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Review Article

Range expansion or contraction? A bibliometric and systematic review of biological invasions of animals in the context of climate change

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Abstract

Climate change may affect the invasiveness of invasive alien species (IAS) by altering habitats and the distribution of hosts, altering the frequency and intensity of extreme climatic events, and by prompting changes to land use patterns, which collectively may facilitate species movement, and increase opportunities for IAS to cross historical geographic barriers. The impact of climate change on range contraction/expansion of IAS is complex and remains controversial. To elucidate this important issue, we conducted a review to examine numerical and thematic trends in research related to climate change and IAS. We also conducted a systematic review of the predicted effects of climate change on range contraction/expansion of animal IAS reported in the literature. This comprehensive analysis aimed to identify the most probable outcomes of climate change on the spatial distribution of IAS. American, Australian, and British researchers have published the largest number of papers on the subject and have had the greatest influence on the research topics investigated. In terms of productivity (number of documents), Plos One (n=101) published the most papers; however, in terms of network influence (total link strength), Biological Invasions (TLS=13,289) ranked highest. "Climate change", "invasive species", "global warming", "biodiversity" and "biological invasion" are the most common informative words in the word

clouds. Additionally, "invasive alien species", "fire" and "risk assessment" were identified as the emerging areas of research in the climate and IAS field. Insecta (41.58%), Actinopterygii (12.87%), and Amphibia (7.93%) were among the most studied animal taxa in research focused on climatic effects on animal IAS. The geographic range of most invasive species (71.28%) is expected to expand under projected climate change. However, the range of some species is predicted to both contract and expand, depending on the scenario and context (20.8%). Notably, our review found that few invasive species are expected to contract their range under climate change (7.2%). Our results show that most IAS will expand their range and occupy more new habitats in the future due to climate change.

Keywords*:* Biodiversity, Climate change, Conservation, Invasive Alien species, Range Expansion, Range Contraction

Introduction

There is increasing concern that rapid growth in biological invasions complicates the conservation of biodiversity (Pejchar and Mooney, 2009). According to the Convention on Biological Diversity (CBD, 2005), invasive alien species (hereafter IAS) are species that have been transported outside their native range due to deliberate or unintentional human activities. Their introduction to new habitats can result in ecological (e.g., Stout and Morales, 2009; Iacarella et al., 2015), social (e.g., McNeely, 2001; Reaser et al., 2007), and economic (e.g., Pimentel et al., 2005; Adelino et al., 2021; Diagne et al., 2021) impacts. It is estimated that there are more than 17,000 IAS worldwide **(**IPBES, 2019**)** and these are a major cause of extinctions (Azra et al., 2022). IAS are usually characterized by high reproduction rates, dispersal ability, and adaptability (Hellmann et al., 2008; Bogale and Tolossa, 2021), which collectively increase their ability to disperse, colonize, and invade ecosystems outside their native range.

IAS may threaten native diversity in various ways. For example, invasive species may drive reductions in the population sizes and genetic variation of native species (Richardson, 2016), and/or alter genetic structure and phylogenetic relationships (Blackburn et al., 2019) through hybridization with native species (Vilà et al., 2011). Collectively, these changes can decrease the evolutionary potential of native species. Invasive species can also perturb ecosystem structure and processes (Katsanevakis et al., 2014; Egoh et al., 2020), increase disease transmission to nonresistant species and populations (Kelly et al., 2009; Chinchio et al., 2020), alter food webs (Simon and Townsend, 2003), and affect species interactions (Abdullah Al Mahmud et al., 2018). The severity of IAS effects (i.e., invasiveness) depends on various factors. The characteristics of the invasive species in interaction with the ecosystem and community it is invading drive complex

interactions that determine the trajectory of the outcome (Sakai et al., 2001; Carboni et al., 2016). For example, the ability of invasive species to adapt to environmental variations (Broennimann et al., 2007), their level of specialization (Brown, 1984), evolutionary history (Pyšek and Richardson, 2007), extent of native range (Guo et al., 2012), as well as genomic variation and phenotypic plasticity (Theoharides and Dukes, 2007) significantly influence their capacity to survive, thrive, and dominate in novel environments. Furthermore, these intrinsic characteristics will interact with availability of suitable habitats (Capinha et al., 2015), landscape heterogeneity and connectivity (Theoharides and Dukes, 2007; Searcy et al., 2006; Li and Shen, 2020), characteristics of habitat patches (Knight and Reich, 2005), native species richness (Smith and Shurin, 2006), and climate condition (Capinha et al., 2015) to determine if the invasive species is able to establish, spread, and if autocthonous limiting factors, such as competition, predation, and parasitism, control the invasive species in novel contexts.

Climate change can have a wide range of effects, including abiotic (e.g., changes in precipitation patterns, increased frequency of extreme weather events, alterations in snow and ice cover, and rising sea levels) and biotic (e.g., shifts in species range, changes in phenology, alterations in species interactions, and disruptions to ecosystem services). Climate change and IAS are broadly regarded as critical crises worldwide. Importantly, their effects may interact synergistically (Finch et al. 2021, Azra et al., 2022). It is widely acknowledged that climate change has made significant contribution to biological invasions (Bellard et al., 2013). Climate change may affect invasiveness of IAS through a number of routes, such as by altering available habitats and host species, the intensity and frequency of extreme climatic events, alterations to land use patterns, creation of suitable habitats, and altered invasive pathways. Collectively, these changes can facilitate species movement and opportunities to cross historical geographic barriers (Finch et al., 2021; Bogale and Tolossa, 2021; Smith et al., 2012; Seebens et al. 2015). Positive selection for traits that enhance reproductive success of species in warmer climate, availability of "empty" niches, and ability to adapt to local conditions facilitate the invaders' ability to develop, produce offspring, and invade larger areas under climate change (Broennimann et al. 2007; Jarnevich et al. 2014).

A comprehensive meta-analysis by Petitpierre et al. (2012) showed that 15% of IAS show evidence of range shifts to the new areas that have historically not been within their climatic niche in their native ranges. Also, a systematic review by Bellard et al. (2018) reaffirmed the importance of climate change as a force behind changes in the future distribution of IAS. Many IAS may benefit

from climate change in all of the steps of the invasion process, including the initial movement of a species from its native range to a new environment (transportation), adaptation to the new environment, utilization of available resources, and reproduction (colonization), sustaining a population over time in the new area (establishment), and range expansion and moving beyond the initial point of colonization (spread) (McNeely 2000; Sutherst 2000; Walther et al. 2009).

Predicting how IAS will respond to the changing climate is challenging given the sensitive and complex interactions between the characteristics of the invader, the structure and characteristics of the invaded community, and complex impacts of climate change and other perturbations on the ecological community. However, it is essential to understand and predict how climate change interacts with IAS in order to formulate effective management plans for preventing and controlling the introduction of these species into new areas (Finch et al., 2021). Reflecting the importance of this issue, many articles have been published to predict relationships between climate change and IAS (e.g., Colberg et al., 2024; Kumschick et al., 2024). The rapid growth of research on this global crisis necessitates a review of what is known about the patterns of IAS response to climate change and the factors that drive responses of IAS in different contexts and ecological systems. Furthermore, a comprehensive review of the trends and future research directions for IAS and climate interactions is highly needed (Bellard et al., 2016).

