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Biological invasions and their potential economic costs in Morocco

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Biological invasions pose substantial economic threats globally, yet detailed cost assessments for many Global South nations, especially in Africa, remain scarce. This study presents the first comprehensive breakdown of the potential economic costs of biological invasions in Morocco. We identified 343 invasive alien species, comprising approximately 1.11% of the country's biodiversity. Using the *InvaCost* database, we retrieved cost estimates for 137 species with available records. We calculated the mean annual cost per species, adjusted these values both socio-economically (using World Bank Purchasing Power Parity) and climatically (via Köppen climatic regions), and extrapolated them based on species prevalence in Morocco. This yielded an estimated annual economic impact ranging from US$1.14 billion (conservative adjusted value) to US$5.13 billion (maximum scenario). Across all estimations, damage costs consistently exceeded management costs by one or two orders of magnitude. Plant feeding insects such as *Phenacoccus madeirensi*, *Bemisia tabacc*i, and *Cydia pomonella* emerged among the costliest species, threatening agriculture and food security. High-impact animals included the Asian tiger mosquito (*Aedes albopictus)* and the brown rat (*Rattus norvegicus)*, both affecting public health and social welfare. In freshwater systems the common carp (*Cyprinus carpio*) imposed substantial fisheries losses. Invasive plants, particularly *Euphorbia* and *Cenchrus* species, were also widespread and contributed heavily to projected costs. Despite challenges in extrapolating cost data from other regions, this study underscores the urgent need for more research and for targeted management and policy interventions to minimize the spread of invasive species and reduce their economic toll. Proactive measures in Morocco, coupled with international collaboration, will be critical to mitigating this socio-ecological crisis and ensuring long-term sustainability.

Keywords Invasive species, Economic impacts, Management strategies, Morocco, Biological invasions, InvaCost

Globalization has led to unprecedented growth in the number, reach, and impact of biological invasions, with adverse effects on ecological and socioeconomic systems worldwide[1,2]. The increase in biological invasions is primarily due to the intensification of international trade and transport networks, resulting in the proliferation of pathways for the introduction and establishment of invasive alien species[3–5]. Biological invasions are considered as a major driver of global change, along with land-use and climate changes, which threaten ecosystems by altering biodiversity and functioning of ecosystems[6,7], resulting in severe negative impacts on ecosystem services, human health, food security, and national economies[1]. Despite the substantial threat, the ability to prevent and effectively mitigate biological invasions has remained inadequate in numerous countries[8,9]. For most taxonomic groups, the rate of first records has been steadily increasing annually, with no sign of saturation in the long term[10]. Future projections indicate that this upward trend will persist, and often accelerate, at least for the next three decades[11]. Countries with a high level of economic activity face increased vulnerability to

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harm from biological invasions, and more often document the presence of alien species[12,13]. However, they also possess greater potential to mitigate such damage, rendering them at lower risk than nations with more limited resources and lower import levels. Consequently, a nation's economic capability partially determines the efficacy of investing in the detection, control and prevention of invasive species. Developing economies such as those in the African continent, with fewer resources directed towards tackling ecological crises, will likely experience more dire impacts of biological invasions[14,15].

Intense research efforts in invasion science over the last few decades have provided a more comprehensive understanding of the environmental impacts of invasive alien species[16], but only recently have there been major developments in the evaluation of their economic impacts[17,18]. Invasive species are estimated to have cost more than US $423 billion annually globally and have been increasing four-fold every decade since the 1970s[9]. With much progress in cost collection and standardization, economic analyses have provided cost assessments at various geographical scales, for different countries and taxonomic groups, various habitats, and several economic sectors[18–23]. Moreover, numerous studies have shown that allocating greater investments toward prevention and other management measures during the initial stages of biological invasions increases the chances of attaining overall net benefits[24–28]. Given that prevention outweighs the efficacy of post-invasion mitigation and restoration, management strategies should prioritize early intervention in the invasion process[15,27]. Such an intervention would involve rapid response, risk assessments, managing pathways and vectors, and early detection[1]. Building global collaborations and promoting evidence-based innovations are essential to effectively mitigate the ecological and economic impacts of invasive species. To that end, resources for minimizing the negative effects of invasive species should be allocated based on comprehensive assessments of their distribution and economic impact, a practice currently deficient in most countries worldwide[29]. However, to fully realize the benefits of effective management, more effort must be made to improve data availability, particularly in emerging countries integrated into global trade[26].

Morocco, situated in the northwest corner of Africa, is just 15 km from Europe across the Strait of Gibraltar. It boasts a rich history as an international commercial hub and is one of Europe's largest trading partners in Africa. Indeed, it serves as a vital transportation node and commercial intermediary for numerous African nations, particularly those located in the hinterland. The country's geographical diversity is evident in its extensive coastline, stretching 3500 km along the Atlantic and the Mediterranean oceans. Morocco features three major topographical zones, each with its unique characteristics. The verdant plains in the north thrive as agricultural centers, while the Rif region in the extreme north showcases a blend of plains and mountains. Dominating the landscape, the Atlas Mountains serve as the country's backbone. The climate across Morocco exhibits significant variation, transitioning from a Mediterranean climate in the northern coastal regions to mountainous areas with winter snow, and extending to extremely arid deserts in the south. This diversity in ecosystems, alongside high arrival rates of incoming alien species via trans-Mediterranean and trans-Atlantic routes of trade, as well as transport and tourism, makes the country increasingly susceptible to the introduction of many alien species, some of which may become invasive. However, there are currently no studies estimating the distribution and economic impacts of these species in Morocco, nor identifying the regions and sectors most adversely affected. From there, more research effort is required, given, for example, the presence of invasive species with considerable negative economic impacts[30], such as the tomato leaf miner[31] and the silver nightshade, which pose a threat to various crops in Morocco[32]. Furthermore, the most recent evaluation of the cost of environmental degradation to Moroccan society, estimated at approximately US$ 3.9 billion or 3.5% of the country's GDP in 2014, did not include an assessment of biological invasions[33].

Currently, the management of biological invasions in Morocco and the wider Maghreb region primarily revolves around implementing restrictive measures, preventing introductions, and controlling and handling harmful exotic species. However, these efforts are across various legal texts from different institutional structures and enforced by various competent services, often lacking comprehensive knowledge of invasive species. Better coordination among these services is required, leading to less fragmented governance and more effective collaboration. Additionally, the scarcity of data on invasive species, including inventories, prioritization, introduction pathways, propagation dynamics, and their responses to environmental pressures, hampers integrated research efforts. As a result, the effective management of these species remains challenging, making it difficult to accurately estimate the economic and biodiversity costs[34].

The *InvaCost* database provides the most current, comprehensive, and standardized compilation of global economic costs linked to biological invasions[17]. Through various analyses, this database has facilitated descriptive studies on the economic impacts of invasive species across different regions and countries[35–39]. In particular, the costs of invasive species in Africa have been examined[14], revealing lower reported costs than in other continents such as North America[39], Europe[36], or Asia[38]. Also, there is a notable geographic imbalance in research efforts and financial resources, with a significant portion of African costs data originating from South Africa[40,70]. Despite concerted efforts, the availability of cost data specific to Morocco within the *InvaCo*st database remains limited, even following thorough searches in non-English languages[19]. Such unavailability of data underscores the need for compiling comprehensive lists of invasive species and mapping their distribution across Morocco to better understand their potential economic impacts. Our study aims primarily to provide a state-of-the-art overview of alien invasive species in Morocco, raise awareness about their potential impacts, and serve as a preventative approach to highlight emerging threats. Additionally, it seeks to stimulate further research to address the significant knowledge gaps in the regions. Here, we provide a projected cost assessment, drawing upon a global analysis of invasive species currently present in the country.

Results

Observed invasive alien species in Morocco

Based on a review of biodiversity databases, published papers, and other materials (Table S1), we compiled species reported as invasive in Morocco (Fig. 1). By normalizing and harmonizing nomenclature using the GBIF Backbone Taxonomy and removing duplicates, we identified a total of 551 invasive species cited in the literature as established in the country. After verifying native status through expert consultation and cross-referencing multiple authoritative databases (e.g., BIEN and WCVP for plants; WoRMS, AlgaeBase, GRIN Global, IUCN, and others for animals, algae, and fungi), the list was refined to 343 IAS introduced to Morocco.

