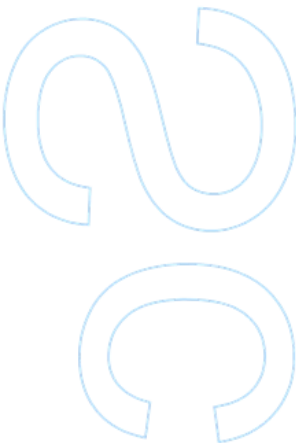
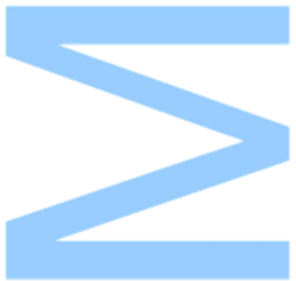


Policy-oriented research in invasion science: status, trends, gaps and lessons

Eva Malta Pinto
Dissertação de Mestrado apresentada à
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Master in Ecology and Environment

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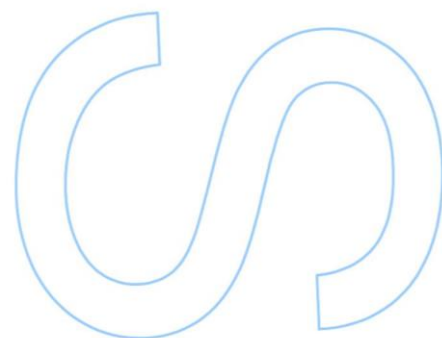
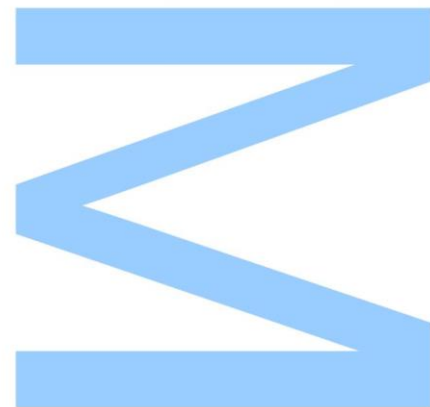
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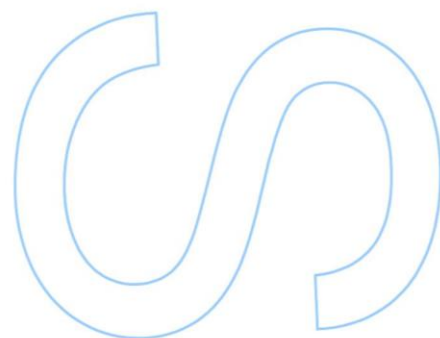
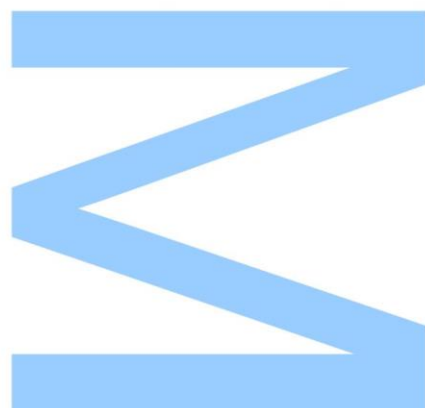




Todas as correções determinadas
pelo júri, e só essas, foram efetuadas.

O Presidente do Júri,

Porto, ____ / ____ / ____



*"If I have seen further,
it is by standing on the shoulders of Giants"*

Isaac Newton

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Abstract

Invasive alien species (IAS) are one of the main drivers of global change. Due to intensifying globalization patterns, such as trade and transport, the last decades have seen an increase in the ecological, economic, and sociocultural impacts of these species.

Since introductions are strongly associated with human activities and movement, the management of these species has become an ever more relevant topic on international environmental policy debates, with the Convention on Biological Diversity (CBD) being one of the most important ones, placing IAS on the forefront of national policy goals and priorities. IAS policy measures can range from preventive regulations to direct management actions, depending on the need, magnitude, and scale of the problem. The use of scientific-based policy tools can contribute to the design and implementation of more effective policies.

To better understand the connection between IAS policy and research, as well as identify trends and gaps in policy-oriented invasion science, a systematic literature review was performed, according to an analytical framework based on a standard protocol. The literature review included 2135 publications which were individually reviewed and classified into categories that allowed to achieve the proposed objectives.

The results suggested there are positive feedbacks between international agreements and policy-oriented research, as important periods in IAS policy (e.g., COP10 of the CBD) were also the same periods during which the amount of published research conducted with a policy focus increased. At national levels, however, policy-oriented research seems to be more driven by economic factors (such as a country's research capability) or the level of IAS impacts (economic and/or environmental). Furthermore, it was shown that cooperative, as well as knowledge and capacity-building policy instruments are more recommended by research, than legislative and regulatory ones.

The study also supports the idea that policy-mixes adapted to local contexts should be applied in IAS policy design.

Keywords: invasive alien species, invasion science, policy, literature review, science-policy interface

Resumo

As espécies exóticas invasoras são uma das maiores causas de mudanças globais. Devido à intensificação de padrões de globalização, como o comércio e transporte, os impactos ecológicos, económicos e socioculturais destas espécies aumentaram nas últimas décadas.

Uma vez que a introdução destas espécies está associada a atividades humanas, a gestão das mesmas tem se tornado um assunto cada vez mais relevante em debates de política ambiental internacional, sendo a Convenção da Diversidade Biológica (CBD) um dos mais importantes, já que contribuiu para a colocação da gestão de espécies exóticas invasoras em objetivos ambientais de políticas nacionais. As medidas de gestão de espécies exóticas invasoras podem variar entre regulações de carácter preventivo e ações diretas de gestão, dependendo da necessidade, magnitude, e escala do problema. O uso de ferramentas de gestão baseadas em processos científicos pode contribuir para a conceção e implementação de políticas mais eficazes.

Para compreender melhor a ligação entre política e investigação no campo das espécies exóticas invasoras, bem como identificar tendências e lacunas na pesquisa orientada para a política de gestão, conduzimos uma revisão sistemática de literatura, de acordo com uma estrutura analítica baseada num protocolo predefinido. A revisão da literatura incluiu 2135 artigos, que foram revistos individualmente e classificados de acordo com categorias definidas.

Os resultados sugerem que há uma ligação positiva entre acordos internacionais e investigação orientada para a política, uma vez que os períodos mais importantes na política de gestão de espécies exóticas invasoras (e.g. a COP10 da CBD) foram também os períodos em que a quantidade de investigação focada na política de gestão aumentou. A nível nacional, no entanto, este tipo de investigação aparenta ser mais influenciado por fatores económicos (como a capacidade de investigação de um país) ou pelo nível de impacto destas espécies (económicos e/ou ambientais). Para além disso, ficou demonstrado que instrumentos de política baseados na cooperação, bem como na construção de conhecimento e capacitação são mais vezes recomendados pela investigação, do que instrumentos legais e regulatórios.

