). Furthermore, we describe the trend in reported costs to infer their development over time, as well as future trajectories.

Methods

Data compilation and extraction

To estimate the cost of biological invasions to the Mexican economy, we used the most up-to-date version of the InvaCost database (InvaCost_3.0; Diagne et al. 2020b). This database comprises 9,823 cost entries compiled from three data resources (full details and data openly available at https://doi.org/10.6084/m9.figshare.12668570), including costs from non-English sources (Angulo et al. 2021a). In order to gather additional cost data from Mexico, we contacted several specialists from national authorities; among them the secretary of environment (Secretaría de Medio Ambiente y Recursos Naturales), GBIF representatives of the Latin-American node, and authorities from the project “GEF – invaders” carried out by the National Commission for the Knowledge and Use of Biodiversity web page (https://biodiversidad.gob.mx/especies/Invasoras/informacion-proyecto) (CONABIO 2020). These additional data were included in addition to the InvaCost v3.0 data aforementioned (see Suppl. material 1). Individual cost records from 35 individual species were standardized to a common currency: 2017 US$ (see Diagne et al. 2020b for detailed information on conversion). Using the “Official_country” column, we filtered entries for Mexico (*n* = 107) and consequently costs were presented as MXN$ (exchange rate for 2017: US$ 1 = MXN$

18.92; World Bank 2020). As we filtered costs at this country-scale, we thus omitted larger-scale regional or continental costs that might have included Mexico and inflated our costs. Thus to our knowledge, InvaCost is the most comprehensive repository of the costs that have been reported for IAS in Mexico, following a systematic and standardised methodology to collect any related information (Diagne et al. 2020b). We provide our final dataset in Suppl. material 1.

Estimating total costs across descriptors

Deriving the total cumulative cost of invasions over time requires consideration of the duration of each cost occurrence. We thus estimated the duration of a cost as the number of years between the probable starting and ending years (i.e., the reported duration over which the cost was incurred) considering information provided in the "probable starting year adjusted" and "probable ending year adjusted" columns (Suppl. material 1). For example, a cost of US$ 10,000 between 1991 and 2000 would be expanded to become US$ 1,000 per year, with this latter cost estimate representing a single entry associated to the same source reference in the expanded database. When the exact starting and/or ending year were unknown, the year of publication of the primary data source was conservatively considered as the starting or ending year, and then the other information was derived (starting or ending year) based on the duration of costs, if explicitly provided in the source. To estimate the total cumulative cost, we thus expressed all the costs on an annual basis for the defined periods of their occurrence using the function "expandedYearlyCosts" from the invacost R package (Leroy et al. 2020; R version 3.6.2, R Core Team 2020) and then summed them. As such, the initial 107 entries (Suppl. material 1) became 251 entries when cost data were provided on an annual basis (and two missing cost figures removed that could not be annualised), with each expanded entry thus corresponding to a single year. We used the expanded database for the following analyses because it was necessary for cost comparability, and it further allowed us to decode temporal cost dynamics in a relevant way. Further information on this process is provided in Leroy et al. (2020).

The invasion costs were specifically described by summing all entries according to five descriptive columns of the most up-to-date version of the database (specific details on each descriptive field of the database are available at doi.org/10.6084/m9.figshare.12668570):

(i) Method reliability: illustrating the perceived reliability of cost estimates based on the type of publication and method of estimation ("high" or "low"). We acknowledge that the nature of reported costs differed markedly among sources; we classified entries as highly reliable when they originated from peer-reviewed material or official reports, as well as grey literature with reproducible methods. On the other hand, low reliability entries did not fulfil these criteria;

(ii) Implementation: referring to whether the cost estimate was actually realised in the invaded habitat ("observed") or whether it was expected ("potential");

*(iii)*Environment (column: Environment_IAS): corresponding to whether the cost was incurred from biota that are either “aquatic”, “terrestrial”, or “semi-aquatic” (species that spend part of their life cycle in water or are associated with it for foraging/reproduction);

(iv) Type of cost (column: Type_of_cost_merged): grouping of costs according to the categories: “damage”, referring to damages or losses incurred by invasion (i.e., costs for damage repair, resource losses), and “management”, comprising control-related expenditure (i.e., monitoring, prevention, management, eradication).

(v) Impacted sector: the activity (agriculture, environment, forestry, authorities-stakeholders, public and social welfare, fishery or health) that was impacted by the cost. Individual cost entries not allocated to a single sector were modified to “mixed”.