We used a bibliometric method involving several components to review and summarize publications on IAS and climate change. Bibliometrics refers to the quantitative study of literature to illuminate how science, technology, and scholarship have evolved over time, which helps researchers to integrate, visualize, classify, and summarize the knowledge available on a research topic into one document (Hou et al. 2015; Olisah and Adams, 2021). Hence, bibliometric studies facilitate the assessment of patterns and changes in a field, identifying research focus areas, analyzing the research status in detail, identifying leading researchers, describing cross-boundary webs of collaboration, evaluating scientific progress, and exploring future research directions (Liu et al. 2011; Boudry et al., 2018; Geng et al. 2017; Skaf et al., 2020). In recent years, a bibliometric approach has been applied in various subjects in environmental sciences (e.g., Olisah and Adams, 2021; Verrall and Pickering, 2020; Su et al., 2021).

The impact of climate change on range contraction/expansion of IAS remains uncertain and controversial. While some studies have shown that climate change increases IAS potential to colonize new habitats and therefore facilitate their range expansion (e.g. Kriticos et al., 2003;

Bracewell et al., 2012; Barbet-Massin et al., 2013; Gilioli et al., 2014; Meynard et al., 2013; Tingley et al., 2014; Tonnang et al., 2015), others show that climate change can lead to range contraction and may limit IAS distribution (e.g., Canning-Clode et al., 2011; Bellard et al., 2013; Meynard et al., 2013; Rodolfo-Metalpa et al., 2014; York et al., 2014). Limited understanding of the effects of climate influences on the spread of IAS has impeded scientists' capacity to assess, forecast, and address the expanding impacts of this global issue.

Many researchers have reviewed the prior literature to provide a perspective on the effects of climate change on IAS. These reviews found that the leading publications on this topic have been mostly from Europe (e.g., Smith et al., 2012; Bellard et al., 2014; Finch et al., 2021; Marambe and Wijesundara, 2021; Azra et al., 2022). Also, a substantial body of research in this field has explored the impact of climate change on specific groups of IAS. While these studies contribute valuable insights, efforts to synthesize the relationship between climate change and IAS often remain narrowly focused and fragmented. As a result, there is a need for a more comprehensive understanding that integrates these findings into a broader context.

In the present study, we first used a bibliometric approach to (1) identify the leading journals and most influential papers in the field, (2) examine trends in research collaboration using analysis of co-authorship, (3) determine the mode, structure, key points, and trends of past and current studies, and (4) determine temporal and spatial patterns in the literature. Second, we conducted a systematic review of studies reporting range expansion or contraction of animal IAS under climate change. The two components are integrated: bibliometrics reveals research trends and gaps, while the systematic review quantifies the direction of range dynamics. We focused this review on animal invasive species. We selected a sample of studies on the effects of climate changes on IAS that have been published in Scopus database journals of high-repute published up to 19 November 2024. Additionally, we conducted a systematic review of the most important papers published on the effects of climate change on the range contraction/expansion of animal invasive species that were identified in our bibliometric analysis. We end with specific, actionable policy recommendations to improve the effectiveness of management to mitigate the effects of the changing climate on IAS.

Materials and methods

Bibliometric analysis

The process of collecting data was performed between 1990 and November 19, 2024, utilizing the Scopus database. The search terms included "invasive species" OR "alien invasive species" AND "climate change" OR "global warming" AND "animals" contained in title or abstract, with the oldest article being published in 1990 and the latest from 2024. The 34-year period was divided into three phases including 1990 to 2008, 2009 to 2014, and 2015 to 2024 based on the number of works published. This study highlights the temporal trends in IAS research and underscores the significance of examining changes and developments across different years.

Data collection consisted of three phases. (1) bibliometric details for the retrieved records were obtained from the Scopus database. The records encompassed research article published between 1990 and 2024. (2) The bibliometric data was converted to CSV format so that it could be analyzed with the R package Bibliometrix (Aria and Cuccurullo, 2017). (3) Finally, the quality of the records was checked in Microsoft Excel, and duplicates, spelling errors, and incomplete records were corrected. Items that failed quality control were excluded from the study.

The search string initially generated a total of 1,390 articles. The final search string excluded any gray literature such as books, book chapters, conference proceedings, reports, working papers, notes, letters, erratums and short surveys with potentially irrelevant studies. The search string also primarily focused on literature available in English, potentially introducing a language bias. Non-English publications may not have been adequately represented in this search. According to the results obtained from the Scopus database, a minor portion of the articles have been published in languages other than English, including Chinese (n = 8), Spanish (n = 3), German (n = 1), French (n = 1), Polish (n =1), and Italian (n = 1). The decision to limit the search to English-language publications was made due to resource constraints and the desire to maintain consistency in the analyses. Omitting non-English publications from systematic reviews had a negligible impact on the overall conclusions, suggesting that it could serve as a feasible methodological shortcut, particularly in the context of rapid reviews. Only studies that primarily focus on animal invasive species and climate change were included, following a thorough screening of titles and abstracts.

A total of 626 research articles formed the final dataset and were downloaded for the bibliometric analysis. An additional systematic review (Section 2.5) was conducted separately with 155 initially retrieved papers, of which 101 met inclusion criteria after full-text screening. We used the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) protocol for identifying, and selecting publications (Page et al., 2020; Fig.1). The articles were read by three

authors (AM, MRA, RKH), and the final summary of the articles was carried out by the first author. We only selected published articles that address the topic of climate change and its impact on the range contraction or expansion of the animal invasive species. We read the abstracts of the articles and selected them if they addressed the topic; otherwise, we removed them.