O nosso estudo suporta a ideia de que a combinação de vários instrumentos de política, adaptados aos contextos específicos em que se inserem deve ser a norma na conceção de políticas de gestão de espécies exóticas invasoras.

Palavras-chave: espécies exóticas invasoras, ciência de invasões, política, revisão de literatura, interface ciência-política

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List of abbreviations

CITES – Convention on International Trade in Endangered Species of Wild Flora and Fauna

CBD – Convention on Biological Diversity

COP – Conference of Parties

CMS – Convention on the Conservation of Migratory Species of Wild Animals

CS – Citizen Science

IAS – Invasive Alien Species

IPPC – International Plant Protection Convention

EU – European Union

MEA – Millennium Ecosystem Assessment

UNCLOS – United Nations Convention on the Law of the Sea

1. Introduction

1.1. Invasive alien species as a global change driver

Invasive alien species (IAS) are species that are intentionally or unintentionally transported by humans to new geographic areas, overcoming biogeographical barriers, and becoming established with the potential to spread (Blackburn et al. 2011; Richardson et al. 2000). In most governmental or policy documents, however, the definition of IAS usually also includes the mention that the introduction is likely to cause harm (or impact), either to the environment, economy, or human health (Beck et al. 2008; CBD 1992; IPBES 2018).

IAS are a major driver of global environmental change and are one of the greatest drivers of biodiversity loss worldwide (IPBES 2019). IAS can modify habitats (e.g., by affecting ecosystem functioning) or impact native species' directly through competition, predation, transmission of diseases or hybridization (Pyšek et al. 2020).

IAS can also affect agricultural, aquaculture and forestry systems or damage infrastructures and landscapes causing great economic losses for nations globally (Diagne et al. 2021). In North America, for example, the economic costs related to IAS (i.e., related to damage, management or both) have increased from 2 billion US dollars per year in the early 1960s to over 26 billion per year in the 2010s (Crystal-Ornelas et al. 2021).

The impacts of IAS on human well-being are not limited to the monetary losses, as they can also affect public health (e.g., cause allergies, skin damage or other diseases) (Pyšek and Richardson 2010), the provisioning of cultural ecosystems services and even, change the socioecological relationships of people with nature, especially in indigenous communities (Pyšek et al. 2020; Vaz et al. 2017).

Despite significant, though geographically uneven, investments in diverse management actions, the rate of introductions and the emergence of new invasions is increasing substantially with time showing no signs of saturation (Seebens et al. 2017).

The introduction of alien species that become invasive is strongly shaped by trends in trade and transportation, which have intensified in the past decades (Hulme 2009). Globalization, that allowed for easier and more rapid movement of people, resources, and products, ultimately contributed for the increase in the number of pathways of introduction and the intensification of the dissemination of alien species and IAS (Hulme 2009). Alongside climate change, changes in pathways for the movement of invasive

species, will possibly drive further changes in the invasion process and, ultimately the magnitude and frequency of IAS worldwide (Finch et al. 2021; Walther et al. 2009).

1.2. Environmental policy: How it started and why we need it

The industrial revolution has changed the way humans live. It was a stepping-stone in the history of civilization which not only supported unprecedented levels of economic prosperity and living conditions, but also changed the way humans interacted with the environment and its resources (Steffen et al. 2011).

As part of the complex biosphere of Earth, humans have a foundational relationship with the environment, depending on it for survival and well-being. However, since the dawn of industrial civilization this relationship has been rather undervalued and unsustainable (Soga and Gaston 2016; Steffen et al. 2011).

The effects certain human activities have on the environment started being generally perceived in the second half of the 20th century, after the publication of some influential documents (Cocklin 2009). Among them is Rachel Carson's 1962 book, *Silent Spring*, which raised alarm over the devastating impacts the use of agricultural chemicals was having on bird populations.

With the increasing realization that the environment is a limited public good that should be protected (or at least managed under the principles of sustainability), environmental policy became part of the political agenda, and legislation (e.g., the United States' National Environmental Policy Act, 1969), with environmental management strategies becoming more frequently adopted (Cocklin 2009). It would not be until later, however, that the focus of environmental policy would shift from a more local, regional perspective to a more transnational, global one, with the understanding that most environmental problems transcend national borders (Dalby 2016). The United Nations Conference on Human Environment (1972), is considered to have been the first major global conference on environmental issues, placing them at the forefront of international concerns. While international agreements on the environment can be traced back to the 1940s, the number of agreements, treaties, and conventions has increased significantly since the 1980's (Cocklin 2009).

More recently, international environmental policy has become even more prominent, as the globalization of people and business creates difficulties for environmental control on such standardised mass production activities at the country level (Huppés and Simonis 2009; Lindén and Carlsson-Kanyama 2007).

International policy, on any given domain, can be difficult to approve, implement, and/or manage, since it requires complex deliberations among nations, and may result in the surrender of national sovereignty in expense of a centralized authority (Cocklin 2009). Environmental public policy can be even more of a challenge since environmental issues often involve trade-offs among public policies, and between these and the interests of powerful businesses. Given the influence large-scale business entities have on the economy and modern civilization, the solutions to environmental problems are not always the ones that would be supportive of the public good nor scientifically viable (Atkinson 2014). Environmental policy has therefore become a way for democratic governments to protect collective goods (provided by the environment) from the side effects that the pursuit of private (or other) interests can have on them (Atkinson 2014; Cocklin 2009).

1.3. Governance and the policy process

Governance can be seen as “all the processes of governing, whether undertaken by a government, market or network, whether over a family, tribe, formal or informal organisation or territory and whether through laws, norms, power or language” (Bevir 2012). Therefore, the process of governance, essential to the structure and organization of societies, involves processes of decision-making, accountability, control, and behaviour. One actor can influence another – a more vertical and hierarchical kind of governance - or actors mutually influence each other – a more horizontal type of governance (Bouwma et al. 2015).

Since many environmental challenges emerge from the external effects that economic activities have on collective goods (Huppés and Simonis 2009), talking about environmental policy is mostly talking about public policy, with the main goal being that the government needs to influence private actors' behaviour to control, to some extent, the negative consequences of private interests on public goods (Huppés 2001; Huppés and Simonis 2009).

The policy process, in a concise and simplistic way, can be summed up as: a problem is translated into operational goals, the appropriate policy instruments are chosen, and their implementation achieves the defined goals. Policy instruments are, therefore, the means of applying policy, acting as a link between policy design/formulation and policy implementation (Huppés and Simonis 2009), and are important, not only to influence private behaviour, but also for guiding behavioural relations between public bodies, individuals and/or private organisations (Huppés 2001).

