Policy-Oriented Research in Invasion Science: Trends, Status, Gaps, and Lessons

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Invasive alien species are a major driver of global environmental change. Escalating globalization processes such as international trade and long-distance transport have contributed to an increase in the ecological, economic, and sociocultural impacts of biological invasions. As a result, their management has become an increasingly relevant topic on environmental policy agendas. To better understand the role of policy in invasion science and to identify trends and gaps in policy-oriented research, a systematic literature review was conducted covering 2135 publications. The results highlight that international policy instruments are contributing to an increased interest in pursuing policy-oriented research. Specifically, key historical periods in policy development (e.g., the Convention on Biological Diversity's COP10 in 2010) coincide with periods of active policy-focused research in invasion science. Research is, however, more applied to local scales (i.e., subnational, and national) and is more focused in places with high research capacity or where severe environmental or economic impacts are well documented.

Keywords: environmental management, nonnative species, policymaking, science–policy interface, social dimensions of conservation

Invasive alien species are a major driver of global social–ecological and environmental change (IPBES 2019, Pyšek et al. 2020). The scale and extent of biological invasions are strongly shaped by trends in trade and transportation, which have intensified over the past century (Hulme 2009). Even though biological invasions can result from deliberate or accidental introductions, invasive alien species are often considered externalities—that is, the impacts of one's activity experienced by unrelated third parties (Huppes and Simonis 2009).

In recent decades, biological invasions have increased in importance on international and national environmental policy agendas, but more political attention over alien species has been warranted (Shine 2007). Policy action (or inaction) toward invasive alien species depends on many factors, including pathways of introduction, the stage of the invasion process, the extent and features of invaded areas, and the cost-effectiveness of available management tools (Hulme 2006, Keller and Perrings 2011, Jarić et al. 2020). Furthermore, the benefits and costs of invasive alien species for people; the way people perceive them; and the framing of invasives as a societal problem by politicians, bureaucratic authorities, scientists, educationists, and cultural commentators also shape policy action or inaction (Stoett 2010).

Despite social–ecological complexity and variability, the management of invasive alien species, as a policy goal, can be approached in several ways. Nonetheless, a general consensus arises from preventive policies, which are cost-effective to limit new species introductions in the long run (Simberloff et al. 2005, Hulme 2006, Robertson et al. 2020). Preventive policies can be implemented by the application of pre- and postborder measures (e.g., bans of specific species, inspections, quarantine measures, sanctions, risk assessment) and also through increased public awareness, cooperation, capacity building, and innovation (McNeely et al. 2001, Bouwma et al. 2015). When invasive alien species are present but are not yet well established, early-warning and rapid-response systems can be implemented to contain their spread or (where feasible) to eradicate them (Robertson et al. 2020). Public awareness, management cooperation, and political coordination are crucial, as are research and innovation, to allow accessibility to adequate and efficient early-detection tools (McNeely et al. 2001, Bouwma et al. 2015). Once species become well established, the focus of management turns to direct control options (e.g., mechanical removal, chemical control, biological control; Wilgen et al. 2011, García-Díaz et al. 2021) that mitigate the impacts of biological invasions or to adaptation that sees invasions as part of novel ecosystems (Robertson et al. 2020).

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Table 1. Policy instruments considered when analyzing research papers.

Policy instruments	Definition and purpose	Examples	Source
Legal instruments	Legislation and laws at all levels.	International and regional conventions and agreements, legislation (national, supranational, subnational)	Panayotou (1994), Shine and colleagues (2000), Secretariat of the Convention on Biological Diversity (2001a), Gunningham and Sinclair (2005), Knill and colleagues (2011), Taylor and colleagues (2012), Bouwma and colleagues (2015)
Regulatory instruments	The government applies "command and control" principles to influence actors' behavior. Can be prohibitive or prescriptive.	Prohibitions or bans, licenses, permits, standards, listings, inspections, quarantine measures, protection status (environments, species), import or export restrictions	
Economic and fiscal instruments	Stimulate actors to behave in a certain way by financially rewarding or discouraging it.	Taxes, penalties, tariffs, subsidies, fees, tradable permits, offsetting, funds or grants	
Information and communication instruments	Influence behavior through disseminating information to actors.	Education campaigns, labelling or certifications, guidelines, technical training	
Agreement-based or cooperative instruments	The government or involved actors jointly and on a voluntary basis decide on actions and behavior.	Codes of conducts or codes of practice, multilateral cooperation or collaboration, multilateral coordination	
Knowledge and innovation instruments	Participating actors jointly increase their knowledge by engaging in social learning. Knowledge is both information and capacity to act.	Research, public participation, technical innovation	
Planning and policy-support instruments	Plans and strategies (formulating public policy priorities and goals).	Management plans, management strategies, conservation strategies	

One of the most comprehensive international policy instruments pertaining to invasive alien species is the Convention on Biological Diversity (CBD), which calls on its parties to "prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats, or species" (article 8(h)). Many other legal instruments pertaining to invasive (or alien) species exist in specific countries (e.g., South Africa's National Environmental Management: Biodiversity Act (NEMBA), the United States' National Invasive Species Act (NISA), or Portugal's decree law no. 92/2019), geographic regions (e.g., the European Union' regulation no. 1143/2014), environments (e.g., wetlands; Ramsar Convention), sectors (e.g., fisheries; a fisheries act in some countries) or vectors of spread (e.g., ballast water; the Ballast Water Management Convention; Secretariat of the Convention on Biological Diversity 2001a; Turbelin et al. 2017).

However, none of these instruments can be effective without sufficient scientific expertise to lead policy innovation (e.g., Essl et al. 2020). Invasion science is increasingly becoming a topic of interest in the global scientific community with a growing number of research publications each year and numerous dedicated journals, including *Aquatic Invasions*, *Biological Invasions*, *Bioinvasion Records*, *Management of Biological Invasions*, and *NeoBiota* (Richardson and Pyšek 2008, Vaz et al. 2017). However, major gaps between research knowledge and policy implementation persist, and so do mismatches between what knowledge invasion science delivers and what policy agendas prioritize (Knight et al. 2008, Esler et al. 2010, Matzek et al. 2015). Understanding the extent to which policy formulation and research outputs are aligned becomes a necessary step for problem-solving context (after Kueffer and Hadorn 2008) in invasion science.