We used variables (*i*) and (*ii*) to separate the robust cost estimates from the non-robust (Suppl. material 1: Tab “InfoVariables”). Robust estimates comprised those cost entries that were at the same time observed and reliable. Non-robust cost estimates comprised those cost entries reporting potential costs and/or unreliable costs.

We also analysed whether the reported costs pertained to protected areas by distinguishing protected island and protected mainland areas from unprotected ones. We excluded entries for this analysis which spanned both protected and unprotected areas, or which were unspecific. Finally, to analyse the economic costs of IAS over time, we used the "summarizeCosts" function in the R package “invacost” (Leroy et al. 2020). With this function, we estimated the cumulative and average annual costs between 1990–2019 at 5-year intervals. Although costs started in 1992, we opted to project trends from 1990 to capture means from the last two decades completely. This analysis was performed separately according to cost type (damage vs. management), for both robust and total costs.

Results

The total reported cost of IAS to the Mexican economy was US$ 5.33 billion ($MXN 100.84 billion; i.e., 10^9 here and throughout). This monetary cost was estimated on the basis of 251 annualized costs (n = 107 original entries) from 1992 to 2019. From the overall costs, US$ 5.03 billion (n = 238) was empirically observed, whereas only US$ 295.96 million (n = 13) was deemed as potentially occurring (i.e., predicted). The majority of the economic costs was of high reliability compared to low reliability (US$ 4.71 billion, n = 245, vs. US$ 620.99 million, n = 6) (Fig. 1).

Costs across environments, taxa and sectors

Within Mexico, costs inferred from aquatic or semi-aquatic taxa were the greatest (US$ 4.14 billion, n = 75), followed by terrestrial ones (US$ 1.17 billion; n = 131). In the aquatic realm (US$ 1.16 billion), costs were contributed by eight species with individual cost records, including the water hyacinth (*Eichhornia crassipes*) that cost US$ 633.58 million, but also a diverse group of fishes that cost US$ 492.88 million (Suppl. material 3).

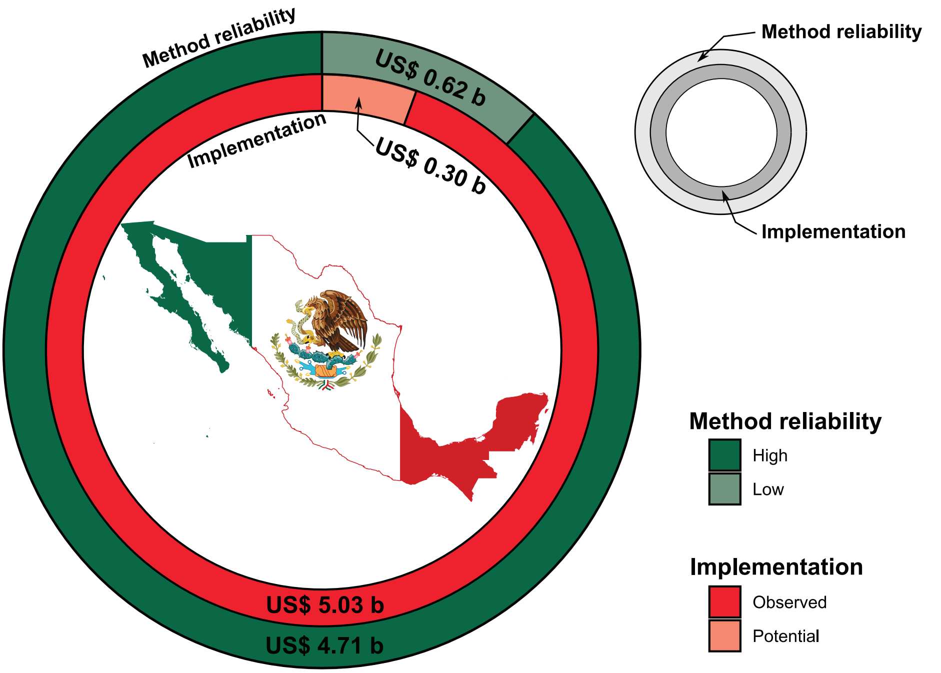

Figure 1. Total economic cost for invasive species in Mexico according to the level of reliability of the cost estimates and whether the costs were empirically observed or not (implementation). Costs are reported in US $, billion (i.e., 10^9).

