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Economic costs of biological invasions in Ecuador: the importance of the Galapagos Islands

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Abstract

Biological invasions, as a result of human intervention through trade and mobility, are the second biggest cause of biodiversity loss. The impacts of invasive alien species (IAS) on the environment are well known, however, economic impacts are poorly estimated, especially in mega-diverse countries where both economic and ecological consequences of these effects can be catastrophic. Ecuador, one of the smallest mega-diverse countries, lacks a comprehensive description of the economic costs of IAS within its territory. Here, using "InvaCost", a public database that compiles all recorded monetary costs associated with IAS from English and Non-English sources, we investigated the economic costs of biological invasions. We found that between 1983 and 2017, the reported costs associated with biological invasions ranged between US$86.17 million (when considering only the most robust data) and US$626 million (when including all cost data) belonging to 37 species and 27 genera. Furthermore, 99% of the recorded cost entries were from the Galapagos Islands. From only robust data, the costliest identified taxonomic group was feral goats (*Capra hircus*; US$20 million), followed by *Aedes* mosquitoes (US$2.14 million) while organisms like plant species from the genus *Rubus*, a parasitic fly (*Philornis downsi*), black rats (*Rattus rattus*) and terrestrial gastropods (*Achatina fulica*) represented less than US$2 million each. Costs of "mixed-taxa" (i.e. plants and animals) represented the highest (61% of total robust costs; US$52.44 million). The most impacted activity sector was the national park authorities, which spent about US$84 million. Results from robust data also revealed that management expenditures were the major type of costs recorded in the Galapagos Islands; however, costs reported for medical losses related to *Aedes* mosquitoes causing dengue fever in mainland Ecuador would have ranked first if more detailed information had allowed us to categorize them as robust data. Over 70% of the IAS reported for Ecuador did not have reported costs. These results suggest that costs reported here are a massive underestimate of the actual economic toll of invasions in the country.

Abstract in Spanish

Costos económicos de las invasiones biológicas en Ecuador: La importancia de las islas Galápagos. Las invasiones biológicas, al ser resultado de la intervención humana a través del comercio y la movilidad, son la segunda causa más importante de pérdida de biodiversidad. Los impactos de las especies exóticas invasoras (EEI) en el medio ambiente son bien conocidos, sin embargo, los impactos económicos aún son poco estimados, especialmente en países megadiversos donde las consecuencias económicas y ecológicas de estos efectos pueden ser catastróficas. Ecuador, uno de los países megadiversos más pequeños, carece de una descripción completa de los costos económicos de las EEI dentro de su territorio. En este estudio, investigamos los costos de las investigaciones biológicas, utilizando "InvaCost", una base de datos pública que compila todos los costos monetarios registrados asociados con las EEI de fuentes tanto en inglés como en español. Encontramos que entre 1983 y 2017, los costos reportados asociados con las invasiones biológicas oscilaron entre US$86,17 millones (considerando sólo los datos más robustos) y US$626 millones (incluyendo todos los datos de costos) pertenecientes a 37 especies y 27 géneros. Además, el 99% de los costos registrados fueron en las Islas Galápagos. Al utilizar sólo datos robustos, el grupo taxonómico identificado más costoso fueron las cabras salvajes (*Capra hircus*; US$20 millones), seguido de los mosquitos *Aedes* (US$2,14 millones), mientras que organismos como especies de plantas del género *Rubus*, la mosca parásita (*Philornis downsi*), las ratas negras (*Rattus rattus*) y los gasterópodos terrestres (*Achatina fulica*) representaron menos de 2 millones de dólares cada uno. Los costos de los taxones mixtos (es decir, plantas y animales) representaron los más altos (61% de los costos robustos totales; US$52,44 millones). El sector de actividad más afectado fue el de las autoridades del parque nacional, que gastó alrededor de 84 millones de dólares. Los resultados de datos robustos también revelaron que los gastos de gestión fueron el principal tipo de costos registrados en las Islas Galápagos; sin embargo, los costos reportados por pérdidas médicas relacionadas con los mosquitos *Aedes* que causan la fiebre del dengue en el Ecuador se habrían clasificado en primer lugar, si la existencia de información más detallada nos hubiera permitido clasificarlos como datos robustos. Más del 70% de las EEI conocidas para Ecuador no tuvieron costos reportados. Estos resultados sugieren que los costos aquí discutidos son una subestimación masiva del costo económico real de las invasiones en el país.

Abstract in Portuguese

Custos econômicos das invasões biológicas no Equador: importância das Ilhas Galápagos. As invasões biológicas, como resultado da intervenção humana por meio do comércio e da mobilidade, são a segunda maior causa da perda de biodiversidade. Os impactos das espécies exóticas invasoras (EEI) no meio ambiente são bem conhecidos. No entanto, os impactos econômicos ainda nem tanto, especialmente em países megadiversos onde as consequências econômicas e ecológicas desses efeitos podem ser catastróficas. O Equador, um dos menores países megadiversos, carece de uma descrição abrangente dos custos econômicos das EEI em seu território. Neste estudo, usando o "InvaCost", um banco de dados público que compila todos os custos monetários associados às EEI de fontes em inglês e espanhol, investigamos os custos econômicos das invasões biológicas. Descobrimos que, entre 1983 e 2017, os custos relatados associados às invasões biológicas variaram entre US$86,17 milhões (considerando apenas os dados mais robustos) e US$626 milhões (incluindo todos os dados) pertencentes a 37 espécies e 27 gêneros. Além disso, 99% das entradas de custos registradas eram das Ilhas Galápagos. Apenas com dados robustos, o grupo taxonômico mais custoso identificado foi de cabras selvagens (*Capra hircus*; US$20 milhões), seguido por mosquitos Aedes (US$2,14 milhões). Por outro lado, organismos como espécies de plantas do gênero Rubus, uma mosca parasita (Philornis downsi), o rato-preto (Rattus rattus) e os gastrópodes terrestres (Achatina fulica) representaram menos de US$ 2 milhões cada. Os custos dos táxons mistos (ou seja, plantas e animais) representaram os mais altos (61% dos custos robustos totais; US$52,44 milhões). O setor de atividade mais impactado por esses custos foram as autoridades do parque nacional, que gastaram cerca de US$84 milhões. Os resultados de dados robustos também revelaram que as despesas de gerenciamento foram o principal tipo de custo registrado nas Ilhas Galápagos. No entanto, os custos registrados de perdas médicas relacionadas aos mosquitos Aedes, que causam a dengue no Equador, teriam ficado em primeiro lugar, se tivéssemos informações mais detalhadas que nos permitiram classificá-los como dados robustos. Mais de 70% das espécies invasoras não apresentam custos para o Equador. Esses resultados sugerem que os custos relatados, neste trabalho, estão subestimados quanto ao custo real das invasões no país.