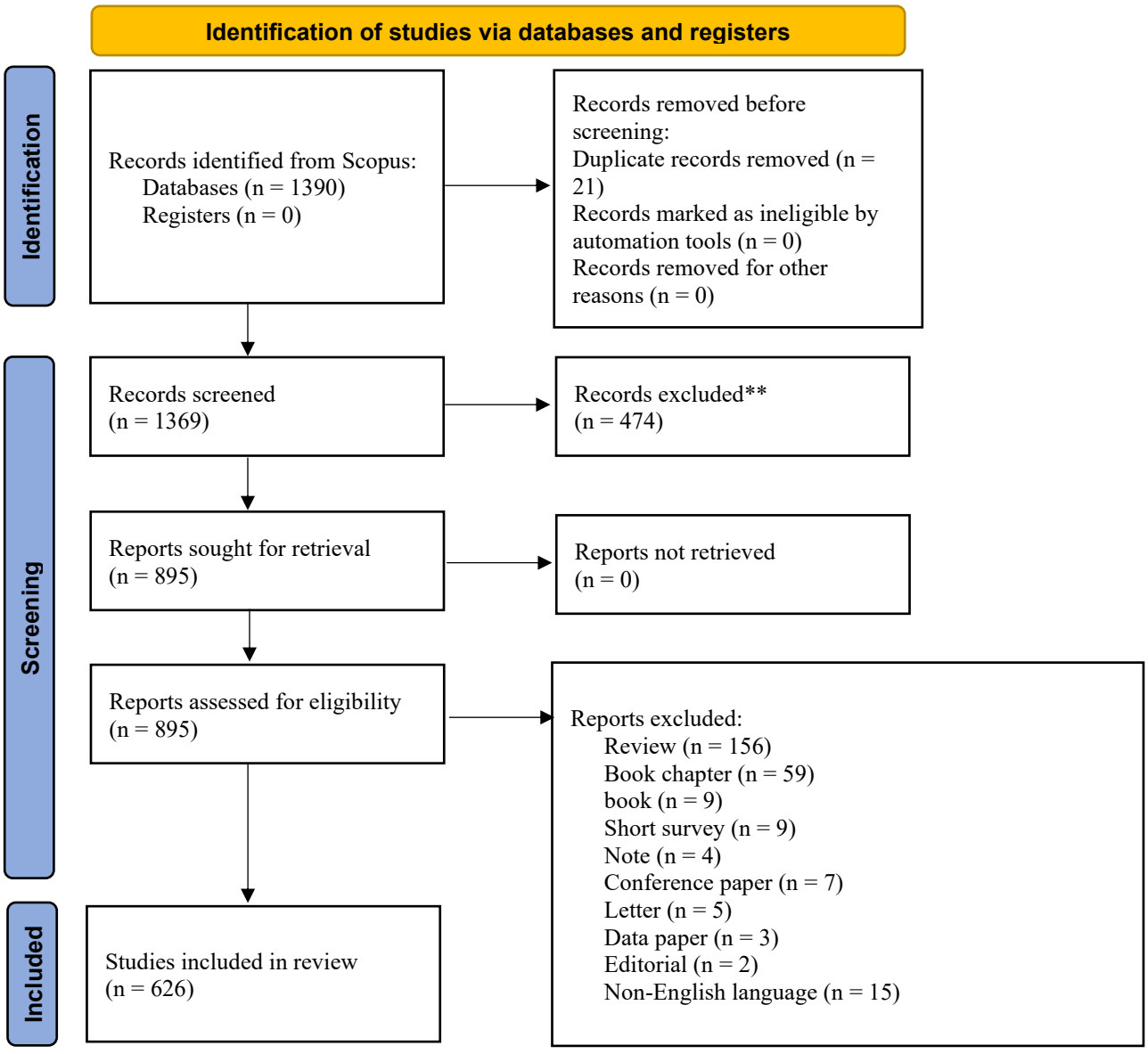

Figure 1. Selection process flowchart, based on PRISMA software

Microsoft Excel 2019, VOSviewer 1.6.16, and the R package Bibliometrix were used for analysis and visualization. Co-occurrence analysis was performed using VOSviewer with a minimum co-occurrence threshold of 5, clustering resolution of 1.0, and full counting method. Authors, country, and year of publication were extracted from the retrieved records from the Scopus database (www.scopus.com/sources) and were mapped in Excel. Country, journal, and keyword networks were generated and visualized in VOSviewer (Gao et al., 2018; van Eck and Waltman, 2010).

In addition to generating word clouds, Sankey plots, and hotspot analysis, we conducted a co-occurrence analysis to create clusters of keywords with a high degree of co-occurrence (Neff and Corley, 2009). Keywords were considered the primary unit of analysis as they encapsulate the main themes of a publication (Verrall and Pickering, 2020). In the co-occurrence graph, node size represents frequency, and line thickness corresponds to the number of related keywords (Neff and Corley, 2009).

Word clouds visually depict word frequency. The frequency at which a term appears in the material being analysed determines the size of the text in the image representation. Word clouds are used to find the center point of written text (Alkhammash, 2023). In bibliometric studies, the use of a word cloud to evaluate the most prevalent words indicates that most of the work is concentrated in those areas. In addition, words in smaller letters indicate potential study directions (Mulay et al., 2020). A word cloud translates texts to tags, which are words whose relative value can be viewed in the resulting cloud through their size and color (Mulay et al., 2020).

To address the relationships between countries and the terminology utilised in the field of invasive species, we created a three field plot. A "three field plot" is a graphical representation that visually depicts the relationships among three distinct entities. It provides insights into the global nature of research collaborations and the distribution of research activities in a given field (Rusydiana, 2021). We used the three field plot to visually summarize complex relationships and interactions among countries, authors, and keywords in research related to IAS and climate change.

To identify the thematic areas and key topics in research related to the IAS and climate change, the following questions need to be answered: Which specific areas of research are currently being explored in the field of invasive species? Which topics should receive more attention in the future? How has research in this field evolved over time?

Thematic analysis is crucial for explaining keywords related to IAS and climate change. These keywords indicate developing themes and have the characteristics of density and centrality. The vertical axis represents density (degree of development), whereas the horizontal axis represents centrality (degree of relevance). The greater the number of relationships a node has with other nodes in the thematic network, the greater its significance and degree of development. Four clusters can be identified in a thematic map (Alkhammash, 2023):

(1): Low density and low centrality (emerging themes): The topics placed in the lower left quadrant need further exploration due to underdevelopment or being emerging subjects. These subjects have limited significance across the network and their development is slow within the network; however, they may present attractive opportunities for further research. (2): High density and high centrality (basic themes): The topics located in the lower right quadrant are the primary themes in the body of research and are central to the development of the field. These topics have high relevance across and inside networks. By identifying and developing these topics, bibliometric studies highlight the opportunities for further investigation. (3): High density and low centrality (niche themes): Topics in the upper left quadrant are internally well-connected but have limited external connections, indicating their limited significance in terms of connection to broader research topics. (4): High density and centrality (motor themes): Topics in the upper right quadrant represent the major themes in the field and are central to the literature. They have high relevance and connectivity within and across the network. Given their centrality, bibliometric studies can shed light on their exact nature and guide future research.

In addition to co-occurrence network analysis and thematic maps, the authors conducted thematic evolution analysis to understand the development IAS and climate change over time. Sankey diagrams can be used to illustrate themes and their development over time (Xiao et al., 2022). Each box in the diagram represents a theme, with the size of the boxes indicating frequency (Xiao et al., 2022). The lines connecting the boxes show the evolution of a theme with line thickness corresponding to link strength.

Range expansion/contraction of IAS due to climate change

As previously noted, the impact of climate change on range contraction/expansion of IAS remains controversial. While some studies have shown that climate change facilitates IAS range expansion, others show that climate change can lead to range contraction. To examine the predominant effects of climate change on invasive alien animal species, particularly in terms of their range dynamics

(expansion or contraction), a comprehensive review was conducted focusing on articles published in recent years. The aim of this part of the survey was not to explore how climate change influences the expansion or contraction of animals ranges. Instead, the focus was on synthesizing findings from recent decades to determine whether research predominantly reports an increase or decrease in the distribution ranges of invasive alien animal species. In other words, this paper does not analyze the processes through which climate change affects animal ranges but rather evaluates the outcomes of existing research on this topic. By evaluating the outcomes of existing studies, this review aims to establish a clearer picture of the prevailing trends in IAS range dynamics under the influence of climate change. The Scopus database was searched for records published from 2007 to April 2023 **(**this period was chosen because species distribution models became methodologically robust after 2007**)** using the following string: ("range expansion" OR "expansion" OR "contraction" OR "range contraction" OR "range shift$") AND ("invasive alien species" OR "alien species" OR "invasive species") AND ("climate change" OR "global warming") AND "animals". With these keywords, a total of 155 relevant papers were retrieved in the form of full records and cited references. We just focused on English language papers. Only studies that explicitly used species distribution models (SDMs), niche models, or empirical long-term field data to predict or measure range expansion or contraction were included. Experimental studies without spatial distribution data, review papers, and opinion pieces were excluded. Among the downloaded papers, only studies were used that directly addressed the range contraction or expansion of animal invasive species due to climate change. After full-text screening, 101 studies explicitly reporting range expansion or contraction outcomes were included. Exclusion reasons: no spatial data (n=32), review/opinion (n=15), non-English (n=7). We extracted some important information from the articles including author/year, species name, class, region, spatial scale, the effect of climate changes on the studied species (i.e. range expansion/range contraction), and key findings. Inter-rater agreement (Cohen's kappa = 0.87) was calculated based on independent screening of 20% of articles by two authors (AM and MRA). The statistical analyses conducted on the data extracted from the papers were limited to descriptive statistics, such as the frequency percentage of each category (for example, regarding the spatial scale of the study we classified papers in three main categories including local, national, and global). Studies were categorized as "expansion" if >50% of scenarios/projections showed range increase, "contraction" if >50% showed range decrease, and "both" if outcomes were mixed by scenario or region.