In the present article, we describe how the research literature on biological invasions refers to different policy approaches and instruments as a way to provide an overview on the status of policy-oriented invasion science. Specifically, we answer the following questions: Question 1: Are key international policy instruments related to invasive alien species (i.e., international conventions, international research initiatives) contributing to an increase in the volume of policy-oriented research in this field? Question 2: Is policy-oriented research in invasion science contributing to policy development and setting policy priorities or are policy expressions and instruments driving invasion science research? Question 3: What are the major gaps and opportunities for policy-oriented invasion science? The answers to these questions are pulled together to contextualize and examine the links between policy and research—namely, by exploring whether policy events potentially drive research interest and vice versa, which contributions invasion research has been delivering to policy needs and vice versa, and how research and policy can be better aligned to ensure more efficient and transparent problem solving in invasion science.

A systematic review of policy-oriented research in invasion literature

As a basis for our study, we gathered published literature pertaining to policy-orientated invasion science research (defined as research on invasive alien species that mentions

policy instruments; see table 1). To do so, we followed the general guidelines for conducting systematic reviews (Higgins et al. 2019). It involved two major steps: a literature search in Scopus and the ISI Web of Science to gather sources and evidence pertaining to policy-orientated invasion science research and a literature review with the extraction of relevant information and data analysis. Further details on these steps are provided below (see supplemental figure S1 for the conceptual framework).

Literature search. The search for relevant literature was grounded on a set of keywords related to invasive alien species and policy. The list of initial keywords was based on a list of reference papers and expert knowledge. Then, keywords were selected using the Scopus engine: For each new keyword added to the string, the first 10 results from Scopus were checked for relevance. The final search string captured the most relevant papers considering our scope and included 28 keywords related to invasive alien species and 8 keywords related to policy (see supplemental tables S1 and S2 for details on keyword selection and the terms used in the final search string).

Using the final search string, a search for peer-reviewed literature was conducted using Scopus and the ISI Web of Science in October 2020. We considered research papers and reviews published since 1950, broadly coinciding with Elton's (1958) book, which, arguably, "launched the systematic study of biological invasions" (Richardson and Pyšek 2008). The search was restricted to English publications in order to ensure comparability in the use of invasive alien species and policy terminologies. To analyze potential language bias, a comparison of Scopus results as a function of language was made: From the 3403 publications retrieved, only 4.5% (n = 153) were non-English publications (the top three other languages were German, Spanish, and French).

The records retrieved from the literature search in Scopus and the ISI Web of Science were combined (n = 5535). We used the package "revtools" in R (Westgate 2019) to eliminate duplicated records automatically by DOI correspondence (exact function) and then manually by a title similarity analysis (stringdist function). Using the same R package, the title, abstract, and keywords of each publication were screened for relevance, and irrelevant records were discarded—for example, those that mentioned policy but not in relation to invasive alien species or studies that used the term *invasive species* for political and ethical discussions (see supplemental table S3 for all exclusion criteria). In case of doubt, the record was included, and the full text was reviewed in the literature review phase.

To analyze the reliability of our search in Scopus and the ISI Web of Science, the first 50 relevant records retrieved by a search in Google Scholar using a general search string: *"invasive species" AND "policy"* were checked and compared with the publications in our database. A total of eight additional records, identified as adequate, were missing and were added to the database.

Literature review. The content of each individual record from our database (n = 2974) was reviewed in depth. For inclusion in the final database, the articles had to be policy oriented according to our criteria: They had to mention policy instruments (see table 1) to contextualize the need for research (i.e., policy driving research) or as explicit policy recommendations (i.e., research that contributes to policy). The articles that met these criteria were classified according to different categories pertaining to the publication characteristics and the invasive alien species features (see table 2). The data regarding publication characteristics included the publication year, the paper's relationship to policy, the scale, the thematical focus of the publications related to invasive alien species policy themes, the research methodology, the geographic location of the study, and the country, when applicable. Information on invasive alien species features included terminology, the taxonomic group, and the type of invaded environment. The records that were not considered relevant after full text analysis were excluded, resulting in a final database that included 2135 records.

The data extracted from our final database was subjected to descriptive univariate analyses and statistical analysis. To understand whether key international policy instruments are potentially contributing to more policy-oriented invasion science (question 1), the number of published records per year was plotted against the years of important international policy instruments. The percentage of records from distinct categories (terminology, thematical focus, and research methodologies) per year was also plotted. When temporal trends were analyzed (i.e., analysis using the number of publications per year), we performed an anomaly detection of time series test, using the R package "anomalize" (Dancho and Vaughan 2020) to test for significant positive anomalies in the temporal trend (i.e., the years in which there were statistically significant positive deviations from the trend; see supplemental figure S2 for details on the statistical analysis). To evaluate whether policy-oriented research in invasion science is contributing to policy development and setting policy priorities (or vice versa; question 2) the percentage of the answer categories in the relationship to policy category (i.e., driven by, contributes to, and both) per year was plotted, and the results were discussed considering the years of important international policy instruments. To assess the gaps and potential opportunities for policy-oriented invasion science (question 3), our categories (scale, taxonomical focus, and environment) were analyzed using bar plots. The number of published records across geographic regions and countries was mapped using a geographical information system software (QGIS version 3.16 software).

A general look into policy-oriented literature in invasion research

Our initial keyword search retrieved over 59,500 publications that included terms pertaining to biological invasions. Within this search, hits with policy-related keywords represented approximately 5% (3250 publications) of the total

Table 2. Categories used for data extraction and analysis and respective answer categories with definition and examples where relevant.