In the terrestrial realm, the class Insecta dominated (US$ 1.07 billion; n = 56), followed by six further classes, each contributing cost below US$ 25 million. Costs inferred from semi-aquatic taxa (US$ 2.99 billion; n = 17) were mostly caused by mosquitoes of the *Aedes* genus (US$ 2.99 billion; n = 14), with further minor contributions from the American bullfrog *L. catesbeianus* (US$ 9.71 thousand; n = 3). Costs with unspecified or mixed habitat designations (US$ 17.51 million; n = 45) contributed the remainder (Fig. 2).

The majority of reported economic costs were due to resource damages and losses (US$ 4.29 billion; 81%, n = 57). Management costs (e.g. for prevention, control and eradication) totalled substantially less at US$ 1.04 billion (19%, n = 194; Fig. 2). From impacted sectors, the highest costs were incurred by the agriculture activity sector (US$ 1.01 billion; n = 43), followed by costs characterized as impacting fisheries (US$ 517.24 million; n = 39). Costs impacting mixed sectors comprised the largest share (US$ 3.76 billion; n = 33; Fig. 2). All other sectors incurred less than US$ 100 million (Suppl. material 2).

Overall, 12 recorded classes, and 35 species (including viruses taxa), were associated with economic costs. Insecta was the most diverse (n = 9 species), followed by Mammalia (n = 7), Liliopsida (n = 4), Actinopterygii (n = 3), and Magnoliopsida (n = 3). Similarly, insects were the costliest (US$ 4.05 billion), followed by the class Liliopsida, containing *E. crassipes* totalling at US$ 633.63 million. All other specific classes, including mammals which contributed only US$ 14.31 million despite their diversity, caused less than US$ 100 million in costs (Suppl. material 3).

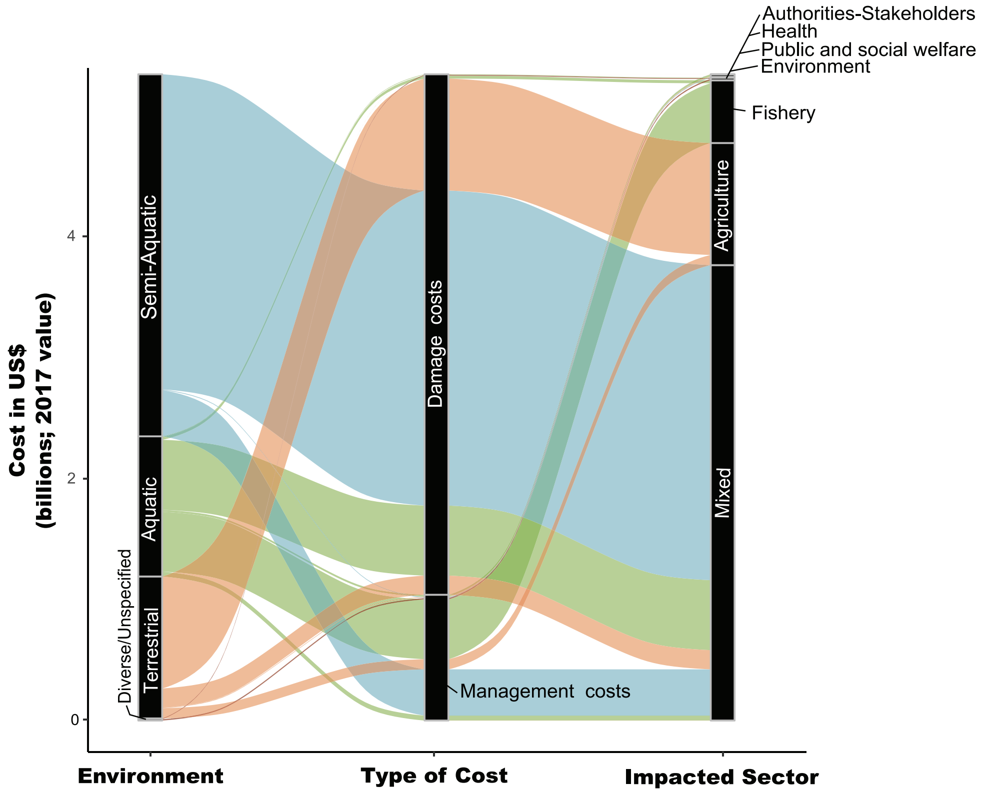

Figure 2. Alluvial plot illustrating flows of invasion costs from different environments to socioeconomic sectors according to types of costs associated with invasive species in Mexico. Costs are reported in US$, billion (i.e., 10^9).