Planning and strategic instruments are mostly related to the first stages of policy design, contributing to understanding and formulating public policy priorities and goals (Matei and Dogaru 2012). Through expert-based strategic planning, they help policy makers or other policy actors to discern what to do, why to do it and how (Matei and Dogaru 2012).

Legislative and regulatory are the most commonly used policy instruments, and are closely related to one another since regulations are usually underpinned by legislation (Bouwma et al. 2015; Cocklin 2009).

Legislative instruments are binding in nature and can be followed by sanctions, in case of non-compliance. National legislation is a legislative instrument applied by national governments. Conventions (or multilateral agreements) are legislative instruments at the transnational scale. Regulatory instruments (also called “command-and-control”) are also legally binding and are designed to regulate behaviour. They can either be prohibitive (e.g., forbid certain behaviour) or be prescriptive (e.g., require certain behaviour) (Bouwma et al. 2015).

Both legislative and regulatory instruments fit into a hierarchal type of governance, in which governments, legitimated by public elections, use their authority for the design and application of rules (Bouwma et al. 2015).

Economic and fiscal instruments (e.g., subsidies or taxes) are based on a government that influences market mechanisms. Having a more voluntary character, the purpose is to stimulate the involved actors into acting a certain way by financially rewarding or punishing certain behaviours (Bouwma et al. 2015). The advantage of these instruments, especially when applied to environmental policy goals, is that they have a potential to correct market failures (Cocklin 2009; Huppés and Simonis 2009).

Other types of policy instruments, based on other types and modes of governance, have been gaining space in the policy arena since restrictions or obligations alone have proven not to be completely effective in managing all the types of problems society has to deal with (Jordan, Wurzel, and Zito 2005; Werdingtyas, Wei, and Western 2020).

Information and communication instruments (e.g., education campaigns or ecolabels), aim to influence individual and/or collective action by providing information to citizens and other actors, with the purpose of changing their behaviour through knowledge (Bouwma et al. 2015). There is the chance that people chose to ignore them, and, therefore, it may not lead to compliance in a direct way. Nevertheless, it gives citizens the opportunity to make more informed decisions (Bouwma et al. 2015).

More related to self-governance, there are the agreement-based or cooperative instruments, in which actors (private or public) that share a common agenda agree to behave a certain way (Bouwma et al. 2015). Although voluntary, actors rely on one another to achieve their shared objective, which motivates compliance (Bouwma et al. 2015; Cocklin 2009).

In a more knowledge-building and networking governance perspective, there are knowledge and innovation instruments, which appeared more recently in the literature and aim to develop shared knowledge between actors and promote innovation (Bouwma et al. 2015). Research, technological innovation, and public participation can fit into this category, since these are activities that support the engagement in social learning and build knowledge and the capacity to act (Bouwma et al. 2015).

1.4. Invasive alien species policy

Because of the increasing impacts of IAS and the increase of awareness of their impacts by policymakers, the management of these species has become a common topic in international and national environmental policy debates (Shine 2007). The policy goal for managing IAS can depend greatly on many different factors including the stage and extent of invasion, the invaded environment, the impact and management costs, among others (Keller and Perrings 2011).

IAS management approaches include prevention, early detection, and rapid response to their introduction, as well as control and eradication for already introduced and often widespread species (Simberloff, Parker, and Windle 2005). Due to the intrinsic nature and ecology of IAS, a preventive approach is usually preferred under a cost-benefit perspective, being considered as the first line of defence. Preventive-type policies can be applied through the enactment of legislation and regulations of trade and movement, that should be enforced with inspections and sanctions (McNeely et al. 2001). Prevention can also be achieved in other ways, using different types of instruments and means, such as education campaigns to increase public awareness or through investments in research that contribute to the development of scanning tools (McNeely et al. 2001). While not so common, economic, and fiscal instruments can also be applied (e.g., tariffs on imported species) (Ranjan 2005).

When IAS are already established, measures must be directed to the control or even adaptation. Various options are available for control, ranging from mechanical removal, chemical control, biological control (Wilgen et al. 2011).

Invasion by alien species, like most environmental problems, has a global scope, since the ecological and socioeconomical process transcends borders, underlining the importance of both regional and international collaborations that can contribute to the development and implementation of solutions and for more coordinated and effective management responses (Clout and Poorter 2005).

Policies relating to the management of IAS can be found on international, regional, national, and local levels. The most comprehensive international policy instrument that mentions IAS 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 8h). A much older instrument is the 1952 International Plant Protection Convention (IPPC), which applies primarily to plant pests (although it does not mention IAS directly, many plant pests are alien species). Other instruments mention IAS (or alien or non-native species) in specific regions (e.g., Europe and Antarctica), environments (e.g., wetlands), sectors (e.g., fisheries) or vectors (e.g., ballast water), although none of these are specific for IAS management (Secretariat of the Convention on Biological Diversity 2001).

Recently, more policy instruments are being designed specifically directed at IAS. For example, at the supranational level, the Regulation (EU) 1143/2014 on invasive alien species provides measures to be taken across Europe for the prevention, early detection and rapid eradication and management of invasive species, particularly those on the list of "Invasive Alien Species of Union Concern". Many countries have specific legislation on invasive species too such as South Africa (NE:MBA), the USA (NISA) and Portugal (Decree Law No. 92/2019).

1.5. Motivations and objectives of a review of policy-oriented research

Over the last few decades, there has been an exponential increase in the number of new publications and journals, and invasion science is not an exception (Vaz et al. 2017). The access to this scientific information is an important way of gathering knowledge and coming up with possible solutions, therefore being an essential step in policy design and application (Browne, Pagad, and Poorter 2009).

Most policy tools, especially related to environmental problems, have scientific foundations. For instance, risk assessment, in which the risk of invasion of a certain alien species is quantified, is an important tool to compile national or lists of potential invasive

species (e.g., Ou, Lu, and O'Toole 2008). The calculation of invasion risk is based in ecological principles of invasion.

Various types of ecological modelling, including species distribution models, allow the prediction of possible expansion in area and number of IAS and develop management priorities (e.g., Vicente et al. 2013). Cost-benefit analyses and bioeconomic models combine the analysis of economic and ecological impacts to help understand which management actions produce better results with a more effective allocation of management funds (Epanchin-Niell 2017), aiding management decisions (e.g., McDermott, Irwin, and Taylor 2013).

Molecular or genetic tools, like the detection of environmental DNA, have been increasingly used for the early detection and monitoring of new invasions in freshwater ecosystems (Blanchet 2012).

The development of indicators is also essential to monitor the progress parties have made toward meeting global policy goals, although most existing indicators are not completely adequate to monitor invasions (Vicente et al. n.d.).

Horizon scanning has also been applied to IAS-related problems, by bringing experts in different subject areas together to discuss a common issue and develop viable solutions (e.g., Bayón and Vilà 2019).