Of these 343 IAS introduced to Morocco, 28.9% ($n=99$) have direct cost data documented in the *InvaCost* database, while 23.0% ($n=79$) have cost data available for closely related sister species. The remaining 48.1% ($n=165$) lack any cost entries (Fig. 2a.). After filtering for only reliable estimates—those reported, observed and traceable—the final dataset included cost data for 137 species (80 with direct cost data entries and 57 sister species), excluding unreliable or extrapolated estimates. Of these 137 species, 44 lacked georeferenced occurrence data, while 93 had documented occurrences in Morocco in the GBIF database (Table S1).

Among the 137 invasive species with recorded costs, 64.7% ($n=88$) were plants, 33.1% ($n=46$) were animals, 1.5% ($n=2$) were other taxa, and 0.7% ($n=1$) were bacteria. The subset of the 93 invasive species with recorded costs that also had occurrences was likewise dominated by plants, although at a higher proportion, 73.1% ($n=68$), followed by vertebrates 11.8% ($n=11$), arthropods 9.7%, ($n=9$), and other taxa 5.4% ($n=5$). In contrast, the 207 invasive species with no recorded costs in *InvaCost* were mainly animals 56.7% ($n=118$), followed by plants 40.4%, ($n=84$), Chromista 1.4% ($n=3$), and fungi 1% ($n=2$). The taxonomic distribution of cost-associated locations of invasive alien species in Morocco is illustrated in Fig. 2b.

Considering the invasive alien species established in Morocco with recorded costs and locations, plants emerged as the predominant taxonomic group (Fig. 3). Among the most widespread are *Nicotiana glauca* (tree tobacco) recorded at 288 locations, *Ricinus communis* (castor bean) at 211, *Oxalis pes-caprae* at 179, *Arundo donax* (giant reed) at 127, and *Schinus molle* (false pepper) at 100 locations. Other frequently observed plants include *Lycium ferocissimum* (77 locations), *Arctotheca calendula* (76), *Opuntia ficus-indica* (71), *Agave americana* (67), and *Datura stramonium* (59).

Among animals, the freshwater fish *Gambusia holbrooki* is notable, with 57 recorded occurrences illustrating its successful spread in freshwater habitats. Other widespread animal invasive species include the Mediterranean fruit fly (*Ceratitis capitata*, 10 locations), Norway rat (*Rattus norvegicus*, 9 locations), Ruddy duck (*Oxyura jamaicensis*, 8 locations), cotton leafworm moth (*Spodoptera littoralis*, 8 locations), and pumpkinseed fish (*Lepomis gibbosus*, 7 locations). Most other animal species are recorded at fewer than 5 locations, reflecting a moderate spatial spread relative to plants.

Estimated costs of invasive alien species in Morocco

Costs obtained from *InvaCost* for the 137 IAS were expanded to annual costs, comprising 1,817 cost entries for the 80 invasive species and 887 cost entries for the 57 sister species (see workflow in Fig. 1). Costs were classified according to type (management or damage) and spatial scale (country-level or site-level). For site-level costs, we estimated annual costs by multiplying the *InvaCost* per-site annual cost by the number of GBIF occurrences of that species in Morocco. For country-level costs, we used mean annual *InvaCost* values, and treated them separately from site-level estimates due to differing cost-allocation assumptions (see Methods, subsection Spatial scales of the costs). Costs were adjusted using (i) a Purchasing Power Parity (PPP) ratio based on *per capita* GDP of the country with original costs relative to Morocco, and (ii) Jaccard similarity index (values ranging between 0.5 and 1) comparing Köppen climate subregions between Morocco and the countries with original costs (see Methods, subsection Socioeconomic and climate adjustments of the costs from other countries, Fig. 1). These two adjustment procedures produced conservative lower-bound estimates, while unadjusted estimates created upper-bound and maximum-scenario estimates. We separately report country- and site-level costs as complementary perspectives (Table 1).

The cumulative global annual economic costs estimated for 137 invasive alien species in Morocco are likely between US$ 1.57 billion and US$ 2.47 billion at the country level, and US$ 1.14 billion and US$ 5.13 billion at the site level (Table 1). At the country level, damage costs were two orders of magnitude higher than management costs: US$ 1.47–2.32 billion for damage versus US$ 97.60-149.32 million for management. However, at the site level, management costs had a higher maximum scenario than damage costs: US$ 83.21 million-3.60 billion for management versus US$ 1.06–1.56 billion for damage (Table 1).

Cost breakdowns by taxonomy, typology and impacted sector

At the country-level, 50 invasive alien species had available costs from other countries that could be extrapolated to Morocco. The ten most expensive species (> US$ 50 million, Fig. 4a; Table 2) included five insects representing Hemiptera, Lepidoptera (two species), Diptera and Tysanoptera, and five plants from the Poales (two *Sporobolus* species and three *Cenchrus* species).

The costliest insect was *Phenacoccus maderiensis* (Hemiptera; US$ 886.3 million; adjusted costs), inferred from its sister species *P. solenopsis* in India, where it causes severe agricultural losses in cotton fields. *Cydia pomonella* (codling moth; Lepidoptera; US$ 245.4 million; adjusted costs) ranked second, with costs derived from China where it damages agriculture, while *Ceratitis capitata* (Mediterranean fruit-fly; Diptera; US$ 89.9 million; adjusted costs) had costs from Argentina, reflecting both crop losses and high management expenditures. *Spodoptera littoralis* (African cotton leafworm; Lepidoptera; US$ 85.5 million; adjusted costs) was inferred from its sister species *S. frugiperda* (fall armyworm) in Africa, where it devastates maize production and incurs control costs. *Frankiniella occidentalis* (western flower thrip; Thysanoptera; US$ 53.1 million; adjusted costs) was associated with agricultural crop losses in Norway.