Protected area impacts

When considering only the data that had explicit information for protected areas, we observed higher costs in unprotected lands than in protected areas in Mexico. Interestingly, costs on protected islands were all robust and most of the cost in protected mainlands was not (Fig. 3a). Invaders in unprotected areas (n = 20 entries), such as silverleaf whitefly *Bemisia tabaci*, showed the highest costs through agricultural impacts (Fig. 3b). Janitor fish (*Pterygoplichthys* sp.) and *E. crassipes* caused the greatest impacts in unprotected aquatic ecosystems in Mexico. The costs in unprotected terrestrial areas were focused on IAS of agricultural importance, relating exclusively to damages in that sector. Otherwise, in protected areas the highest costs were assigned to be incurred by authorities and stakeholders and were not species-specific (Fig. 3c, d). Without considering these costs for unspecified species, invasive mammals presented the greatest shares of economic impacts in protected areas on islands (Fig. 3c), with most economic impacts by rodents (mainly rats), cats and goats, and through management interventions from official authorities. In mainland protected areas, most species-specific economic costs

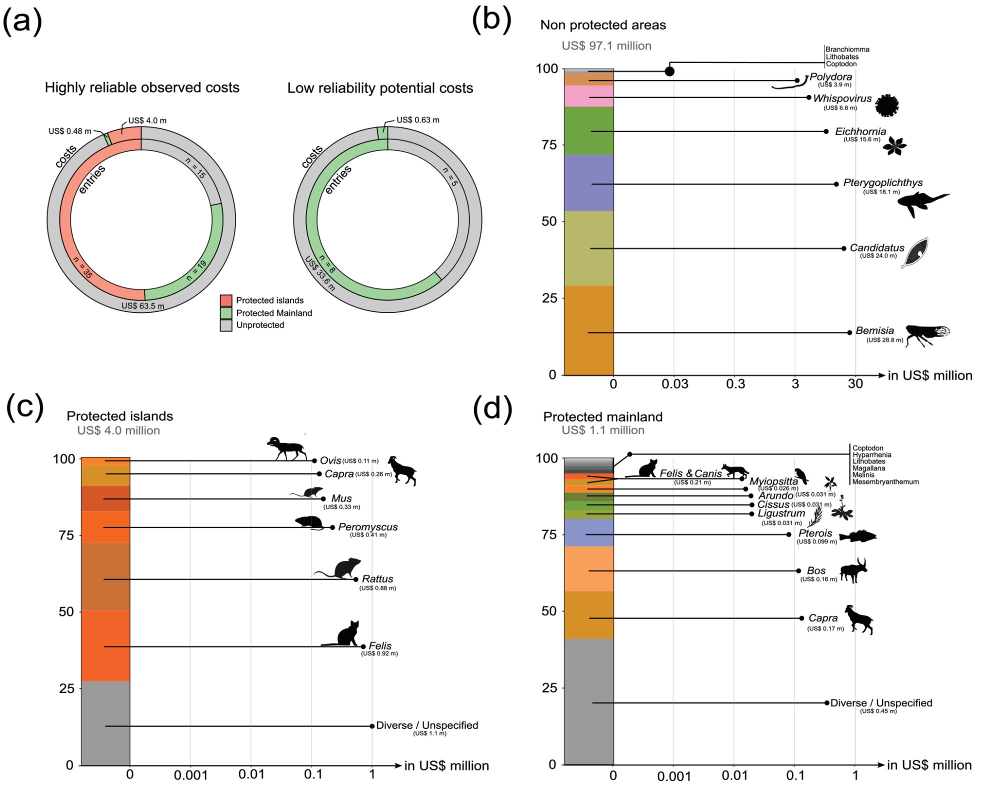

Figure 3. Invasion costs of invasive alien species with regards to the protection status of lands **a** relative number of entries and invasion costs in unprotected lands, protected islands and protected mainland for robust cost estimates (reliable and observed costs), and for non-robust cost estimates (unreliable and/or potential costs). Invasion costs in **b** unprotected lands **c** protected islands and **d** protected mainlands, considering percentage cost contributions in Mexico across taxa. For (**b, c** and **d**) costs include reliable and unreliable as well as observed and potential.

were caused by invasive goats and cows, as well as jointly between palm weevils and mites (Fig. 3d), mainly through monitoring, control, or mitigation also performed by official authorities. Plants showed minor economic impacts versus animals in mainland protected areas (US$ 0.12 million, Fig. 3d), and protected islands (US$ 0.03 million).