While the understanding that there needs to be a coordination between science and policy is well-known, some studies have pointed out that there can be mismatches between research focus and policy stakeholders' priorities, especially in relation to study sites and species (Bayliss et al. 2013). Also, there are major issues with research-policy implementation gaps in invasion science and the conservation arena, with basic research still being overrepresented in comparison to applied research, which in general is more relevant to managers and policy stakeholders (Knight et al. 2008; Matzek, Pujale, and Cresci 2015).

This thesis evaluates the status of policy-oriented research in invasion science, thereby contributing to a better categorization and classification of policy instruments related to IAS management, research, and policymaking. To do so, a systematic literature review and analysis is followed to summarize existing knowledge and identify possible knowledge gaps (Haddaway et al. 2015). Specifically, the extensive literature review presented in this thesis aims to answer the following questions:

1. Is research contributing to agenda setting when it comes to IAS policy development or are policy expressions and instruments driving research in biological invasions?
2. Is policy-oriented research directed at policy-makers' priorities and "real world" problems (in terms of studied species, environments, and main topics)?
3. Is research and policymaking coordinated or does research present new ideas and recommendations for policy-makers and policy application?
4. What are the major challenges and opportunities for policy-oriented invasion science?

2. Methods

2.1. Overview of the analytical framework

The systematic review of published policy-oriented research in invasion science was conducted based on a standard protocol (Higgins et al. 2019). Figure 1 synthesis the framework followed.

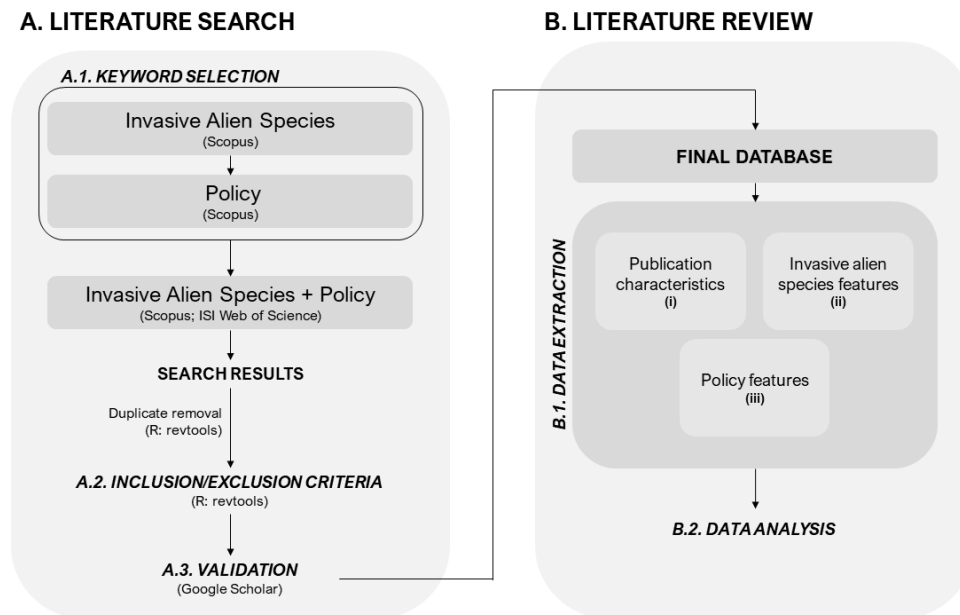


Figure 1. Analytical framework and workflow. The Literature Search (A) consisted of the selection of two sets of keywords, one for IAS-related terms and policy-related terms (A.1). After keyword selection, the search was conducted in two search engines (Scopus and ISI Web of Science) and search results were combined. Duplicates were removed and records were selected based on inclusion/exclusion criteria (A.2). Finally, the validity of the search was evaluated (A.3). In the Literature Review (B) phase, publications included the final database were individually reviewed and classified accordingly in categories (B.1). Categorized data was then subject to data analysis (B.2).

First, the literature search (A) was performed. The first step of this phase was the selection of relevant keywords (A.1). Then, using the final set of keywords, searches were performed in Scopus and ISI WOS search engines. Results from both databases were extracted and combined, duplicates were removed, and the selection of relevant records was performed, guided by exclusion and inclusion criteria (A.2). Finally, an evaluation of the reliability of the search was made (A.3). In a second phase, the literature review (B) was performed. Full-text analysis of individual records allowed to classify them into categories in order to extract relevant information (B.1). Finally, quantitative data analysis of the multiple variables was performed, to analyse status and trends and accomplish the study goals.

2.2. Literature search

Keyword selection (A1)

For the search, two sets of keywords were used: one set included IAS related terms and the other included policy related terms. These search terms were selected using the Scopus database. Each term was added hierarchically, by apparent suitability, and for each term added, the first 10 references in the results were evaluated regarding the relevance for the study (Appendix, Table A1). The final search string used the keywords presented in Table 1. Truncation and wild cards symbols (denoted by *) were used to find alternative word endings (e.g., legislati* can be legislation, legislative, legislator).

Table 1. Final sets of keywords used for literature search (IAS related terms and policy related terms).

	INVASIVE ALIEN SPECIES RELATED TERMS	POLICY RELATED TERMS
KEYWORDS	"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant" OR "invasive animal" OR "alien species" OR "alien taxa" OR "alien plant" OR "exotic species" OR "exotic plant" OR "exotic animal" OR "non-native species" OR "non-native plant" OR "non-native animal" OR "introduced species" OR "introduced plant" OR "introduced animal" OR "non indigenous species" OR "non indigenous plant" OR "allochthonous species" OR "invasive vegetation" OR "invasive pests" OR "alien pests" OR "exotic pests" OR "non-native pests" OR "introduced pests"	"policy" OR "legislati*" OR "convention" OR "treaty" OR "*legal*" OR "law" OR "politic*" OR "directive"

After keyword selection, the search for peer-reviewed literature was conducted using the search engines Scopus and ISI Web of Science. Searches were conducted in October 2020.

The time span of our search was 1950-2020. The beginning of the time period was defined considering the period of the publication of Elton's (1958) book which "launched the systematic study of biological invasions" (Richardson and Pyšek 2008).

The search was limited to research papers and reviews since the purpose was to understand the trends in scientific research. Books, book chapters, scientific reports and other research outputs were not considered.

The search was also limited to research published in English. Keeping the review restricted to one language ensured comparability, especially when analysing the use of terminology. However, to analyse the potential language bias, a comparison of the results by language in the Scopus search was made. From the 3403 search results in Scopus, 3250 were in English (used for the database) while 154 were in other languages (top 3: German, Spanish, and French). Since this value is low compared to the database, language bias was considered inconsequential for the purpose of this study.