Abstract in French

Coûts économiques des invasions biologiques en Équateur : l'importance des îles Galapagos. Les invasions biologiques, résultant de l'intervention humaine par le commerce et la mobilité internationaux, sont la deuxième cause de perte de biodiversité. Les impacts des espèces exotiques envahissantes (EEE) sur l'environnement sont bien connus, mais les impacts économiques sont mal estimés, en particulier dans les pays à biodiversité méga-diverse où les conséquences économiques et écologiques de ces effets peuvent être catastrophiques. L'Équateur, l'un des plus petits pays méga-divers, ne bénéficie toujours pas de description complète des coûts économiques des espèces exotiques envahissantes pour son territoire. Ici, nous avons étudié les coûts économiques des invasions biologiques en utilisant "InvaCost", une base de données publique qui compile tous les coûts monétaires associés a ces invasions, provenant de sources en langues anglaise et non-anglaise. Nous avons constaté qu'entre 1983 et 2017, les coûts déclarés associés aux invasions biologiques variaient entre 86,17 millions de dollars américains (si l'on considère uniquement les données les plus robustes) et 626 millions de dollars américains (si l'on inclut toutes les données disponibles), appartenant à 37 espèces et 27 genres. De plus, 99 % des entrées de coûts enregistrées pour l'Équateur provenaient des îles Galápagos. D'après les données les plus robustes, le groupe taxonomique le plus coûteux est celui des chèvres sauvages (*Capra hircus*; 20 millions de dollars), suivi des moustiques du genre *Aedes* (2,14 millions de dollars), tandis que des organismes comme des espèces végétales du genre *Rubus*, des mouches parasites (*Philornis downsi*), les rats noirs (*Rattus rattus*). et des gastéropodes terrestres (*Achatina fulica*) représentaient moins de 2 millions de dollars US chacun. Les coûts des taxons mixtes (c.-à-d. plantes et animaux indifférenciés) sont les plus élevés (61 % des coûts robustes totaux, soit 52,44 millions de dollars américains). Le secteur d'activité le plus impacté est représenté par les autorités des parcs nationaux, qui ont dépensé environ 84 millions de dollars. Les données les plus robustes ont également révélé que les dépenses de gestion constituaient le principal type de coûts enregistrés dans les îles Galápagos; toutefois, les coûts déclarés pour les pertes médicales liées aux moustiques *Aedes* causant la dengue en Équateur continental auraient été classés au premier rang si des informations plus détaillées nous avaient permis de les catégoriser comme des données robustes. Plus de 70 % des EEE recencées en Équateur n'ont pas de coûts déclarés. Ces résultats suggèrent que les coûts rapportés ici sont une sous-estimation massive du fardeau économique réel des invasions biologiques dans le pays.

Abstract in German

Wirtschaftliche Kosten biologischer Invasionen in Ecuador: die Bedeutung der Galapagos-Inseln. Biologische Invasionen infolge menschlicher Eingriffe durch Handel und Mobilität sind die zweitgrößte Ursache für den Verlust der biologischen Vielfalt. Die Auswirkungen invasiver gebietsfremder Arten

(IAS) auf die Umwelt sind allgemein bekannt. Die wirtschaftlichen Auswirkungen werden jedoch nur unzureichend geschätzt, insbesondere in Ländern mit großer Vielfalt, in denen die wirtschaftlichen und ökologischen Folgen dieser Auswirkungen katastrophal sein können. In Ecuador, einem der kleinsten Länder mit großer Vielfalt, fehlt eine umfassende Beschreibung der wirtschaftlichen Kosten von IAS in seinem Hoheitsgebiet. Hier haben wir mithilfe von "InvaCost", einer öffentlichen Datenbank, die alle mit IAS verbundenen monetären Kosten aus englischen und nicht englischen Quellen zusammenstellt, die wirtschaftlichen Kosten biologischer Invasionen untersucht. Wir haben festgestellt, dass zwischen 1983 und 2017 die mit biologischen Invasionen verbundenen Kosten zwischen 86,17 Mio. USD (unter Berücksichtigung nur der robustesten Daten) und 626 Mio. USD (unter Einbeziehung aller Kostendaten) zu 37 Arten und 27 Gattungen lagen. Darüber hinaus stammten 99% der erfassten Kosteneinträge von den Galapagos-Inseln. Aus nur belastbaren Daten ging hervor, dass Wildziegen (*Capra hircus*; 20 Mio. USD) die teuerste taxonomische Gruppe waren, gefolgt von *Aedes*-Mücken (2,14 Mio. USD). Jedoch, Organismen wie Pflanzenarten der Gattung Rubus, einer parasitären Fliege (*Philornis downsi*), schwarze Ratten (*Rattus rattus*) und terrestrische Gastropoden (*Achatina fulica*) machten jeweils weniger als 2 Millionen US-Dollar aus. Die Kosten für gemischte Taxa (d. H. Pflanzen und Tiere) waren am höchsten (61% der gesamten robusten Kosten; 52,44 Mio. USD). Der am stärksten betroffene Aktivitätssektor waren die Nationalparkbehörden, die rund 84 Millionen US-Dollar ausgaben. Die Ergebnisse robuster Daten zeigten auch, dass die Verwaltungsausgaben die Hauptkosten auf den Galapagos-Inseln waren. Die Kosten für medizinische Verluste im Zusammenhang mit *Aedes*-Mücken, die auf dem ecuadorianischen Festland Dengue-Fieber verursachen, wären jedoch an erster Stelle gestanden, wenn wir durch detailliertere Informationen als robuste Daten eingestuft werden könnten. Über 70% der für Ecuador gemeldeten IAS hatten keine Kosten gemeldet. Diese Ergebnisse deuten darauf hin, dass die hier gemeldeten Kosten die tatsächliche wirtschaftliche Belastung durch Invasionen im Land massiv unterschätzen.

Keywords
Damages, economic costs, InvaCost, invasive alien species, mainland Ecuador, management

Introduction

Invasive alien species (IAS) are defined as non-native species that, as a result of human transportation or trade, establish in a new ecosystem where they may cause environmental impact, economic harm or affect human health (Convention on Biological Diversity 2009). Most worrisome is that the number of invasive species and invasion events – as well as their associated deleterious impacts in invaded areas – shows no sign of abatement in the near future (Seebens et al. 2017, 2018). Whether their introduction has been intentional or accidental (McNeely 2001), IAS pose serious threats to biodiversity, ecosystem stability (Vilà et al. 2010), health (Shepard et al. 2011; Schaffner et al. 2020), human livelihood and well-being (Pejchar and Mooney 2009; Simberloff et al. 2013), and the economy (e.g., Pratt et al. 2017; Diagne et al. 2021a; Cuthbert et al. 2021). Some examples of their numerous ecological impacts include the transformation of landscapes by removing trees (e.g. the beaver *Castor canadensis* in Chile and Argentina; Papier et al. 2019), decline or elimination of native species through competition or predation (e.g. by the ant *Solenopsis geminata* in the Galapagos Islands; Herrera and Causton 2008), ecosystem and restructuration and function modification (e.g. by invasive aquatic bivalves *Dreissenia* spp.; Karatayev et al. 2014), and decreasing biodiversity in protected areas and islands (Bellard et al. 2017; Holmes et al. 2019).

