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Economic costs of protecting islands from invasive alien species

Thomas W. Bodey[1] | **Elena Angulo**[2] | **Alok Bang**[3,4] | **Céline Bellard**[2] | **Jean Fantle-Lepczyk**[5] | **Bernd Lenzner**[6] | **Anna Turbelin**[2] | **Yuya Watari**[7] | **Franck Courchamp**[2]

[1]School of Biological Sciences, University of Aberdeen, King's College, Aberdeen, UK

[2]Université Paris-Saclay, CNRS, AgroParisTech, Ecologie Systématique Evolution, Orsay, France

[3]Society for Ecology Evolution and Development, Wardha, India

[4]School of Arts and Sciences, Azim Premji University, Bangalore, India

[5]School of Forestry & Wildlife Sciences, Auburn University, Auburn, Alabama, USA

[6]Bioinvasions, Macroecology, Global Change Group, Department of Botany and Biodiversity Research, University of Vienna, Vienna, Austria

[7]Forestry and Forest Products Research Institute, Tsukuba, Japan

Correspondence
Thomas W. Bodey, School of Biological Sciences, University of Aberdeen, King's College, Aberdeen AB24 3FX, UK.
Email: thomas.bodey@abdn.ac.uk

Present address
Elena Angulo, Estación Biológica de Doñana (CSIC), Avda. Americo Vespucio 26, 41092 Sevilla, Spain.

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Abstract

Biological invasions represent a key threat to insular systems and have pronounced impacts across environments and economies. The ecological impacts have received substantial focus, but the socioeconomic impacts are poorly synthesized across spatial and temporal scales. We used the InvaCost database, the most comprehensive assessment of published economic costs of invasive species, to assess economic impacts on islands worldwide. We analyzed socioeconomic costs across differing expenditure types and examined temporal trends across islands that differ in their political geography—island nation states, overseas territories, and islands of continental countries. Over US$36 billion in total costs (including damages and management) has occurred on islands from 1965 to 2020 due to invasive species' impacts. Nation states incurred the greatest total and management costs, and islands of continental countries incurred costs of similar magnitude, both far higher than those in overseas territories. Damage-loss costs were significantly lower, but with qualitatively similar patterns across differing political geographies. The predominance of management spending differs from the pattern found for most countries examined and suggests important knowledge gaps in the extent of many damage-related socioeconomic impacts. Nation states spent the greatest proportion of their gross domestic products countering these costs, at least 1 order of magnitude higher than other locations. Most costs were borne by authorities and stakeholders, demonstrating the key role of governmental and nongovernmental bodies in addressing island invasions. Temporal trends revealed cost increases across all island types, potentially reflecting efforts to tackle invasive species at larger, more socially complex scales. Nevertheless, the already high total economic costs of island invasions substantiate the role of biosecurity in reducing and preventing invasive species arrivals to reduce strains on limited financial resources and avoid threats to sustainable development goals.

KEYWORDS
biodiversity, economic impact, government, InvaCost, overseas territory, political geography, socioeconomic

Costos económicos de proteger a las islas de las especies invasoras

Resumen: Las invasiones biológicas representan una amenaza importante para los sistemas insulares, además de tener impactos pronunciados en el ambiente y en la economía. Los impactos ecológicos han recibido atención sustancial, mientras que los impactos socioeconómicos se encuentran pobremente sintetizados en las escalas temporales y espaciales. Usamos la base de datos InvaCost, el análisis más completo de los costos económicos de las especies invasoras, para evaluar los impactos económicos sobre las islas a nivel mundial. Analizamos los costos socioeconómicos en varios tipos de gastos y examinamos las tendencias temporales en las islas que difieren en su geografía política – islas estado-nación, territorios ultramarinos e islas de países continentales. En las islas han ocurrido gastos de más de $36 mil millones de dólares entre 1965 y 2020 debido a los impactos de las especies invasoras. Las islas estado-nación produjeron los mayores costos de manejo y el mayor total, mientras que las islas de los países continentales produjeron costos de una magnitud similar, ambas con gastos mucho más elevados que los de los territorios ultramarinos. Los costos de las pérdidas por daños fueron significativamente más bajas, aunque con patrones cualitativamente similares entre las diferentes geografías políticas. El predominio del gasto en el manejo difiere del patrón hallado en la mayoría de los países analizados y sugiere que hay vacíos importantes en el conocimiento del alcance de muchos de los impactos socioeconómicos relacionados con los daños. Las islas estado-nación gastaron la mayor proporción de su producto interno bruto en contrarrestar estos costos, al menos una orden de magnitud mayor que las otras localidades. La mayoría de los costos fueron asumidos por las autoridades y los accionistas, lo que demuestra el papel clave que tienen los organismos gubernamentales y no gubernamentales en cómo se atienden las invasiones insulares. Las tendencias temporales revelaron incrementos en el costo en todos los tipos de islas, lo que potencialmente refleja los esfuerzos por combatir a las especies invasoras a escalas más grandes y socialmente más complejas. Aun así, el elevado costo económico total de las invasiones insulares fundamenta la función que tiene la bioseguridad en la reducción y prevención de la llegada de especies invasoras para reducir presiones sobre los recursos financieros limitados y evitar amenazas para las metas de desarrollo sustentable.

PALABRAS CLAVE

biodiversidad, geografía política, gobierno, impacto económico, InvaCost, socioeconómico, territorio ultramarino

【摘要】

生物入侵是岛屿系统面临的主要威胁, 对环境和经济都产生了明显的影响。生态方面的影响已得到很多关注, 但社会经济方面的影响仍缺少时空尺度上的综合分析。本研究使用 InvaCost 数据库, 包含已发表的入侵物种经济成本最全面的评估数据, 来评估全球岛屿在生物入侵中面临的经济影响。我们分析了不同支出类型的社会经济成本, 并研究了不同政治地理的岛屿 (岛屿民族国家、海外领地和大陆国家的岛屿) 中社会经济成本随时间变化的趋势。结果显示, 从 1965 年到 2020 年, 岛屿由于入侵物种的影响产生的总成本 (包括破坏和管理) 超过 360 亿美元。民族国家的总成本和管理成本最高, 大陆国家的岛屿产生的成本规模相近, 都远远高于海外领地的成本。破坏导致的成本明显较低, 在不同政治地理的岛屿中有相似的情况。而管理支出占主导地位的情况则在我们研究的大多数国家中有所不同, 表明在许多与破坏有关的社会经济影响程度方面仍存在重要的知识空缺。民族国家用于这些成本的国内生产总值比例最高, 至少比其他地区高一个数量级。大多数费用由当局和利益相关者承担, 反映了政府和非政府机构在应对岛屿入侵问题中的关键作用。时间趋势分析表明, 所有类型的岛屿承担的成本都随时间推移而增加, 可能反映了在更大、更复杂的社会范围内应对生物入侵的努力。然而, 岛屿入侵问题的总经济成本已经很高, 这强调了应关注生物安全来减少和预防入侵物种的引入, 以减缓对有限财政资源的压力, 并避免对可持续发展目标的威胁。**【翻译: 胡怡思; 审校: 聂永刚】**