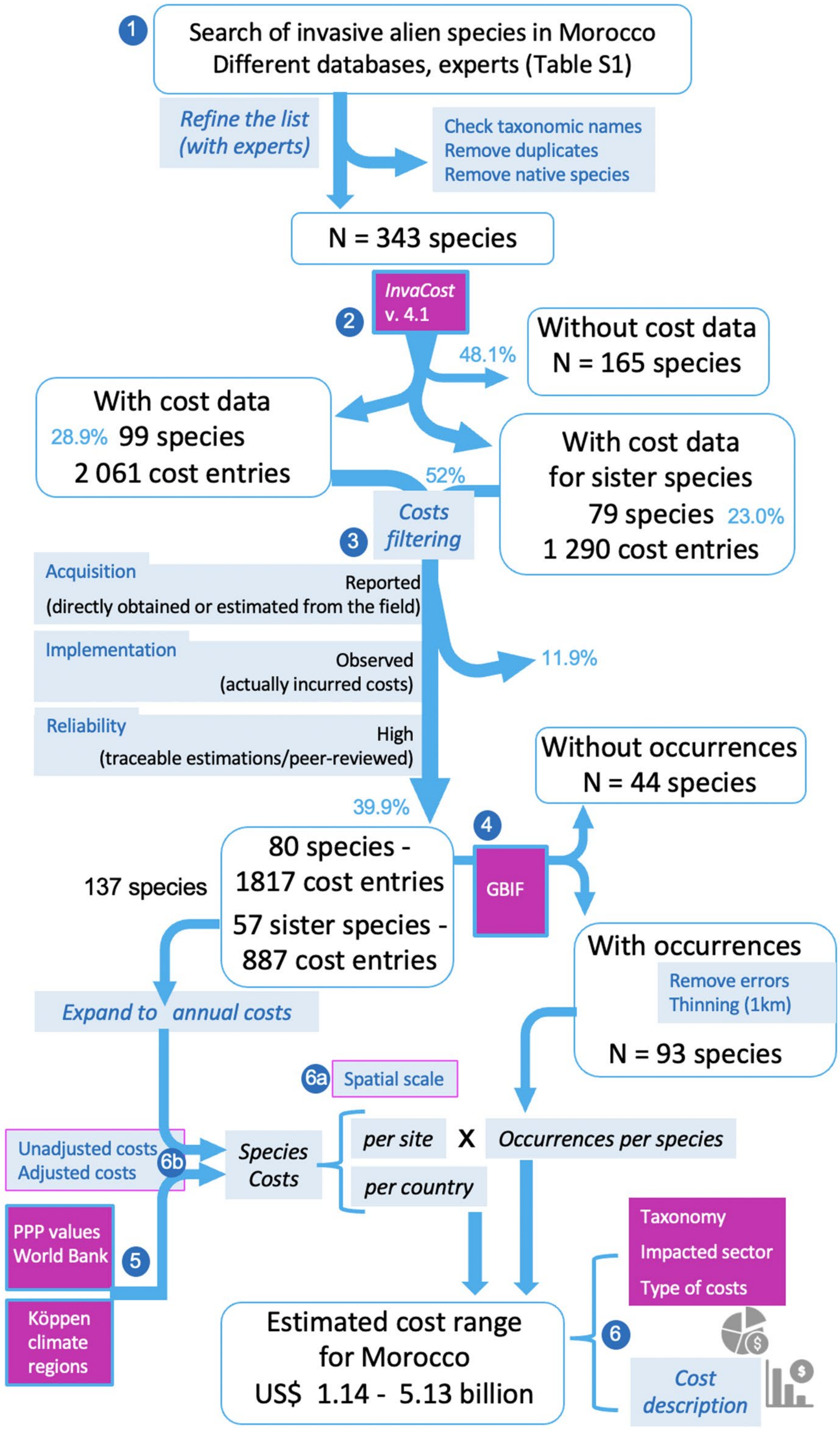

Fig. 1. Workflow summarizing the methodological steps used to estimate costs for Morocco: (1) Compilation of the list of invasive alien species in Morocco from various databases and expert assessments. (2) Identification of species with recorded costs in InvaCost or with closely related "sister species" that have costs in InvaCost. (3) Filtering to retain robust costs and expanding cost estimates. (4) retrieval of species occurrences in Morocco using GBIF. (5) Adjustment of estimated costs using World Bank purchasing power parity values and climate similarity to reflect Morocco's economic and environmental context. (6) Presentation of the estimated costs for Morocco separately by spatial scale (country- and site-level annual costs) and for adjusted and unadjusted annual costs (6a and 6b, respectively).

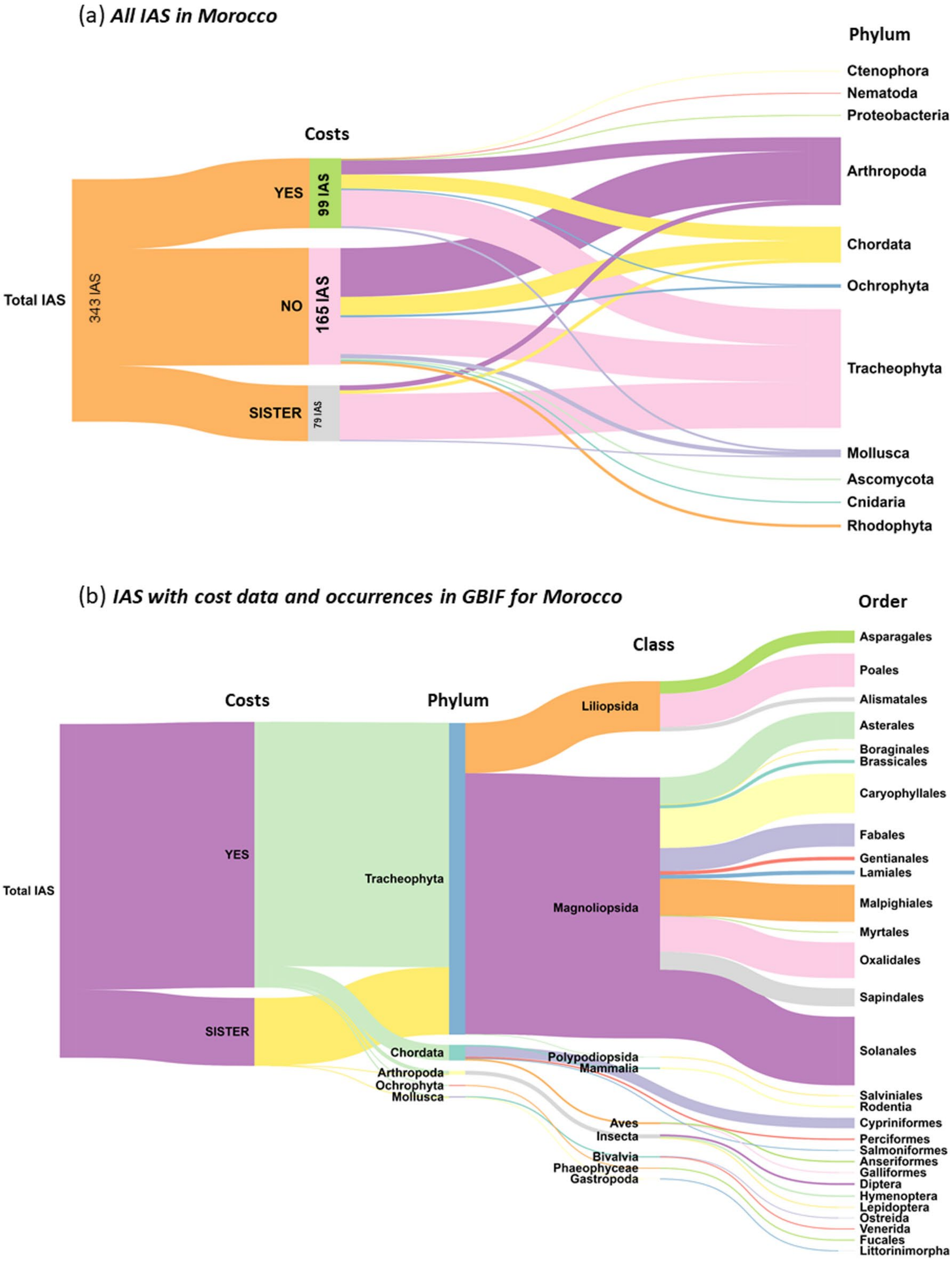

Fig. 2. (**a**) Comprehensive Taxonomic Visualization of Invasive Alien Species (IAS) in Morocco. The Sankey diagram illustrates the taxonomic distribution of invasive alien species in Morocco categorized by economic cost status. The first node represents the total number of IAS recorded. The second node divides species into three cost-related groups: IAS with documented economic costs (YES), IAS without documented costs (NO), and IAS with costs reported for closely related "sister species" in InvaCost (SISTER). The final node breaks down these groups by phylum, showing the number of IAS within each taxonomic category. The width of flows corresponds to species counts, highlighting the relative proportions of taxa across cost categories. (**b**) Taxonomic distribution of IAS that have cost data and occurrences in GBIF for Morocco. The Sankey diagram presents the number of occurrence locations for IAS present in Morocco that have documented economic costs, categorized taxonomically by phylum.