Categories	Answer categories with definitions and examples where relevant	Source
Publication year	Year of publication	Extracted directly from research paper.
Relationship to policy	Driven by (policy instruments are mentioned in research to contextualize and underline the need for such research)	Based on our definition of "policy-oriented" research
	Contributes to (policy instruments are mentioned in research as recommendations based on said research)	
	Both (policy instruments are mentioned in the research to both contextualize and underline the need for such research and as recommendations based on said research)	
Scale	Subnational (regions and subregions of counties, both administrative and geographical)	Based on and adapted from Jänicke (2015), Arriagada and colleagues (2018)
	National (country level)	
	Regional (within one continent but in multiple countries; e.g., Mediterranean region)	
	Supranational (European Union—member countries cede authority and sovereignty on at least some internal matters to the group, whose decisions are binding on its members)	
	Multinational or multiregional (several countries from different regions; several regions without geographical or administrative connection)	
	Global (whole world)	
	Not applicable (i.e., the study doesn't not have spatial dimension)	
Thematic focus[a]	Biodiversity and Environment (publications focusing on general invasive alien species management issues, conservation of important habitats or important species, biodiversity and environmental conservation)	Based and adapted from Shine and colleagues (2000), McNeely and colleagues (2001), Secretariat of the Convention on Biological Diversity (2001a), Faulkner and colleagues (2020)
	Security and safety (publications focusing on phytosanitary, animal health, public health and human well-being, biosecurity—related to the protection against pests and diseases that arrive through international trade and transport—and biosafety—related to hybridization or genetically modified organisms—concerns)	
	Sectors and pathways (publications focusing on trade and commerce related to sectors such as forestry, agriculture, horticulture, fisheries, aquaculture, husbandry, pets, and wood packaging or other introduction pathways related to human activities such as transport—shipping, air and roads—territorial planning and land use, hunting, zoos, recreational activities, tourism and biological control)	
Methodology	Assembling and creating new data (biological; ecological studies of, e.g., habitat, diet, density, distribution; modelling studies; economic studies, e.g., cost assessment)	Based and adapted from the IPBES categorization of "policy tools and methodologies"
	Assessment and evaluation (reviews; policy reviews; biological or ecological reviews, e.g., review of threats to a certain location or review of impacts of a certain species; reviews of management methods used for certain species)	
	Public discussion, involvement, and participatory process Social study approaches (e.g., stakeholder engagement, education and analysis of willingness to pay)	
	Selection and design of policy instruments (design of risk assessment framework, indicator development, development of decision support tools)	
	Implementation, outreach and enforcement (studies reporting the implementation of management initiatives or programs)	
	Training and capacity building (studies reporting the implementation of training or capacity building initiatives; e.g., study program)	
Geographical region	Europe	Based on the United Nations Statistic Division categorization of geographic regions
	Asia	
	Oceania and the Pacific	
	Africa	
	North America	
	Latin America and the Caribbean	
	Antarctica	
	Global	
	Not applicable	
Country	Country name	Based on the United Nations Statistic Division categorization of countries or areas

Table 2. Continued.

Categories	Answer categories with definitions and examples where relevant	Source
Terminology	Invasive alien species	Extracted directly from research paper
	Invasive species	
	Exotic species	
	Introduced species	
	Alien species	
	Nonnative species	
	Nonindigenous species	
	Allochthonous species	
Taxonomy	Animals Mammals Birds Herpetofauna Fish Insects Crustaceans Mollusks Other invertebrates Multiple or all	Based on Seebens and colleagues (2017) Some categories were adapted (some groups were merged, and some groups were added)
	Plants	
	Others	
	Multiple or all	
Environment	Terrestrial	Based on IPBES units of analysis
	Aquatic	
	Both	

[a]This category is not mutually exclusive.

results, more than twice the results found in a previous study from Esler and colleagues (2010), in which they reported about 2% of search hits with policy keywords in an invasion ecology literature search.

It is possible to identify an increasing trend of search results for invasion science through the years and a similar trend of increased search results for those with policy-related keywords (figure 1). There is no doubt that scientific interest in biological invasions has grown substantially over the last two decades, accompanying the growth of research in environmental science and ecology in general (as was previously shown in Vaz et al. 2017), and policy-oriented invasion science seems to also be accompanying this tendency (figure 2a).

From our literature review, it appears that the difference in the amount of research that is being driven by policy, contributing to policy, or both is not substantial (figure 2a). In fact, most research papers were both driven by policy instruments and contributed directly to their development or improvement (886 papers, 41.5% of all publications). Nevertheless, those only driven by policy were a bit more common (i.e., policy instruments appeared only to contextualize the need for research; 749 papers, 35% of all publications) than papers that only contributed to policy (i.e., policy instruments appeared only as direct recommendations of the research; 502 papers, 23.5% of all publications).

A more notorious incidence of policy-oriented studies appears to emerge at the end of the first decade of the 2000s (figure 2a). Particularly in 2010 and 2011, the number of policy-oriented publications in invasions shows a steep increase (figure 2a). This pattern coincides with the launch of the tenth Conference of the Parties of the CBD, where the Strategic Plan for Biodiversity 2011–2020 was adopted alongside the consideration of an Aichi target focused explicitly on invasive alien species: "By 2020, invasive alien species and pathways are identified and prioritized, priority species are controlled or eradicated, and measures are in place to manage pathways to prevent their introduction and establishment" (target 9).

Temporal overview on policy-oriented research in invasion science

The first policy-oriented publications captured by our search were from the 1970s and were focused on sanitary concerns and the impacts of industry-related activities (figure 3c). Specifically, the Gee and Whittem's (1973) review of existing Australian plans for the control of alien animal diseases, and Odum's (1974) recognition of exotic species as a threat to inshore coastal aquaculture and the legal obligations of practitioners to deal with them. These topics of interest are in line with wider trends during the 1970s, when the spread of alien species became a subject of concern in both the scientific and policy communities because of increasing evidence of alien species as vectors of diseases and pests in natural and production ecosystems (Krebs 2001, Stork et al. 2014).