Inclusion/exclusion criteria (A.2)

Using the package “revtools” from R software (Westgate 2019), the records retrieved from the literature search were combined (n= 5535; Fig. 2) and were subjected to an initial screening to eliminate irrelevant or duplicated information. First, duplicates were removed both automatically by doi correspondence (exact function) and manual selection through title similarity (stringdist function). In a second step, title, abstract and keywords were screened for relevance and non-relevant records were discarded e.g., those that mentioned policy but not in relation to IAS, or studies that mentioned invasive species as a conceptual analogy for human relationships. The detailed inclusion and exclusion criteria used is described in Table 2. In case of doubt, the record was included, and the full text was reviewed in the next phase.

Search validation (A.3)

To validate the reliability of the search, the database was compared to the first fifty records retrieved by Google Scholar using the most general keywords for each group ("invasive species" AND "policy"). A total of 8 records were identified and added to the database (16% of the suitable records retrieved).

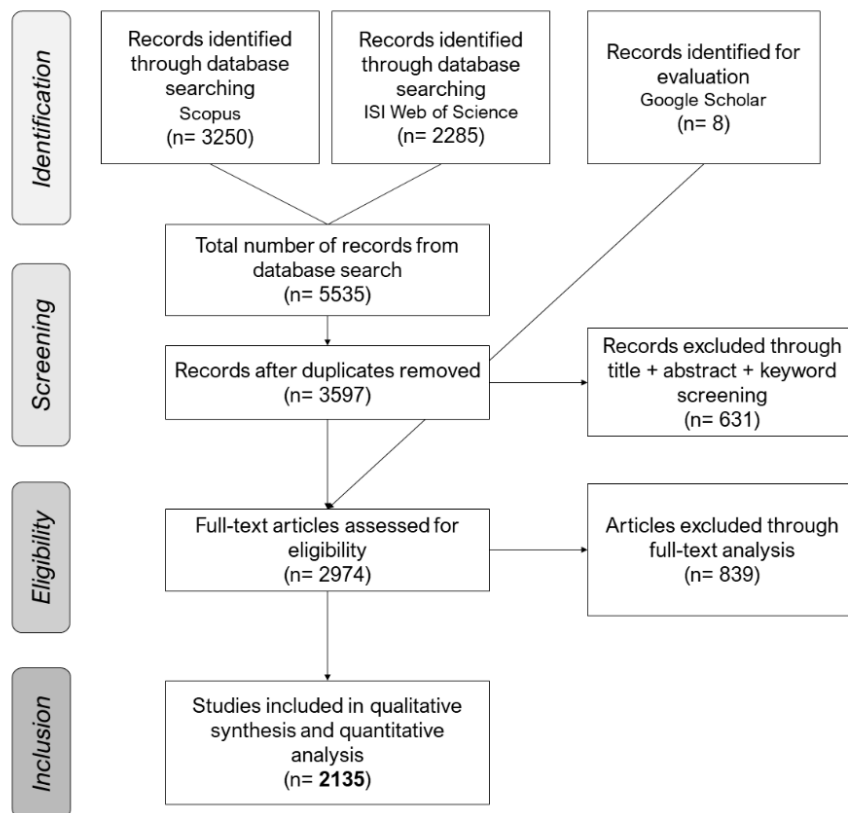


Figure 2. Number of records at each step of the literature search and review.

Table 2. Inclusion and exclusion criteria applied for record selection.

CRITERIA APPLICATION	EXCLUSION CRITERIA	INCLUSION CRITERIA
TYPE OF RECORD	Book chapters, books, corrections/corrigendum; editorial material, letters; meeting abstracts; news items, systematic literature reviews	Research articles, reviews, paper proceedings, forum papers.
INVASIVE ALIEN SPECIES	Conceptual or ethical discussions about invasive species; Focus on invasive native species; Presents dilemmas in managing invasive species; Clinical terms which use alien/exotic species for referring to an organism outside the human body or animals in laboratory experiences; Record simply mentions invasive alien species in the abstract.	All records unless otherwise stated in the exclusion criteria.
POLICY	Record does not mention policy in relation to invasive alien species; Record just mentions that species was illegally introduced; Record mentions laws in the context of laws of ecology or physics.	All records unless otherwise stated in the exclusion criteria.

2.3. Literature review

Data extraction (B.1)

In order to analyse the status and trends of policy-oriented research in invasion science, the content of each individual record from the final database (n = 2974; Fig. 2) was reviewed in-depth and classified according to the categories shown in Table 3.

First, data regarding publication characteristics (i) was extracted. This information included year, research methodology, scale, and geographical location of study. Then, categories related to IAS features (ii) were reviewed and extracted, including terminology, role of IAS in study, taxonomic group, and IAS environment. Finally, a policy-related category (iii) was defined and included data on the publications' thematical focus considering main IAS policy topics, whether policy instruments were mentioned in the context of the study or as recommendations and which types of policy instruments were mentioned.

Additionally, all records that were not considered relevant by the full text analysis and following the same inclusion/exclusion criteria as the initial screening, were also excluded, resulting in a final database of 2135 records.

Data analysis (B.2)

Quantitative data analysis of the multiple variables around the three main categories (i.e., publication characteristics, IAS features and policy features) was performed using descriptive univariate analyses.

To examine how policy-oriented research has evolved through time and to compare the temporal trends in publications with the years of adoption or publication major international policy instruments, the total number of records published each year was plotted. The proportion of records from distinct categories (i.e., methodologies, terminology, and taxonomic groups) published each year (expressed by percentage) was also assessed, allowing to understand the temporal evolution of specific characteristics in policy-oriented invasion science. Then, to evaluate geographical focus, the number of records in each region and country was mapped using a geographical information system software (QGIS software). These analyses contributed to investigate the first proposed research goal (objective 1). Then, to assess if policy-oriented research is being directed at policy-makers priorities (in terms of species, environments, and thematical focus) (objective 2) and to evaluate the role of policy instruments in invasion

science (objective 3), results were analysed using bar plots and radar charts. The final objective (objective 4) was addressed by analysing all results in a critical manner.

Table 3. Categories used for data extraction and analysis. There are three main categories (i – publication characteristics; ii – IAS features; iii – policy features. Each main category is divided into several classes, and some classes are further divided into subclasses (see Appendix, Table A3 for more information on description and sources).