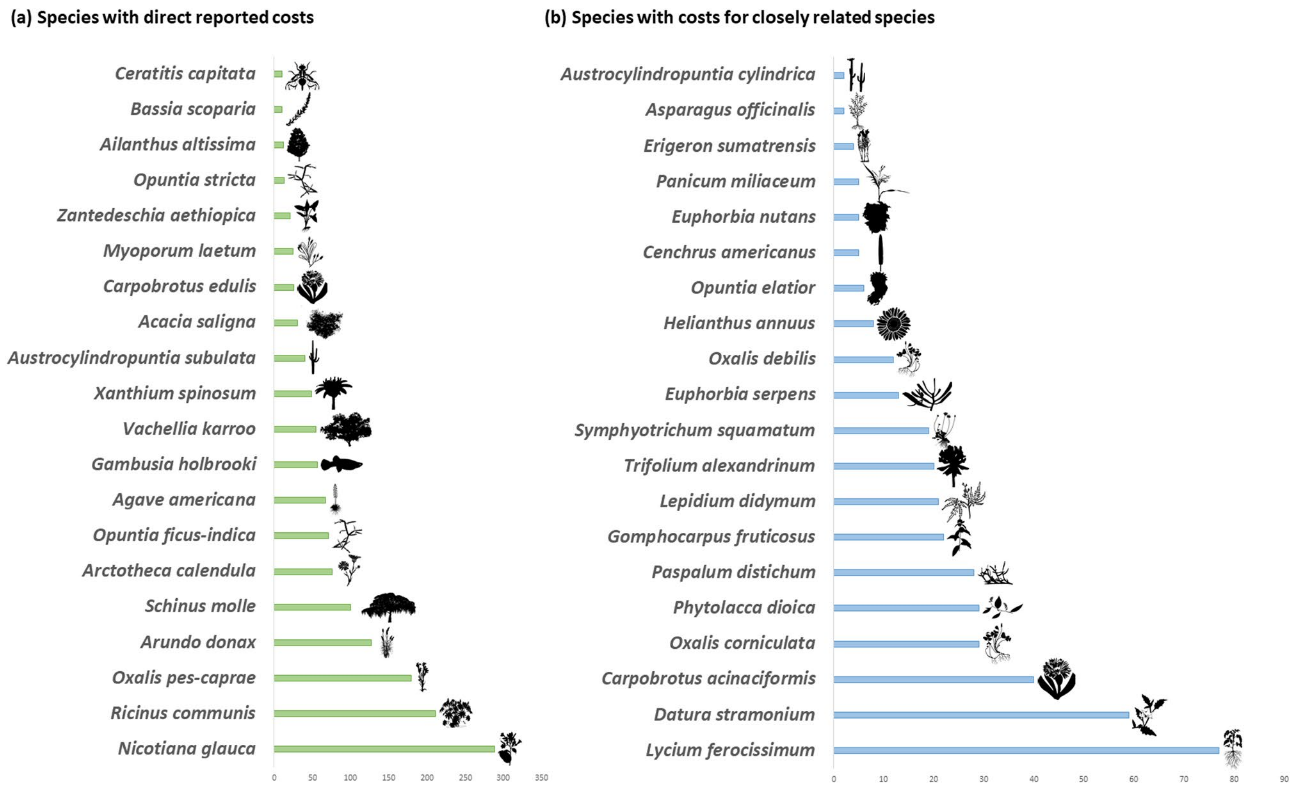

Fig. 3. Number of occurrence locations in Morocco for invasive alien species recorded with economic costs in the InvaCost database. The bar graph shows only the top 20 widespread species. (**a**) Species that have direct reported costs while (**b**) shows species that have only costs for closely related species. Species silhouettes are included to visually represent taxonomic identity. (sourced from PhyloPic).

	Spatial scale	Adjusted cost (US$ million)	Unadjusted cost (US$ million)
Total costs	Country level	1,571. 07	2,470. 31
	Site level	1,142. 38	5,132. 17
Damage costs	Country level	1,473. 47	2,320. 98
	Site level	1,059. 16	1,562. 80
Management costs	Country level	97. 60	149. 32
	Site level	83. 21	3,569. 38

Table 1. Total annual costs (2017 US$ millions) for Morocco are estimated with a lower bound (adjusted costs, conservative) and an upper bound (unadjusted costs, maximum scenario), and at two different Spatial scales (country level and site level - i.e. Corrected by the number of occurrences within the country) depending on the data available in InvaCost. Total costs report cumulative global annual economic costs estimated for 137 invasive alien species in Morocco, and these amounts are divided by the type of cost: damage and management.

For plants, costs of the two *Sporobolus* species (US$ 38.5 million; adjusted costs) were derived from sister species of the same genus reported in Australia for research programs on control and management, while costs for the three *Cenchrus* species came from *C. clandestinus* (US$ 36.1 million; adjusted costs) in Argentina, where it was reported to cause rice yield losses.

At the site level, 110 invasive alien species had available costs in other countries that could be extrapolated to Morocco. The ten species with the highest costs (> US$ 20 million; adjusted costs; Fig. 4b; Table 2) included five insects, two vertebrates (a mammal and a fish), two plants, and one mollusc. The codling moth, *C. pomonella* (US$ 217.07 million; adjusted costs) was the most expensive invasive alien species with costs reported for production losses (e.g., rejection of trucks with infected fruits) in Argentina and China, and management costs to control or eradicate the moth in Argentina, Canada and China. The white fly *Bemisia tabaci* was the fourth costliest species (Hemiptera; US$ 122.37 million; adjusted costs), and their costs were crop losses coming from different sites in the United States (California and Arizona) and Mexico (Mexicali valley). Another Lepidoptera, the African cotton leafworm (*S. littoralis*; US$ 122.12 million; adjusted costs) was also inferred (as for the country-level costs) from its sister species the fall armyworm in various sites in India and Ethiopia, causing a

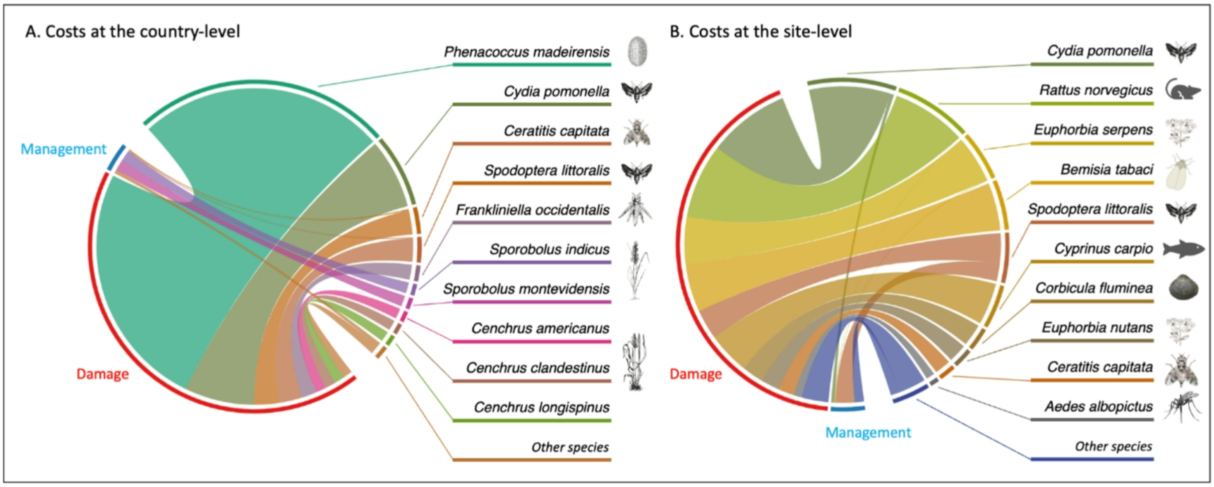

Fig. 4. Estimated adjusted costs associated with the invasive alien species in Morocco, categorized by type of cost (red for damage and blue for management). (**A**) Costs estimated based on species with available costs at the country level. (**B**) Costs estimated based on species with available costs at the site level and occurrences in GBIF for Morocco.

	Species	Adjusted cost (US$ million)	Unadjusted cost (US$ million)	Kingdom	Order
A	*Phenacoccus madeirensis*	866. 27	1, 299. 40	Animalia	Hemiptera
	Cydia pomonella	245. 45	396. 49	Animalia	Lepidoptera
	Ceratitis capitata	89. 88	129. 77	Animalia	Diptera
	Spodoptera littoralis	85. 51	167. 79	Animalia	Lepidoptera
	Frankliniella occidentalis	53. 08	96. 50	Animalia	Thysanoptera
	Sporobolus indicus	38. 52	47. 11	Plantae	Poales
	Sporobolus montevidensis	38. 52	47. 11	Plantae	Poales
	Cenchrus americanus	36. 32	67. 17	Plantae	Poales
	Cenchrus clandestinus	36. 15	66. 27	Plantae	Poales
	Cenchrus longispinus	36. 15	66. 27	Plantae	Poales
B	*Cydia pomonella*	217. 07	343. 62	Animalia	Lepidoptera
	Rattus norvegicus	191. 28	312. 86	Animalia	Rodentia
	Euphorbia serpens	122. 95	194. 16	Plantae	Malpighiales
	Bemisia tabaci	122. 37	173. 22	Animalia	Hemiptera
	Spodoptera littoralis	122. 12	149. 23	Animalia	Lepidoptera
	Cyprinus carpio	107. 08	128. 84	Animalia	Cypriniformes
	Corbicula fluminea	56. 72	80. 44	Animalia	Venerida
	Euphorbia nutans	47. 29	74. 68	Plantae	Malpighiales
	Ceratitis capitata	41. 25	3, 448. 15	Animalia	Diptera
	Aedes albopictus	21. 72	32. 57	Animalia	Diptera

Table 2. The ten species with the highest adjusted costs (2017 US$ millions). (A) Costs estimated from species with available costs at the country level, and (B) costs estimated from species with available costs at the site level (combined with GBIF occurrence records for Morocco).

variety of different costs and affecting mainly the agriculture sector (damage losses in maize) and authorities and stakeholders (control, eradication and research). Two diptera were in the last position of the tenth costliest invasive species at the site level, and were the Mediterranean fruit-fly (*C. capitata*; US$ 41.24 million; adjusted costs) with agricultural losses in crops reported for Australia, and the Asian tiger mosquito (*Aedes albopictus*; US$ 21.72 million; adjusted costs) for which reported costs were medical care (from Chikungunya and West Nile virus) and came from different sites in France, Italy and Greece.