Temporal cost development

Between 1992 and 2019 the available cost estimates reached a total of US$ 5.33 billion, which led to an average annual cost of US$ 177.64 million overall. Disentangling costs by their level of robustness indicated opposing trends between robust costs estimates (Fig. 4a) and total cost estimates (Fig. 4b). Focusing on the highly reliable and observed costs, we in turn found different temporal patterns between damage and management costs. Recorded damages and losses (average annual cost of US$ 114.39

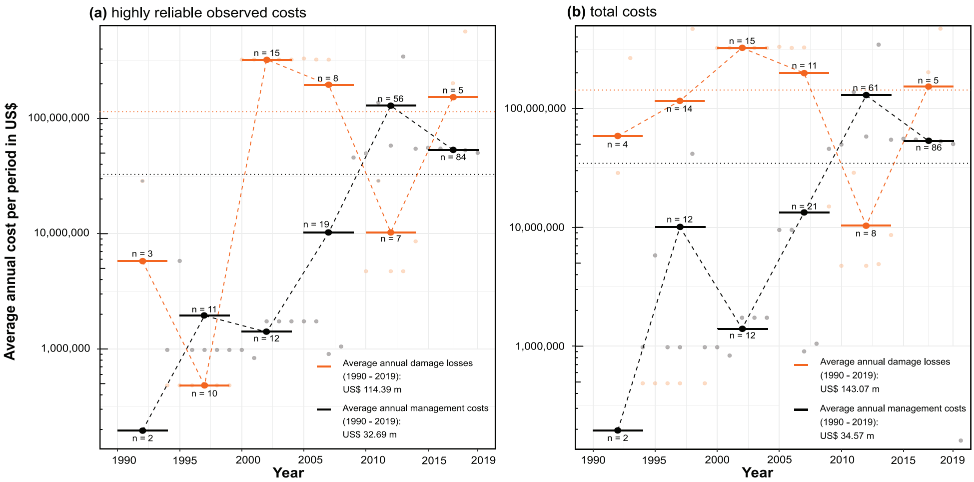

Figure 4. Temporal trends using **a** robust cost estimates (reliable and observed costs) and **b** total cost estimates, in management costs (black) and damage costs (brown) from 1990 to 2019. Periodic averages are presented on a $\log_{10}$ scale. Points represent annual totals. Numbers indicate annualized cost entries per 5-year intervals.

million per year) showed fluctuating dynamics over time, but a general upwards trend marked by a significant increase between the mid-1990s and 2005. In contrast, management costs (average annual costs of US$ 32.69 million per year) showed an apparent increase over time, even though the mean annual cost tended to decrease for the most recent years (Fig. 4a). For total costs (Fig. 4b), damage costs similarly fluctuated at a relatively stable magnitude, with an average of US$ 143.07 million per year, whereas management increased and averaged at US$ 34.57 million per year.

Discussion

In the present study, we report the first synthesis of monetary costs from IAS in Mexico. The total cost of over US$ 5 billion was determined using reported costs of IAS from 1992 to 2019 in the country. Most of the available costs were empirically observed and highly reliable, incurred in aquatic or semi-aquatic environments, and impacted primarily agriculture and fisheries, where specified. Moreover, the present study identifies key structural differences in invasion costs between protected and unprotected areas, with protected areas incurring far lower invasion costs, and those that occurred being primarily driven by management actions from authorities – in contrast to unprotected sites that mostly reported damages. However, many costs in protected islands and mainland areas were not unambiguously associated with the species that were managed.