CATEGORIES / QUESTIONS	CLASSES / SUBCLASSES
(i) PUBLICATION CHARACTERISTICS	
<p>TEMPORAL What year was the study published in?</p>	<p>Year</p>
<p>SCALE What is the scale of the study?</p>	<p>Subnational</p> <hr/> <p>National</p> <hr/> <p>Regional</p> <hr/> <p>Supranational</p> <hr/> <p>Multinational / Multiregional</p> <hr/> <p>Global</p> <hr/> <p>NA</p>
<p>METHODOLOGY What is the study methodology focused on?</p>	<p>Assembling data and knowledge</p> <hr/> <p>Assessment and evaluation</p> <hr/> <p>Public discussion, involvement and participatory process</p> <hr/> <p>Selection and design of policy instruments</p> <hr/> <p>Implementation, outreach and enforcement</p> <hr/> <p>Training and capacity building</p>
<p>GEOGRAPHICAL REGION Where was the study</p>	<p>Europe</p> <hr/> <p>Asia</p> <hr/> <p>Oceania and the Pacific</p> <hr/> <p>Africa</p> <hr/> <p>North America</p> <hr/> <p>Latin America and the Caribbean</p> <hr/> <p>Antarctica</p>

	Global
	NA
COUNTRY	Name country
(ii) IAS FEATURES	
TERMINOLOGY What is the main terminology used?	Invasive alien species
	Invasive species
	Exotic species
	Introduced species
	Alien species
	Non-native species
	Non-indigenous species
	Allochthonous species
ROLE What is the role of IAS in the study?	Subject
	Threat
	Other
TAXONOMY Which IAS taxonomic groups are studied?	ANIMALS
	Mammals
	Birds
	Herpetofauna
	Fish
	Insects
	Crustaceans
	Molluscs
	Other invertebrates
	Multiple / All
PLANTS	
OTHERS	
MULTIPLE	
ENVIRONMENT	Terrestrial

IAS studied are related to what type of environment? Aquatic
 Combination

(iii) POLICY FEATURES

	BIODIVERSITY AND ENVIRONMENT	General Important Habitat Important Species
	SECURITY AND SAFETY	Phytosanitary Animal health Public health Biosecurity Biosafety
<p>THEMATICAL FOCUS* What is the thematical focus of study considering IAS policy-related themes? *This category is not mutually exclusive</p>	SECTORS AND PATHWAYS	Forestry
		Agriculture
		Biological control
		Horticulture
		Fisheries
		Aquaculture
		Hunting
		Husbandry
		Ornamental
		Tourism
		Pet
		Energy
Transport		
Territorial planning and land use		
Wood packaging		
Zoos		
Recreational activities		

		Trade
POLICY INSTRUMENTS – RELATION TO STUDY Policy instruments are mentioned to contextualize the study, or as recommendations?	Context	
	Recommendations	
	Both	
		(L1) International agreements
		(L2) Regional agreements
LEGAL (CONTEXT)		(L3) Supranational legislation
		(L4) National legislation
		(L5) Subnational legislation
		(L6) Update / Revise legislation
LEGAL (RECOMMENDATIONS)		(L7) New legislation
		(L8) Law enforcement
		(L9) Political engagement
		(R1) Bans / Prohibitions
		(R2) Licences
		(R3) Permits
		(R4) Standards
		(R5) Listing
REGULATORY		(R6) Inspections
		(R7) Quarantine measures
		(R8) Other import / export restrictions
		(R9) Protection status (species)
		(R10) Protection status (local)
		(R11) Industry/activity-related regulations
		(E1) Taxes
ECONOMIC AND FISCAL		(E2) Penalties
		(E3) Tariffs
		(E4) Subsidies

TYPES OF POLICY INSTRUMENTS

Which types of policy instruments are mentioned?

*This category is not mutually exclusive

** When Policy Instruments – Relation to Study is “Both” then these categories were considered twice (one for context and one for recommendations)

	(E5) Fees
	(E6) Tradeable permits
	(E7) Payment for ES
	(E8) Funds / grants
	(E9) Bonds
	(E10) Deposit-Refund system
	(E11) Offsetting
	(E12) Liability rules
	(E13) Property rights
INFORMATION AND COMMUNICATION	(I1) Education
	(I2) Labelling / Certifications
	(I3) Guidelines
	(I4) Technical training
AGREEMENT-BASED OR COOPERATIVE	(C1) Codes of conduct / Codes of practice
	(C2) Cooperation / Collaboration
	(C3) Coordination
KNOWLEDGE AND INNOVATION	(K1) Research
	(K2) Public participation
	(K3) Technical innovation
PLANNING AND POLICY SUPPORT	(P1) Conservation / biodiversity strategies
	(P2) Local management plans
	(P3) IAS management plans
TYPES OF RECOMMENDED ACTIONS***	Accommodation
	Containment
	Control
	Early detection and rapid response
	Eradication
	Management (general)

*** When "IAS Management plans" are mentioned as recommendations

	Mitigation
	Monitoring
	Prevention
	Prioritization

3. Results

3.1. Policy in invasion science

The number of records containing IAS keywords retrieved using only Scopus as a search engine was 59538. Among these, 3250 presented policy-related keywords (5.46%) (Appendix, Fig A1).

From the total set of records retrieved from the literature search (Scopus and ISI; $n = 5535$), 38.6% were considered suitable for the literature review after duplicate removal and screening (corresponding to 2135 records).

3.2. Temporal trends

The earliest record from our search is from 1973, corresponding to a review of exotic animal disease control plans (Gee and Whitem 1973) and from that time until 1986, some records were sporadically published (e.g., Hedgpeth 1980; King and Moody 1982; Warman and Todd 1984). From 1986 onward, records on IAS policy were published yearly, with a substantial incremental increase in publications since 2000. Two distinct periods of increase can be pinpointed, one from 2002 to 2011 and another from 2012 to 2019 (Fig. 3).

The number of international policy instruments that mention IAS also tended to increase throughout the years (Fig. 3; for more information on these instruments, including specific sections on IAS and used terminology, see Appendix, Table A2).

The terminology used in policy-oriented research is mainly “introduced”, “exotic” or “alien species” before 1999, at which point “invasive species” and “invasive alien species” started being used as main terminology (Fig. 4).