Regarding the vertebrates, the rodent *Rattus norvegicus* (US$ 191.28 million; adjusted costs) was the second costliest with damage costs from the United Kingdom and China, impacting health, public and social welfare. The highest costs for Cyprinus *carpio* (US$ 107.08 million; adjusted costs) corresponded to an analysis done in the Gippsland lakes in Australia which included losses to the native commercial fishery and to recreational fishing, tourism and commerce. There are also some minor management costs regarding control and eradication of this carp from different lakes in Australia and Spain. The Asiatic clam, *Corbicula fluminea* (Venerida; US$ 56.72 million; adjusted costs) was reported to cause damage losses in a nuclear plant in the United States.

Finally, two *Euphorbia* plant species (*E. serpens*; US$ 122,95 million, and *E. nutans*; US$ 47.29 million; adjusted costs) were in the top ten costliest species, but the costs were retrieved for two sister species (*E. stenoclada* and *E. esula*). Damage losses affecting the environment, the public and social welfare and the authorities and stakeholders were reported from different sites in the United States; while management costs, mainly control, were reported in different sites of Canada and Spain.

Regarding impacted sectors (Fig. 5), agriculture bears the highest costs, particularly from the most damaging insects and plants, as well as some birds such as the ruddy duck (*Oxyura jamaicensis*) or the pheasant (*Phasianus colchicus*). Authorities and stakeholders also incur substantial expenses for control and eradication of species like rodent and invasive fishes. Crustaceans and molluscs, including the red swamp crayfish (*Procambarus clarkii*) and the Asian clam (*Corbicula fluminea*), primarily affect fisheries, with additional repercussions on public and social welfare (e.g., water-related industries).

Geographic distribution of cost

The geographic distribution of costs reflects both the occurrence records and associated site-level adjusted costs for each species (Fig. 6). Costs are unevenly distributed across Morocco, with higher costs concentrated in major urban and coastal areas, including Marrakech, Casablanca, Tangier and Rabat, while other regions show lower estimated costs.

The region with the greatest share of IAS-related costs is Marrakech-Safi (US$ 335,128,837.24), followed by Casblance-Settat (US$ 191,698,455.86), Rabat-Sale-Kenitra (US$ 122,196,490.04), and Tanger-Tetouan-Al Hoceima(US$ 118,889,300.22). Other notable but smaller totals include Draa-Tafilalet (US$ 67,572,996.66), Fes-Meknes (US$ 54,931,349.22), Oriental-Rif (US$ 39,793,891.86), and Souss-Massa (US$ 32,923,976.43). Regions with minimal estimated costs include Beni Mellal-Khenifra (US$ 502,065.84), Guelmim-Oued Noun (US$ 292,409.33), and Laayoune-Boujdour-Sakia El Hamra (US$ 277,277.31), while Dakhla-Oued Ed-Dahab recorded no costs (Fig. 6).

Discussion

This study presents the first comprehensive analysis of invasive alien species in Morocco, providing quantitative estimates of their potential economic costs and mapping their geographic distribution. The urgency of this research stems from the need to identify invasive alien species and map their spread across Morocco, which is a prerequisite for assessing both their ecological and economic impacts. We identified 343 invasive alien

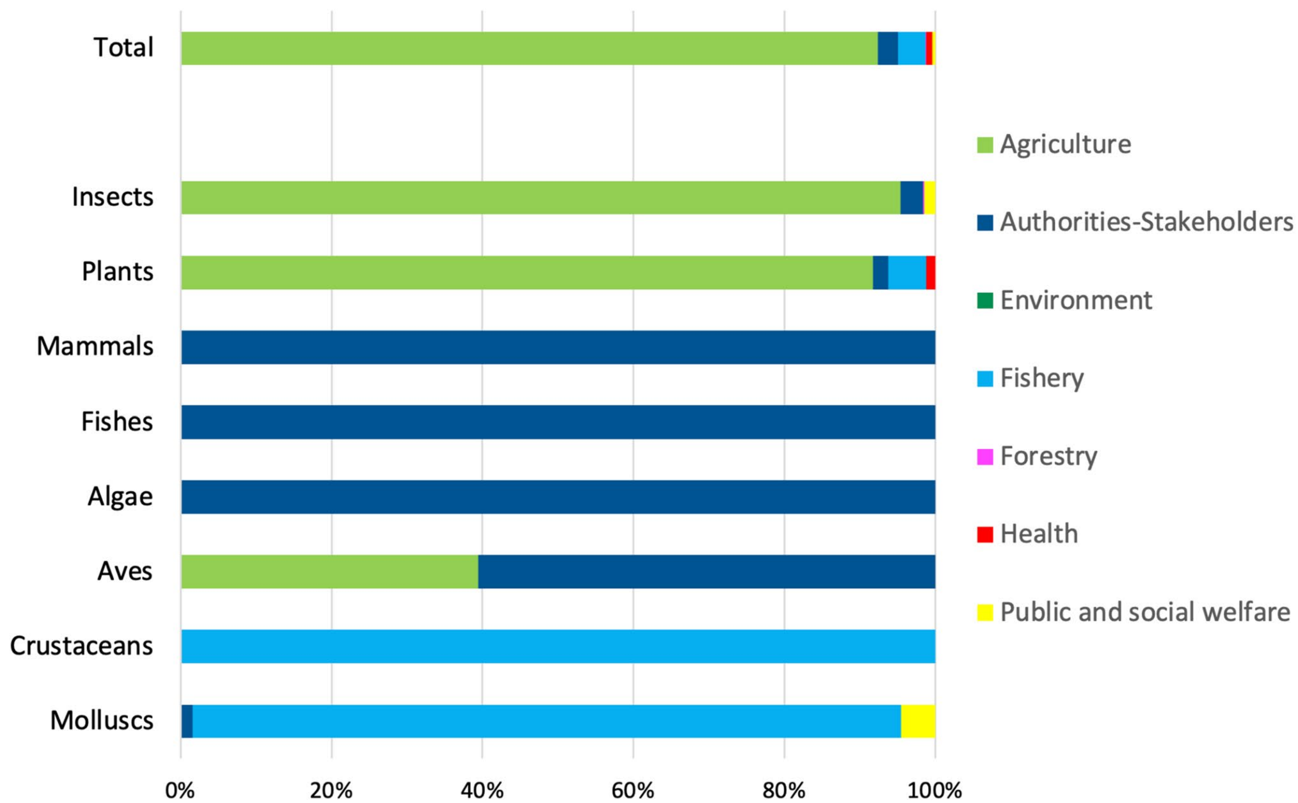

Fig. 5. Relative proportions of estimated costs (US$ 2017) of invasive alien species in Morocco, categorized by taxonomic group and impacted sector. Costs are based on estimates reported at the country level.

