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Research Letters

Biological invasions are as costly as natural hazards

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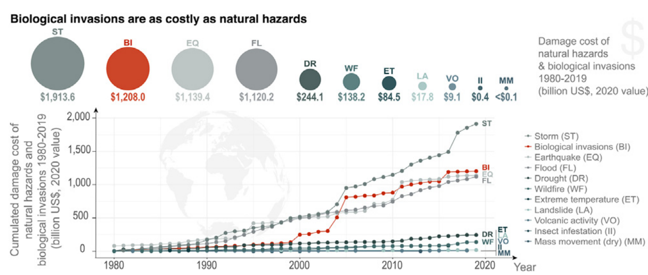
HIGHLIGHTS

- Damage costs from biological invasions and natural hazards are of similar magnitude.
- Global biological invasion costs increased by 702% from 1980–1999 to 2000–2019.
- Invasion costs increased faster than natural hazard damages over time (1980–2019).

GRAPHICAL ABSTRACT



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ABSTRACT

Natural hazards — such as storms, floods, and wildfires — can be disastrous phenomena and so can biological invasions, for which impacts are often irrevocable and insidious. Yet, biological invasion awareness remains low compared to natural hazards, and investments to manage invasions remain vastly underfunded and delayed. Here, we quantified biological invasion costs relative to natural hazards, to raise awareness and political leverage. Analysing biological invasions and natural hazards damage cost data over 1980–2019, economic losses from biological invasions were of similar magnitude to natural hazards (e.g., $1,208.0 bn against $1,913.6 bn for storms and $1,139.4 bn for earthquakes). Alarmingly, invasion costs increased faster than natural hazards over time. Similar biological invasions impact magnitudes to natural hazards and faster cost growth rates urge commensurate recognition, coordination and action towards invasions in policies.

Introduction

Biological invasions are a growing component of global environmental change (e.g. Pyšek et al., 2020). A subset of alien species — those that are invasive — have emerged as a major driver of biodiversity loss (e.g., Bellard et al., 2016) and gen-

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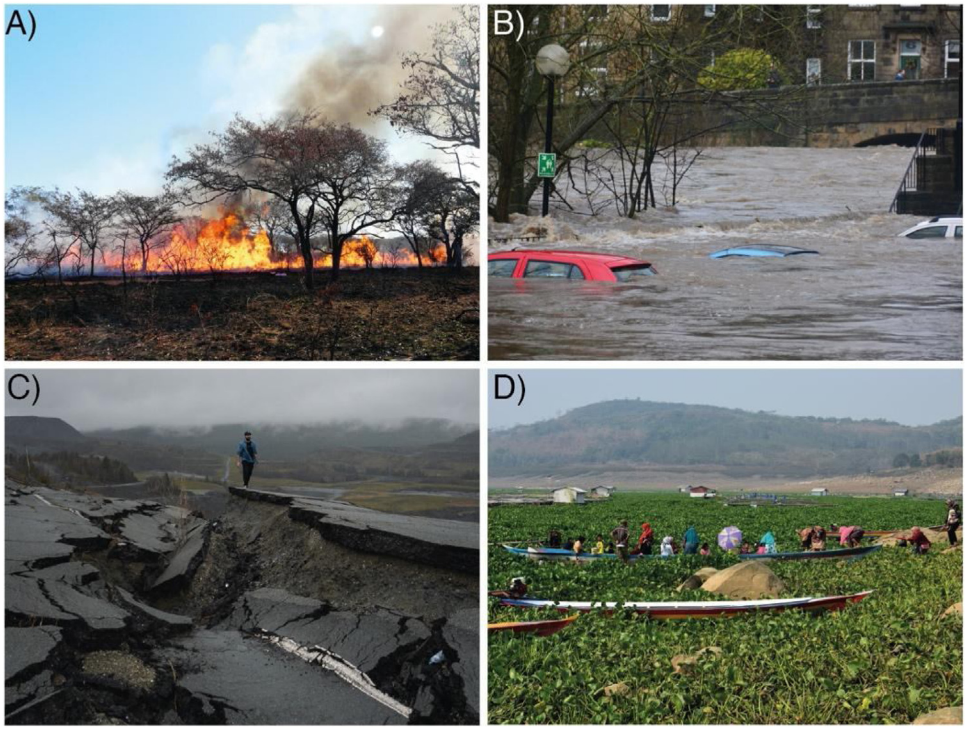