Results

The number of publications related to IAS exhibited an average annual growth rate of 14% between 1990 and 2024 (Fig S1). The 34-year period was divided into three phases based on the number of works published every year: 1990 to 2008 (less than 30 publications per year), 2009 to 2014 (less than 50 publications per year), and 2015 to 2024 (rapid increase in publications). The peak number of annual publications was in 2024, with 86 publications. Overall, 4,150 authors have contributed to IAS research (mean 6.6 authors per paper, which is plausible for interdisciplinary climate-IAS research) with the majority (93%) of publications involving multiple authors.

Based on total link strength (TLS), Biological Invasions (TLS = 13,289) ranked highest, followed by Plos One (TLS = 1,117), Global Change Biology (TLS = 859), and Science of the Total Environment (TLS = 619). While Plos One published the most papers (n=101), Biological Invasions had substantially higher network influence per publication. Regarding the number of published documents, Plos One (n = 101), Science of the Total Environment (n = 51), and Scientific Reports (n = 43) were the leading or most prolific journals in the field of IAS (Table 1, Fig S2). High-ranking universities were the University of California (n = 315), Stellenbosch University (n = 141), the University of Minnesota (n = 121), and the University of Tasmania (n = 93), respectively.

Table 1. Table 1. List of 10 high-ranking journals in terms of publications on IAS, ranked by the number of published documents.

Journal	Documents	Citations	TLS*
Plos One	101	4087	1117
Science of the Total Environment	51	1422	619
Scientific Reports	43	749	546
Global Change Biology	37	1991	859
Ecological Applications	28	1094	527
Ecology	28	1038	492
Oecologia	21	511	335
Conservation biology	18	866	317
Pest mangment science	16	255	487
Journal of experimental biology	16	2030	173

*Total link strength (TLS): The cumulative strength of the links of an item with others (Gao et al., 2018).

Our results showed that domestic collaborations were more common than international collaborations (Table S1, Fig.2). With the exception of Spain, UK, Germany, and New Zealand research is often conducted with few international collaborations.

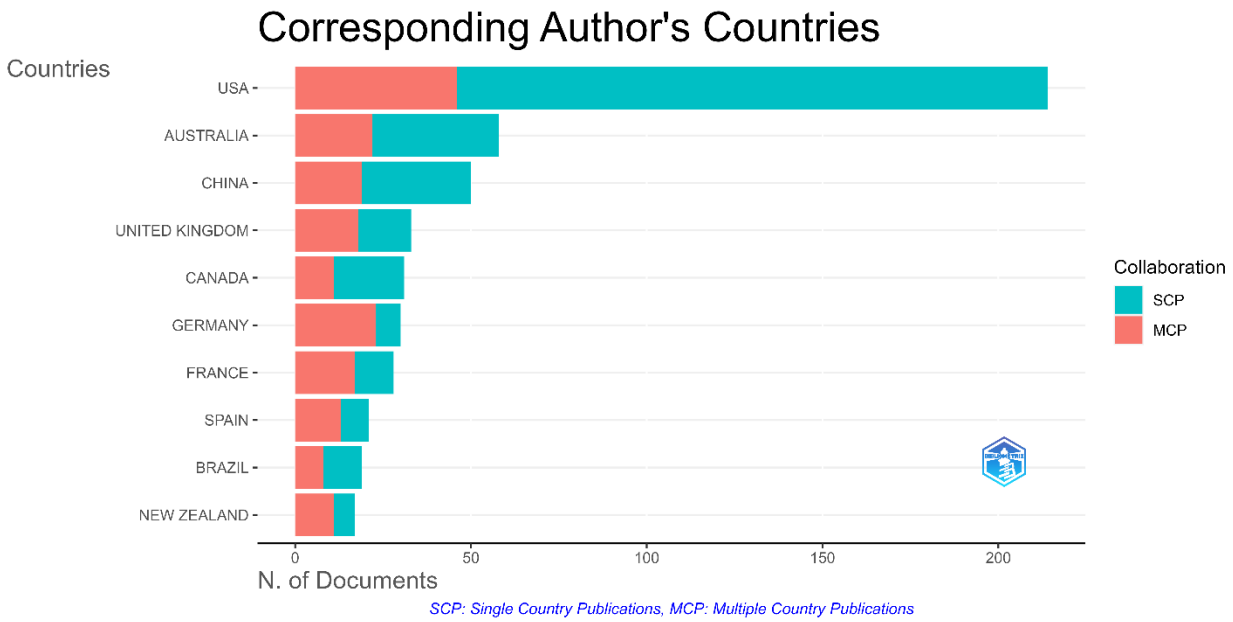

Figure 2. The global contribution by country of corresponding author's country. The red and blue bars represent works produced through international and domestic collaboration, respectively.

Country collaboration network:

American, British, German, and Australian researchers have published the largest number of studies (Fig. 3). Americans had the largest number of collaborations (TLS = 277), followed by the British (TLS = 255), French (TLS = 197)**,** and Australians (TLS = 174) (Table 2, Fig.3). The first cluster (red) encompasses 29 countries, mostly in Europe and Asia. The second cluster (green) encompasses 18 countries from the Americas, Asia, and Europe. The third cluster (blue) encompasses 14 countries, mostly in the Americas, as well as the Netherlands. The fourth cluster (yellow) includes mainly European countries, along with New Zealand. The fifth cluster (purple) encompasses nine countries mainly from Africa, as well as Switzerland and Germany.

Table 2. Ten high-ranking countries in terms of TLS related to "animal invasive species and climate change" between 1990 and 2024 (as of 21 November 2024).