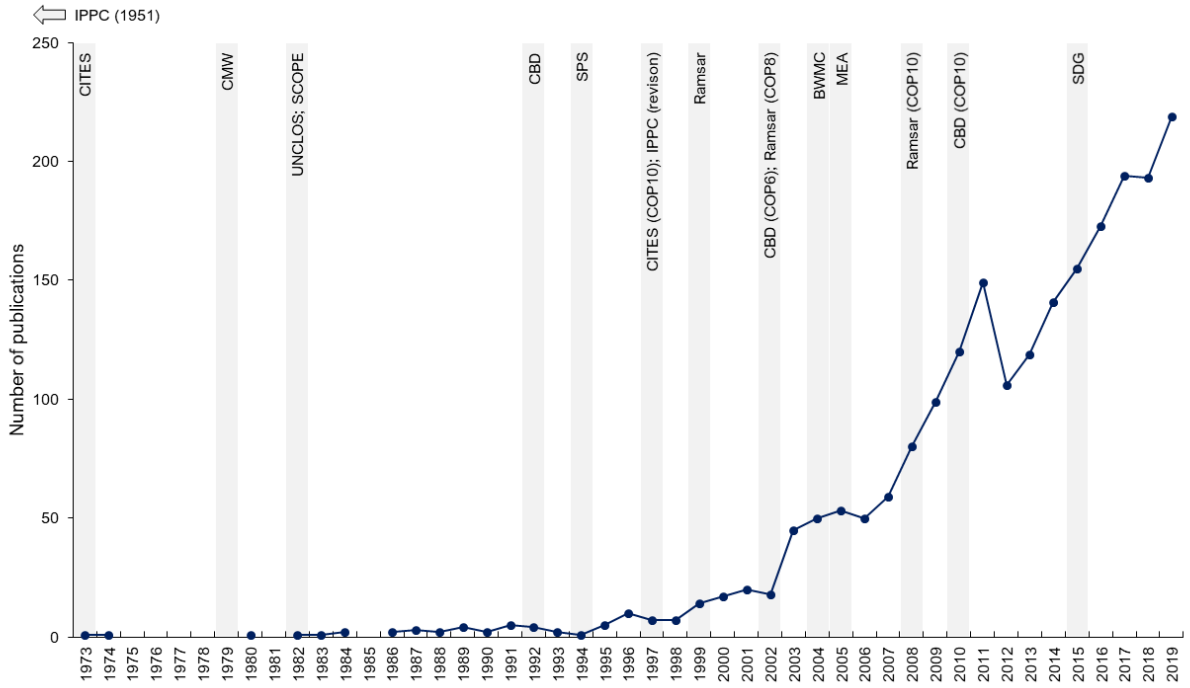


Figure 3. Temporal trends in the number of policy-oriented publications in invasion science from 1973 to 2019. Vertical grey bars represent the year of adoption or publication of the main international policy instruments that mention IAS.

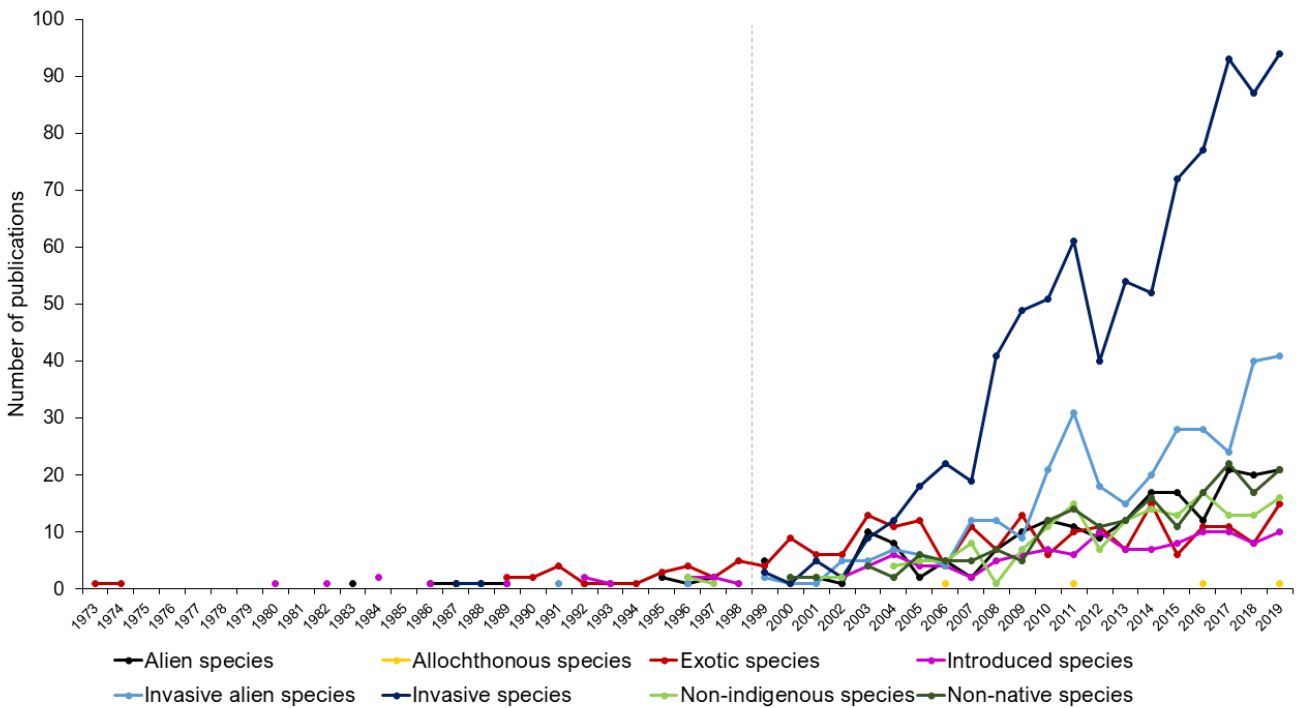


Figure 4. Number of policy-oriented records that mention each type of IAS terminology throughout the years. The year at which point the terms “invasive species” and “invasive alien species” started to be more applied is identified by a dotted grey line (1999).

Publications until 2000 are mostly reviews, with some observational/experimental research periodically being performed in some years (Fig. 5). There are two records related to the selection and design of policy instruments in 1992, however, this category only became a persistent part of policy-oriented literature from the 2000s onwards (Fig. 5). Similarly, the first records that are public discussions are from 1996 and only from 2000 onwards did they start being a constant presence in policy-oriented research (Fig. 5). Studies pertaining to implementation, outreach and enforcement start to appear in the late 1990s. There are only four records that reported training and capacity building and they only appear after mid-00s.



Figure 5. Proportion of records in each methodological category, per year.

In terms of taxonomical focus, early studies are mostly directed at several taxonomic groups (or all – IAS in general), and animals, with plants only becoming more relevant for policy-oriented research in the mid-90s. Other IAS taxonomic groups only start being more studied in a policy context from 2001 onwards (Fig. 6).