Fig. 1. Pictures of natural hazards impacts and invasive alien species. A) Wildfire, South Africa, 2014 B) Flood, Bingley UK, 2015 C) Earthquake, 2021 and D) Invasive water hyacinth clogging waterways (*Eichhornia crassipes*) Jatiluhur, Purwakarta Regency, West Java, Indonesia, 2021. Pictures by A) Anna Turbelin, B) Chris Gallagher on Unsplash, C) Dave Goudreau on Unsplash, and D) Eka P. Amdela on Unsplash.

erate massive and rising economic costs (Diagne et al., 2021). Invasive alien species (henceforth 'invasive species') are defined as species present in a region as a result of human actions with harmful impacts to societies and the environment, such as reducing crop yields, damaging critical infrastructures, and disrupting ecosystem service provisioning (Pyšek et al., 2020) (see Fig. 1). Biological invasions also exacerbate human health risks and cause hundreds to thousands of human deaths annually, through disease emergence and spread, lethal bites and stings, or complicated allergies (e.g., Mazza et al., 2014; Vilà et al., 2021). If emerging pathogenic microorganisms were to be considered as invasive species (Nuñez et al., 2020; Hulme et al., 2020; Hulme, 2020), then the annual human mortality toll of biological invasions would be far greater (HIV alone, spread from apes in Africa, was responsible for ~680 thousand deaths in 2020 worldwide, https://www.who.int/data/gho/data/themes/hiv-aids).

Surprisingly, given their huge environmental, health and socioeconomic impacts, awareness of the severity of biological invasions remains low (Courchamp et al., 2017). Investments in the management of invasions have been vastly underfunded and delayed, causing trillion-dollar impacts that could have been avoided (Cuthbert et al., 2022; Ahmed et al., 2022). Management of biological invasions has been shown to be rarely proactive and often delayed, with most countries focusing on costly post-invasion measures which are rarely successful. The underfunding towards biological invasions is also highlighted by the total lack of reported investments in management in many countries of the world (Cuthbert et al., 2022). Therefore, even if damages from biological invasions have been shown to be high, societal concern has been insufficient to warrant adequate management investment by decision makers.

This lack of awareness and concern is all the more remarkable, when natural hazards such as earthquakes, floods and wildfires have received substantial societal attention and investment for mitigation or adaptation. Indeed, biological invasions and natural hazards are comparable phenomena, with notable similarities such as their dynamics of occurrence and impact, and difficulty of prediction and control (Ricciardi et al., 2011). Although nations invest in preparedness and emergency response plans for extreme (and typically rare) natural hazards, similar precautions for invasive species are not comprehensively applied by most nations, possibly because the socioeconomic consequences of natural hazards are better understood by the public than those of invasions. Consequently, more systematic accounting is needed to accurately prioritise biological invasions to protect human assets and human lives. In the absence of actions, even after the publication of substantial economic costs to societies [now reaching $2000 bn (United States dollars) when considering damage losses and management costs between 1970–2020] (Diagne et al., 2021), there is a growing urgency to highlight the risks of ignoring biological invasions in policies, legal frameworks and decision-making processes globally. Monetary value is a metric allowing for standardised, quantitative comparison, and is understandable by a wide audience. Therefore, contextualising the size of economic costs from biological invasions relative to that of natural hazards could help to raise awareness and political leverage.

The spatial and temporal scales over which natural hazards impact the natural environment cover many orders of magnitude, ranging from landscape to large (e.g. continental) scales, and from seconds to millennia. Some natural hazards, such as avalanches or floods, can create large impacts in seconds (including direct human deaths), whilst others such as drought are more gradual in their manifestation. Impacts of invasions are likewise complex and may fully manifest only decades after introduction when invaders are already well-established (Pyšek et al., 2020; Spear et al., 2021). The concept of invasion debt means that currently impactful invaders reflect legacies of socioeconomic activities several decades ago, whereas impacts from recent aliens arriving from current pathways may have not yet been realised (Essl et al., 2011). In this regard, biological invasions may typically be considered as a slow-onset hazard, as they emerge gradually over time — but their impacts are cumulative and profound, including species extinctions, massive costs and even human deaths (Pyšek et al., 2020; Diagne et al., 2021; Mazza and Tricarico, 2018). These differences in speed and pattern of manifestation of hazards influence how humans perceive and respond to them. Despite comparable societal and ecological impacts (Ricciardi et al., 2011), sudden-onset acute hazards tend to attract more attention than slow-emerging chronic ones (Staupe-Delgado, 2019). Accordingly, slow-onset hazards may dampen societal and political awareness of risk and impede rationale to invest in long-term mitigation. Similarly, risk awareness may be influenced by the association of human fatalities with natural hazards and our bias in overestimating rare causes of death, while simultaneously underestimating common ones (Lichtenstein et al., 1978). Although both natural hazards and biological invasions may cause human fatalities (Mazza and Tricarico, 2018), deaths caused by invasions (e.g., invasive pathogen/parasite vectors or allergic reactions) are often less direct and rarely attributed solely to invaders.