Invasive alien species are also responsible for a variety of substantial losses across many socio-economic sectors (Bacher et al. 2018). As an illustration, it has been shown that a reduction of 10–16% of yield crops globally was associated with invasive insects (Bebber et al. 2013), but invasive species can also cause losses of human-made goods and services (Binimelis et al. 2007), destruction of infrastructure over sectors like forestry (Scheibel et al. 2016), fisheries (Rosaen et al. 2012), and agriculture (Paini et al. 2016), among others. Such sectors often drive the economy of a country, and the effects of biological invasions can hinder its sustainable economic growth, especially in developing countries (Early et al. 2016). Yet, only a few studies have reported monetary estimates of the costs of biological invasions. The existing assessments report losses worth billions yearly; for instance, previous studies estimated costs of around US$120 billion in the USA (Pimentel et al. 2005), US$14.45 billion in China (Xu et al. 2006), EUR 12 billion in Europe (Kettunen et al. 2008) and US$70 billion globally for invasive insects alone (Bradshaw et al. 2016). Moreover, across most activity sectors, the economic costs of biological invasions can be divided into two categories: "Damage", referring to the direct and indirect economic losses caused by invasive species, and "Management" referring to the expenditures on actions dedicated to controlling or eliminating invasive species (Bradshaw et al. 2016; Diagne et al. 2020a). However, these economic assessments come from less diverse regions of the world, highlighting the lack of such evaluations for mega-diverse countries (i.e. hotspots for biodiversity), where biological invasions might pose bigger ecological threats and where these studies can provide guidance for better redirection of resources (i.e. monitoring, management and mitigation) to counter IAS impacts.

Ecuador, one of the smallest of the world's 17 mega-diverse countries, harbors unique ecosystems as well as an extraordinary number of endemic species (Mittermeier et al. 1998; Myers et al. 2000). It is divided into three continental regions (i.e. Amazon, mountains, coast) plus the Galapagos Islands. Ecuador is among the five richest places in the world for birds, reptiles and amphibians (Bass et al. 2010). Approximately 20% of its national territory – distributed across 50 protected areas- is under the maximum category of protection, according to the national environmental legislation and the National System of Protected Areas (SNAP, Ministerio de Ambiente de Ecuador 2014). The most famous of these protected areas are the Galapagos Islands, declared a UNESCO World Heritage Natural Site in 1978. They are regarded as a "living museum and showcase of evolution" due to their peculiar fauna and flora (UNESCO, 2020). They attract interest not only from tourism (more than 271,238 visitors in 2019; Dirección del Parque Nacional Galápagos 2019), but also from international funding to invest in their protection and conservation, for example, a major contribution from the UNESCO-World Heritage over US$2.19 million for the "Galapagos Invasive Species" account (UNESCO 2008).

The Galapagos Islands have been invaded by many species from a variety of taxa representing an exceptional threat to this vulnerable insular ecosystem. Up to 2017, the number of alien terrestrial and marine species recorded in the islands was 1,522

(Shackleton et al. 2020, appendix 2). Among these, 810 were plant species, 63 pathogens, 50 marine invertebrates and 3 marine plants (Shackleton et al. 2020, appendix 2). Of the introduced plant species, at least 32 were considered invasive (Atkinson et al. 2012). Many plant species, out of control today, were introduced with ornamental and/or agricultural purposes in the four inhabited islands of the archipelago (i.e. Floreana, Isabela, San Cristobal and Santa Cruz). Among the worst plants regarding their impacts on biodiversity and ecosystems services are *Cedrela odorata* (Spanish cedar), *Cestrum auriculatum* (orange cestrum), *Cinchona pubescens* (quinine tree), *Lantana camara* (multicoloured lantana), *Psidium guajava* (guava), *Rubus niveus* (blackberry) and *Tradescantia fluminensis* (small-leaf spiderwort) (Gardener et al. 2013), which outcompete Galapagos endemic and native flora (Guézou et al. 2010).

In addition, there are 545 species of introduced insects and 77 other terrestrial invertebrates (Toral-Granda et al. 2017) from which at least six species are considered invasive (Atkinson et al. 2012). Two species of ants, *Wasmannia auropunctata* (little fire ant) and *S. geminata* (tropical fire ant), are considered the most serious threats to the hatchlings of endemic birds and reptiles in the Galapagos Islands. Particularly, *S. geminata* is regarded as an environmental and economic pest, being documented on 20 islands and islets and having major impacts on around 25 endemic or threatened taxa including land tortoises, iguanas and many seabirds (Wauters et al. 2014). But undoubtedly, vertebrates have the most devastating impacts on the biodiversity on the islands. These invasions originated from the introduction of pigs, goats, cattle, cats, dogs and birds in the early 19th century. Since then, 27 vertebrate species have been reported to live on the islands from which 20 have established feral populations (Phillips et al. 2012a). Introductions of vertebrates have driven some local extinction; for example, the land iguana (*Conolophus subcristatus*) on Santiago Island (Phillips et al. 2005; Cayot 2008). Feral goats threaten 55–60% of the endemic plant species (Atkinson et al. 2012). Over the course of 50 years, invasive alien species in the Galapagos Islands have therefore been the focus of numerous management projects, which in total have been costly, yet not systematically compiled. Identifying these costs would help to inform and prioritize optimal management planning.

Invasive species also have impacts on mainland Ecuador. For example, in the public health system, *Aedes* mosquitoes are a medically important vector of arboviral diseases, such as dengue fever and chikungunya in the whole country and throughout Latin America. Control of the *Aedes* species remains the principal means of preventing and managing outbreaks but it requires considerable investment of time and resources. People living on the urban periphery are particularly vulnerable and are in need of public health management strategies that integrate local, policy-relevant research that guides the design, implementation and evaluation of dengue management (Stewart Ibarra et al. 2014). Invasive species also greatly impact the agriculture sector. Fruit exportation depends on the appropriate control of fruit flies from the family *Tephritidae* and their presence has triggered monitoring and eradication campaigns in areas of papaya, melon and mango cultivation in the Santa Elena and Los Ríos regions in Ecuador (Cañadas et al. 2014). Invasive potato tube moths (PTM, Lepidoptera: Gelechiidae), in their larval stage, feed on potato, a major staple crop in highland Ecuador (i.e. Andean region), representing serious agricultural problems in the poorest regions of Central Ecuador where monitoring programs are most needed (Dangles et al. 2010). Yet, these costs are generally unknown, very case-specific and/or difficult to contextualize.