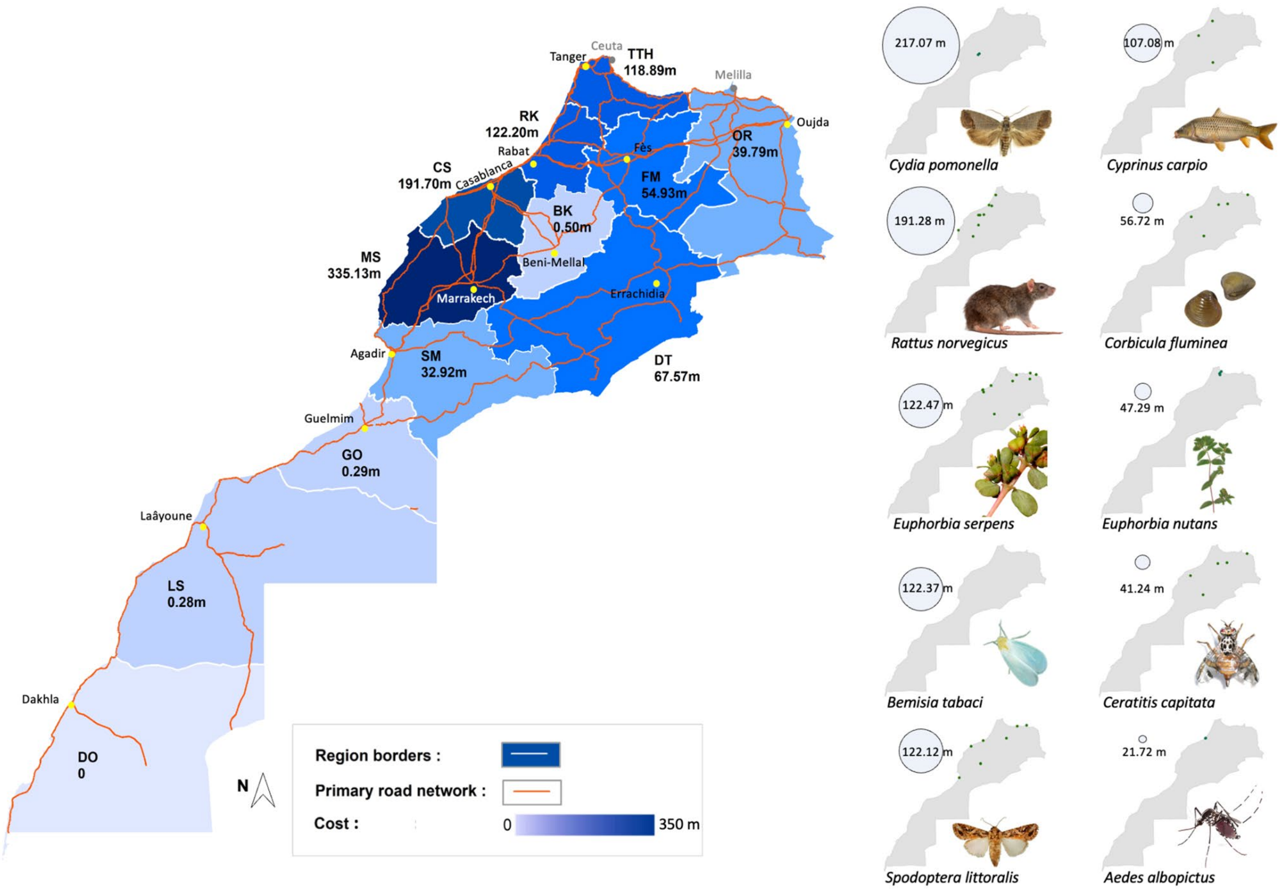

Fig. 6. Geographic distribution of estimated adjusted costs in Morocco (2017 US$ million -m-), and occurrences of the ten costliest invasive alien species. Abbreviations of the regions on the map are: BK Beni Mellal-Khenifra; CS Casablanca-Settat; DO Dakhla-Oued Eddahab; DT Draa-Tafilalet; FM Fez-Meknes; GO Guelmim-Oued Noun; LS Laayoune-Sakia El Hamra; MS Marrakech-Safi; OR Oriental; RK Rabat-Sale-Kenitra; SM Souss-Massa; TTA Tangier-Tetouan-Al Hoceima. Darker shades indicate areas with higher economic costs. Green circles represent the occurrences of the ten costliest IAS, with light blue circle volume proportional to their relative costs. occurrences are retrieved from GBIF. Maps created using Arcgis Desktop 10.8 (https://desktop.arcgis.com).

species, representing more than 1% of the nation's biodiversity[46]. Yet Morocco remained absent from the *InvaCost* database, underscoring a severe reporting gap for Africa[58]. By extrapolating costs from other countries, we estimated a potential annual economic cost of between US$ 1.57 and US$ 2.47 billion (using species with country-level data) and between US$ 1,14 and US$ 5.13 billion (using species with site-level data). These figures suggest that Morocco faces a disproportionately high toll compared to the entire African continent's estimated mean annual costs of US$ 2.6 to US$ 8.6 billion in 2019[14].

The broad cost range reflects two dimensions of the estimations: (i) the wide cost distribution by the distinction between adjusted (conservative) and unadjusted (maximum) scenarios, and (ii) the spatial scale of cost reporting (country or site-level). Socio-economic and climatic adjustments account for differences between the countries origin of the cost data and Morocco. Country-level extrapolations rely on reported national costs, while site-level estimates scale local costs to the number of invasion sites within Morocco. Despite methodological differences, the consistency of these approaches lends robustness to our results. Taken together, the bounds define a conservative baseline and a potential maximum scenario, both underscoring the significant financial burden that IAS impose on Morocco[60]. However, both estimates remain underestimations as most of the costs of IAS present in Morocco are not recorded (48% did not have reported costs in *InvaCost*).

Our estimates also align with previous attempts to quantify the hidden costs of invasion in Morocco. Eschen et al.[43] projected IAS damages in Moroccan agriculture alone at US$ 1.66 billion annually, based on literature and stakeholder interviews. Such efforts remain rare, reflecting the scarcity of African data[14]. For instance, IAS costs in the Mediterranean basin[35] have been described for only 15 out of 26 countries, mainly in Western Europe (France, Spain, and Italy), with only 11 records from African countries such as Libya (US$ 593.04 million, $N=8$) and Egypt (US$ 147.16 million, $N=3$). Notably, Morocco was entirely absent. Thus, extrapolating known cost for documented species remains currently the most feasible approach for data-poor regions[44].

Management and damage costs

Because our cost estimates are derived from globally reported values in the *InvaCost* database and are subsequently scaled to Morocco using socioeconomic and climatic adjustments, they retain elements of global cost patterns despite local calibration. When disaggregating costs reveals a clear imbalance between damage-related and management-related expenditures. At the country level, damage costs (US$ 1.47 to 2.32 billion) far exceeded management costs (US$ 97.6 to 149.3 million) mirroring global patterns of underinvestment in proactive control[28,29]. At the site level, however, while damages remained substantial (US$ 1.06–1.56 billion), management reached a much higher maximum estimate (US$ 83.2 million-3.57 billion). This inversion may reflect the strong influence of the countries from which cost data were originally reported. For example, approximately half of the costs used come from Spain, where site-level management costs were the predominant observed costs of biological invasions[71].

These contrasting results highlight the importance of methodological transparency when extrapolating IAS costs across spatial scales. They reinforce two key conclusions: (i) damages are the dominant but preventable cost component, and (ii) management costs, though less frequently reported, can escalate rapidly if delayed. Both points align with global evidence that proactive management and early detection are far more cost-effective than reactive responses[27,28,59].

The costliest species

Morocco's cost profile mirrors broader patterns, with insects and plants dominating[23,54], but reveals distinctive vulnerabilities. Agricultural pests such as fruit flies and moths carry particularly heavy costs, reflecting the country's dependence on fruit and cereal exports. Morocco's geographic position as a Mediterranean gateway likely increases exposure to alien pests through trade, while also making it a bridgehead for further spread into Europe[3,4].

The adjusted costs for the 10 most expansive IAS (Table 2) ranged from ~US$ 21 million (*Aedes albopictus*) to nearly US$ 870 million (*Phenacoccus madeirensis*), reflecting strong taxonomic and functional heterogeneity. *P. madeirensis* alone accounted for nearly one billion USD in damages, underlining the disproportionate impacts of small-bodied, plant-feeding insects on agriculture and livelihoods[47]. Similarly, *Cydia pomonella* and *Ceratitis capitata* impose hundreds of millions in estimated costs, consistent with their global notoriety as destructive invaders of orchards and fruit crops[48,49]. These results reinforce global *invaCost* findings that invasive insects, particularly agricultural pests, generate some of the highest reported costs worldwide[45,61,62]. This is particularly concerning for Morocco, where agriculture contributes 13–15% of GDP and sustains nearly one-third of the workforce.

Plants also feature prominently among Morocco's costliest IAS. Invasive grasses such as *Sporobolus* spp. and *Cenchus* spp. carry tens of millions in estimated costs, reflecting their aggressive spread and competitive displacement of local vegetation. Such findings echo the underappreciated but significant impacts of invasive plants globally[63–65], where management expenditures and crop growth losses often rival or exceed those of better-known animal invaders[50]. Similarly, *Euphorbia serpens* and *E. nutans* generate estimated costs exceeding US$ 100 million, showing that even low-profile weeds can cause severe agricultural and land-management losses[65]. In a country where arable land is scarce, small reductions in crop productivity translate into disproportionately high costs.