关键词: 生物多样性, 经济影响, 政府, InvaCost, 海外领地, 政治地理学, 社会经济

INTRODUCTION

Invasive alien or non-native species, species that have been distributed beyond their natural range through human agency, are one of the driving forces of the restructuring of global and regional species communities (Capinha et al., 2015; IPBES, 2019; Russell et al., 2017). A subset of these species, termed invasive alien species (IAS), can have severe, multifaceted impacts in their novel environments (Blackburn et al., 2011; Diagne, Leroy, et al., 2021; Reaser et al., 2007). Invasive species regularly cause ecological devastation in island ecosystems and are a leading cause of native species extinctions (Bellard et al., 2016; Blackburn et al., 2004; Doherty et al., 2016), a particular problem in these hotspots of global biodiversity with high endemism and evolutionary distinctiveness (Fernandez-Palacios et al., 2021; Kier et al., 2009; Whittaker, 2007). These IAS also severely degrade ecosystem integrity (e.g., loss of ecosystem services such as inshore productivity [Graham et al., 2018]); cause declines in local economies (e.g., through crop damage or reduced availability of wild food stocks [Ballew et al., 2016; Naylor, 1996]); and can have significant impacts on human health by increasing welfare costs and hospitalizations (Mwebaze et al., 2010).

These severe impacts are particularly problematic because, simultaneously, islands are global hotspots of invasion (Bellard et al., 2016, 2017; Turbelin et al., 2017) and have experienced dramatic increases in alien species richness (Moser et al., 2018; Seebens et al., 2017). Increased recognition of the importance of islands to global biodiversity has resulted in substantial IAS management efforts and expenditure on islands worldwide (Bellard et al., 2017; Russell et al., 2017; Veitch et al., 2011, 2019). The smaller spatial scale of many islands increases the feasibility and implementation of many management options (Jones et al., 2011, 2016). Indeed, the removal of IAS from islands has proven to be a successful way to support many endangered species globally (Russell et al., 2017; Veitch et al., 2011, 2019). In addition, islands are often ideal testing grounds for developing management strategies and techniques across invasion stages, from early detection (e.g., using environmental DNA [Takahara et al., 2013]), to population management of target IASI (e.g., using stable isotope techniques [Bodey et al., 2011]), to complete eradication (Carter et al., 2021; Veitch et al., 2011).

Although islands are fertile locations for such work, many of these management and mitigation strategies for IAS remain costly to implement, requiring significant resources, strategic planning, and workforce capability to enact effectively. Such efforts come with unavoidable economic costs (Diagne, Leroy, et al., 2021), which means the political and administrative situation of an island can substantially influence the implementation of IAS management. For example, the vast majority of independent small island states are considered to be developing economies. In contrast, island overseas territories (OTs) that may be geographically nearby and topographically similar are exclusively administered by economically more developed nations with greater financial resources to potentially deploy (Churchyard et al., 2014; Dawson et al., 2014; Sieber et al., 2018; Vaas et al., 2017). Examples in the Caribbean include a range of islands comprising OTs (e.g., U.S. Virgin Islands, Montserrat, Martinique), independent nation states (NSs) (e.g., Jamaica, Haiti, Dominica), and offshore islands of otherwise continental countries (e.g., the Swan Islands, Honduras, and Islas Caracas, Venezuela). This discrepancy in the availability of internal and external financial resources may create differences in the ability or incentives to control IAS. Political and administrative differences may thus significantly affect investment in IAS management when other contrasting, and often urgent, societal needs exist.

An economic rationale is often considered necessary for justifying action (or inaction) concerning IAS. Cost–benefit analyses are often conducted as prioritization exercises (Carter et al., 2021; Dawson et al., 2014; Holmes et al., 2019), but typically these tend to be on a case-by-case basis, either operationally or in a specific location. However, more generalized modeling suggests that prevention of IAS impacts is less cost-intensive than post-establishment responses (Ahmed et al., 2022; Cuthbert et al., 2022; Leung et al., 2002). Beyond island- or even country-specific contexts, a global synthesis of the economic costs of IAS on islands is lacking (Reaser et al., 2007). This is concerning because such a synthesis would help identify knowledge and management gaps locally and internationally and would highlight actions that can produce synergies across sectors or locations. Such mutually beneficial scenarios are particularly important for addressing multifaceted threats, such as those posed by invasive species.

To address the need for a more thorough understanding of the costs of invasive species on islands, we used the recently developed InvaCost database (Diagne et al., 2020) to synthesize total reported costs of IAS on islands worldwide. Total costs are split between management costs (e.g., control, biosecurity, eradication) and damages incurred (e.g., agricultural losses, health costs). Specifically, we compared management costs and damage losses associated with IAS among islands differing in political geography (independent NSs, OTs, and islands of continental countries [ICCs]). We hypothesized that the cost ratio between management and damage will be equivalent across the 3 island categories. That is, the economic impacts of IAS are felt, and responded to, similarly on all islands. However, there should be a positive relationship between gross domestic production (GDP) and total expenditure, and as a result of their ties to larger and often financially wealthier states, OTs and ICCs should have proportionately greater expenditures compared with independent island NSs. Finally, in light of the ongoing increase in, and recognition of, IAS impacts, we hypothesized that all islands would experience increases in total costs over time.

METHODS

InvaCost data set

We used the InvaCost database 4.0 (published June 2021), a publicly available living repository in which the monetary impacts of invasive species globally are compiled (https://doi.org/10.6084/m9.figshare.12668570). Diagne et al. (2020) developed InvaCost via standardized literature searches (in the Web of Science platform, Google Scholar, and Google search engine) and opportunistic, targeted searches where data gaps were identified. Analogous searches were conducted in >10 non-English languages (Angulo et al., 2021). Additional targeted searches, specifically for economic costs on islands, were made in the gray literature and global funding databases (e.g., www.thegef.org). These costs (n = 100) were added and all costs were

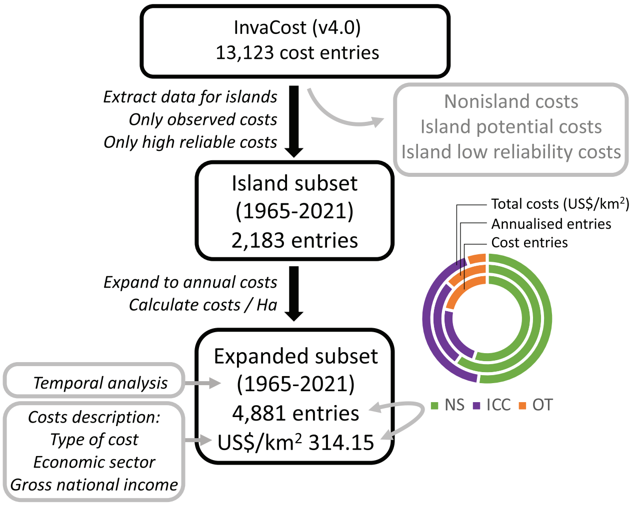

FIGURE 1 Workflow showing the extraction and filtering processes used to determine the reported economic costs of invasive alien species on islands. Shown are proportion of entries, proportion of annualized costs records, and proportion of total costs in US$ millions km^{-2} spent by island type. ICC, island of continental country; OT, overseas territory; NS, nation state

standardized to a common currency (2017 US$, hereafter $) based on the annual average market exchange rate incorporating inflation factors (https://data.worldbank.org/indicator/FP.CPI.TOTL?end=2017&start=1960).