So far, there has been no national assessment of all the economic costs incurred by IAS in Ecuador, although such cost assessments are of strong interest for both research and management purposes (Dana et al. 2013; Diagne et al. 2020a). Using the "InvaCost" database, we addressed this knowledge gap. Our aims were to (*i*) quantify all the reported economic costs of IAS in Ecuador, (*ii*) evaluate the distribution of such costs across space, taxonomic groups, impacted sectors and over time, and (*iii*) assess the highest types of costs incurred, whether damage costs or management expenditures.

Methods

Data compilation, structure, and extraction

We extracted costs data associated with IAS from the "InvaCost" database (Invacost 3.0; Diagne et al. 2020b). "InvaCost" is a comprehensive and harmonized compilation and description of monetary costs associated with biological invasions (9,823 entries, full data and details in https://doi.org/10.6084/m9.figshare.12668570). This database results from a systematic literature search made in three bibliographic repositories (i.e. Web of Science, Google Scholar and Google search engine), as well as specific searches directed towards pre-defined sources, experts and stakeholders (i.e. "Targeted Collection" through e.g. webpages of official organizations and institutions, national biodiversity managers, conservation practitioners, researchers specialized in biological invasions). As a result, "InvaCost" also includes data published in languages other than English (Angulo et al. 2021a). All sources were screened for relevant cost information and collated to a standardized currency, i.e. 2017 equivalent US Dollars (US$), based on exchange rates provided by the World Bank (see Diagne et al. 2020b for details). Each entry collated in "InvaCost" contains a cost estimate depicted by a unique combination of cost descriptors (currently >60 columns in the database) including: (i) the bibliographic information of the documents reporting the costs; (ii) the information on the impacted area (e.g. location, spatial scale, environment – aquatic or terrestrial, and whether the location corresponded to a protected area and/or an island); (iii) the taxonomy of the IAS causing the cost, (iv) the temporal extent over which the cost occurred, or was predicted to occur; and (v) the typology of each reported cost (e.g. type of cost – management actions or economic damages; impacted sector – activity, market or societal sector related to the cost; and the reliability of the cost value). Finally, a set of variables reported the raw and standardized cost values (see below), as well as the original currencies.

From this data assembly we selected cost entries specific to the country of Ecuador (column “Official_country”), resulting in 153 entries (herein, "raw data"; Data are provided in the Suppl. material 1: S1a). Data for Ecuador comes from 19 references collected in the Web of Science (two references corresponding to six entries), Google Scholar (two references corresponding to 19 entries) and Google (two references corresponding to eleven entries). The remaining 14 references (117 "raw data" entries) were collected by the "Targeted Collection" specifically focused on Ecuador. Together, these data provided information about 27 Genera and 37 invasive species. All cost data were carefully revised and checked to identify potential duplicates and errors, and all modifications to the original data were sent to the dedicated email address (updates@invacost.fr) for consideration and correction in a future update of "InvaCost".

Data processing

We annualized all "raw data" entries (except six entries due to lack of precise information about the duration of the costs) to consider the temporal frame in which they occurred. This was necessary because the duration of reported costs is very heterogeneous, varying from few months to several years. To estimate annual costs of invasions, our cost entries were expanded along the number of years during which each cost occurred. For this purpose, we used the "expandedYearlyCosts" function of the "invacost" R package (Leroy et al. 2020; R version 3.6.2, R Core Team 2020) to derive each cost entry of the raw robust data to annual estimates for each year of cost occurrence. This function considers information provided on both the starting and ending years ("probable starting year adjusted" and "probable ending year adjusted" columns; Suppl. material 1: S1a) of each cost occurrence. When information was not available on the actual years of the cost, we used the publication year of the original reference as a basis for estimating the duration (Diagne et al. 2020b). This way, we obtained a total of 464 annualized costs entries (Suppl. material 1: Table S1b).

Temporal description of the costs

From the resulting expanded database and the year in which the costs occurred, we calculated the cumulative and average costs of invasive species in Ecuador for the period 1983 to 2017, using the function "summarizeCosts" from the same "invacost" R package. We analyzed and provided average costs in five-year intervals over the above-targeted period.

Data filtering

Once all the data were annualized, we filtered the data using two important descriptors of the costs: the reliability of the cost estimate and the implementation of the cost (columns “Method_Reliability”, and “Implementation” respectively of the database, Suppl. material 1: Table S1b). The reliability of the cost entries was categorized as ‘High’ if the approach used for cost estimation in the original source was reported, reproducible and traceable, and ‘Low’ if otherwise. The implementation of the cost entries was categorized as ‘Observed’ if the cost was actually incurred in the focal area, and ‘Potential’ if the cost was not empirically observed but only predicted to occur (see

Diagne et al. 2020b for details on criteria used). Costs that were both observed and of highly reliable were considered “robust”. Thus, we obtained a first dataset that we called herein "robust data" containing 317 entries representing data for 26 genera and 36 species (Suppl. material 2: Table S2). Excluded entries are classified as "non-robust" (147 entries, i.e. ‘Low’ reliability and/or ‘Potential’ implementation), this group of entries reports costs for one additional genus and species that is thus not included in the "robust data" (Suppl. material 2: Table S3).

Analyses of the robust data using cost descriptors

Invasion costs estimates were analyzed based on three descriptors:

i. Taxonomy of the invasive species causing the cost at the Genus level of (“Genus” column in the database; Suppl. material 1: Table S1). However, when multiple species were associated with the same costs, those entries were reclassified as "Mixed-taxa".

ii. Socio-economic sectors impacted by the invasive species cost (“Impacted_sector” column in the database; Suppl. material 1: Table S1) as the following: "Agriculture", "Authorities-stakeholders", "Forestry", "Health", "Environment" and "Mixed". The "Mixed" category was assigned when reported costs affected two or more economic sectors and it was not possible to assign individual values.

iii. Type of cost reported (“Type of cost_merged” column in the database; Suppl. material 1: S1) as (a) "Management" costs, i.e. expenditures associated with impeding the spread of the invasive species (i.e. management, control, eradication, monitoring), (b) "Damage" costs, monetary losses either direct (e.g. yield reduction, degradation of infrastructures) or indirect (e.g. repairing the impact of the invasive species, medical care of ill patients), (c) "Unspecified"costs, referring to other costs that could not be unambiguously associated to exclusively one of two previous categories (i.e. indirect costs).