Here, we quantify and compare the costs of biological invasions and natural hazards at three scales: *(i)* globally, *(ii)* regionally and *(iii)* nationally (i.e., the USA as a case study). At all these scales, our objectives were to: *(i)* compare the total costs of biological invasions to natural hazards of societal concern; and *(ii)* examine the temporal trends among biological invasion and natural hazard costs to compare their rates of change.

Materials and methods

Invasive species cost data collection and filtering

We compared biological invasion costs to natural hazards at the global scale, the regional scale and at a representative national scale with high data availability (i.e., the USA). To quantify economic losses generated by the impacts of biological invasions, we used data from the InvaCost database version 4.1 — the most up-to-date, comprehensive, standardised and robust data compilation and description of economic cost estimates associated with invasive species worldwide (https://doi.org/10.6084/m9.figshare.12668570 Diagne et al., 2020) — downloaded using the *data()* function from the invacost R package version 1.1–4 (R Core Team 2020) (Leroy et al., 2020). We filtered the database to only include costs that were actually incurred (classified as observed in the "Implementation" field) and labelled as highly reliable ("Method_reliability" field). Because cost assessments for natural hazards generally only account for direct costs, therefore omitting indirect, business interruption, intangible, and risk mitigation costs (Kreibich et al., 2014), we decided to only include damage costs ("Type_of_cost_merged" field) — economic losses resulting from direct or indirect impacts of invasive species (Diagne et al., 2020) — and explicitly exclude post-invasion management or mixed costs to avoid inflating costs attributed to biological invasions. We also constrained the data to damage costs because management spending or investment reflects a human decision making process that may lead to cost unevenness (due to e.g., government policy differences), whereas damage costs are a more standardised measure of actual, realised economic impact. The filtered dataset is available in Supplementary Material Data S1.

Highly reliable observed damage costs for the USA from invasive species were obtained by filtering InvaCost 4.1 data as described above and retaining entries attributed to "United States of America" in the "Official_country" field. We adapted the TDWG World Geographic Scheme for Recording Plant Distributions Standard (TDWG, 2001) to reclassify InvaCost field "Geographic_region" and obtain the breakdown of highly reliable observed damage costs by continental regions. The list of countries and matching regions is available in Supplementary Material Data S2.

As costs may be recorded as a single or multi-year estimate, to obtain annualised costs we expanded the database using the *expandYearlyCosts()* function from the invacost R package version 1.1–4 (R Core Team 2020) (Leroy et al., 2020) (see Turbelin, 2022).

Natural hazards cost data collection and filtering

Global and regional cost data for natural hazards are available from EM-DAT, CRED/UCLouvain, Brussels, Belgium international disasters database (www.emdat.be) — the global database on natural and technological disasters, which includes geographical, temporal, human and economic data on the occurrence and effects of more than 21,000 disasters in the world at country level, from 1900 to present. Only natural hazard events which fulfil at least one of the defined criteria are reported. These criteria include: 10 or more people dead; 100 or more people affected (e.g. injured, homeless); country of where the event occurs declares a state of emergency or an international assistance appeal. Data were downloaded on 06 April 2022 [query id x0lcUA], using the following filters: Disaster Classification: Natural; Location: Asia, Africa, Americas, Europe, Oceania; and from 1980 to 2019. As for InvaCost data, we adapted the TDWG World Geographic Scheme for Recording Plant Distributions Standard (TDWG, 2001) to reclassify the EM-DAT field "Continent" (Supplementary Material Data S3).

Natural hazard cost data for the USA were obtained via Billion-Dollar Weather and Climate Disasters from NOAA National Centers for Environmental Information (NCEI) (2022). These data were downloaded on 06 April 2022 (Supplementary material data S4). We added the USA as a national case study because of its relative data completeness to see if we obtained similar results when using a national database with different inclusion criteria of events. Weather and climate events reported in the NOAA NCEI dataset are those with direct cost (incl. physical damage to residential, commercial and government/municipal buildings, material assets within a building, time element losses, vehicles, boats, offshore energy platforms, public infrastructure and agricultural assets) equal to or above $1bn USD — which account for more than 80% of the damage from all recorded weather and climate events.