Data selection

We considered only highly reliable (entries assigned as *high* in the "Method-reliability" column of the database) and observed (entries assigned as *observed* in the "Implementation" column) costs. This excluded entries that were not from the peer-reviewed literature or official reports, or were otherwise not reproducible (assigned *low* reliability in the database), and those predicted on future organism invasions (labeled as *potential* in the database). However, we retained studies where costs observed at a small scale on an island were extrapolated to larger areas of the same location. We also omitted a few database entries with no value in the "Cost_estimate_per_year_2017_USD_exchange_rate" column. We considered this approach provided minimum but robust estimates of the economic costs of IAS.

To derive island costs specifically (Figure 1), we screened the full database by the metadata columns "Official country" and "Location." The official country column was used to locate all costs associated with island NSs (i.e., all countries surrounded by oceanic waters smaller than continental Australia). The location column was then used to capture all costs associated with islands of continental nations (e.g., the Galapagos [offshore islands of continental Ecuador] and Reunion [OT of France]). Costs without geographic precision (e.g., islands) or that spanned islands of differing political geographies were excluded ($n = 3$ in total).

Cost and island descriptors

All costs were categorized by cost type, affected sector, and species. For cost type, we used the 3 categories from the database's "Type of cost merged" column for categorization: management (e.g., control, biosecurity, eradication effort), damage (e.g., infrastructure repairs/losses, health impacts), and mixed (costs not accurately separable between the 2 aforementioned categories, plus a small quantity of unspecified costs [~0.05% of the total]). We combined the "Impacted sector" column into broad socioeconomic categories: authorities and stakeholders (principally governmental and nongovernmental actors), primary industries (agriculture, forestry, etc.), health and social welfare, environment, and mixed (costs without definable detail across multiple sectors, including a small unspecified amount [~$270,000]). We used the "Species" column to determine costs for individual species; this analysis was necessarily restricted to costs with precise values attributable to specific species (i.e., a multispecies eradication without detailed breakdowns would be excluded because costs could not be accurately assigned among multiple targeted species).

We then added additional classifiers to identify island types and metrics suggested to predict IAS impacts. Island type distinguishes islands among 3 distinct political geographic categories: island NSs (all sovereign island nations present); ICCs (any island, from small rock stacks to large archipelagos, that is an insular component of an otherwise continental political entity, regardless of distance from continental to insular location, e.g., Corsica is an ICC of France); and OTs (islands that are politically an integral part of, or in some way dependent on, another state for ultimate governance while being geographically separated from that country's territorial waters, e.g., New Caledonia is an OT of France). We added multiple metrics hypothesized to influence the likelihood of IAS impacts or arrival rates (IUCN, 2018): the World Bank's gross national income (GNI) assessment (4 groups: lower, lower middle, upper middle, upper [World Bank, 2019]); average GDP of the relevant country from 1970 to 2018 (World Bank, 2021) for the NS itself or for the continental country or ultimate administrative country of the ICC or OT in question; population density (people per square kilometer of land area); merchandise imports (current US$); and number of international tourist arrivals (all from World Bank, 2021 [https://data.worldbank.org/]). Estimates, such as average GDP, are typically not available for individual OTs due to their complex administrative relationships, and other measures, such as the UN World Economic Situation and Prospects reports, do not provide appropriate country-level resolutions.

Finally, to allow for comparisons across locations, costs were standardized to a common metric of dollars per square kilometer based on the information provided by the "Spatial scale" column. When necessary, we returned to the primary source for clarification. Scaling to the areas over which costs are recorded facilitates comparisons in the same way as scaling to a standard currency. For example, spending $1 million on IAS management over an entire country would potentially produce very different outcomes than the same value directed to a smaller in-country location. When no more precise scale was available, we adopted a conservative approach by assuming that the cost applied either to the entire named island or islands or, if even this level of precision was lacking, the entire country. This resulted in the exclusion of a few references with indeterminable areas (e.g., "3 ponds" or "fishing boat"). Because dollars per square kilometer can be skewed by large costs over very small areas (e.g., eradication of red fire ants [*Solenopsis invicta*] from <1 ha of Auckland airport, New Zealand, at a scaled cost of >US$40 million km^{-2} [Kean et al., 2021]), we examined how costs varied when considering all cost estimates, cost estimates only for areas >1 ha, and cost estimates only for areas >5 ha.

Estimating total costs

To assess the total economic impact of average annual and cumulative costs, we annualized the cost values to standardize the temporal frame of occurrence. We expanded entries that reported costs spanning multiple years to determine annual expenditure, providing an accurate assessment of the economic costs of IAS through time. Multiyear costs were expanded using the expandYearlyCosts function from the invacost package in R 4.0.3 (Leroy et al., 2022; R Core Team, 2020), based on the "Probable starting year adjusted" and "Probable ending year adjusted" columns. When this information was unclear in the primary source ($n = 4$ entries totaling ∼$120,000), we conservatively considered that these costs occurred in a single year based on the ending year determined from the source as the relevant period. This resulted in an expanded data set of 4881 annual costs covering 1965–2021 (Figure 1).

We used this expanded data set (Appendix S2a) to assess area-corrected costs across islands of differing political geographies in relation to cost types, socioeconomic sectors, geographic location, species, and economic indicators. For ICCs and OTs, we also compared the costs in these locales with the total documented costs (following the same filtering steps in "Data Selection") for the relevant continental country. Relationships between the total costs recorded for IAS and the 4 metrics of GDP, population density, imported goods, and international arrivals were examined using linear models with a Gaussian error structure. The IAS costs were the independent variable, and each metric in turn was the dependent variable. Although other potential island-level classifiers are available (e.g., total number of IAS present, arrival dates, or extent of spread), such data are temporally and spatially incomplete relative to each other and to the economic cost time frames, as well as being occasionally contradictory. For example, cost data may relate to a specific IAS but be reported many years before or after any assessment of its distribution. Given these widespread temporal and spatial discrepancies and absences across sources, interpretation of results would be highly problematic, with the potential to conflate genuine absences of relationships with absences of relevant data.