Recently, IAS in Mexico have been most notably investigated by the project "GEF invaders" (De Alba et al. 2017). This project, managed by the National Commission of the Knowledge and Use of Biodiversity (CONABIO), invested more than US$ 30 million on IAS costs between 2014 and 2018. Furthermore, another office in Mexico which contribute to the study of IAS, i.e. the National Commission of Natural Protected Areas (CONANP) belonging to the Ministry of Environmental and Natural Resources (SEMARNAT), has a budget of US$ 224 million per year (SEMARNAT 2021). Even if all was counted as targeting IAS, these expenditures would overall still remain lower than 5% of the total cost of invasions in Mexico, highlighting a need for much higher investment if this country is to lighten the burden that biological invasions have on its economy. By comparison, the US$ 5.33 billion of total costs of invasions represents no less than a fifth of the amounts Mexican migrants working abroad sent home in 2017: the single largest foreign source of income for Mexico and an amount higher than any other sector (including the oil industry) (BBVA-CONAPO 2017).

There are nearly 350 recognised IAS reported in Mexico (CONABIO 2020). However, InvaCost only reported cost data for 35 species, suggesting a huge underestimation of invasion costs in Mexico – since costs are available for only 10% of known IAS. This proportion is similar to that reported in other studies, which have found that less than 10% of invaders have reported costs: Germany (Haubrock et al. 2021a), France (Renault et al. 2021), the United Kingdom, (Cuthbert et al. 2021b), Asia (Liu et al. 2021), Argentina (Duboscq-Carra et al. 2021) or Australia (Bradshaw et al. 2021). Even if one cannot conclude that actual costs should be ten times higher, the very high overall economic costs we found for only 10% of IAS in Mexico hints at a real, total cost that is staggering. These unreported costs included species that are widely established in Mexico, such as fishes of the *Tilapia* genus, which were introduced to increase food supply and are now considered to be competitively displacing and driving extinction of native species (Fitzsimmons 2000), or recently recorded invaders such as the redclaw crayfish *Cherax quadricarinatus* (Haubrock et al. 2021b). Other examples include the freshwater snail *Tarebia granifera*, that causes severe damages on rice cultures, displacing native species (Contreras-Arquieta and Contreras-Balderas 2000), as well as the tree *Eucalyptus globulus*, that has degraded habitat quality and altered the availability of vulnerable water resources (Morton 1980; Becerra et al. 2018). Nevertheless, our results underline the costs of some known most harmful species which occur in the country, the costliest being mosquitoes which drive marked impacts through the vectoring of pathogens and parasites that cause disease (Medlock et al. 2012), impacting the health system economically. According to Contreras-Balderas and Gutiérrez (2009), at least 36 of the IUCN 100 of the world's worst IAS (van der Weijden et al. 2007) are established in Mexico, and many of them were included in the present study, such as *Eichhornia crassipes*, *Arundo donax*, *L. catesbeianus*, *Felis catus*, *Capra hircus*, *Mus musculus*, *Rattus rattus*, among others, and are particularly economically costly (Cuthbert et al. 2021a). *E. crassipes* and *A. donax* were also among the costliest species in Spain (Angulo et al. 2021b), while mammals appear to be also very costly in other countries such as France (*Rattus* and *Felis*, (Renault et al. 2021)), Japan (*Rattus*, (Watari et al. 2021)) or Ecuador (*Capra* and *Rattus*, (Ballesteros-Mejia et al. 2021)), mainly due to the management of these species in islands (e.g. invasive rodents, (Diagne et al.

2021a)). Nevertheless, increased efforts to determine the economic impact from other species (as we mentioned above) with currently no recorded costs in InvaCost are urgently needed to fill this knowledge gap.

Major investments have only been applied to manage IAS in Mexico over recent years. In 2007, the Mexican government – through the established CONABIO – called upon academic and government institutions as well as representatives of organized civil society to assemble the National Advisory Committee on IAS that developed the National Strategy on Invasive Species in Mexico (NSISM). The NSISM acted as a guiding document to strategically and coordinately face the challenges posed by biological invasions and their costs, allowing compliance with the commitments acquired by Mexico as part of the Convention on Biological Diversity. There have been several policies in response to the need to control IAS in protected areas of the world according to Aichi Biodiversity Targets, i.e. Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization to the Convention on Biological Diversity (IPBES 2019). Therefore, these increasing national developments by the NSISM may explain the rapid growth in management costs for IAS in Mexico in the early 2000s, as well as cost reporting. Contrastingly, fluctuations in damage costs might reflect inconsistencies in cost reporting over time, rather than an actual, empirical reduction in that type of economic impact. No costs were reported in Mexico before 1992, which is relatively late compared to other countries (Haubrock et al. 2021a).