Standardizing cost values to USD 2020

To compare costs across years and between databases, we standardised all cost values to US Dollars (USD) 2020 using the consumer price index (CPI) (2010 = 100) data, which are available from the World Bank Open Data (https://data.worldbank.org/indicator/FP.CPI.TOTL). These data were downloaded using the 'wbstats' R package (version 1.0.4) (Piburn, 2020) on December 14, 2022. InvaCost cost values are expressed in USD 2017 — the methodology used to convert raw costs in local currencies for a given year to USD 2017 is described in Diagne et al. (2020). We used the function *adjustInflation()* (Turbelin, 2022) to adjust the 2017 USD cost estimate values to 2020 USD values. The function draws the 2020 CPI value (118.6905016) from the World Bank Open Data file to convert 2017 USD costs to 2020 USD costs using the following formula:

$$\mathrm{Cost(2020USD)} = (1 + ((\mathrm{CPI}_{2020} - \mathrm{CPI}_{2017})/\mathrm{CPI}_{2017})) \times \mathrm{Cost(2017USD)}$$

Natural hazard costs from the EM-DAT database are expressed in thousands of USD *(i)* in the value of the year of occurrence and *(ii)* adjusted for inflation to the current USD value — at the time of our analysis it was USD 2020. We converted the costs from thousands