Analyzing temporal trends

For the analysis of temporal trends, we excluded costs that occurred after 2020 ($n = 13$), although publication lags will result in incomplete data for other recent years as well (median publication lag, i.e., the difference between publication and impact years of the study, was 3 years). Temporal trends were assessed using the summarizeCosts function of the invacost package (Leroy et al., 2022) and were examined independently for total reported costs across all islands, across island types separately, and for exclusive management and damage costs.

RESULTS

The complete islands data set consisted of 2183 unique cost entries on a minimum of 246 different islands, resulting in 4881 annualized costs spanning from 1965 to 2021. These costs summed to $36.6 billion from a cumulative 396 million km^2. Total area-corrected costs summed to US$km^{-2} 316 million. Over half of the cost entries and annualized costs were reported from NSs (Figures 1 & 2; Appendix S2b). This translated into 52% of the total reported economic costs occurring in NSs, with ICCs reporting 43% of the total costs, and only 5% recorded in OTs (Figures 1 & 2; Appendix S2b). Geographically, spending on islands was dominated by the Pacific region (69% of the total costs), including NSs and islands with political ties to countries in Oceania, Europe, and South and North America (Figure 2).

Spending ratios across island types

Across all islands, the large majority of the total costs (88%) were classified as management related. Exclusive damage costs comprised only 1% of the total, and the remainder (11%) were classified as mixed (Figure 3a). Across political geographies, NSs spent the most on the management of IAS (>160 million US$km^{-2}), with almost $100 million km^{-2} spent on management on ICCs, and ICCs accounted for the vast majority of mixed costs (Figure 3a; Appendix S2c). The ratio of management spending to damage incurred was of a similar magnitude in NSs and OTs (at over 100:1), although this was halved in ICCs, likely as a result of greater quantities of mixed costs (Appendix S2c). Although the area over which costs were incurred significantly affected the total amounts recorded, with rapid responses to early IAS detections leading to effective but expensive eradications at small scales of 1–5 ha, it did not qualitatively change comparisons (Appendix S2f).

Influence of GDP on recorded costs

As a proportion of GDP, there were large differences between island types. NSs lost the greatest fraction of their income to total IAS costs, an order of magnitude higher than the

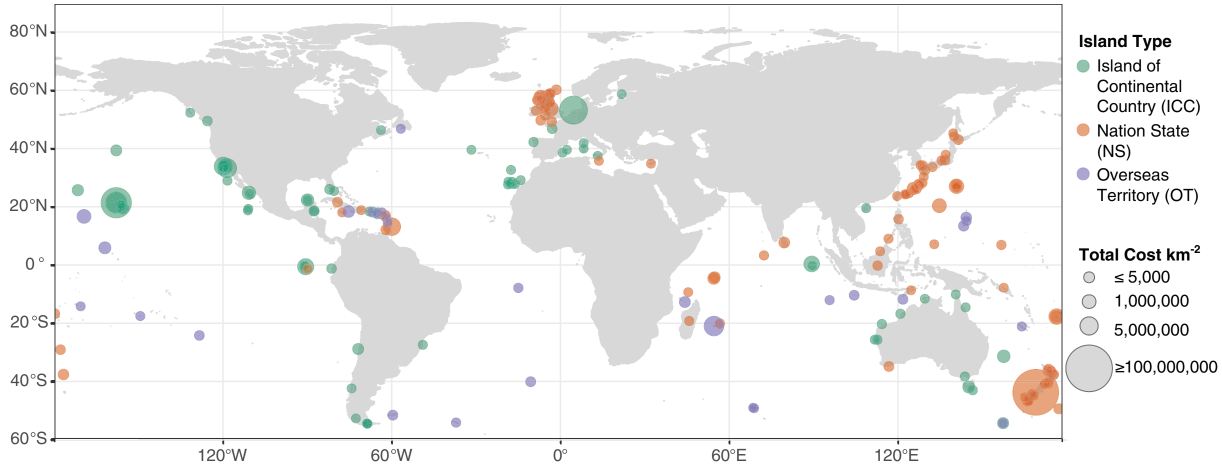

FIGURE 2 Global locations and magnitudes of total reported economic costs of invasive alien species on islands. All costs are in 2017 US$km^{-2}

proportion of GDP lost in ICCs and 2 orders of magnitude higher than that of any OT's administrative country (Figure 3b; Appendix S2c). Reported costs in OTs were an order of magnitude lower for both management and damage than for other island types (Figure 3a; Appendix S2c). A comparison of the raw 2017 US$ costs on ICCs and OTs with costs of the relevant continental and ultimate governing nations showed that sums incurred on islands were consistently lower (with the exception of Ecuador). Although the degree of disparity varied considerably, it remained much greater between countries and OTs than ICCs (Appendix S2d). Costs from upper and upper-middle income countries dominated the data set, with lower and lower-middle income countries representing only 0.3% of all annualized costs (Appendix S2e). Lower-middle income nations were particularly poorly represented because relatively few lower income countries are island states or coastal nations. The extent of foreign visitors and population density, hypothesized predictors of IAS emergence risk, were not significant predictors of the reported economic costs of IAS across NSs and ICCs (Figure S2). Although GDP and import quantities were significantly correlated with IAS costs, these relationships were driven by values for the United States, and were not present when this data point was removed (Appendix S2g).

Considering all costs by socioeconomic sectors revealed dominant spending incurred by the authorities–stakeholders category (89% of annualized costs) (i.e., governmental departments or nongovernmental organizations, including conservation agencies or charities concerned with the management of IAS). Most remaining costs were attributed to primary industries (6%) and environment (4%) categories (Figure 3c). However, sector-related impacts were not spread evenly across island types. Primary industry costs were mainly incurred by OTs, with some spending in NSs. Environmental costs were dominated by ICCs, and the limited health and social welfare costs were documented overwhelmingly in NSs (Figure 3c).

In terms of the costliest species (considering only costs clearly assignable to single species), there was almost no overlap among island types or between the principal species incurring management or damage costs (Figure 4). Taxonomic groups incurring the highest costs across all island types chiefly comprised insects (US$137 million km^{-2}), particularly ants (98% of insect costs), flowering plants (US$50 million km^{-2}), and mammals (US$16 million km^{-2}) (Figure 4). For example, some of the highest total costs on ICCs and OTs are spent on tropical kudzu (*Pueraria phaseoloides*), swamp stonecrop (*Crassula helmsii*), and the little fire ant (*Wasmannia auropunctata*), whereas in NSs major costs were incurred in relation to the stoat (*Mustela erminea*), small Indian mongoose (*Urva auropunctata*), African tulip tree (*Spathodea campanulata*), and, most significantly, the red fire ant.