Results

Overall description of costs over time

Taking into account only the "robust data" (i.e. "observed" and "highly reliable" cost data), the total economic costs of biological invasions in Ecuador amounted to US$86.17 million from 1983 to 2017 (n = 317, Fig. 1). On average, expenditure on invasive species was US$3.75 million per year (Fig. 2). Annual costs increased from ca. US$0.35 million per year in the second half of the 1990s, to ca. US$6.37 million per year during the 2000s but decreased to ca. US$2.5 million per year during the last decade (probably in part due to the time lag to report costs). Most of these costs were documented between 2007 and 2009 (Fig. 2), when international projects for eradication of invasive species, mostly in the Galapagos Islands, were put into place (Carrión

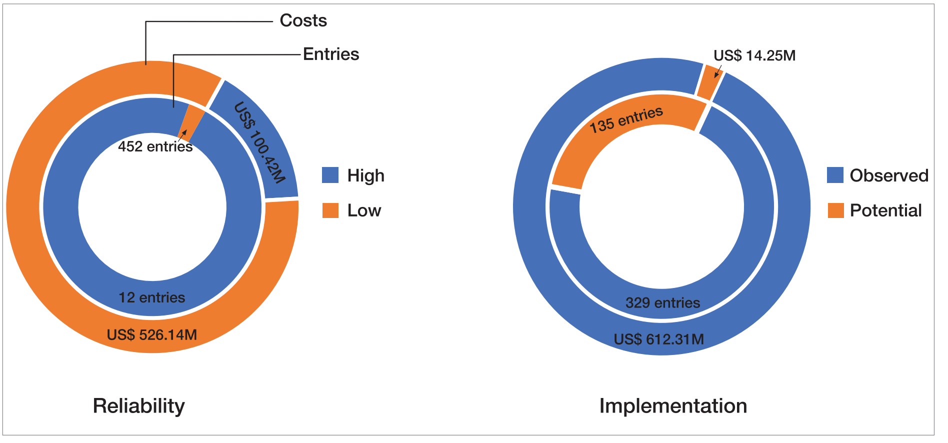

Figure 1. Distribution of economic costs (outer circles US$ million) and number of entries (inner circles) of invasive species in Ecuador according to: (**a**) level of reliability of the cost entries (High and Low); (**b**) implementation of the cost reported (Observed and Potential). "Robust data" is the combination of highly reliable entries and observed implementation, whereas "Non-robust" data is otherwise.

et al. 2011). Accounting for all cost entries (i.e. including both "low reliability" and "potential" costs), the total economic cost was US$626.56 million (*n* = 464 annualized costs). From this amount, the 85.72% were driven by costs deemed either as potentially occurring (i.e. predicted; US$14.25 million) and/or marked as low reliability (US$526.14 million; Fig. 1). Specifically, the low reliability data correspond mostly to data on *Aedes* mosquitoes dengue fever cases (Suppl. material 1: Table S1). From here on, all results are based on "robust data" unless stated otherwise.

The costs entries of Ecuador came almost exclusively from the Galapagos Islands (99%, corresponding to US$86.17 million, n = 315 entries, Fig. 3), whereas the remaining 1% were reported for either the entire country and/or for mainland Ecuador (US$1.67 million, n = 2 entries, Fig. 3). Including "non-robust data" only increased the percentage of cost entries reported for mainland to 5%. Costs from islands were reported for either the entire archipelago or for independent islands (Fig. 3). The island with most costs was Isabela Island (US$13.91 million, n = 38 entries), followed by Santiago Island (US$8.97 million, n = 38 entries). The islands of Pinzón and Santa Cruz each reported costs of ca. US$1 million (n = 3 and n = 155 entries, respectively), whereas San Cristobal, Marchena and Pinta islands reported costs less than US$1 million (n = 9, and two n = 5 entries, respectively). Costs at the scale of the entire archipelago amounted to US$48.45 million (n = 38 entries).

Cost descriptors

Expenditures on "Management" constituted the large majority of the type of economic costs reported for Ecuador, with US$86.06 million (99.8%; n = 314 entries) involving control, eradication, monitoring and administrative management actions. The remaining 0.2% of the costs are divided between economic costs due to "Damage"

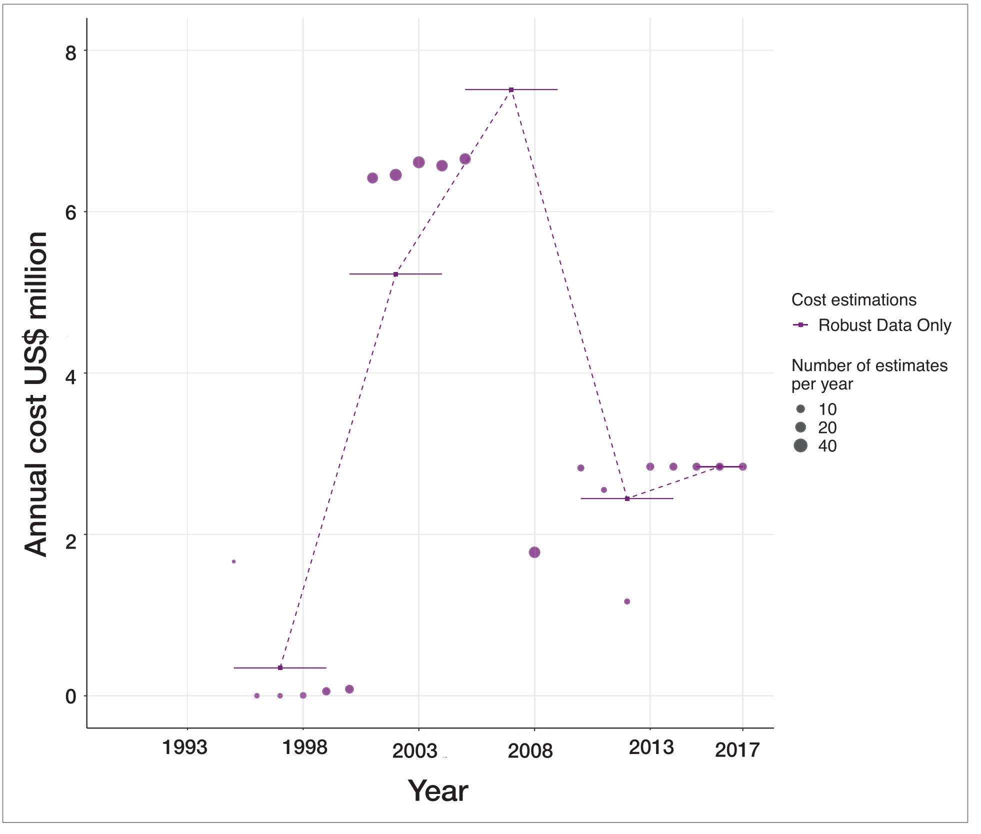

Figure 2. Temporal trend of the total costs in 2017-equivalent US dollars incurred by invasive species in Ecuador over time. Only *robust data* is represented (i.e. both observed and highly reliable). Each point represents the cumulative cost for a given year whereas its size is proportional to the number of estimates for that particular year. Average annual costs are calculated in 5-year periods and are represented by dots and horizontal solid lines. Dashed lines connect the average annual costs for these 5-year periods.

of US$0.01 million (n = 1 entry) and "unspecified" costs amounting to US$0.107 million (referring to indirect costs; n = 2 entries). When including "non-robust data", damage losses, are all associated with medical care (US$525.9 million; eight entries, Suppl. material 2: Table S3) due to dengue cases, which is about five times higher than the reported expenditures on management of the *Aedes* mosquitoes (US$2.14 million, "robust data", n = 6 entries, Suppl. material 2: Table S4).