Country	Citations	TLS
USA	21114	277
UK	11855	255
France	7590	197
Australia	8155	174
Italy	6297	139
Canada	6066	116
Switzerland	5452	123
Netherland	5119	63
Germany	5068	186
South africa	4826	74

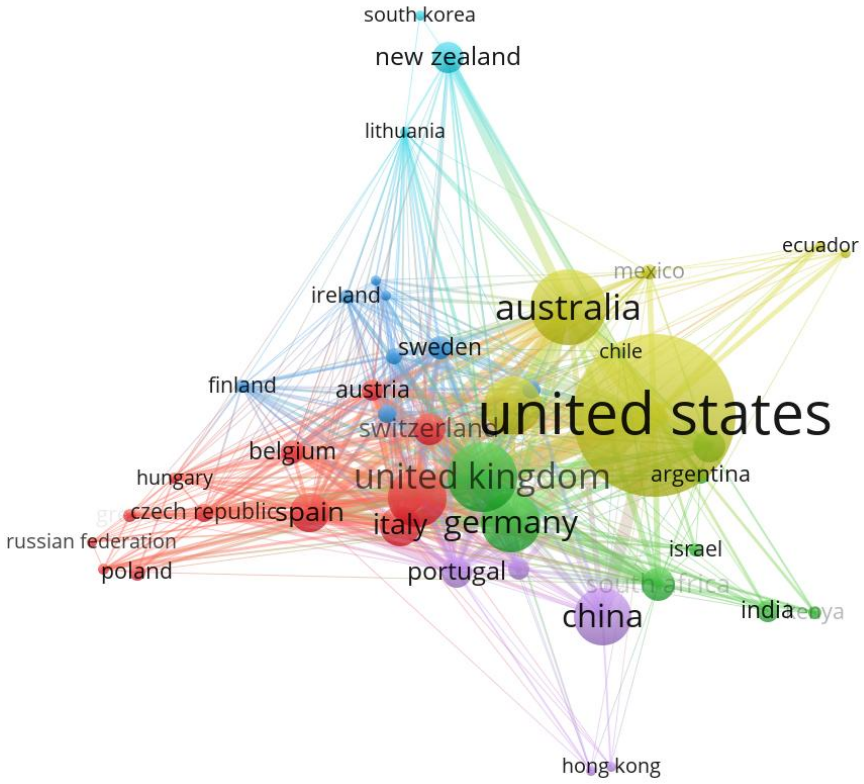

Figure 3. Structure map of countries co-authorships in invasive species research. The co-authorship analysis of countries reflects the collaboration relationship between countries in this field, as well as the degree of collaboration. The larger nodes represent the high-ranking countries in the field of invasive species research; the thickness and length of links between nodes represent the cooperative relationship between countries.

The highest frequency of international collaboration was between USA and Canada (n = 155), followed by USA and Australia (n = 144), USA and UK (n = 134), Australia and UK (n = 92),

USA and Germany (n = 87), USA and China (n = 79), USA and Spain (n = 79) and UK and Germany (n = 77). Figure 4 provides a detailed graphical overview of research published across the world. The high-ranking countries in terms of productivity of IAS and climate research were USA (n = 310), Australia (n = 190), UK (n = 170), and China (n = 156) respectively (Fig.4).

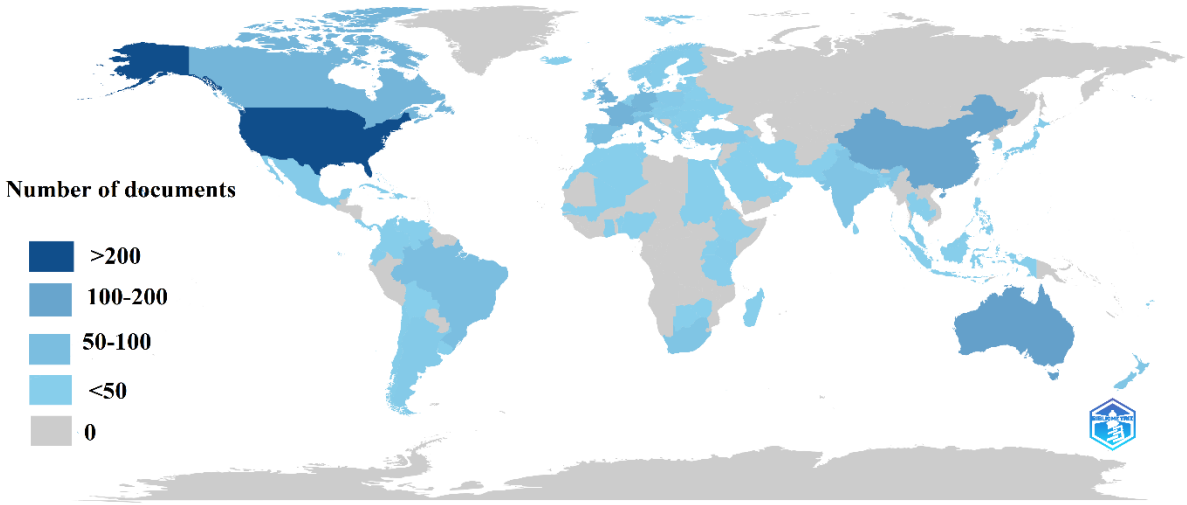

Figure 4. Countries' scientific research publications in the IAS field. The five high-impact countries were the USA, Australia, the UK, China, France, and Canada.

"Climate change", "invasive species", "global warming", "biodiversity", and "biological invasion" are the most common informative words in the word clouds (Fig. 5). The results show that the frequency of "climate change", "invasive species", "biodiversity", and "biological invasion" has increased significantly in author keywords from 1990 to 2024 (Table S2).

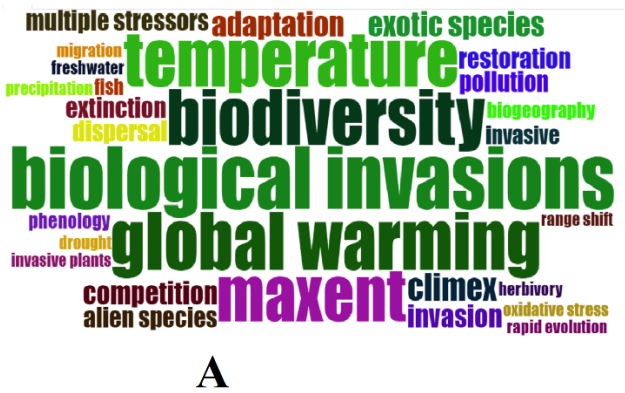

Figure 5. Word cloud for "author keywords" (A) and "titles" (B).

Figure 6 illustrates the three field plot for the 10 most prolific countries in IAS research, as well as their most important contributions to the field. The thickness of the links represents the flow of information between elements. Authors from the USA, China, Australia, UK, and Canada have published the largest number of works on IAS. There are geographical preferences for certain keywords; for instance, there is a strong relative preference among authors from the USA for “climate change”, and “invasive species”, and for “climate change” among authors from Australia.