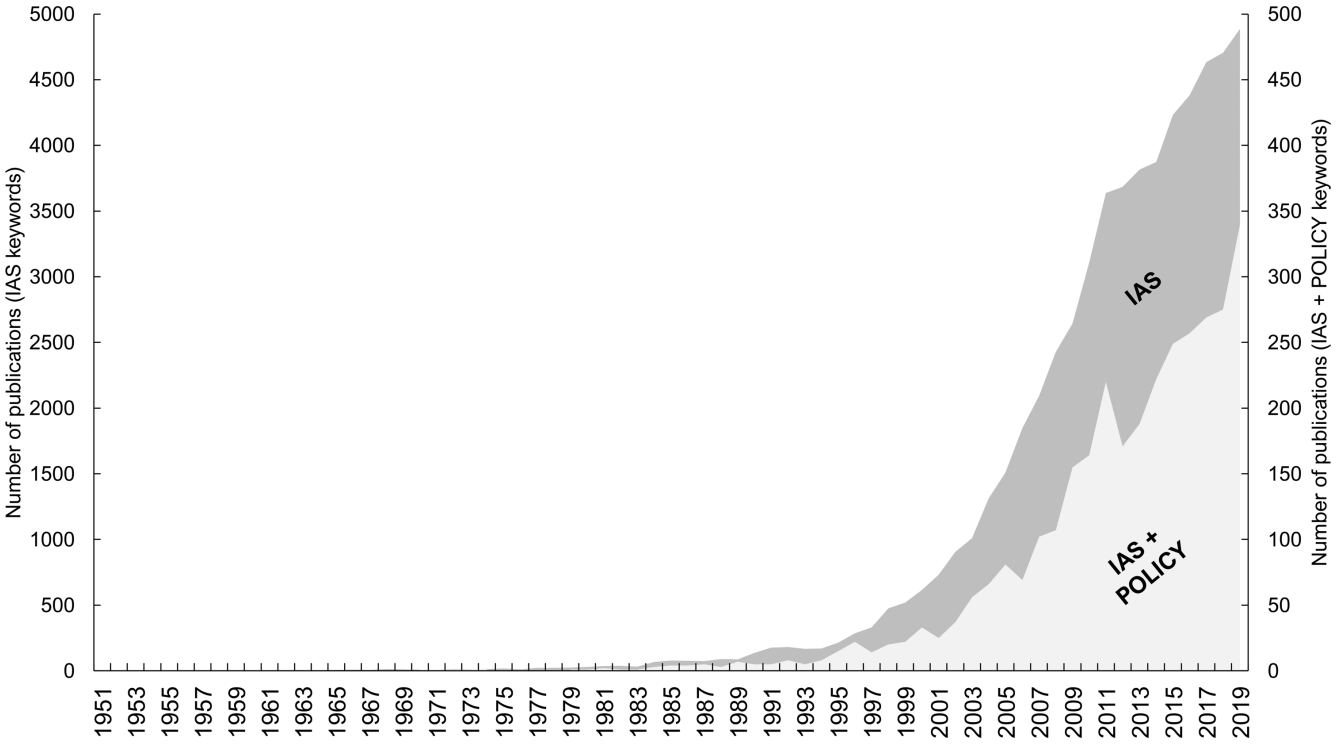

Figure 1. Results from the keyword search. The temporal trends in the number of publications were retrieved using only keywords related to invasive alien species, and the temporal trends in the number of publications were retrieved using keywords related to both invasive alien species and policy.

During the 1980s, policy-oriented publications concerning biological invasions were sporadic (e.g., Hedgpeth 1980, Warman and Todd 1984, King and Moody 2012) and were mostly related to biodiversity and environmental conservation (figure 3a). Throughout this period, international agreements such as the Convention on the Conservation of Migratory Species of Wild Animals and the United Nations Convention on the Law of the Sea were adopted (figure 2a, table 3). Although neither of these was focused on invasive alien species, they emphasized their role as threats to biodiversity and ecosystems (table 3).

The term *alien species* was first captured in a policy-oriented research paper in the early 1980s, relating to the conservation of Antarctic living resources (figure 2b; Brown 1983), whereas, in international policy instruments, it was first used in the United Nations Convention on the Law of the Sea (in 1982; table 3). The term *alien species* was also used in subsequent conventions, including the CBD in 1992 (table 3), with later international policy instruments regularity adopting the term *invasive alien species* (see below).

Since the late 1990s, an exponential increase in policy-orientated invasion science research has become prominent (figure 2a). The SCOPE (Scientific Committee on Problems of the Environment) program, a pioneer international initiative on biological invasions (Drake et al. 1989), has been acknowledged as a major trigger for the rapid growth in the field of invasion science (Richardson 2011, Simberloff 2011) with clear links to policy (e.g., initiatives that assessed the threat of invasive species in protected areas; Shackleton et al. 2020). It was also during this time that several conventions concerning invasive alien species (or conferences of the parties of certain conventions) were adopted, including the CBD (1992), the Ramsar Convention (COP 7–1999), and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (COP 10–1997). Notably, during the late 1990s, the Global Invasive Species Program was created to help minimize the spread and impact of invasive alien species. The Global Invasive Species Program was focused on policy and governance (Secretariat of the Convention on Biological Diversity 2001b) and may have also influenced the interest in policy-oriented research before its discontinuation several years later. Still, most policy-orientated research until the mid-1900s relied on assessment and evaluation (i.e., reviews) and less on assembling data and knowledge, and little attention was given to other approaches (figure 4a).

In fact, until the 2000s, most publications were either reviews of ecological impacts or of policies and management options related to invasive alien species (e.g., Mac Donald 1988, Baker 1990, Hutchings 1992) or were observational or experimental research (e.g., monitoring of a certain invasive population or biological descriptions of certain species; figure 4a; Hickley 1987, Callaghan et al. 1997, Reichard and