The most impacted activity sector was "Authorities-stakeholders" (i.e. those governmental services or organizations allocating efforts and resources for managing invasive species, Diagne et al. 2020b) with US$84.03 million; N = 309 entries (Table 1). Costs impacting "Mixed" sectors amounted to US$2.14 million (particularly mixed costs affecting both "Authorities-stakeholders" and "Health" US$2.14 million n = 6 entries, Table 1). "Agriculture" reported costs for US$0.001 million (n = 1 entry). With the inclusion of "non-robust data", the "Mixed" sector (mixing "Authorities-stakeholders" and "Health") would have been ranked in first place due to US$525.9

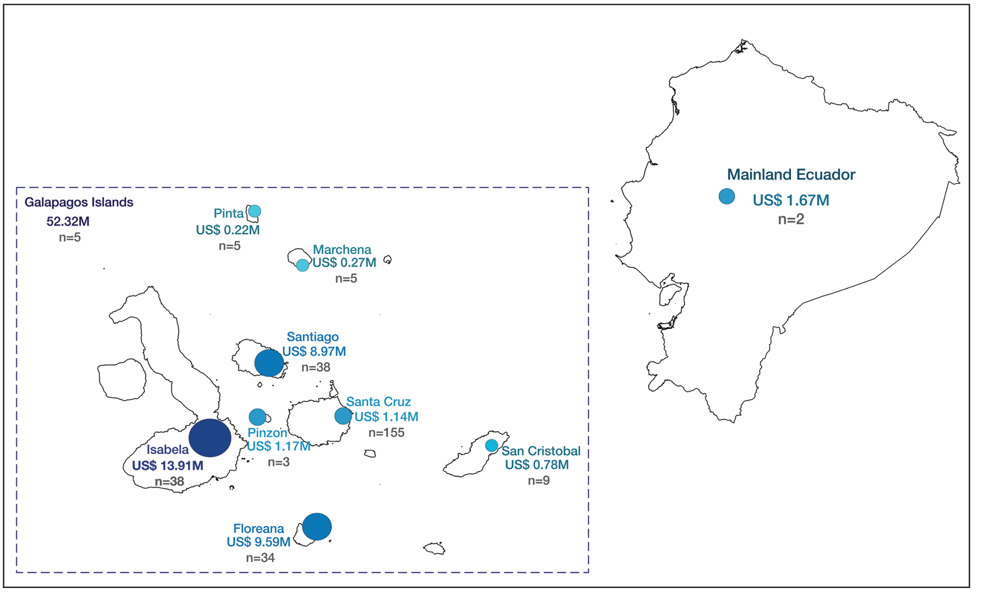

Figure 3. Maps of the economic costs of invasive species in Ecuador: Only *robust data* is represented (i.e. observed and highly reliable). Values are reported for islands and mainland Ecuador. Bubble size represents the amount of costs in US$ millions grouped by similar colors. Dashed lines denote the costs reported for the entire archipelago.

Table 1. Total economic management costs per impacted activity sector taking into account only *robust data* (i.e. observed and highly reliable).

Impacted sector	Total cost US$ million	Number entries
Authorities-Stakeholders	84.03	309
Mixed	2.14	7
Agriculture	0.001	1

million on damage costs (eight entries, Suppl. material 2: Table S3) caused by *Aedes* mosquitoes dengue fever cases.

Regarding taxonomy, the highest economic costs were reported for "mixed-taxa" (61.4%; US$52.44 million, n = 12 entries, Fig. 4). Animal species were responsible for 35% of the total economic costs (US$30.64 million n = 73 entries) and plant species for 3.6% (US$3.09 million, n = 232). The costliest invasive organisms that we could assign costs to were feral goats with US$23.75 million (n = 38 entries, Fig. 4), followed by *Aedes* mosquitoes with US$2.14 (n = 6 entries). The third most costly organisms were plants belonging to the genus *Rubus* (*R. niveus*, *R. adenotrichos*, *R. glaucus*, *R. ulmifolius* and *R. megalococcus*), whose management caused high costs to "Authorities-stakeholders" (US$2.07 million, n = 118 entries; Fig. 4; Suppl. material 2: Table S4). The parasitic fly (*Philornis downsi*) that affects the survivorship of several species of birds in the Galapagos Islands, has incurred control costs of US$1.60 million (n = 5 entries). In ninth place as the costliest invasive genus in Galapagos was the timber tree

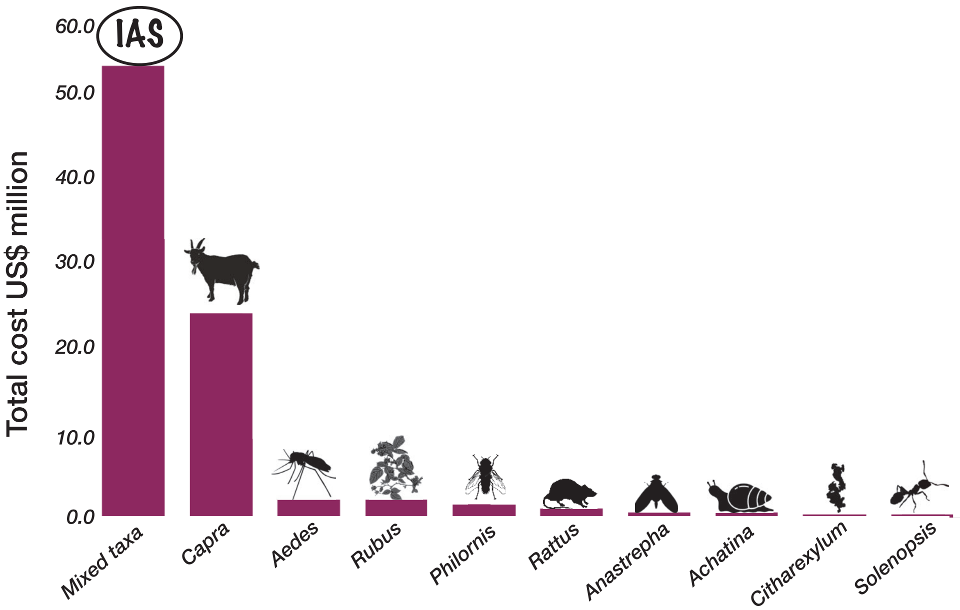

Figure 4. The ten costliest genus in Ecuador. IAS represents costs for multiple species. Costs are reported in million US dollars.

(*Citharexylum gentryi*), a native tree from lowland coastal and Amazonian Ecuador and considered highly invasive in the Galapagos Islands and which incurred costs of US$0.47 million (n = 25 entries). Information for all the 27 genera causing costs in Ecuador is given in Suppl. material 2: Tables S3, S5. The entire costs reported in the database came from organisms in terrestrial environments. Here, we considered the *Aedes* mosquitoes terrestrial, since all the incurred costs are related to their adult life stage (i.e. control – for health and resources spent by health authorities due to dengue fever).