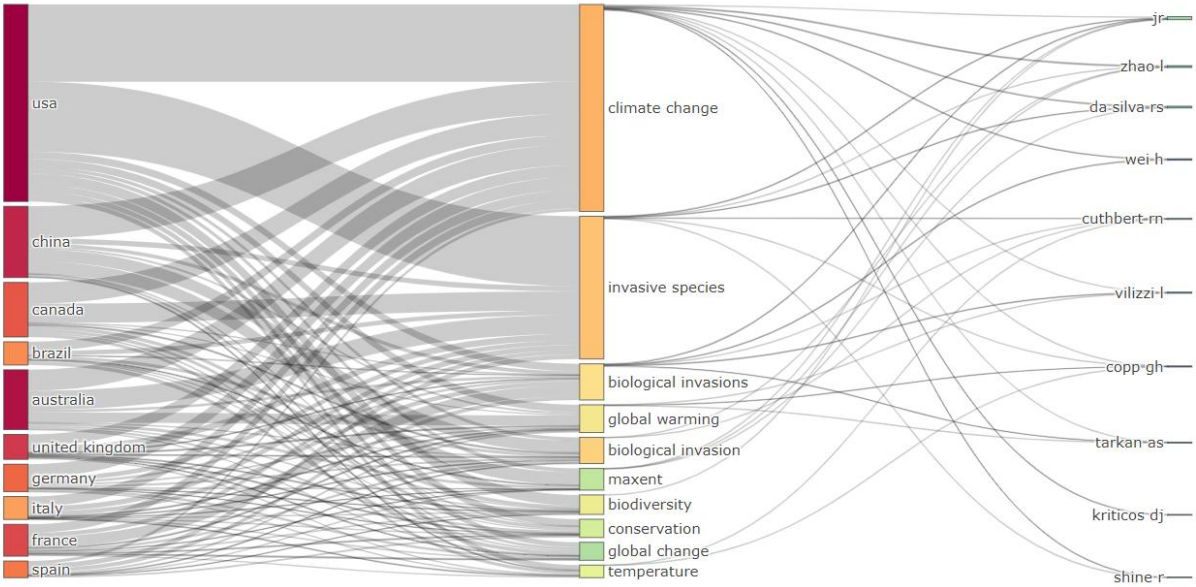

Figure 6. Three-field plot for the corresponding author's country (left column), keywords (middle column), and authors (right column).

We found four research foci in the literature which represent hot-spots in the research (Van Eck and Waltman, 2010), including (1) global climate change and invasive species (2) biological control of invasive species, (3) disturbance (fire and drought), and (4) range contraction/expansion and species distribution models (Fig.S3). According to the results of the thematic map, global change, drought, temperature, biodiversity, conservation, and ecosystem services are the motor themes. Moreover, invasive alien species and risk assessment are emerging themes that require further development (Fig.7).

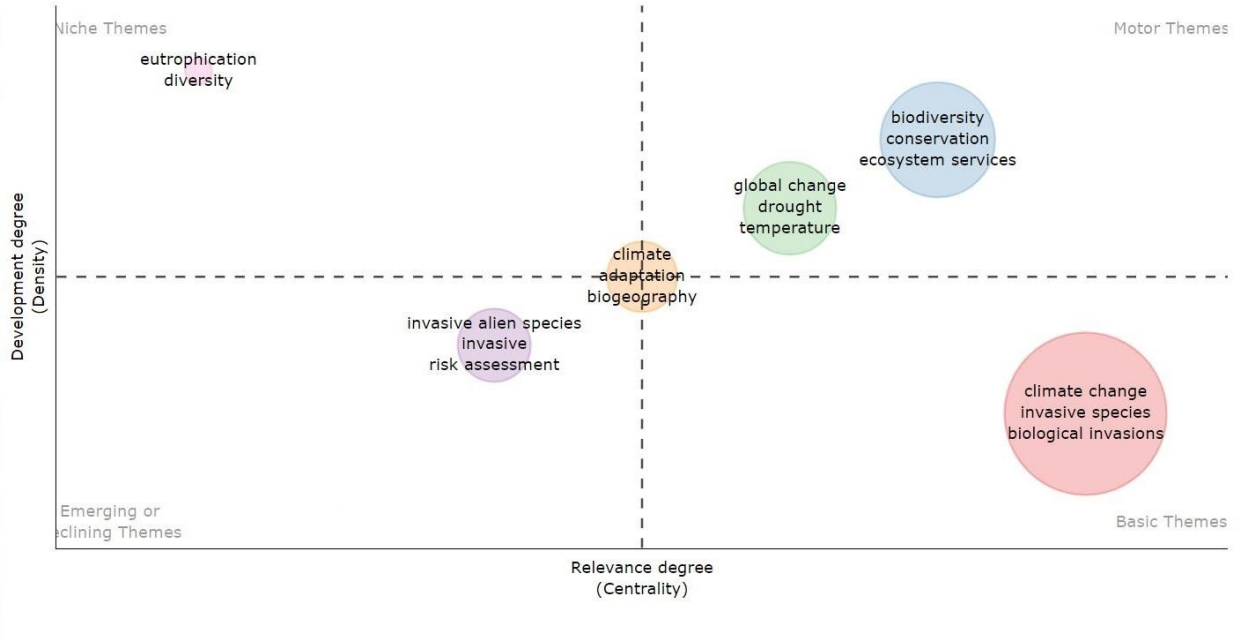

Figure 7. Thematic map in invasive alien species. The thematic map was constructed based on author keywords and was mapped into four themes: niche (left top), motor (top right), emerging or declining (left bottom), and basic themes (right bottom).

From a general perspective, "invasive alien species" is present in all themes across time. It is noticeable that the term "climate change" was first used in 1990 to 2014, with additional developments in 2015 – 2019, and sustained interest in 2020 – 2023. Some objective indicators, such as "global change", have only emerged recently (2020 to 2023) (Fig.S4).

Range expansion/contraction of animal IAS in the context of climate change.

Our literature review revealed that animal IAS analysed were distributed among various classes as follows: Insecta (41.58%), Actinopterygii (12.87%), Amphibia (7.93%), Mammalia (5.94%), Reptilia (4.95%), and Bivalvia (5.94%) (see Table S3). Regarging the spatial scale of analysis, the largest group of studies were conducted on a global scale (31.68%), followed by local (22.77%), national (18.81%), regional (15.84%), continental (6.93%) and international (3.97%) scales of research (Fig.8) (Table S3).

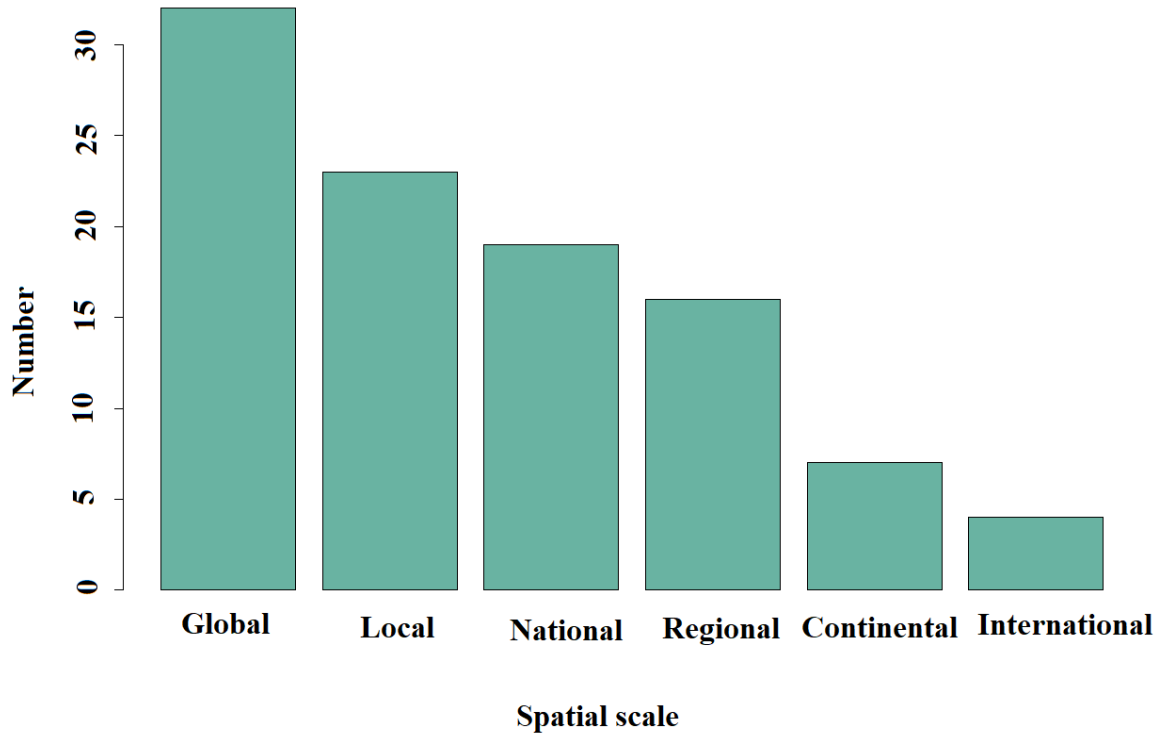

Figure 8. Spatial scales of studies on animal invasive alien species (IAS) in the context of climate change (n = 101 studies).