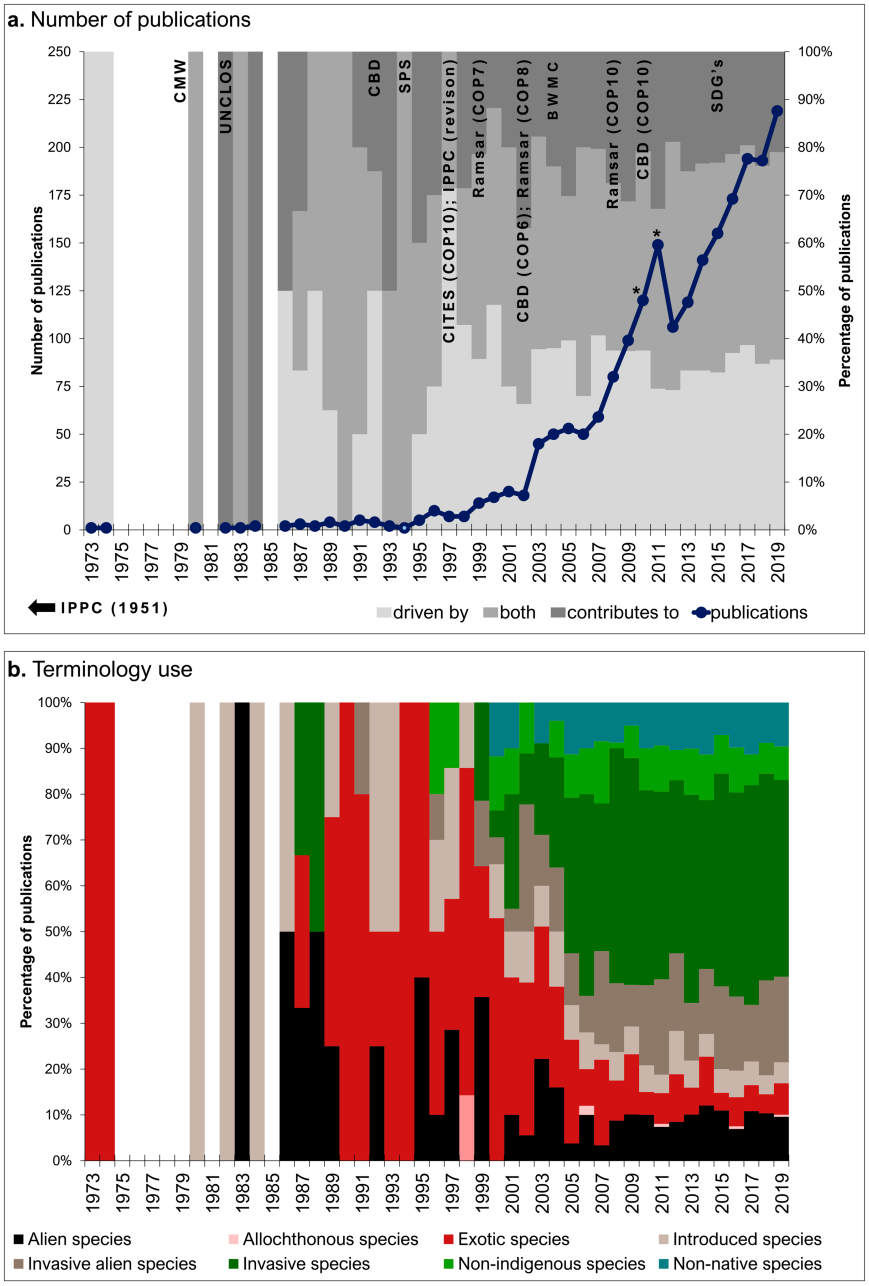

Figure 2. (a) Temporal trends in the number of policy-oriented publications in invasion science from 1973 to 2019 and in the percentage of publications' relationship to policy. The points marked by an asterisk (*) are positive anomalies from the statistical analysis. The year of adoption or publication of the main international policy instruments that mention invasive alien species is identified. (b) The percentage of terminology use in publications per year.

Hamilton 1997). Such might suggest that, although it was policy oriented (i.e., driven by existing policy instruments or contributing to their development or improvement), the invasion research concerned systems knowledge (after Kueffer and Hadorn 2008) without explicit application in policy and management.

From 2000 onward, policy-oriented research became widely focused on sectors or pathways of invasive species introductions (figure 3b; e.g., Schuppli and Fraser 2000, Rouget et al. 2002). This focus can also be linked to the international policy agenda; the sixth Conference of Parties of the CBD, in 2002, defined the guiding principles for the implementation of article 8(h). One principle in particular "urges Parties… to promote and carry out, as appropriate, research and assessments on: …Analysis of the importance of various pathways for the introduction of invasive alien species" (decision VI/23, article 24.c).

Also since the 2000s, the term *invasive* started to be more commonly used in policy-oriented invasion science (figure 2b). *Invasive* as a term referring to alien species, had already been adopted during the seventh Conference of the Parties of the Ramsar Convention and the US "Invasive Species" executive order 13112 in 1999 (table 3) and later used in the CBD–COP 6 documents in 2002 (table 3). In general, from 2004 onward, there seems to be a prevalence for the term *invasive*, as a replacement for the earlier terms *exotic* and *introduced* and their associated connotations, possibly as a reaction to the highly cited Richardson and colleagues (2000) and to Pyšek and colleagues' (2004) calls for standardizing invasion-related terms in the early 2000s.

Besides changes in terminology, a shift toward the development of transformation and target knowledge in policy-oriented research also appears to emerge in the 2000s. For example, socioecological studies that included public participation (e.g., questionnaires and surveys) gained prominence in policy-oriented invasion research (figure 4a; e.g., Fischer and van der Wal 2007, Andreu et al. 2009), allowing for the consideration of stakeholder's perceptions and opinions and the inclusion of local and indigenous knowledge in scientific research (García-Llorente et al. 2008, Caceres-Escobar et al. 2019). Ultimately, these types of studies can contribute to the success of conservation and management outcomes (Reed 2008, Sterling et al. 2017). Other analyses have shown an increase in publications dealing with stakeholder engagement in invasion science during the 2000s, and particularly since 2009 (Shackleton et al. 2019).

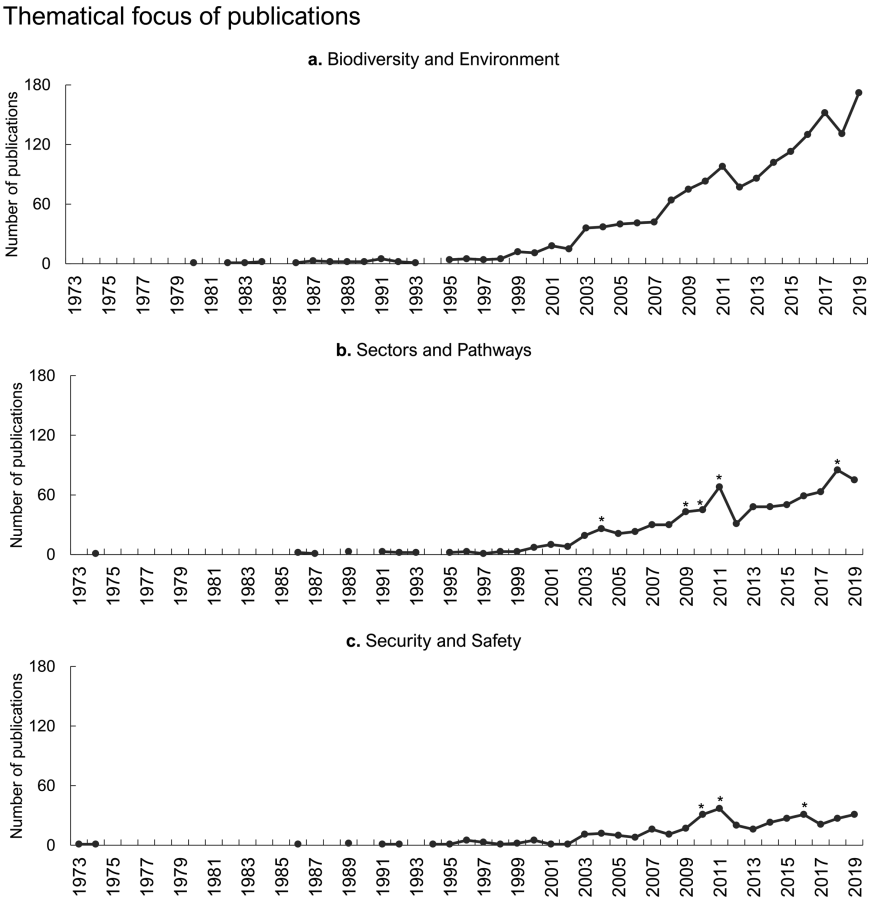

Figure 3. The n umber of publications related to each thematical theme throughout the years: (a) biodiversity and environment, (b) sectors and pathways, and (c) security and safety. The points marked with an asterisk (*) are positive anomalies from the statistical analysis.