Management actions on "mixed-taxa" of invasive species have fallen most heavily upon governmental organisms such as the Galapagos National Park Directorate and/or other institutions such as the Charles Darwin Foundation, incurring expenditures of US$52.44 million (n = 12 entries; Suppl. material 2: Tables S2, S4).

Discussion

Central role of the Galapagos Islands in invasion costs reported for Ecuador

Our findings showed that biological invasions cost the Ecuadorian economy at least US$86.17 million between 1983 and 2017, and that most of these expenses were reported between 2007–2009 (Fig. 2). The highest recorded costs were associated with a combination of two or more plant/animal species, but the costliest identified taxonomic group was the goat, followed by the *Aedes* mosquito. We also found that the economic sector "Authorities-stakeholders" sustained the largest economic costs, mostly through management actions in the Galapagos Islands. Our conservative approach of only retaining "robust" data (i.e. both observed and highly reliable) excluded another US$526.14 million that were classified as potential and/or unreliable costs (i.e. "non-robust data"). The high predominance of management expenditures in the Galapagos Islands might be explained by two reasons that we explore below: the emblematic history of this unique archipelago that helps secure funding to control and/or eradicate invasive species more than in mainland Ecuador, and island isolation, coupled with increasing tourism, as a reason to invest in management actions to protect these ecosystems from the damage caused by invasive species.

The World Heritage status and the history of Charles Darwin formulating his theory of evolution after visiting Galapagos, promoted the Galapagos Islands to a flagship conservation area that helps attract major resources for both research and conservation. It has led to the establishment of institutions like the Charles Darwin Foundation and its Research Station that attracts researchers from all around the world and in turn has promoted the transfer of ideas and expertise (in both directions, local and international institutions and individuals). This has also enabled the securing of substantial amounts of funding for conservation. For example, the funding of a multi-partner 6-year program (US$43 million) for managing invasive species (Gardener et al. 2009), from which a US$6.1 million program was established to eliminate feral goats from Santiago Island (Cruz et al. 2009) as part of the Project Isabela (~10.5 million US$) – the world's largest restoration effort – for the elimination of invasive mammals at the archipelago level (Carrión et al. 2011). Twenty-one plant eradication programs began in 1996, but only four were successful, eradicating *Rubus adenotrichos*, *R. megalococcus*, *Pueraria phaseoloides* and *Cenchrus pilosus* from Santa Cruz Island (Atkinson et al. 2012). It seems that plant species are much more difficult to eradicate than other groups of organisms (Gardener et al. 2009). Several eradication programs for invasive ants have been conducted across the archipelago, achieving local removal from Santa Fe and Isabela islands for the tropical fire ant (Wauters et al. 2014), and from Santa Fe and Marchena for the little fire ant (Causton et al. 2005). The joint efforts between researchers and local authorities have also helped to put in place legislation and oversee the proper implementation of programs to control invasive pests such as feral pigeons and limit the spread of dengue-carrying mosquitoes (Phillips et al. 2012b; Toral-Granda et al. 2017).

At the same time, the status as a protected area and a World Heritage site makes the Galapagos Islands an important hub for ecotourism that now underpins the national economy. Tourism has grown from 1,000 tourists per year in 1960 up to >270,000 tourists in 2019 (Dirección del Parque Nacional Galápagos 2019). The continuous pressure posed by tourism, population growth and the increasing trade between mainland and the archipelago resulted in the official establishment of biosecurity protocols in 1999. They started in 2000 with the release of a list of permitted, restricted and prohibited products and goods from the Quarantine Inspection System of Galapagos (SICGAL), and inspection of goods from cargos and luggage from new arrivals to stop potential harmful organisms from becoming established (Zapata 2007; Cruz Martínez et al. 2007). Then, in 2007, the invasive alien species management plan (Plan de Control Total de Especies Introducidas) was developed (Toral-Granda et al. 2017). Finally, in 2012, a dedicated agency of biosecurity (ABG; Agencia de Regulación y Control de la Bioseguridad y Cuarentena para Galápagos) was established with its mission to control, regulate and reduce the risk of introduction and spreading of exotic species that endanger the biodiversity of the islands, the local economy and human well-being (Toral-Granda et al. 2017; https://www.gob.ec/abg). Moreover, getting a comprehensive legal and administrative framework to address already established invasive populations (i.e. control and eradication programs, quarantine actions, and legislation) was crucial for the Galapagos Islands and in turn for Ecuador's economic interests because of the high value of tourism; an industry whose net benefits were extrapolated to be around US$392 million in 2016 (Schep et al. 2014). The investment of US$86 million over the last three decades protecting both the Galapagos unique biodiversity and dependent tourism revenues is a good choice for conservation but at the same time a very cost-effective economic strategy. The Galapagos Islands' main source of revenue is their endemic species (i.e. tourism, conservation) which leads to a differential managing strategy in comparison to mainland Ecuador where introduced species can be the major source of revenue such as crops (e.g. bananas and coffee) and other introduced species that are not invasive. Therefore, the perception and pressure for management can be very different (Nuñez et al. 2018).

Limitations and ways forward

Quality control in databases is crucial for ensuring accurate assessments and conclusions, particularly in invasion science, where results are used to inform conservation managers, practitioners and environmental policy makers. We chose to use a highly conservative and robust dataset to draw our conclusions, and then delineated the pitfalls in our interpretation of the cost distribution. We are aware that our decisions to include or exclude some data might have consequences on our quantitative conclusions. For example, *Aedes* mosquitoes occupied third place in our list of the costliest species in Ecuador because we excluded its data from the most robust dataset; yet this species complex ranks much higher in economic costs assessments for other South American countries (such as Argentina, Duboscq-Carra et al. 2021) or even the whole continent (Central and South America, ranked 2nd -US$12.9 million; Heringer et al. 2021). Sheppard et al. (2011) provides a detailed account of the high costs of *Aedes* mosquitoes across the Americas between 2000 and 2007 (Reference ID 73; Suppl. material 1: Table S1a). Yet, we can only speculate about the real economic burden that this species generated in Ecuador due to dengue fever, as national details were not provided in that case. Dengue cases are considered under-reported in Latin America in general (Hotez et al. 2008) despite estimated losses being in the same order of magnitude as other neglected diseases such as tuberculosis, leishmaniasis or intestinal helminths (Torres and Castro 2007). Furthermore, this finding emphasizes that managers and researchers, whenever possible, should provide finer-scale and more complete information, when providing economic cost data for invasive species impacts; e.g. at least the main descriptors, such as spatial and temporal scale of the cost, the taxa involved, the type of costs and the economic sector impacted (Diagne et al. 2020a, b). In fact, due to the lack of precise information about the duration of the costs, six entries ("raw entries", Suppl. material 1: Table S1a: L149–153) had to be excluded from the entire analysis. One of the excluded entries belonged to *Culex* mosquitoes reported for mainland Ecuador (i.e. an area with not many records), and was the only cost entry we have for the species (Suppl. material 1: Table S1a).