Temporal trends

When all islands were considered together, there was an increasing trend in total reported costs through each decade from 1960 to 2010, with step changes in orders of magnitude in each decade except for the 1990s. The trend for the 2010s remained incomplete due to publication lags, but may not see as substantial an increase (Figure 5). Because management spending comprised the overwhelming majority of reported costs, trends for management exhibit the same pattern as total costs. Damage costs had similar exponential leaps through time while remaining at lower overall values (Figure 5). Trends by island type were far less consistent. In NSs, there was an overall increasing trend but with marked drops in some decades, meaning that it is only since the 2000s that they consistently surpassed costs on ICCs. In contrast, ICC costs initially rose rapidly but only increased comparatively incrementally since the 1980s. Costs on OTs were less consistently reported through time, but were similarly static, even declining in recent decades (Figure 5).

DISCUSSION

We found that total reported costs in insular systems to address the economic impacts of IAS comprised over US$300 million

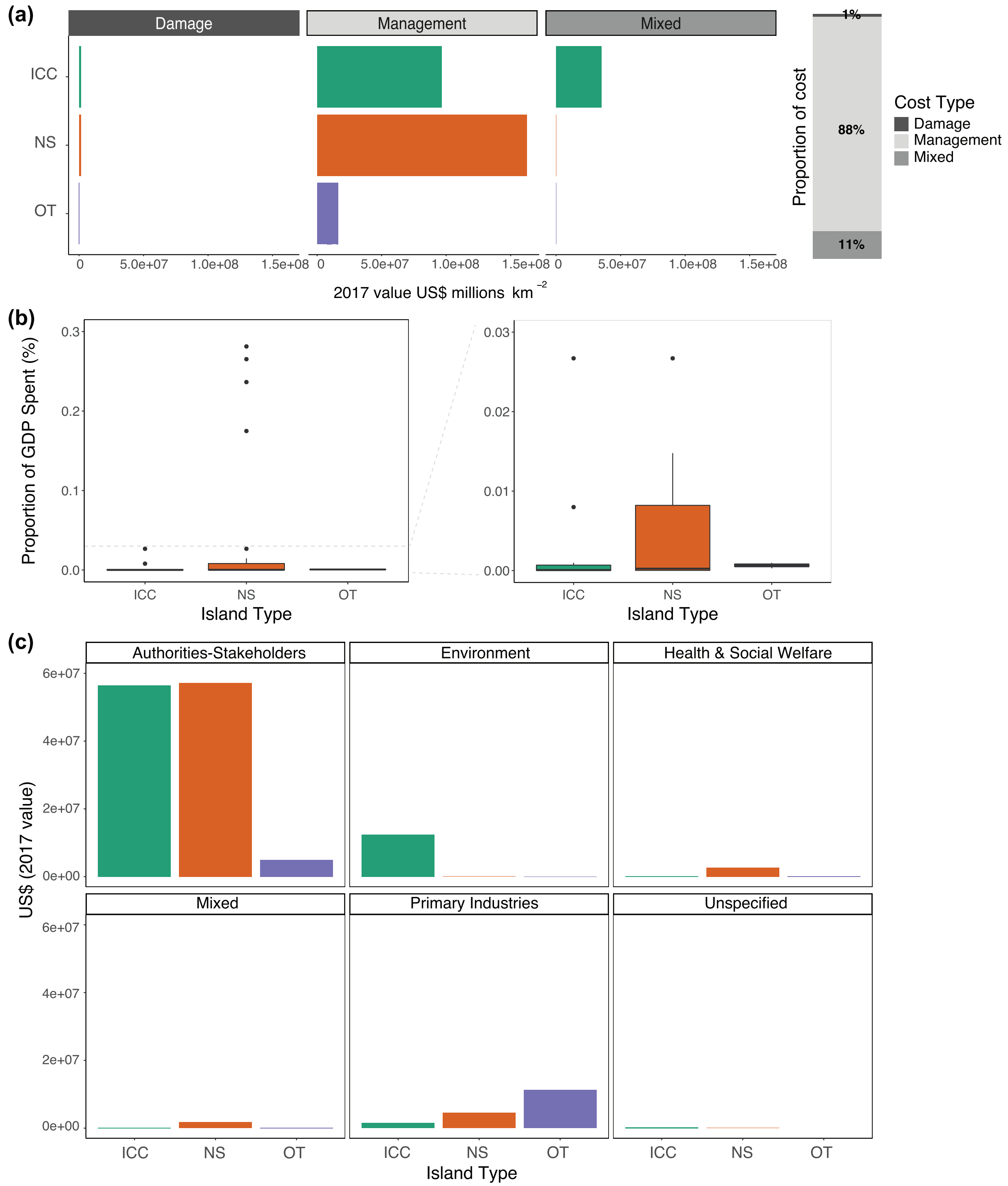

FIGURE 3 Distribution of costs in 2017 US$ millions km^{-2} (a) for proportion across main cost types and in value by island categories, (b) spent as a proportion of gross domestic product (GDP) by island type, shown on 0–0.3% and 0–0.03% scales (vertical lines, interquartile range), and (c) for principal socioeconomic sectors. NS, nation state; ICC, island of continental country; OT, overseas territory

in area-corrected costs over the past 60 years. However, there was significant variation in the types of costs across island types in relation to their political geography. Our hypothesis that the cost ratio between management and damages would be equivalent across island types was not supported by our results. Reported costs for management were always far greater than those for damages, but ratios were lowest for ICCs (e.g., the Galapagos, Hawaii, and Tierra del Fuego). Management spending was approximately twice as high as that in NSs (e.g., Japan, the Seychelles, and Palau), and almost 3 times as high as that in OTs (e.g., Christmas Island, French Polynesia, and Guam). Reported costs in OTs substantially lagged behind ICCs and