Among vertebrates, *Rattus norvegicus* and *Cyprinus carpio* illustrate the dual pressures on terrestrial and aquatic ecosystems. The brown rat exceeds US$ 190 million in costs, consistent with its global role in crop loss, infrastructure damage, and disease spread[51]. Common carp adds over US$ 100 million in costs, linked to habitat alteration and fisheries impacts[52]. The freshwater bivalve *Corbicula fluminea* (US$ 57 million) further illustrates risks to infrastructure and water systems[53]. Together, these examples confirm that IAS costs extend well beyond agriculture to infrastructure, water supply, and ecosystem services.

Beyond these established invaders, emerging species pose additional threats. *Aedes albopictus*, though currently estimated at ~US$ 22 million, is notorious as a vector of dengue, chikungunya, and Zika[55]. Its recent establishment in North Africa[56,57] signals potential escalating public health costs. Similarly, *Frankliniella occidentalis*, with costs exceeding US$ 50 million, exemplifies polyphagous pests that are nearly impossible to manage once widespread. These examples highlight Morocco's dynamic IAS problem, which is likely to worsen under climate change, agricultural intensification, and expanding trade[1,3,12]. Urgent development of early-warning systems and monitoring networks is essential, particularly for species advancing across the Mediterranean.

Geographic patterns of costs in Morocco

The uneven geographic distribution of potential IAS costs reflects a combination of demographic, economic, and ecological drivers. Densely populated regions such as Rabat, Casablanca, Tangier and Marrakech account for the majority of estimated national costs, highlighting the disproportionate vulnerability of Morocco's main demographic and economic hubs. The region with the highest share of national costs is Marrakech-Safi, highlights the particular vulnerability of Morocco's major tourist hubs, which combines extensive infrastructure, agriculture (22% of national useful agricultural land), and international connectivity through Morocco's busiest airport (over 6.3 million passengers in 2019). Similarly, Casablanca-Settat and Rabat-Sale-Kenitra concentrate high value assets, dense populations, and commercial hubs, amplifying IAS-related risks. Tanger-Tetouan-Al Hoceima stands out due to its large seaport and Mediterranean coastal ecosystems. both susceptible to biological invasions.

The Atlantic and Mediterranean coasts more broadly are particularly vulnerable: they contain sensitive ecosystems while also hosting industries critical to the national economy such as fisheries, tourism, and agriculture, all highly susceptible to biological invasions. Commercial seaports such as Casablanca and Tangier are central gateways for trade and transport and, as observed worldwide, act as key entry points for invasive species[68]. This aligns with broader African evidence, where maritime seaports have played a pivotal role in the introduction of exotic taxa, and where prevention and control measures at such hubs remain both challenging and costly[66,67]. Lastly, urban areas and economically dynamic regions tend to have more comprehensive monitoring and reporting systems, which can result in more frequent documentation of invasive species presence compared to sparsely populated or less economically active areas[7]. This indicates that observed spatial patterns may reflect not only true ecological impacts but also differences in surveillance capacity.

Limitations and future research directions

Our cost estimates for Morocco, relying on costs from other countries and compiled in the *InvaCost* database, reflect global patterns and biases[17], particularly the predominance of certain cost types. As a result, these estimates should be interpreted as conservative and potential approximations rather than precise national totals. Despite this limitation, this first national-level assessment provides a crucial foundation for addressing regional knowledge gaps and guiding evidence-based policy.

To account for uncertainty in the extrapolated costs, we produced both unadjusted and adjusted annual estimates. This interval should, however, be interpreted with caution: adjustments based on purchasing power parity (PPP) and climatic differences only partly compensate for contextual mismatches, and thus the resulting range represents an assumption-based uncertainty band rather than a true estimate of variability in economic impacts. Both approaches reduce, but do not eliminate, contextual misalignment between Morocco and the countries from which cost estimates originate.

Additionally, we only applied PPP and climate-similarity adjustments to management costs, leaving damage costs unadjusted. This reflects the fact that global damage costs in *InvaCost* are dominated by losses of capital and infrastructure repair, which tend to be valued using internationally standardized markets and replacement costs and are therefore less tightly linked to local labour prices than management interventions (Bradshaw et al. 2024). However, for some damage components (e.g., residential property values or locally provided ecosystem services), values will also vary with national income levels, so our damage estimates should be interpreted as approximations for Morocco rather than precise local monetary appraisals. Some damage categories, particularly those linked to property and land values, may therefore warrant partial socio-economic scaling in future analyses if more detailed cost structures become available.

We also compared country-level and site-level estimates, which are both subject to biases. Site-level estimates are sensitive to GBIF sampling completeness, as multiplying mean annual costs by the number of occurrence records can inflate values in well-sampled areas. To reduce this effect, we applied a 1-km thinning of occurrence points and used mean annual cost averages per species. Despite their differing data origins, the strong concordance between country- and site-level estimates increases confidence in our approach, although site-level estimates may remain influenced by uneven GBIF sampling. A sensitivity analysis (e.g., random resampling or shuffling of occurrence numbers) could further assess this dependence, but was not feasible here due to strong variation in occurrence densities and the lack of consistent spatial units for site-level costs in *InvaCost*. Future work could explore such approaches to better quantify this source of uncertainty.

Overall, while these limitations warrant caution when interpreting the results, the consistency across scales and explicit treatment of uncertainty enhance confidence in the reliability of our estimates for Morocco. At the same time, some discrepancies between adjusted and unadjusted costs remain, for example for *Ceratitis capitata*, ranging from US$41 million to over US$3 billion, highlight the need for standardized reporting and methodological harmonization[29]. Under-sampled regions, particularly remote or rural areas, may therefore remain underestimated.

Furthermore, only 39.9% of Morocco's known invasive species had available cost information, indicating that our national estimate (US$1.14–5.13 billion annually), although substantial, remains very conservative. The absence of cost information for more than 60% of species means the true national economic burden is likely far higher than reported here.

Failure to act on IAS management results in substantial avoidable costs, often in the millions[27]. In addition to basic research on species that are already invasive, Morocco must therefore prioritize prevention of new introductions through early detection and pathway monitoring. Additional priorities include developing locally derived cost estimates for high-impact species, improving monitoring of environmental and non-market damages, and integrating ecological and economic projections to anticipate future invasions. Future studies should identify potential invaders and their introduction routes, enabling more targeted policies and supporting efficient resource allocation[26].

Future work in Morocco should therefore aim to improve the documentation of economic impacts, and reinforce early detection and pathway monitoring, and strengthen collaboration among researchers, policymakers, and stakeholders. Such efforts will be essential to develop targeted laws and interventions, protect ecosystems from new introductions, strengthen food security, and reduce the growing economic and ecological burden of biological invasions.

Methods

List of invasive species and occurrences in Morocco

To assess the economic costs associated with invasive alien species in Morocco, we first compiled a list of species present in the country using comprehensive databases (Table S1) such as GISD, GRIIS, and the 'Standardising and Integrating Alien Species workflow'[41]. We complemented this with regional resources such as the 'Terrestrial Invasive Alien Species in the Arab Maghreb' and 'Elements for Reflection on Primary Invasive Alien Species in Morocco' lists. Additional systematic searches were conducted in online repositories (Web of Science, Google Scholar and Google search engine), and gray literature. To refine this search, we consulted national experts and stakeholders to gather additional information, e.g., official national managers or researchers that could provide cost data. We removed duplicates (checking to unify the names with the GBIF backbone taxonomy) and considered only those that were taxonomically ranked at the species level (i.e., discarding cases with only genus information). Finally, following expert validation and reviewer feedback, we removed several species incorrectly listed as invasive alien species but confirmed to be native to Morocco, based on authoritative floristic sources and national expertise.

Occurrence records detailing their current invasive distribution in the country were retrieved from the Global Biodiversity Information Facility (https://www.gbif.org, 28 June 2025, GBIF Occurrence Download https://doi.org/10.15468/dl.pdqugs) for all species listed in both datasets. In order to have a reliable dataset, we removed duplicated geographic coordinates (coordinates that were within less than 1 km., i.e., thinning), occurrences without GPS coordinates, and those with erroneous coordinates falling outside terrestrial borders or that could not be georeferenced from the information provided.