Research specifically dedicated to the design and selection of policy tools, such as the development of frameworks or indicators for invasion risk assessment, also became more prominent in the 2000s (figure 4a; e.g., McGeoch et al. 2006, Meyerson et al. 2008, Ou et al. 2008), accompanying technological advances, such as the development of advanced molecular methods and increased computational performance (Richardson and Pyšek 2008). Concurrently, the focus on invasive alien species management started shifting toward a more precautionary approach (Secretariat of the Convention on Biological Diversity 2001a). Again, the 2002 COP of the CBD, with its definition of priority areas and guiding principles (i.e., decision VI/23, guiding principle 1: precautionary approach), might have contributed to motivate the application of research outcomes with policy-oriented invasion focus.

From our data set, studies reporting, implementing, or building capacity toward the management of invasive species were scarce (figure 4a), which may represent a drawback to foster links at the science–management interface (Esler et al. 2010). Nonetheless, such studies appear to have become more popular since 2010 (figure 4a). Examples include Porth and colleagues (2015) and Pertierra and colleagues (2017).

Status and content of policy-oriented research in invasion science

International environmental policy provides institutional support for research and innovation, increasing scientific and public motivation to address issues, and promotes the funding of scientific consortia (Bruyninckx 2005, Liao and Liu 2021). Consequently, it is expected that international policy instruments are driving a sharper focus on invasive alien species (e.g., the CBD and Sustainable Development Goals that have specific targets related to invasive species) and are providing an impetus for policy-oriented research in invasion science. Our literature review suggests a connection between important international policy instruments, particularly the CBD's COP 10, and the volume of published policy-oriented research, as well as a coordination between the thematic focus of publications and terminology use and international conventions.

This effect may become less obvious when we consider legal policy instruments at regional or national scales. For instance, Canada has more legislation relevant for invasive alien species than the United States does (relevant legislation defined by "more than 50% of the document dedicated to multiple invasive species or invasive alien species in general"; Turbelin et al. 2017). However, our literature review shows that the United States has produced substantially more policy-oriented research (373 publications from the United States and only 34 from Canada; figure 5a). Similarly, although most South American countries have legal instruments relevant to invasives and are signatories of a substantial number of international treaties that mention invasive alien species (Turbelin et al. 2017), our search found a low incidence of policy-oriented studies (e.g., Argentina, 12; Ecuador, 10; Chile, 8; Uruguay, 1; figure 5b). This could also be affected by a bias in our data because we included only search terms in English. Conversely, some countries with limited policy have substantial policy-orientated research output. For example, Brazil, India, and China were the focus of substantial numbers of policy-oriented research papers (56, 35, and 38 publications, respectively; figure 5a). However, from these countries, only Brazil has legal instruments with high relevance for invasive alien species (Turbelin

Table 3. International conventions relevant for invasive alien species, type of species considered, terminology used and year of adoption.

International policy development	Type of invasive alien species	Terminology used	Date of adoption
International Plant Protection Convention	Introduced organisms that are pests.	Introduced pests	1951 1997 (revised)
Convention on Migratory Species of Wild Animals	Exotic species that are considered a threat to migratory species.	Exotic species	1979
United Nations Convention on the Law of the Sea	Alien species that threaten the marine environment.	Alien species	1982
Convention on Biological Diversity	Alien species that threaten ecosystems, habitats, and species.	Alien species	1992
Agreement on the Application of Sanitary and Phytosanitary Measures	Pests and diseases that cause sanitary and phytosanitary issues (there is no specific mention of the term "alien species," but many pests and diseases are alien species).		1994
Convention on International Trade in Endangered Species of Wild Fauna and Flora COP10	Alien or exotic diseases that arrive from trade in animals or plants. Exotic species that escape from captivity or are accidentally introduced.	Alien diseases Exotic species	1997
Convention on Wetlands of International Importance COP 7	Invasive species that are a threat to wetlands.	Invasive species	1999
Convention on Biological Diversity COP 6	Alien species that threaten ecosystems, habitats, and species.	Invasive alien species	2002
Convention on Wetlands of International Importance COP 8	Invasive species that are a threat to wetlands.	Invasive species	2002
International Convention for the Control and Management of Ship's Ballast Water and Sediments	"Harmful aquatic organisms" (can include invasive alien species).	Invasive alien species	2004
Convention on Wetlands of International Importance COP 10	Invasive alien species that are a threat to wetlands.	Invasive alien species	2008
Convention on Biological Diversity COP 10	Invasive alien species and pathways (general).	Invasive alien species	2010
Agenda 2030 Sustainable Development Goals	Invasive alien species with an impact on land and water ecosystems.	Invasive alien species	2015

Note: For information on specific sections on invasive species and links to original sources, see supplemental table S4.

et al. 2017). This suggests that factors other than legislation contribute to the different geographical focus patterns of policy-oriented research. Such factors may well be justified by the economic situations of the country and economic incentives, including research and management funding, which can reflect research interest or capacity (Leydesdorff and Wagner 2009).

The economies of the United States of America, India, China, and Brazil are some of the biggest in the world (World Bank 2020), and these countries are among the most adversely affected by invasive alien species (Diagne et al. 2021). In these cases, economic factors (either financial capability that drives research or economic costs that drive political interest) could be acting as key drivers for the interest and production of policy-oriented research. The remaining countries with a high volume of policy-orientated research (i.e., several countries in Europe, Australia, New Zealand, and South Africa; figure 5a) have both legal instruments relevant to invasive alien species and high economic costs related to damage or management (Turbelin et al. 2017, Diagne et al. 2021). These countries also have long traditions of invasion research and substantial research infrastructure, which contribute to the observed differences (van Wilgen et al. 2020).