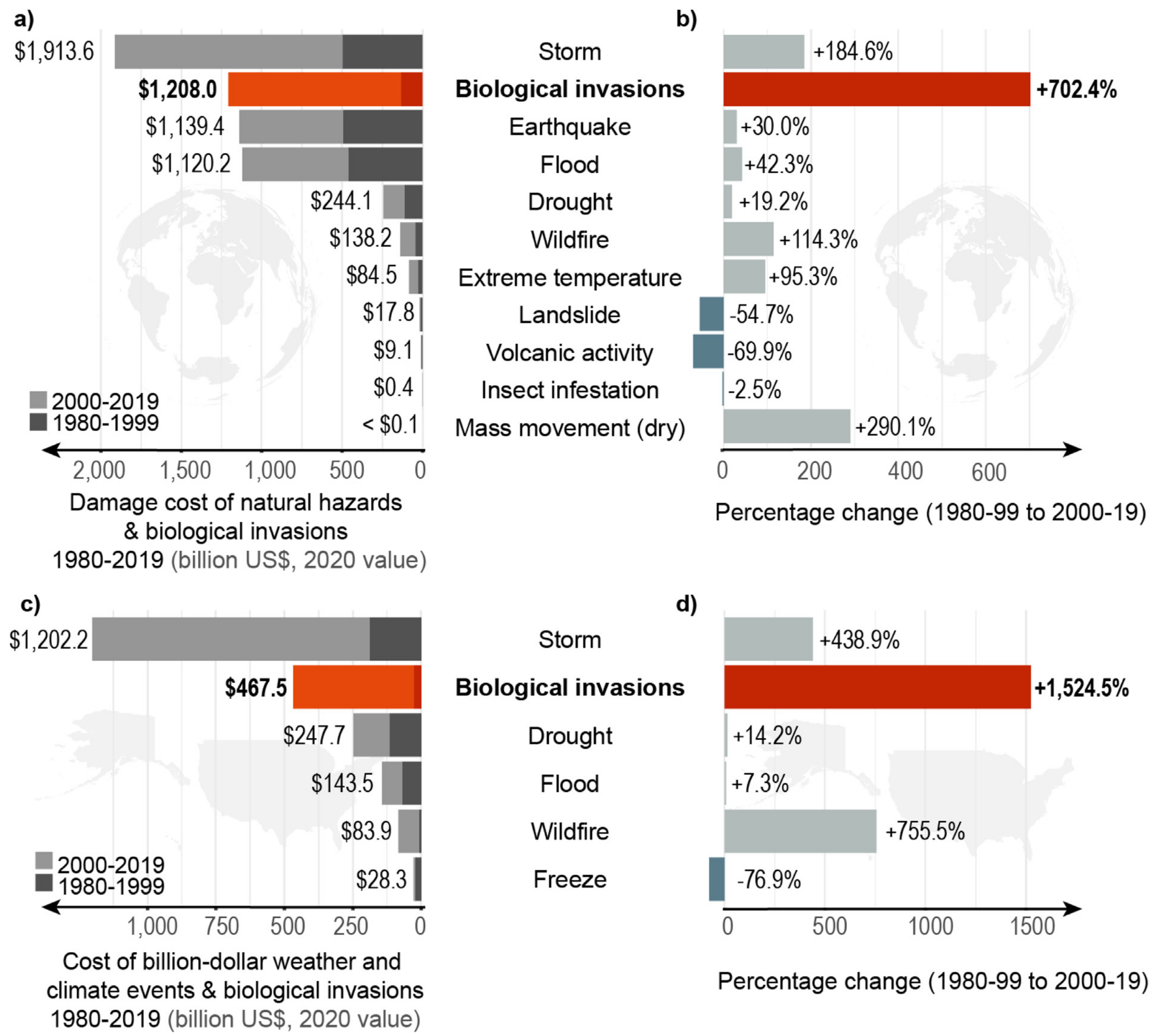

Fig. 2. Raw damage cost and percentage change of natural hazards and biological invasions for the period 1980–2019 for a), b) the world and c), d) the United States of America (USA). Damage costs of natural disasters in the world, the USA, and biological invasions are from the International Disaster Database EM-DAT (www.emdat.be), the National Centers for Environmental Information National Oceanic and Atmospheric Administration (NOAA NCEI; www.ncdc.noaa.gov), and InvaCost 4.1 (www.invacost.fr), respectively. Costs from emerging diseases are not included in biological invasions. Costs in EM-DAT are values of all damages and economic losses directly or indirectly related to the disaster; only natural hazard events which fulfil at least one of the defined criteria are reported (e.g. 10 or more people dead; 100 or more people affected). Weather and climate events reported in the NOAA NCEI dataset are those with direct cost (incl. physical damage to residential, commercial and government/municipal buildings, material assets within a building, time element losses, vehicles, boats, offshore energy platforms, public infrastructure and agricultural assets) equal to or above $1bn USD. Only observed ("Implementation" field) damage ("Type_of_cost_merged" field) costs classified as highly reliable in InvaCost ("Method_reliability" field) are included in this figure. USA damage costs were obtained by retaining entries attributed to "United States of America" in the "Official _country" field of InvaCost 4.1.

of USD to be expressed in USD by multiplying the values by 1000. As the current value adjusted for inflation will change over time, we converted the unadjusted values using the *adjustInflation()* function (Turbelin, 2022), which uses the following equation:

$$\mathrm{Cost(2020USD)} = (1 + ((\mathrm{CPI}_{2020} - \mathrm{CPI}_{yrt})/\mathrm{CPI}_{yrt})) \times \mathrm{Cost}$$

with CPI_{yrt} the CPI of the year of the event occurrence. We followed the same methodology to convert unadjusted for inflation costs of US billion-dollar weather and climate disasters provided by the NOAA NCEI.

Analyses

All analyses were conducted in R and figures were formatted in Adobe Illustrator. The R script and data are available in Supplementary Materials and/or on GitHub (Turbelin, 2022). As the aim of our study is to compare the magnitude of global economic losses from biological invasions to that of natural hazards, we calculated the overall costs by summing all cost estimates provided in the expanded dataset — see Supplementary Material Data S1. The total costs for natural hazards were obtained by summing costs in USD 2020 of all recorded events separately for the global and USA datasets.

The rate of change (ROC) between periods 1980–1999 and 2000–2019 was calculated using the following equation:

$$\mathrm{ROC} = ((\mathrm{Cost}_{2000-2019}/\mathrm{Cost}_{1980-1999}) - 1) \times 100$$

Results

Whereas the impacts by individual invasive species often accrue gradually, the collective impacts of biological invasions over time are massive (IPBES, 2019). Observed damage costs from biological invasions between 1980–2019 amounted to $1,208.0 bn globally