The leading type of costs reported across the assembled dataset was expenditure in management. This is in contrast to results from the analysis of "InvaCost" data in other regions, where damage costs far outweighed management investments, for example, in Asia (Liu et al. 2021), Africa (Diagne et al. 2021b), Central and South America (Heringer et al. 2021), Europe (Haubrock et al. 2021a) or North America (Crystal-Ornelas et al. 2021). Ecuador, particularly the Galapagos National Park, significantly invests in management actions such as prevention (e.g. with the establishment of ABG), monitoring, control or eradication since most invasions controlled, both in the past and currently, are in a late stage of invasions generating high management costs. Yet, it is surprising that Ecuador reports almost no data for damage and loss, although a similar situation occurred in Spain where > 90% of the robust data corresponded to management costs of IAS, while damage costs were only found for 2 out of the 174 species with reported costs (Angulo et al. 2021b). It is, for example, also striking that no damage costs have been recorded for agriculture, forestry or fisheries activities in Ecuador. Agriculture, for instance, is an important sector that makes up 33.9% of the employment in rural areas of Ecuador (which is higher than the 24% reported in other Andean countries of the region (Martínez Valle 2017). It was also the most impacted activity sector by invasive alien species in Brazil (Adelino et al. 2021) and Argentina (Duboscq-Carra et al. 2021), while fisheries was ranked first for Mexico (Rico-Sánchez et al. 2021). In fact, the scarcity of scientific reports on the economic impacts of invasive species from mainland Ecuador makes it difficult to assess the real cost on most activity sectors. Low funding for ecological research in comparison to other disciplines might be one of the causes for the lack of records (Nuñez et al. 2019; Nuñez and Pauchard 2010). Economic evaluation studies are often limited by available data (Gren et al. 2009), that is biased taxonomically and/or geographically (Pyšek et al. 2008) but also on differential funding allocation (Baker 2017). In addition, the complexity of evaluating some types of impacts (e.g. value of extinct or living species, ecosystem services, non-market items) is also probably part of the reason for the undervaluation of damage and losses (Kallis et al. 2013; Meinard et al. 2016; Diagne et al. 2020a).

We found robust costs for only 36 invasive species, whereas the Global Invasive species database reports 125 species known to be invasive in Ecuador (GISD, Pagad et al. 2018). Therefore, more than 70% of the species reported as invasive in Ecuador do not have reported economic costs that are easily accessible. Even higher gaps between the number of species to be known as invasive and the number of species from which costs are reported, have been found in other countries in Central and South America, for example in Argentina and Mexico, where they report costs for only 10% of the known invasive species (Duboscq-Carra et al. 2021; Rico-Sánchez et al. 2021) and other parts of the world, such as Germany (Haubrook et al. 2021b) or France (Renault et al. 2021). In this study, we further noticed the bias on publication language. Half of the cost entries (51%, 78 out of 153 raw entries) were derived from the search in

Spanish. Not only were there fewer publications about economic costs for Ecuador when compiling data with the most common search engines, but a large portion of the publications were obtained from directly contacting conservationists and managers ("Targeted Collection", Suppl. material 1: Table S1a). This strong bias was also found in other countries, such as Russia, (Kirichenko et al. 2021), Japan (Watari et al. 2021), France (Renault et al. 2021) or Spain (Angulo et al. 2021b). For all these reasons, despite our dedicated efforts for assembling the most complete database (Angulo et al. 2021a; Diagne et al. 2020a, 2020b), our cost estimations probably remain much underestimated. All the foregoing emphasizes the complexity of estimating costs accurately and completely, and stresses the need for most reliable cost assessments in the future – particularly for those countries (such as Ecuador) that have limited capacities to act against invasive species (Early et al. 2016; Rouget et al. 2016; Faulkner et al. 2020).

Conclusions

This study is the first attempt to construct an economic assessment of biological invasions of Ecuador, by standardizing and compiling available information from both English and Spanish sources. Our results show a disproportionate lack of investment in mainland Ecuador compared to the Galapagos Islands. However, the lack of accessible published data limits our effective assessment of the economic costs of biological invasion in the whole territory. Despite our efforts to find more information, there is still a need to investigate other sources of information (e.g. internal reports, theses, conference proceedings and the grey literature in general) to gain a more comprehensive overview. In turn, assessments of economic impacts of invasive species might benefit from having reports and projects published more accessible to the public.

Contrary to other countries in the region – whether mega-diverse or not (Heringer et al. 2021; Adelino et al. 2021; Duboscq-Carra et al. 2021), Ecuadorian institutional authorities, at least in the Galapagos Islands, have invested actively in invasive species management actions. One of the reasons is the body of research about the massive impact that invasive species have on the Galapagos resident biota (Jäger et al. 2009; Jäger et al. 2013; Rivas-Torres and Rivas 2018; Cooke et al. 2020), triggering investment to control or eradicate these species. However, ecological damage is more difficult to monetize and consequently, fewer costs are reported. Despite the massive economic costs reported here, and the important knowledge gaps we identified for these costs, we stress that economic costs are but one aspect of the impact of biological invasions, and that the biodiversity impacted by this threat is infinitely invaluable, in Ecuador and beyond.

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Supplementary material 1

Database of Economic costs of biological invasions in Ecuador

Authors: Liliana Ballesteros-Mejia, Elena Angulo, Christophe Diagne, Brian Cooke, Martin A. Nuñez, Franck Courchamp

Data type: database

Explanation note: Dataset on costs of invasive species in Ecuador extracted from InvaCost database (Diagne et al 2020) and descriptions of the column names.

Link: https://doi.org/10.3897/neobiota.67.59116.suppl1

Supplementary material 2

Tables S2–S5

Authors: Liliana Ballesteros-Mejia, Elena Angulo, Christophe Diagne, Brian Cooke, Martin A. Nuñez, Franck Courchamp

Data type: tables

Explanation note: **Table S2.** Economic costs (only robust data; US$ million) discriminated per genus, impacted sector and type of cost in Ecuador. Impacted sectors are: Authorities-stakeholders (Auth-stak), Mixed (combination of two or more) and Agriculture. Costs are sorted in decreasing order per sector. **Table S3.** Economic costs (only non-robust data; US$ million) discriminated per genus, impacted sector and type of cost in Ecuador. Impacted sectors are: Authorities-stakeholders, Mixed (combination of two or more sectors). Costs are sorted by alphabetic order of the genus. **Table S4.** Economic costs (only robust data; US$ million) and number of cost entries of all the invasive species reported for Ecuador grouped by genus and ordered decreasingly from the costliest to the less costly. **Table S5.** Economic costs (only non-robust data; US$ million) and number of cost entries of all the invasive species reported for Ecuador grouped by genus and ordered decreasingly from the costliest to the less costly. Note that genus *Felis* is the only genus that does not report entries considered robust data.

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