We found that 71.28% of studies predicted that animal IAS will expand their range under future climate change (Table S3)**.** Only 7.2% of the studies found or predicted clear range contraction (Table S3)**.** Also, 20.8% of studies showed both contraction and expansion in different locations and contexts (Table S3)**.** Most studies that were conducted on a global scale (51.6%) showed range expansion. Only a small proportion (9.67%) of these studies showed range contraction of IAS, and 38.73% showed mixed outcomes (both expansion and contraction)**.** Among global-scale studies, 51.6% predicted range expansion, and the majority of these focused on insects (51.6% of global studies), suggesting taxonomic bias may influence the perceived generality of range expansion patterns. At a global scale, the majority of studies have focused on insects (51.6%). Also, most of the studies (81.35%) at smaller scales (local and national) showed range expansion of IAS. Nearly all of the studies conducted in developed countries found or predicted range expansion of IAS (97%) (Table S3)**.** This finding likely reflects publication and funding biases, not actual geographic distribution of IAS impacts.

Discussion

IAS can seriously threaten food security, agro-ecosystems, and biodiversity on a global scale (Early et al., 2016; Turbelin et al. 2017; Savary et al. 2019). Invasive species also threaten human health and cause human mortality annually through the emergence and spread of infections, direct harm from animals, and allergic reactions to bites and stings (Mazza et al., 2014; Vilà et al., 2021). The challenges of managing IAS can become more complicated under a changing climate (Bogale and Tolossa, 2021). Climate change can promote biological invasions by increasing habitat disturbance (Chown et al., 2016), altering environmental factors, and providing vacant niches that can be rapidly filled by IAS (Diez et al., 2012; Wolkovich and Cleland, 2014; Turbelin et al., 2023). Considering the harmful ecological, social, and economical impacts of IAS, and recent concerns about the possibility of worsening IAS problems due to climate change, we urgently need to predict the effect of climate change affects species (Dukes and Mooney, 1999; Bellard et al., 2018).

This study conducted a global assessment of the response of animal IAS to climate change based on the published papers indexed in the Scopus database. A detailed bibliometric analysis was conducted to describe trends in knowledge evolution, potential research hotspots and to better understand dominant themes in research on IAS response to climate change from 1990 to 2024. Our bibliometric analysis included 626 research articles; the systematic review synthesized 101 studies reporting range dynamics.

From 2014 to 2021 we found that research on IAS and climate change accelerated rapidly; during this period, there was a sharp increase in the number of annual publications. The maximum number of annual publications in our dataset was 86 (2024). The smallest number of publications belonged to 1990 (n = 1, 0.001%) and the largest to 2024 (n = 86). In 2008 and 2021, total annual publications exceeded 100 and 500 for the first time, respectively these figures refer to global IAS literature overall, not our specific dataset. The increase in the number of publications on IAS can be attributed to several interconnected scientific, environmental, and societal factors such as rising awareness of biodiversity threats, technological advancements, globalization, shift towards interdisciplinary research, climate change, public interest and citizen science, and scientific collaboration and open access. As IAS continue to pose challenges, research efforts are expected to grow, fostering innovation and informing global strategies to mitigate their impacts.

The USA and Australia were identified as the countries with the most active scientists in the field of IAS. The USA, UK, Germany, and Australia showed the strongest international research collaborations. Our results showed that most of the studies on IAS were conducted in American and European countries. Despite the growing importance of attention to the effects of IAS, the majority of studies have been conducted in these nations, while relatively limited information has been published on IAS in the rest of the world (Peh, 2010; Nghiem et al., 2013). This is despite the great risk posed to low- and middle-income countries or the Global South by IAS, as people living in these countries are heavily reliant on agriculture and natural resources for their livelihoods (Nghiem et al., 2013; Pratt et al., 2017). IAS pose significant threats to nutrition and food security, particularly in developing nations (Early et al., 2016). Additionally, a substantial portion of the world's biodiversity is concentrated in low- and middle-income countries, which urgently require data-driven strategies to inform effective conservation programs. Therefore, producing qualitative and quantitative information on the effects of IAS in these countries is a key stage in mitigating the adverse effects of invasions on ecosystems (Pimentel, 2011; Pratt et al., 2017). However there are limitations to interpreting the results of this section. Perhaps one of the reasons for the low level of study in the rest of the word is that many authors in some countries cannot pay publication fees for many of the high-ranking journals. Therefore, many of the papers coming from these countries are published in journals that are not indexed with Scopus. On the other hand, since we only considered studies published in English, there are other published studies in other languages. "Global climate change and invasive species", "biological control of invasive species", "disturbance" (fire and drought) and, range contraction/expansion and species distribution models" were identified as four research hotspots in the literature. Research on biological control and natural disturbances and their interaction with IAS are a priority for reducing the impacts of IAS and help identify patterns of ecosystem resilience and inform restoration efforts post-disturbance. Therefore, by addressing these research hotspots, scientists aim to develop proactive strategies for mitigating the ecological, economic, and social impacts of IAS in a rapidly changing world.

The motor themes present strong centrality, high density, remarkable development, and great importance for structuring research on the topic (Su et al., 2022; Urhan et al., 2023). The themes "global change" "drought", "temperature", "biodiversity", "conservation" and "ecosystem services" are motor themes. The keywords of this theme support the view that global change and ecosystem services are interrelated (Bellard et al., 2018; Gallardo et al., 2019). Therefore, paying

attention to the conservation of biodiversity plays an important role in minimizing the negative effects of global environmental changes on ecosystem services (e.g. Civantos et al., 2012; Urhan et al., 2023).

According to the thematic map, "climate change", "invasive species" and "biological invasions" come under the basic or transversal themes with low density and high centrality. The themes of "invasive alien species", "fire" and "risk assessment" mainly represent emerging themes, which is consistent with Theoharides and Dukes (2007) who asserted that environmental disturbances facilitate the establishment of invasive species. Globally, increasing wildfire (D'Antonio, 2000; Mack et al., 2000), expansion of agricultural activities (Chytrý et al., 2009) and changes in native community composition under climate change (Diez et al., 2012) are the most relevant disturbance factors. It should be noted that fire regimes are changing across the world (e.g., Littell et al. 2018), while the impacts of these changes on community composition are poorly understood and require further studies (Bieber et al., 2022). There is a need to provide efficient methods for assessing risks from IAS to support policies and prioritize actions (Roy et al., 2018; Wang et al., 2022). Also, McGeoch et al. (2016) emphasize that due to the very large number of invasive species which have already been identified and the very high likelihood that more species will become invasive in the future, rapid assessment schemes for prioritizing responses are crucial.