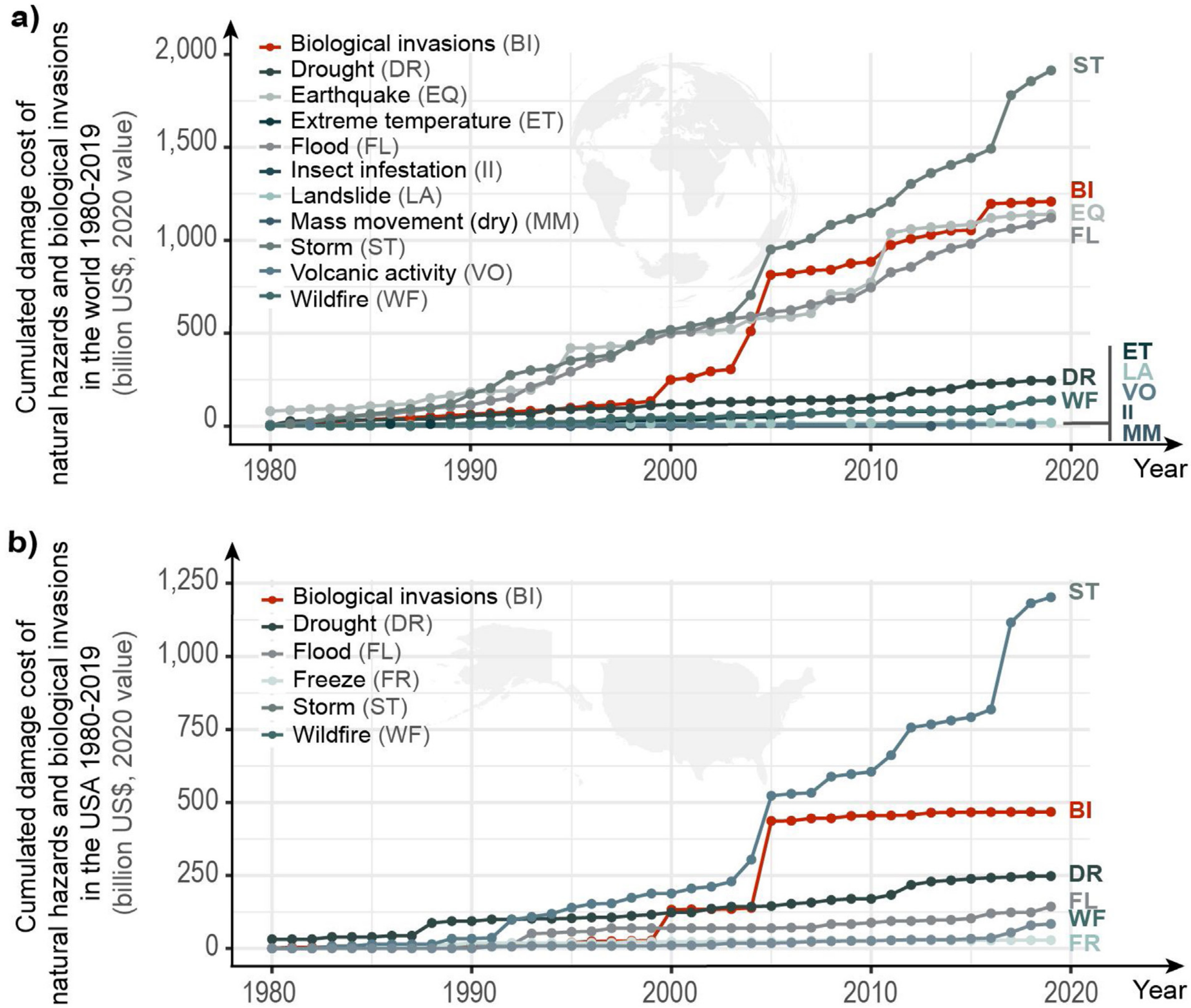

Fig. 3. Cumulated annual damage cost of natural hazards and biological invasions for the period 1980–2019 a) globally and b) the United States of America (USA). Information on the data and sources is the same as for Fig. 2.

(Fig. 2a), with a 702 % increase in reported losses from 1980 to 1999 to 2000–2019 (Figs. 2b and 3). When compared to economic losses and damage costs from natural disasters reported in EM-DAT (2022) over the same period, biological invasions were less costly than storms ($1,913.6 bn), but exceeded earthquakes ($1,139.4 bn), floods ($1,120.2 bn) and all other hazards. Similarly, when comparing reported economic losses from biological invasions in the United States of America (USA) to the cost of disaster events reported in National Centers for Environmental Information National Oceanic and Atmospheric Administration (NOAA NCEI, 2022) between 1980–2019, biological invasions damage costs ($467.5 bn) were lower than costs from storms ($1,202.2 bn), but exceeded that of droughts ($247.7 bn), floods ($143.5 bn), wildfires ($83.9 bn) and freezes ($28.3 bn) (Fig. 2c). Costs recorded in NOAA NCEI account for more than 80% of the damage from all recorded weather and climate events. Nonetheless, if increasing the costs of disaster events provided up to 100% — with biological invasion costs remaining the same — then biological invasions would still rank second. The percentage increase in biological invasions damage costs in the USA was nevertheless more than twice that of all natural hazards (Figs. 2d and 3). The ranking of biological invasions compared to natural hazards was, however, variable among continental regions, ranging from the costliest in Oceania and Pacific, to the fourth costliest in Europe and Temperate Asia (Figs. 4, S1 and S2).