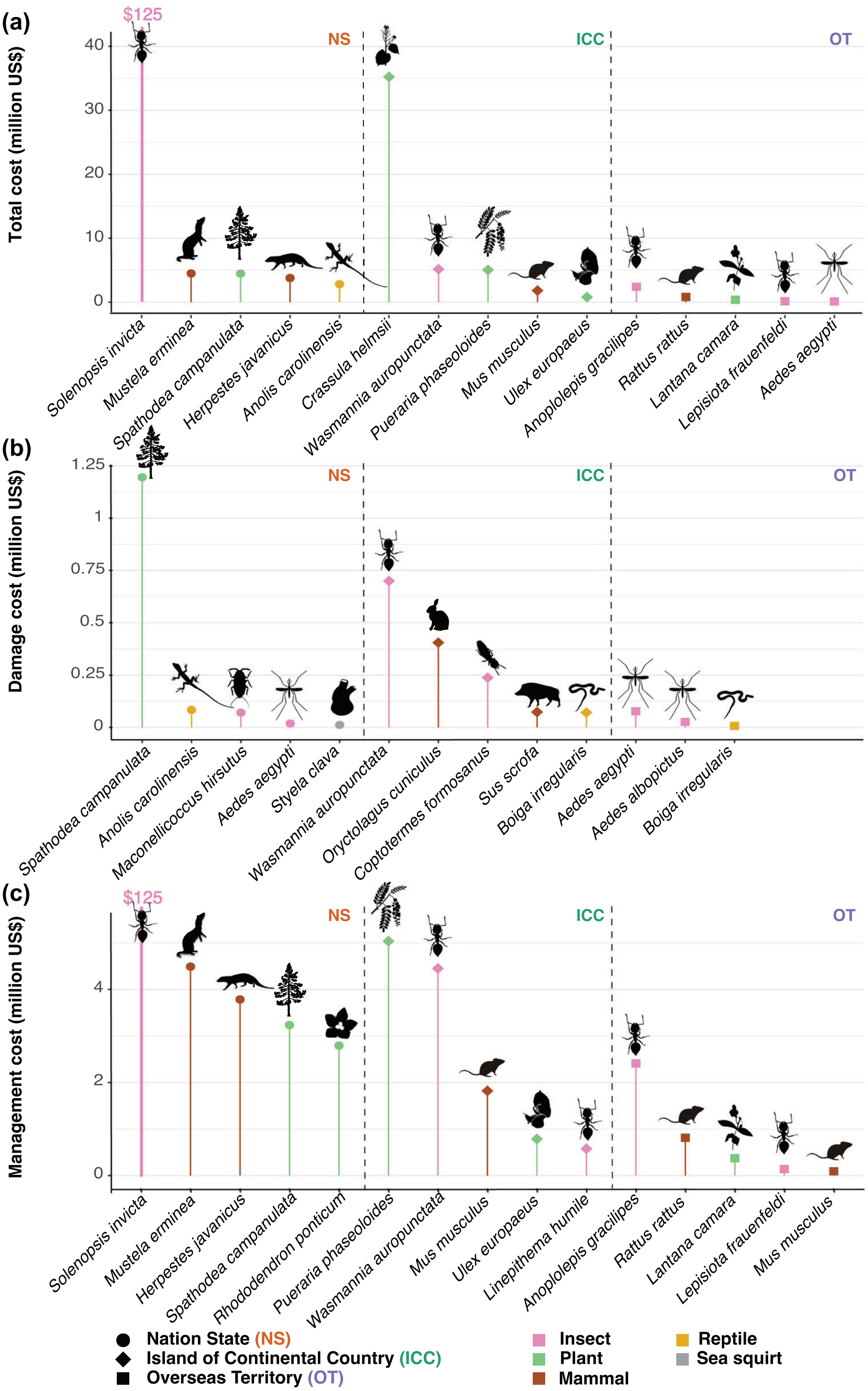

FIGURE 4 The top 5 most costly invasive species by island type for (a) all costs, (b) damage costs, and (c) management costs. All costs are in US$ km^{-2}. There was almost no overlap between species across different island types. Only 3 species had reported damage costs in overseas territories (OTs)

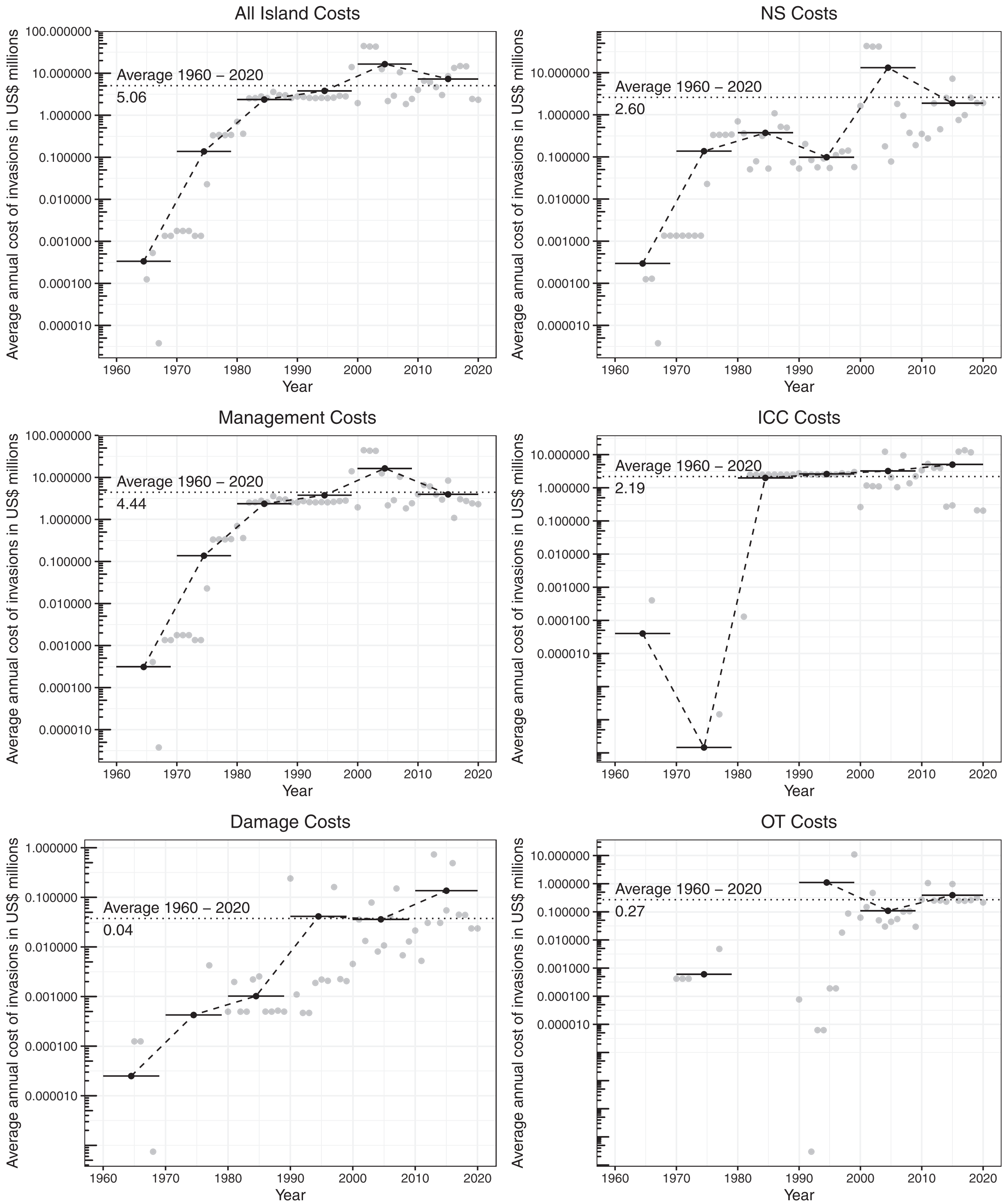

FIGURE 5 Temporal trends in reported total spending on the economic impacts of invasive alien species across different types of costs and island types (gray dots, annual values; solid lines, decadal mean; dashed lines, overall mean across all years analyzed). The *y*-axes scales are logarithmic and differ

NSs under any comparisons despite the formers' connections to wealthier governing countries. Similarly, although globally costs increased through time, trends across island types were very different. Changes in costs were broadly exponential in NSs, but only incremental in ICCs and OTs in recent decades. This likely reflects a complex combination of factors, including the continuing emergence of IAS, variation in capacity or political willingness to address these threats, and changes in available technologies.