"Invasive species", "climate change", "biological invasions" and "biodiversity" are ranked second to fifth the main keywords, respectively. As an increasingly important element in global environmental change (Pyšek et al., 2020), invasive species have altered the composition of communities, function and structure of ecosystems, and have significantly impacted biodiversity, economy and human health across the world (Iqbal et al., 2021; Yang et al., 2021; Feng et al., 2022). In addition, climate change may directly or indirectly affect biological invasions by changing the likelihood of introduction or establishment, as well as modifying the distribution range, environmental impacts, or management of alien species (Hulme, 2017).

With the growing mobility of humans and their goods and services, the transfer of species---both intentional and unintentional---has significantly increased. While many intended benefits of species relocation, such as food, fiber, and recreational opportunities, have been achieved, there are also instances where both deliberate and accidental introductions have led to negative consequences (Lassuy and Lewis, 2013). For centuries, Europe has been a center of international trade, resulting in the introduction of numerous species. While some of these species have

beneficial effects---such as certain introductions aimed at enhancing fisheries---many others have significant negative impacts. These harmful species span a wide range of taxa, including viruses, bacteria, fungi, and animals, and they affect all nations and regions across Europe (Keller et al., 2011).

Species distribution models (SDMs) are essential tools for quantifying species niches. These models analyze the relationships between species occurrence and environmental factors, serving as the benchmark for predicting potential invasion risks and future extinction rates (Vaissi and Rezaei, 2023). Most studies conducted at large spatial scales predict a decrease in the distribution range of vertebrates with projected climate change. For instance, Bellard et al., (2018) showed that when predictions are made on large spatial scales, the ranges vertebrate species are more likely to contract than expand. Their results showed that the reduction in spatial range is mainly due to the oceans impeding the movement of species under climate change (Bellard et al., 2018). The discrepancy with our findings (where most animal IAS show expansion) may be due to differences in taxonomic scope (animals vs. plants), time period, and search strategy; this is a hypothesis requiring further testing.

On the other hand many researchers predicted the range expansion of IAS species with climate change. Based on the literature review, geographic ranges of most of IAS are expected to expand under future climate change scenarios (e.g. Vaissi and Rezaei, 2023; Azimi et al., 2023). Furthermore, while the geographic ranges of some IAS are predicted to both contract in places and expand in others (e.g. Crespo-Pérez et al., 2015; Zingore et al., 2020; Marchioro and Krechemer, 2021), few IAS are expected to generally contract their ranges under climate change (e.g. Pyron et al., 2008; Wenger et al., 2011; Zhao et al., 2023). In many cases changing climate can favor IAS, leading to new invasions and expansion of the already established IAS (Thuiller et al. 2007).

For example, in some countries, such as the USA, Ireland, and China, studies predict that the range of many IAS will expand (possibly due to the lessened importance of climate as a limiting factor at such scales), while other factors such as land use, edaphic parameters, and biotic interactions become more important (Morales-Castilla et al., 2015; Bellard et al., 2018).

Climate change may challenge the commonly held perceptions regarding the impacts of IAS. For example, the effects of climate change on IAS are likely to vary depending on factors such as taxa, limiting conditions, and ecological context. It is likely that as climate change progresses other alien species may become invasive, and some native species are anticipated to move to new habitats

(Finch et al., 2021). For example, increasing temperatures can have a positive effect on invasive insects by affecting their movements, dispersal ability, growth, phenology, and survival. Conversely, warmer conditions could also negatively impact insects by interfering with host adaptation and altering overwintering conditions (Finch et al., 2021). A number of invasive pathogens rely on the exact timing of precipitation and changes in temperature or moisture (Hamann et al., 2021), while others their activity are facilitated by host stresses (Sturrock et al., 2011; Finch et al., 2021). Currently, human activities facilitate the translocation or dispersal of invasive species across large barriers (Lehan et al., 2013), which is expected to increase due to climate change (Seebens et al., 2015).

Increasing the frequency, magnitude and duration of extreme weather events due to climate change, such as droughts, hurricanes, forest fires, and heatwaves, is another mechanism that can affect the short-term and long-term movements of invasive organisms (Melillo et al., 2014; Weiskopf et al., 2020). For example, strong winds can facilitate the dispersal of propagules, larvae, insects, and birds, cause vegetation loss and development of uncovered soil, and increase the opportunity for invasion (Walther et al., 2009; Finch et al., 2021). Global warming reduces the extent and thickness of sea ice, resulting in greater connectivity for parts of the year (Post et al., 2013)**.** For example, the loss of sea ice has enabled birds and mammals to move between the Pacific and Atlantic oceans more easily (McKeon et al., 2016), which could in turn trigger an increase in the exchange of species that have limited mobility on their own (Viana et al., 2016). The newly transported species could become invasive in their new range (Finch et al., 2021). In addition, studies show that the timing of bird migration is affected by climate change, which could play a role in increasing the geographical distribution of aquatic invasive species transported by birds (Miller-Rushing et al., 2008; Coughlan et al., 2015; Reynolds et al., 2015).

In summary, climate change significantly influences the dynamics of invasive species and in many cases may enable them to expand their ranges by altering ecosystems and creating conditions favorable for their establishment and spread. Rising temperatures, changes in precipitation patterns, and increased frequency of extreme weather events can provide opportunities for invasive species. Climate change may increase the number of invasive species and increase the likelihood of range expansion of these species through (1) converting previously unsuitable habitats to more favorable niches and therefore increasing the likelihood of altitudinal and latitudinal shift, (2) reducing competitive advantage and resilience of native species and therefore creating openings

for invasive species to establish, (3) increasing the rate and intensity of disturbances and creating opportunities for invasive species to colonize newly available niches, (4) amplifying the traits of invasive species such as growth rates, and prolific reproduction and therefore enabling faster establishment and spread, (5) giving invasive species an advantage by affecting ecological relationships such as predator-prey or competition dynamics, and (6) increasing the probability of human-assisted spread of invasive species because of climate-induced changes in human activities. The six mechanisms proposed here are supported by the following references: (1) Thuiller et al. 2007; (2) Bellard et al. 2013; (3) Diez et al. 2012; (4) Hellmann et al. 2008; (5) Walther et al. 2009; (6) Seebens et al. 2015.

Conclusion

Predicting changes to the geographical range of IAS under change climate is essential for local and transboundary management aimed to prevent, control, or mitigate the negative effects of the invasions (Polaina et al., 2021). Climate change may influence biological invasions by changing rates of species introductions, establishment, spread, and impact (Cheng et al., 2017; Hulme et al., 2017; Redding et al., 2019), but the relative impacts on these invasion stages remain unclear.

This study conducted a global assessment of the response of IAS to climate change based on published papers indexed in the Scopus database. Our results show that most invasive animal species will expand their range and occupy more new areas in the future due to climate change. Considering climate change and expanding the distribution range of IAS to different countries, especially countries with high biodiversity, it is necessary to conduct studies and management efforts in many more areas of the world, and especially in developing nations in the Global South. Given the global, transboundary nature of the IAS climate change synergy, expanded international, metareplicated, collaborative studies are important. Specific policy recommendations: (1) prioritize insect-focused global monitoring networks; (2) fund research in under-represented Global South regions; (3) standardize reporting of range expansion/contraction outcomes across scenarios.

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