Discussion

Our results suggest that damage costs from biological invasions and natural hazards are of similar magnitude, each reflecting an enormous and increasing burden on societies. There is inherent uncertainty associated with the position of economic costs from biological invasions compared to that of natural hazards, globally, regionally or within a given nation (exemplified in the USA). Cost assessments for natural hazards typically only account for direct costs and these remain under-recorded (McGlade et al., 2019). Additionally, global or national data on natural hazards costs are not always available for all impacts, but rather for selected hazards that meet a certain impact threshold (see Fig. 2 legend). Likewise, documenting the cost of biological invasions is complex and fragmentary. For example, only about 5% of known invasive species have costs reported in the literature and documented in InvaCost (e.g. 713 of 13,867 invaders reported globally) (Cuthbert et al., 2021). Even for those species, their costs are typically very conservative due to pervasive geographic and sectoral knowledge gaps (Angulo et al., 2021). In addition, whereas it can be assumed that natural hazard costs include some mitigation expenditures, our comparison is only with damage costs of biological invasions, thus explicitly excluding post-invasion management or mixed costs (an additional $339 bn between 1980–2019). Moreover, as for natural hazards, costs are most often lacking monetary valuation of

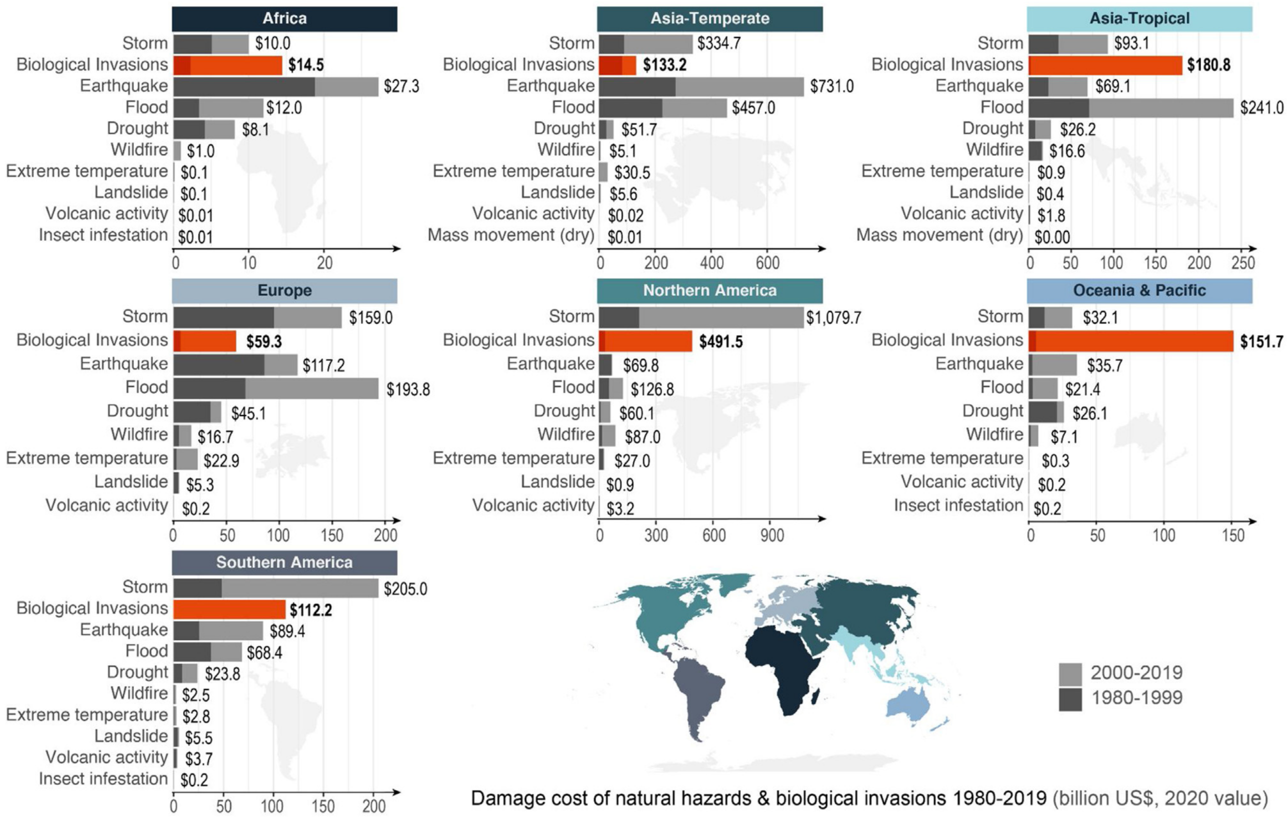

Fig. 4. Damage cost of natural hazards and biological invasions for the period 1980–2019 by geographical region. Damage costs of natural disasters and biological invasions are from the International Disaster Database EM-DAT (www.emdat.be) and InvaCost 4.1 (www.invacost.fr), respectively. All other information on the data and sources is the same as for Fig. 2.