Most policy-oriented studies are performed at either subnational or national scales (figure 4b). Although a global international setting can be extremely important for driving the interest in policy-oriented research, the application of research at more local scales is favored by the fact that each place has specific ecological, economic, and sociocultural characteristics, which allows the adaptation of policy mechanisms to local circumstances and needs (Sovacool and Brown 2010).

Our review highlights that Oceania has the highest number of policy-oriented studies at the national scale (figure 5b). Because all countries in the region are islands and are therefore geographically isolated territories, it makes sense that their research goals follow a view on policy application that has a more national perspective, especially when related to biosecurity (i.e., related to the application of measures specifically aimed at protecting against invasive pests and diseases that arrive through international trade and transport; Whittington and Chong 2007). Also, the best studied animal group was mammals

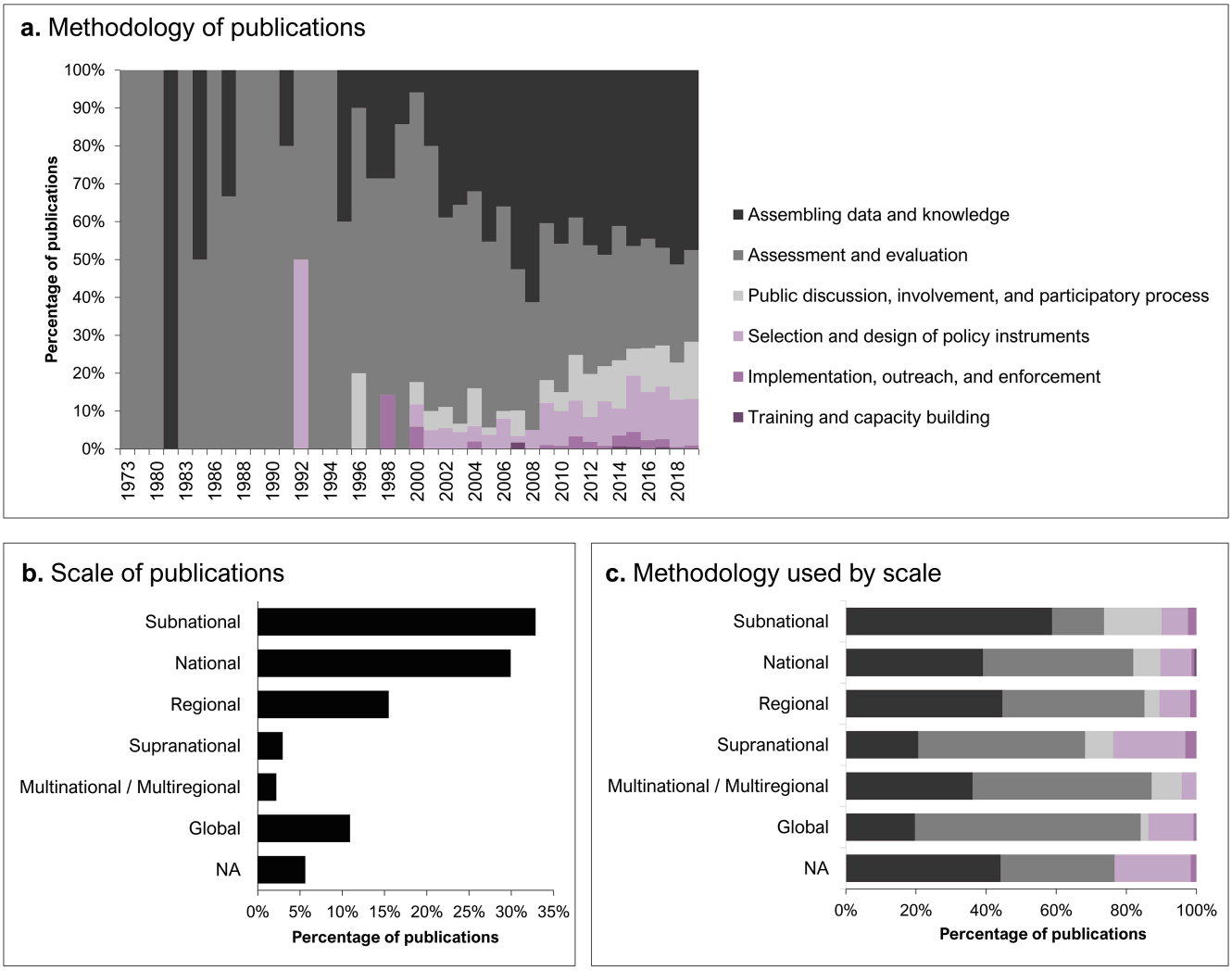

Figure 4. (a) The percentage of publications in each methodological category per year, (b) the percentage of publications performed at each scale, and (c) the percentage of records in each methodological category for each scale.

(see supplemental figure S3). Australia and New Zealand are the regions with high alien mammal richness (Dawson et al. 2017); because they are (large) islands (with rich diversity of endemic native species), the impacts of invasive alien mammals can be devastating for their native flora and fauna (Krull et al. 2014). In 2016, New Zealand implemented a program in which they committed to eradicate, by 2050, the most damaging introduced predators that have severe impacts on native biodiversity, the economy, and the primary sector (Predator Free 2050; Department of Conservation New Zealand 2020). Therefore, in Australia and New Zealand, the taxonomic focus of policy-oriented research seems to be coordinated with policy priorities of these regions. Also, the only research paper found in our search that was related to "Training and capacity building" was one that introduced the first master's program focused on biosecurity in Australia (Bayliss 2015); this demonstrates how the importance of managing invasive alien species is being translated into education and technical training (and these programs are being reported in the scientific literature).