In addition, CONABIO has worked together with the National Commission of Protected Natural Areas (CONANP), which has undertaken actions to manage IAS within protected areas. This has led to the recovery of key ecosystems, both on the mainland and on Mexican islands. Islands and protected areas are highlighted in Mexico due to their biological diversity and high grade of recognized endemism (Donlan et al. 2000). However, the great diversity in protected areas in Mexico is threatened by IAS (Rico-Sánchez et al. 2020). Islands are especially important due to their high diversity of birds and reptiles (Latofski-Robles et al. 2015), generating an attractive target to invest economic resources to potential conservation strategies. The present study thus provides new knowledge on the costs of IAS management in protected areas, and particularly in protected islands.

Overall, costs in protected areas have been shown here to be much lower than costs in unprotected lands, showing also that protected islands, protected mainland or unprotected lands seemed to be threatened by a different suite of species. Disparity in costs among protected and unprotected areas might reflect a lesser extent of human activity in protected areas, in turn resulting in fewer damage costs, but a higher proportion of management costs. Invasive mammals were shown to be particularly costly in protected areas, especially in protected islands, through management by authorities and stakeholders. Indeed, this invasive group has been historically recognized as the principal conservation issue in islands. Rodents, cats and goats appeared the costliest species in Mexican protected islands, as has been found in other countries, such as goats in Galapagos Islands (Ballesteros-Mejia et al. 2021). Strategies for controlling invasive mammals in Mexico, and in particular in islands, have been mostly successful (Aguirre-

Muñoz et al. 2011; Robertson et al. 2017; Samaniego-Herrera et al. 2018), while associated cost information has remained scarce. However, in marine habitats (highly related to the fisheries activity sector where we show costs to the Mexican economy reaching US$ 517 million), eradication represents a greater challenge. For example, we observed control costs or damage to fisheries, such as those for oysters and polychaetes, of more than US$ 3 million. The high connectivity of marine environments through pathways such as shipping favours the dispersal of IAS, making it challenging to regulate invasive marine species arrivals (Giakoumi et al. 2019). Indeed, even new treatments for ballast water can be ineffective towards certain taxonomic groups (Lin et al. 2020).

Nonetheless, the most impactful species in Mexico were from aquatic or semi-aquatic habitats, similar to Spain (Angulo et al. 2021b) but in contrast to other countries such as Germany (e.g. Haubrock et al. 2021a). Although cost differences between these two habitats were small, there is a great difference with regards to the number of entries (n = 75 aquatic/semi-aquatic vs. n = 131 terrestrial), suggesting that the aquatic environment could contribute an additional major cost if data availability increases. This disparity also highlights potential biases in research attention between terrestrial and aquatic environments (Menge et al. 2009), with aquatic invasion costs generally underrepresented compared to terrestrial with respect to numbers of alien species (Cuthbert et al. 2021a). Frequently, impacts of IAS are imparted through the vectoring of pathogens in aquaculture, impacting several species cultured for food, which creates lost incomes. Bondad-Reantaso et al. (2005) have summarized impacts of infectious diseases, such as losses in production, income, employment, market interactions, investment, and consumer confidence. In the present study, we excluded certain documented impacts on the aquaculture of shrimps (Lightner 1999), because costs were presented at a continental scale beyond only Mexico; this would further contribute substantially to the aquatic costs reported here. Indeed, diseases in shrimp culture due to pathogenic IAS have been recognized as among the costliest in the world. A study from Israngkura et al. (2002) recognized loss incomes up to US$ 3 billion in 11 countries (including Mexico) in the period of 1987 to 1994. Nonetheless, aquatic invasions have been found to comprise just 5% of costs at the global scale, and are thus under-represented more generally (Cuthbert et al. 2021a, b).