Cost patterns

Management spending dominated the total costs incurred, comprising almost 90% of all reported costs on islands. This proportion may be even higher given the extent of mixed management–damage costs reported in ICCs (Figure 3). This substantial management-related burden contrasts with most individual countries where costs due to IAS damages consistently outstrip management expenditure (e.g., Diagne, Leroy, et al., 2021; Haubrock, Turbelin, et al., 2021; but see Ballesteros-Mejia et al., 2021). Geographically, management costs were greatest in the Pacific region, and there was a notable lack of reported management costs from island-rich, biodiverse hotspots, such as the Caribbean, Southeast Asia, and the western Indian Ocean (Kier et al., 2009). This suggests that such regions would likely benefit substantially from direct knowledge sharing, which would facilitate the coordination of approaches in such areas as biosecurity, management techniques, and legal instruments. Although such island-rich regions would benefit, the same is also true of continental countries given that management costs are already proportionately greater on islands than continental areas.

The NS category incurred the greatest costs in total and for management. Damage costs were marginally highest on ICCs, and much lower to negligible for OTs. Costs were also incurred by NSs to a far greater (although still extremely small) extent as a proportion of their GDP. This may reflect the greater impact of IAS on NS economies where, for example, damage to crops directly affects the country's capacity to feed itself and increases its import requirements (Mwebaze et al., 2010; Reaser et al., 2007). There may also be an increased reliance on unique biodiversity assets in NSs for generating income from natural capital or ecotourism than either ICCs or OTs (Ballesteros-Mejia et al., 2021; Dolins et al., 2010; Fotiou et al., 2002).

However, the low value of damage costs appears to run counter to these suggestions. There are 3 nonexclusive explanations for this trend. First, lower damage costs may reflect stricter biosecurity protocols that successfully reduce IAS arrivals to some NSs (e.g., New Zealand [Bodey et al., 2022]) and ICCs managed as strict nature reserves (e.g., the Galapagos [Ballesteros-Mejia et al., 2021]). Although such biosecurity expenditure has costs, these chiefly comprise salaries and infrastructure costs that are unlikely to be readily captured by literature searches targeted at costs specifically attributable to invasive species. Such values are not regularly included in reporting of management expenditure (e.g., because of concerns around confidentiality) in the way that equipment purchases typically are. Second, damage costs may be less frequently recorded to precise areas. For example, damage may be reported simply as occurring to forestry in a country, whereas management costs may be more regularly reported in detail (e.g., removal of a pest species from a discrete area). Because we standardized costs by area, this could mean that imprecisely reported costs in the primary source became comparatively smaller when they were applied over larger spatial scales. Finally, the limited damage costs reported in ICCs and OTs may reflect combinations of underreporting and low investment in mitigating such losses due to their relatively small contribution to the governing country's overall economy. This, coupled with small proportions of national populations resident in ICCs and OTs, their spatial isolation, and limited electoral influence, may affect the extent of reporting for these island types in comparison to NSs.

The mitigation of the costs of IAS in NSs has a clear economic rationale, but we found that costs were broadly comparable between NSs and ICCs for both management and damage. However, ICCs comprise many sparsely inhabited and uninhabited locations (e.g., Dirk Hartog Island, Australia, the Aleutian Island chain, the United States, and many tropical motu), where significant recordable economic damages or primary industry-driven management requirements are far less likely. Rather, costs in these locations probably reflect losses to biodiversity and ecosystem function. Although placing monetary values on such losses is complex, particularly where human livelihoods are negligibly affected (Kallis et al., 2013; Nunes et al., 2001; Roberts et al., 2018), ICCs provided virtually all costs incurred by the environmental sector. This reflects significant management spending on IAS control or eradication for ecological restoration following conservation models established in New Zealand (Jones et al., 2016; Veitch et al., 2011, 2019). Under this model, islands can be used to either sustain relict populations or to receive translocations of endangered endemics that may receive exceptional financial support due to their charismatic status and high extinction risk (Russell et al., 2015, 2017). This is demonstrated by the dominance of reported costs from ICCs with successful IAS eradication campaigns including Macquarie Island, Australia (Helmstedt et al., 2016), the California Channel Islands, United States (Parkes et al., 2010), the Galapagos, Ecuador (Carrion et al., 2011), and islands and islets around Mexico (Samaniego-Herrera et al., 2018). Many islands are also protected areas with varying legislative status, making IAS management either a legal requirement or a high priority. The significance of such programs is seen in the extent to which governmental organizations and other stakeholders, such as conservation nongovernmental organizations, incurred most of the reported costs across all islands.

However, it was also apparent that there was almost no consistency in the species generating management or damage costs across island types. Although a number of known impactful species surprisingly do not feature, for example, invasive *Rattus* species (Diagne, Ballesteros-Mejia, et al., 2021), this analysis was restricted to costs specifically attributed to individual species, so multispecies eradication campaigns and nonspecific damages were excluded. Potentially this variation also reflects a lack of uniformity in the reporting of costs incurred by specific species, and no doubt it also reflects some regional, latitudinal, or societal differences. It does, though, strongly suggest there is a need for greater information sharing to synergize experience across locales, particularly because many islands support a relatively homogenous suite of IAS (Capinha et al., 2015). Otherwise, such gaps (whether actual absences or simply a lack of data resolution) have the potential to produce erroneous conclusions on how to effectively allocate budgets and prioritize efforts in what is, necessarily, a triage process (Carter et al., 2021; Holmes et al., 2019). Consideration of approaches from similar contexts, such as neighboring islands, should be used to further guide management approaches, including informing horizon scanning exercises to identify potential threats and actions at local and regional scales (Ricciardi et al., 2017).

Although the number of foreign visitors or extent of imports have been considered high-risk factors for the spread of IAS (IUCN, 2018; Pretto et al., 2012), they did not act as significant predictors of IAS costs incurred on islands. Significant relationships for GDP and imports were only present when the United States (an outlier for both) was included, providing little support for these as predictive metrics. There were also quantitative differences in the reported area-corrected expenditure depending on how small an area was included. Eradications in very small areas (e.g., the detection and removal of red imported fire ants from Auckland airport [Kean et al., 2021]) produced substantial area-corrected costs, but then such rapid reactive responses likely also substantially reduced ongoing chronic costs, highlighting the importance of preinvasion management (Ahmed et al., 2022; Cuthbert et al., 2022). Importantly, qualitative patterns, for example, the dominance of management over damage costs, remained unaltered when these highly localized costs were omitted.