In South Africa, the Working for Water program, a government-administrated invasive species management and public work and employment program that started in 1995, is clearly a driver of progress in both research and policy (van Wilgen and Wannenburgh 2016). Africa was the only region with a greater focus on plants than on animals (see supplemental figure S4). Considering that most of the studies from Africa are from South Africa, it seems that, as for New Zealand, the taxonomic focus of policy-oriented research is aligned with policy goals and priorities. In fact, several research papers from South Africa in our database were directly related to this program (e.g., Görgens and Van Wilgen 2004, Magadlela and Mdzeke 2004, Turpie et al. 2008). Furthermore, the strong partnership between the Centre for Invasion Biology and Working for Water has facilitated good links between academic and state intuitions to drive the production

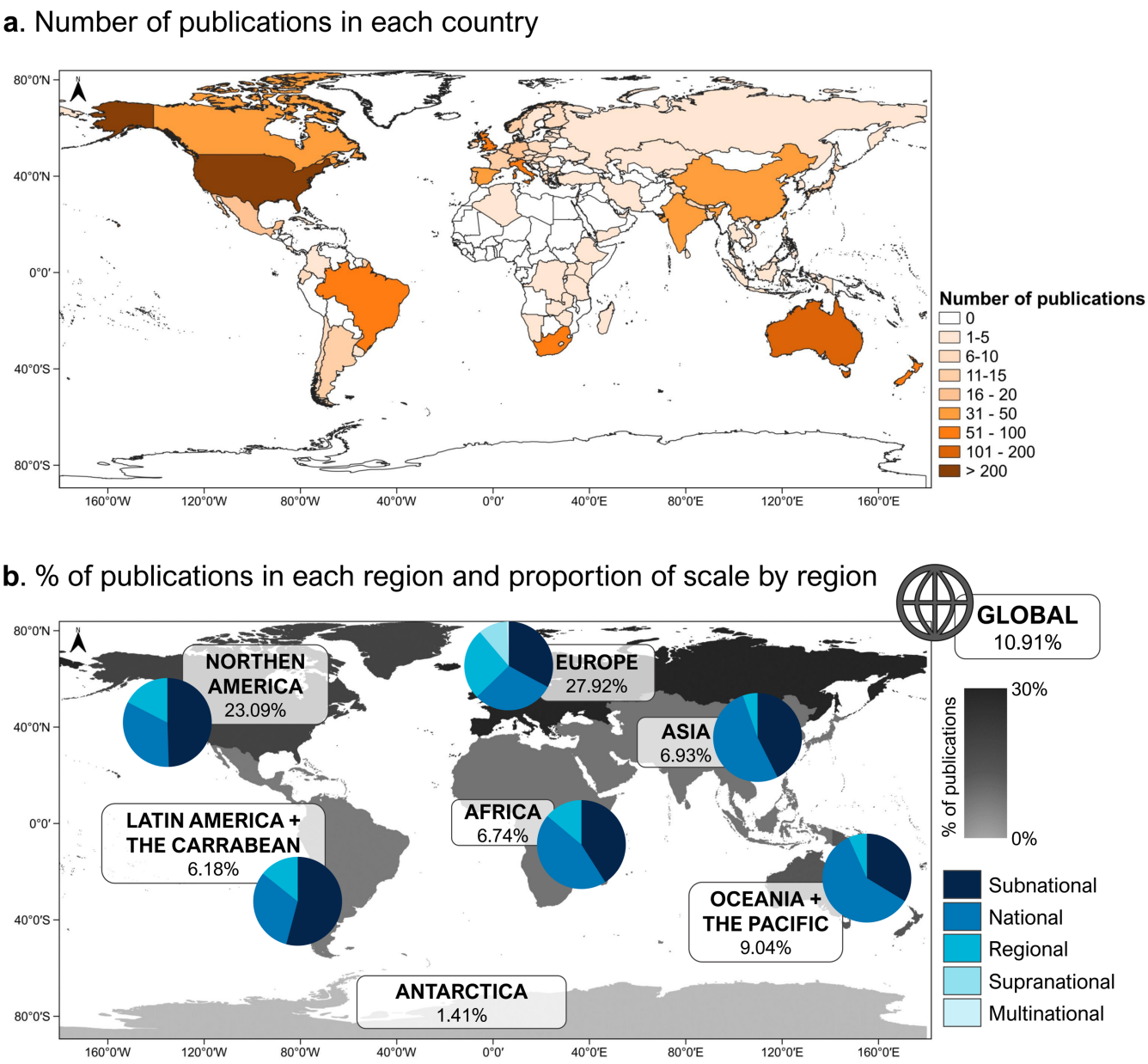

Figure 5. (a) The number of publications as a function of country (including subnational and national studies) and (b) the percentage of publications in each geographical region and of publications done at each scale for each geographical region (the circular plots).

of policy-orientated research (Abrahams et al. 2019, Richardson et al. 2020). This can also explain the high number of policy-oriented studies in South Africa (96 publications; figure 5a).

Conclusions

In summary, our literature review and analysis suggest that the volume of policy-oriented research in invasion science is affected by the international relevance given to invasive alien species policy and management. It seems that the uptake of policy-oriented research in invasion science may potentially surge as a direct response to the international political institutionalization of invasive alien species (Secretariat of the Convention on Biological Diversity 2001a, Shine et al. 2010, Johnson et al. 2017) but also, indirectly, through research initiatives and global strategies that have been created in recent decades. Particularly, international policy events seem to contribute not only to an increase in the volume of policy-oriented research but also to the thematic focus of this research and the terminology used. Specifically, the period during which the most important invasive alien species convention (COP 10 of the CBD with its guiding principles) was launched matched the peak in publication

of policy-oriented research. This also supports the notion that global conventions can produce creative energy directed at collective-action problems (i.e., more policy-oriented research) in addition to the governance, norms, and regulations they promote.

Although guided by international policy agendas, policy-oriented research is more focused at local scales (i.e., subnational and national) and on countries that have the capacity to do research (e.g., the United States) or where the impacts of invasive species are well known and exceptionally high (e.g., Pacific Islands and South Africa). The development and uptake of more policy-oriented research in invasion science need to be promoted, especially in places where the economic impacts remain poorly understood or in areas that lack the adequate legal measures. Such research can support invasive alien species prevention and management in those regions while also contributing to global-scale objectives.

When designing policy-oriented studies, researchers should consider using more applied and innovative methodologies that can directly contribute to policy design or implementation. For instance, the design and selection of policy tools (e.g., risk management frameworks, indicators) that can be directly used by policymakers and managers is crucial. Reporting on management programs or technical and capacity-training programs can contribute to reducing the barrier between science and policy, because it can act as a useful guide for decision-makers facing similar problems. It can also help to address some of the issues related to the potential inaccessibility of science to many relevant stakeholders.

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Supplemental material

Supplemental data are available at *BIOSCI* online.

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