In addition, aquatic costs may be driven by the high economic costs associated with the fishery sector in Mexico, while there were higher costs in the agriculture sector, despite both sectors having similar database entries (n = 39 and n = 43, respectively). These results may also be related to the fact that the terrestrial environment has been the focus of programs aimed at eradicating IAS, as well as strict dispersion controls to avoid invasions, principally by arthropods in Mexico (De Alba et al. 2017). Consequently, there are national programs that address the main IAS for agriculture (i.e., as the most famous and successful efforts to eradicate *Cactoblastis cactorum*) and forestry (i.e., to control *Eucalyptus* disease by the jumping plant lice *Glycaspis brimblecombei*), which have successfully diminished their impacts and consequently monetary damages (De Alba et al. 2017). However, in the aquatic environment, greater efforts to control IAS are required, as species such as shrimps, one of the main fishery products (20% of the production) (INEGI 2010), have been strongly affected by IAS, provoking serious losses to this sector. Moreover, increased investment should be aimed at controlling vector mosquitoes which substantially damage the health sector through human diseases (Medlock et al. 2012); joint costs between *Aedes aegypti* and *Aedes albopictus* caused the greatest economic impacts in Mexico. These species caused high costs also in other American countries such as Ecuador (Ballesteros-Mejia et al. 2021), Argentina (Duboscq-Carra et al. 2021) or even in Central and South America (Heringer et al. 2021) and in the French territories located in the Americas (Renault et al. 2021).

Our results additionally showed that resource damages and losses were higher (US$ 4.29 billion) than management costs (US$ 1.04 billion). These results emphasize that although there are a larger number of entries on management costs, their costs are generally much lower than those of damages and losses to resources. Overall, damage costs are difficult to determine due to often indirect impacts, but further documentation might support the relevance of increasing management efforts, if the actions undertaken are sufficient to mitigate the impacts of IAS. Nevertheless, IAS costs were higher than other natural disasters in Mexico, such as flooding (US$ 1.79 billion) (Haer et al. 2017), droughts (US$ 1.2 billion) (Neri and Magaña 2016), or fires (US$ 8 million) (CONAFOR 2019). Therefore, increased focus is needed in Mexican policies in order to recognize critical impacts that contribute to costs of IAS in the country. In consideration, preventative measures can be highly cost-effective compared to longer-term impacts (Leung et al. 2002), and should be applied at early invasion stages (Ahmed et al. 2021). Accordingly, we suggest further management interventions to be made, particularly at the pre-invasion stage via biosecurity management actions (only 19 out of 107 raw entries reported specifically early detection or prevention measures against IAS in Mexico), to help to reduce longer-term control costs as well as potential damages. Alternatively, that trend could simply reflect a lack of willingness to invest. However, damage and management costs exhibited different trajectories in trends over time, with damages tending to fluctuate overall, and management increase. There may be several reasons for this disparity, including (1) the potential offsetting of damages by higher management investment and (2) cost reporting reflecting research priorities, which may have shifted towards management actions in recent years. However, we stress that damage costs are unlikely to be decreasing empirically, given increasing rates of biological invasion (Seebens et al. 2017), the lack of reported costs for many taxa, and the fact that many impacts from IAS are not monetised (Diagne et al. 2021b).

Conclusion

Invasive alien species have been shown in the present study to have massive impacts on the Mexican economy. However, more information is needed about the specific cost of invasions, with the results presented here likely massively underestimated. Indeed, our data set comprises only 35 of the ~350 IAS (10%) recorded in Mexico (CONABIO 2020). Despite this small percentage of species compiled in this study, it presents the first approximation of IAS costs for Mexico, indicating the magnitude of the impacts that might be realised if a greater number of invasive taxa from the Mexican territory was assessed. Overall, decision making needs to account for the cost of IAS to develop appropriate policy and management responses.

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Supplementary material 1

Database of the economic costs of biological invasions in Mexico

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Data type: Dataset

Explanation note: Dataset on costs of invasive species in Mexico extracted from InvaCost v3.0 and descriptions of the column names.

Link: https://doi.org/10.3897/neobiota.67.63846.suppl1

Supplementary material 2

Economic sectors impacted by IAS in Mexico

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Data type: Number of entries per sector

Explanation note: Economic sectors impacted by IAS in Mexico. Total economic costs in US$ and the number of cost entries are shown. (bil: 10^9).

Link: https://doi.org/10.3897/neobiota.67.63846.suppl2

Supplementary material 3

Economic costs of invasive alien species in Mexico

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Data type: Costs and robustness of invasive alien species in Mexico

Explanation note: Economic costs of IAS in Mexico. Species are sorted by their costs (US$ million); taxonomic class (Class) and environment of each IAS (Environment_IAS) are described; the percentage of robust costs is indicated (Robust) as well as the number of entries for each species. * Class for WSSV (white stain syndrome Baculovirus) is incertae sedis so Family has been added instead.

Link: https://doi.org/10.3897/neobiota.67.63846.suppl3