Estimating costs of invasive alien species in Morocco

Obtaining the costs from invacost database

We then cross-checked the *InvaCost* v.4.1 database[17] (https://doi.org/10.6084/m9.figshare.12668570.v5) to determine whether any of these species incurred economic costs somewhere in the world. Although *InvaCost* compiles cost information obtained from non-English sources[19], the database still did not feature any reported costs for Morocco. To address this gap, we first compared the list of invasive alien species detected in Morocco with those for which costs were available in *InvaCost*. We retained species observed in Morocco with documented costs in *InvaCost* even if those costs originated outside of Morocco, (N = 80 IAS, Fig. 1). We also included IAS lacking direct costs records in *InvaCost* but with costs reported for one or more "sister species" within the same genus (N = 57 IAS). Species falling outside these categories were excluded (workflow in Fig. 1, Table S1).

Each invasive species may have several entries, for example, referring to different types of costs (e.g. damage or management), different countries, or different invasion events. For the 137 IAS retained, we considered only robust costs, defined as those classified as high-reliability in the 'Reliability' column, i.e., cost estimates sourced from official peer-reviewed material and/or material with reproducible methods; observed in the 'Implementation' column, i.e., cost estimates that were actually incurred; and reported, in the column 'Acquisition', i.e., costs directly obtained or estimated from the field[17]. Costs were extracted from the 'Cost_estimate_per_year_2017_USD_exchange_rate' column, ensuring comparability by adjusting all entries to 2017 US dollars. This adjustment factored in inflation using the 2017 Consumer Price Index relative to the year of the original estimate. Each entry also includes the timespan linked with the recorded costs, facilitated by the *expandYearlyCosts* function from the *invacost* R package[42]. This function distributes the total reported cost evenly across probable start and end years, generating an expanded dataset where each entry represents a cost estimate for a specific year. Within the *InvaCost* database, each publication served as a distinct point of reference for reported costs, although the duration over which costs were estimated differed among references. Complete details regarding the compilation and standardization of data stored in *InvaCost* are provided in Diagne et al.[17].

Socioeconomic and climate adjustments of the costs from other countries

Since costs for the 137 IAS in Morocco originated from outside the country, we extrapolated them to the Moroccan context by accounting for differences in socio-economic and climatic conditions, using a simple structured scaling procedure to partially correct the costs.

First, the socio-economic context was incorporated into management costs, which are heavily influenced by local labour and service prices. In contrast, damage costs (such as yield losses, infrastructure damage, or public health burdens) are typically valued in terms of lost production, capital replacement, and infrastructure repair, and therefore are less directly driven by local labor costs and more by prices in internationally traded commodity, property, and health-service markets[72]. Thus, we did not adjust direct damage costs socio-economically to avoid imposing an additional PPP correction on damage values that already reflect the economic and price structure of the country where they were originally estimated. Management costs were adjusted using the ratio of Morocco's GDP per capita at purchasing power parity (PPP) relative to that of the country where the original costs were reported. We computed the PPP ratio like this:

$$\text{PPP ratio} = \text{Source country GDP per capita (PPP)}/\text{Morocco GDP per capita (PPP)}$$

PPP values were obtained for each country and year (of origin of the cost estimates for the 137 IAS present in Morocco) from the World Bank. Due to the lack of pre-1990 data, some costs could not be adjusted and were excluded.

Second, we applied climate similarity indexes based on Köppen climate classifications to reflect ecological compatibility. Because habitat preferences of species depend on climate zones and subzones, this method, though approximate, follows standard practice in transboundary invasive species cost assessments[43]. It provides a cautious adjustment in the absence of species-specific climate elasticity data. We assessed the climatic similarity between Morocco and the countries of origin of the cost estimates using general Köppen climate zone similarities: around 1.0 for costs sourced from Mediterranean climates similar to Morocco (Spain, Portugal), around 0.75 for moderately similar climates (South Africa, Mexico), and around 0.5 for distinctly different climates (Canada, Zambia). To operationalize these, we downloaded Koppen climatic regions for both Morocco and the source countries and applied the Jaccard similarity index:

$$\text{Climate similarity Index} = \text{Number of common climate subregions}/\text{Total subregions across both countries.}$$

We excluded two Atlas-specific subregions (remote, high altitude, with low IAS likelihood). The Jaccard similarity index ranging between 0 and 1 was re-scaled to range 0,5 – 1.

Adjusted cost estimates were calculated by multiplying the original expanded cost from *InvaCost*, by the PPP ratio (country and year dependent) and the scaled-Jaccard Climate similarity index. This approach, while still a simplification, provides a more context-sensitive extrapolation, partially accounting for differences in socio-economic and ecological conditions. Recent global extrapolation studies have applied similar principles by explicitly incorporating socioeconomic predictors such as GDP, population size, and agricultural land area to scale invasion costs across countries[69]. These adjustments allowed them to account for variation in national economic capacity and resource dependence, thereby producing estimates that better reflect regional realities rather than direct transfers of cost values. Our PPP-based adjustment follows the same rationale, correcting for Morocco's lower income levels relative to source countries, while the climate similarity index provides a conservative ecological weighting. When both adjusted and original costs were available, we reported a range of potential costs of IAS in Morocco, with a lower bound (more conservative) using adjusted costs (PPP ratio and climate similarity index) and an upper bound (maximum scenario) using our original unadjusted extrapolated estimates from *InvaCost*.

Spatial scales of the costs

To ascertain a relative annual cost per species, we calculated the annual amount per spatial unit, utilizing the 'Spatial_scale' column, because the scale at which a cost occurs matters. We re-categorized this column in three levels: "site", which refers to an area at the intra-country level, could it be a region, or a well-defined surface area or entity, such as a hectare or a river basin; "country", which refer at costs at the country level; and "interregional", which refers to a scale higher than the country level. We did not consider the interregional scale (no possibility of adjustment), and this was the cause of the loss of five species of the genus *Oxalis*, as the only available costs in *InvaCost* were at this spatial scale. This adjustment was necessary due to the non-uniformity in the number of reported costs and the spatial scale of these costs in *InvaCost* across various species.

For species with costs at the site-level, we extrapolated the economic costs to Morocco, by multiplying the adjusted values of the annual cost per site, obtained from the reported data in *InvaCost*, by the number of occurrences sourced from GBIF in Morocco. If a species had no GBIF occurrences in Morocco, we conservatively assumed the presence of at least one site and used the cost per site as the total national cost for that species. For species with costs reported at the country-level, we directly used the mean values obtained from *InvaCost* and their adjusted counterparts. When species had costs available at both spatial scales, we reported country- and at the site-level estimates separately.

This yielded four cases: (1) only country-level costs; (2) only site-level costs supported by GBIF occurrences; (3) both country- and site-level costs; (4) site-level costs with no GBIF records (conservatively assumed one site). For interpretation, we grouped these into three effective categories: country-level, site-level (including single-site assumptions), and both. Country-level costs reflect broad national assessments, whereas site-level costs capture localized impacts scaled by occurrences. Variation between the two illustrates uncertainty in transferring cost data across contexts.

Accordingly, we presented estimates separately for country- and site-level costs, each with a lower (adjusted costs that take into account the socio-economic and climatic context of Morocco) and upper bound using either direct unadjusted costs from *InvaCost* (See previous subsection).

For the description of the costs, we also took into account the cost typology (i.e., management and damages), as specified in the 'Type_of_cost_merged' column, and the costs incurred by different impacted sectors, as indicated in the 'Impacted_sector' column of *InvaCost*. The original three categories available (damage, management and mixed) were reduced to two (damage and management) by merging management and mixed.

Spatial representation of the costs

To visualize the geographic distribution of potential IAS costs in Morocco, we created a map in which each occurrence of species recorded in GBIF was assigned its corresponding annual cost, adjusted for Morocco's socio-economic and climatic context. These adjusted costs were then summed across all occurrences to produce site-level total costs for each region, allowing the identification of national economic hotspots of invasion.

Data availability

The datasets generated and analyzed during the current study are included in this published article (See Supplementary Table S1).

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Author contributions
EA and AT contributed to the study conception and design. Data collection was performed by CD, EA, FC, and LBM, the methodology was agreed by JEJ, LBM, EA and AT and analyses were performed by JEJ, CD, EA and LBM. Supervision was carried out by EA and AT and funding was provided by FC, EA and DA. The first draft of the manuscript was written by JEJ and visualization items were created by JEJ, AT and EA. All authors commented on previous versions of the manuscript and all authors read and approved the final manuscript.

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Competing interests
The authors declare no competing interests.

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