non-market value losses, indirect impacts or impacts on ecosystem services (Diagne et al., 2020). Consequently, economic costs of biological invasions are also severely underestimated. Despite a likely cost underestimation, both global databases — InvaCost and EM-DAT — can be considered a baseline for global and regional costs of biological invasions and natural hazards, respectively, due to their robust systematic approach in collecting cost information and their 'living' nature, whereby the data are continuously reviewed. Nonetheless, costs should be considered as minimum estimates, and seen in terms of order of magnitude rather than as precise values.

Biological invasions are known to be a major driver of biodiversity loss and ecosystem service disruption (IPBES, 2019). Importantly, biological invasions can interact with multiple natural hazards to exacerbate impacts. Indeed, biological invasions can worsen flood, wildfire and drought risks by modifying ecosystem structure and function [e.g. by damaging river banks (burrowing animals), intensifying fire regimes (woody plants) and guzzling water/choking waterways (aquatic plants, see Fig. 1d); (Turbelin, 2020)]. Reciprocally, hazards associated with climate change (e.g. wildfires, droughts, floods) can promote biological invasions by disturbing or transforming landscapes, thereby changing environmental conditions and creating empty niches which are readily invaded (Diez et al., 2012). Although both natural hazards and biological invasions are difficult to predict and control, the human-mediated movement of species, unlike the occurrence of many natural hazards, could in many cases be slowed or prevented. Whereas damages may be expectedly costlier than efficient management spending due to rising economic, ecological and health impacts, management costs of biological invasions have remained one to two orders of magnitude below their damages (Cuthbert et al., 2022). Worse, of this management expenditure, a very small share has been invested proactively (3%) on measures such as prevention that mitigate future invasion impacts (Cuthbert et al., 2022). Whilst extreme natural hazards (earthquakes, wildfires, hurricanes, etc.) have a highly skewed frequency-magnitude distribution (as do biological invasions; Ricciardi et al., 2011), it is expected that affluent societies will invest in the prevention of these rare events, because their occurrence carries unacceptable costs. The same precautionary approach (investment in vulnerability reduction, rapid response, and risk assessment) should be applied to biological invasions.

Invasion impacts are often irrevocable and insidious, making this aspect of global change a severe concern for humanity that should be of greater focus in policy agendas. Perhaps even more so than for natural hazards, biological invasions require transboundary collaboration, including the need for stronger international legal frameworks to limit new invasive species introductions and spread. While regional variability in cost reporting and incurrence from biological invasions is well known (Diagne et al., 2021), costs of biological invasions remained comparable to natural hazards across all regions globally in terms of their order of magnitude. Moreover, across all regions, with the single exception of Temperate Asia, the costs of biological invasions have been rising at a much faster rate than those of natural hazards. This further underscores the urgent need for internationally-coordinated actions to address the biological invasion problem. Decision makers should prioritise proactive investments such as prevention and rapid eradications to avoid delayed, long-term control measures and damages (Cuthbert et al., 2022). In the last century, biological invasions and their impacts have increased strongly worldwide (Fig. 3), and still show no sign of saturation (Seebens et al., 2017), while climate and global land use changes raise concerns of renewed acceleration (Bellard et al., 2013, 2018; Chytrý et al., 2012). With monetary impacts from biological invasions having already increased at a higher rate than other top hazards over the last 40 years, it is plausible that — without adequate measures implemented — invasive species will remain comparable to the most impactful natural hazards in coming decades. Our results support the view that the prevention of biological invasions merits similar precautionary investments as those applied to extreme natural hazards (Ricciardi et al., 2011).

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Data accessibility statement

Data used for this study are freely available on github and online.

Competing interests

Authors declare that they have no competing interests.

CRediT authorship contribution statement

Anna J. Turbelin: Conceptualization, Methodology, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Ross N. Cuthbert:** Conceptualization, Methodology, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Franz Essl:** Conceptualization, Writing – review & editing. **Phillip J. Haubrock:** Conceptualization, Writing – review & editing. **Anthony Ricciardi:** Conceptualization, Writing – review & editing. **Franck Courchamp:** Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors report no declarations of interest.

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