Underfunding or underreporting

Regardless of the type of cost, it is clear that costs from OTs are substantially lower than that on other island types. This is seen not just in absolute terms, but exceedingly so in relation to the ultimate administrative countries' GDP (Table 2). Because these costs were corrected for area, this was not simply a reflection of the smaller landmass OTs occupy. Instead, it appears that countries maintaining OTs either did not record or did not invest in IAS mitigation at any significant scale in these locales. There is no evidence to suggest that IAS presence is lower in OTs, and, indeed, this would be contrary to the global trend (Seebens et al., 2017).

Although the InvaCost database contains data only on economic values, and so may fail to capture costs of biodiversity or cultural losses, such as the ecosystem functions of extinct island endemics (Wood et al., 2017), this absence should occur across all island types. However, adding additional fields to the database and expanding the search terms used to attempt to capture such costs and losses would aid with assessing these absences across locations. Indeed, future developments could broaden the scope of the InvaCost database to link monetary values with ecological and socioeconomic impacts through integration of information from other standardized global assessments (e.g., EICAT and SEICAT [Bacher et al., 2017; Hawkins et al., 2015]), which would improve understanding of IAS impacts overall. Nevertheless, the effort expended on recording IAS costs in OTs appeared to vary substantially by location. For example, New Caledonia represented the highest number of cost entries, though not the highest spending, in the French departments, while Reunion also had substantial numbers of IAS costs. However, there was simultaneously little data on costs for other French OTs, including Mayotte and Martinique (Renault et al., 2021). This pattern of limited reporting reflects a common theme of undervaluing of the ecological richness of these locations, as is also seen in the United Kingdom (Churchyard et al., 2014). Most OTs are relatively small islands with limited internal resources, and without substantial external support, they will struggle to mitigate IAS impacts or conserve the biodiversity they support (Churchyard et al., 2014; Vaas et al., 2017). Although targeted funding to tackle the impacts of IAS exists (e.g., Darwin Initiative; www.darwininitiative.org.uk), there is clear potential for international collaboration and cooperation to enhance efficacies and synergies, particularly when adjacent countries are likely experiencing similar threats. This can include best practice resources and training courses, such as those provided under the Pacific Invasives Initiative (www.pacificinvasivesinitiative.org).

Our results also highlight the almost complete lack of reported costs from lower and lower-middle income economies, with <1% of all reported island costs occurring in such countries. This trend is seen in many aspects of ecology and conservation (Christie et al. 2021; Lynch et al., 2021; Nunez et al., 2021) and remains here despite significant efforts to incorporate non-English resources (Angulo et al., 2021). Very few lower income countries are either islands or even countries with a coastline, and the only lower income island NS—Madagascar—did have some costs recorded. However, there is a clear absence of costs from lower-middle income island nations in Southeast Asia and the Pacific (Haubrock, Cuthbery, et al., 2021). This absence is likely a product of true knowledge gaps resulting from limited studies due to reduced capacity or competing priorities and an urgent need to increase the ability to disseminate publications and information (Wallace et al., 2020). Given that several of the largely or completely absent countries represent populous and megadiverse biological hotspots (e.g., Indonesia and the Philippines), there is an urgent need to improve understanding of both the damage and management costs of IAS in these locations (Fernandez-Palacios et al., 2021; Kier et al., 2009). Likely impacts include severe negative effects on a range of indicators, including health, productivity, happiness, child poverty, ecosystem services, and biodiversity (United Nations, 2017).

Temporal trends

Given the importance of islands to global diversity, temporal trends in management costs exhibit a potentially encouraging trend. Average decadal management spending showed an increase of over 3 orders of magnitude from 1960 to 2010, and this value was consistently at least 1 order of magnitude greater than damage costs (Figure 3). Although total management expenditure for the 2010s declined slightly, this is likely to reflect publication lag times rather than a genuine reduction. However, it appears that the reasons for spending may differ across islands of differing political geography because trends differed among the 3 island types. Costs for NSs were broadly consistent with the overall pattern of increasing magnitudes of expenditure, reflecting a combination of ongoing increases in rates of introductions (Seebens et al., 2017), increased recognition of the importance of island biodiversity (Fernandez-Palacios et al., 2021), and attempts to tackle IAS at larger, more socially complex scales (Oppel et al., 2011; Russell et al., 2015; Veitch et al., 2019). However, costs on ICCs have largely flattened since the 1980s. This likely reflects early eradication efforts on small uninhabited islands (Jones et al., 2011, 2016; Samaniego-Herrera et al., 2018) that have led to substantial conservation gains (Holmes et al., 2019; Jones et al., 2016). However, translating approaches from uninhabited to inhabited islands is challenging. Logistical difficulties, social challenges, and current higher risk of failure can constrain the capacity or willingness of governments to commit to such endeavors (Carter et al., 2021; Oppel et al., 2011; Russell et al., 2015). A largely stable, although substantially lower, level of recorded costs was also seen on OTs, again suggesting comparative underinvestment or underrecording, although the complications associated with inhabited ICCs are also relevant here (Dawson et al., 2014; Renault et al., 2021).

In summary, using the most comprehensive available data on the economic impacts of IAS on islands, we demonstrated that political geography is central to the type and quantity of economic costs and likelihood of reporting costs. Across all locations, losses due to damage were far smaller than costs accrued managing IAS, likely revealing knowledge gaps as to the extent of many socioeconomic impacts of IAS and difficulties in estimating damages across all locations (Crystal-Ornelas & Lockwood, 2020). There is also a clear disparity in the effective dissemination of cost reporting in the literature, whether through differences in terminology, classifications, or access to publishing (Nunez et al., 2021; Wallace et al., 2020). Importantly, despite islands from all political geographies supporting unique biodiversity, costs were especially low in OTs. Given the importance of OTs to country-specific biodiversity, a greater focus of attention on IAS impacts would improve progress toward the Convention on Biological Diversity's Post-2020 Global Biodiversity Framework (www.cbd.int/conferences/post2020/wg2020-03/documents) in these countries. Such an approach would benefit all islands given the strong overlap between this framework and sustainable development goals (Schultz et al., 2016).

The predominance of spending on management approaches (incorporating all stages from biosecurity through to long-term control and eradication) and the continuing temporal increase in costs across all islands suggest there continues to be the potential to make substantial conservation and development gains in insular ecosystems. This includes the generation of efficiencies of scale over wider management units, regional cooperation and knowledge sharing, and innovations to enhance efficacy (Perrings et al., 2011; Russell et al., 2015). In particular, the high economic burden imposed by biological invasions on islands adds to the weight of evidence that prevention, rather than management, will better protect insular biodiversity (Ahmed et al., 2022). International cooperation and the strengthening of legal instruments would also improve approaches, for example, by addressing key invasion pathways (Turbelin et al., 2022), in turn reducing the financial costs biological invasions continue to accrue worldwide.

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ORCID

Thomas W. Bodey https://orcid.org/0000-0002-5334-9615

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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