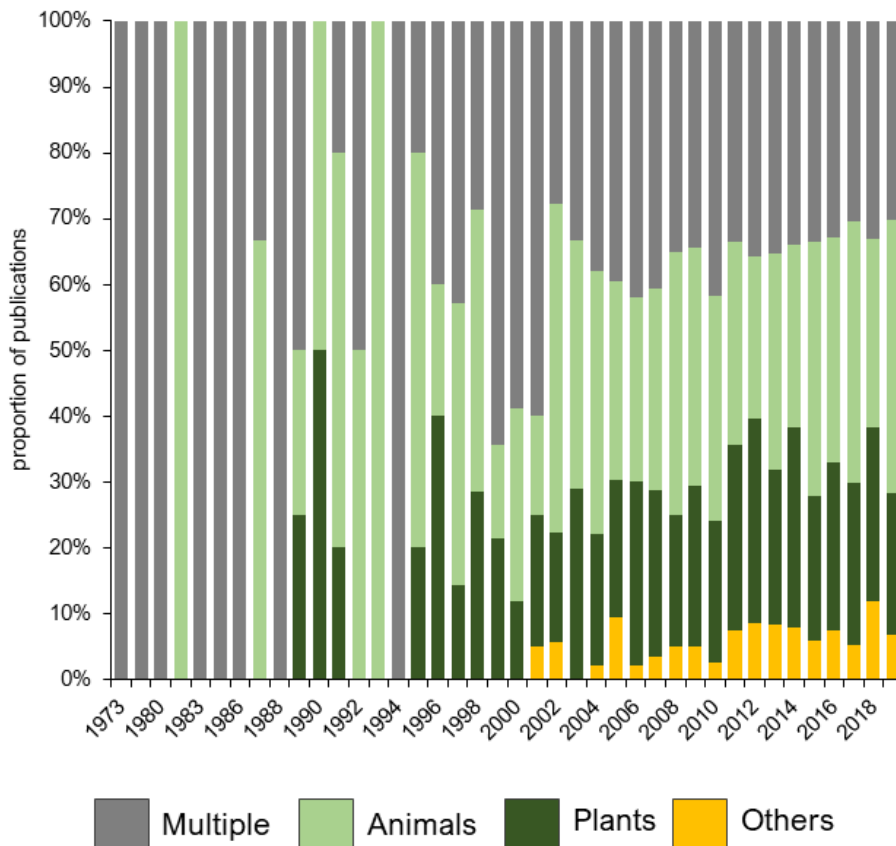


Figure 6. Proportion of records directed at each taxonomical group, per year

As for the main theme of policy-oriented research, early studies were related to Security and Safety (Fig. 7). The sporadic records published in the first half of the 80s mainly focused on Biodiversity, a period when conventions like CMW and UNCLOS (the first one dedicated to the conservation of migratory species and the second to the conservation of the marine environment) were adopted (Fig. 3). In fact, when analysing these records, they are directed at these subjects. From 1986 forward, the three main themes are addressed in the publications following similar trends.

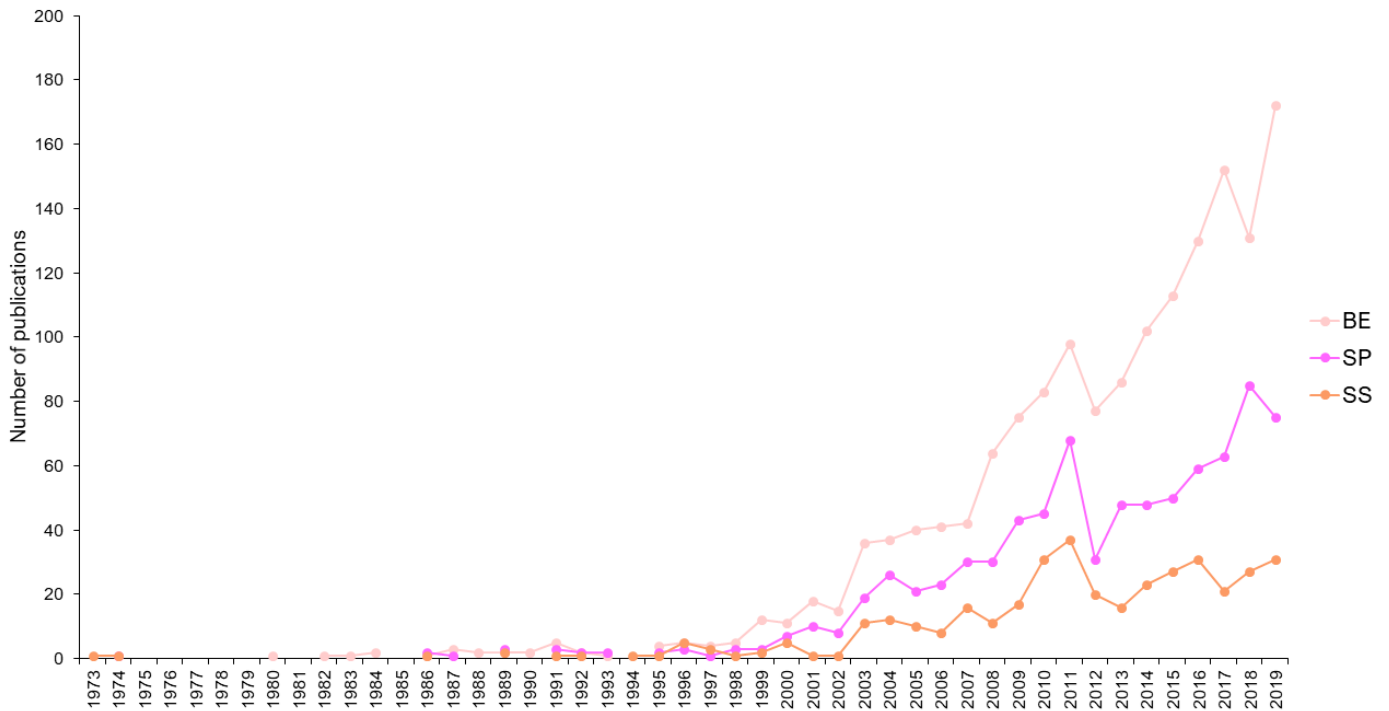


Figure 7. Temporal trends of published records concerning their thematical focus. *BE* – *Biodiversity and Environment*; *SP* – *Sectors and Pathways*; *SS* – *Security and Safety*.

3.3. Spatial patterns and scale

In terms of scale, policy-oriented research in invasion science is mostly performed on a subnational scale, although the percentage of national studies is also relevant (Fig. 8a). The percentage of studies done at each scale decreases with the increase in scale (subnational (31.88%) > national (29.93%) > regional (15.50%) > global (10.91%)).

Supranational studies are few in comparison to other scales (Fig. 8a). However, this scale only represents studies done specifically for the European Union, and, in this perspective, the percentage of studies at this scale is quite relevant (2.95% of all records). The scale that has least percentage of records is multinational / multiregional (2.20%; Fig. 8a). As for studies without scale (i.e., NA), these represent 5.62% of policy-oriented research (Fig. 8a).

Global scale studies are mostly assessments and evaluations (i.e., reviews) – 64.38%, while subnational studies largely focus on assembling data and knowledge (i.e., observational, and experimental research) – 58.53% (Fig. 8b). National and regional scale studies have similar proportions of assessments and evaluations (42.88% and

40.48% respectively) and studies that assemble data and knowledge (39.12% and 44.71% respectively) (Fig. 8b)

Studies related to public discussion, involvement, and participatory process are more developed at the subnational scale (16.38% of subnational studies corresponded to public discussions), with supranational, national, and regional also having some records that fit into this category (7.94%, 7.67% and 4.23%, respectively; Fig. 7b).

As for studies focused on the selection and design of policy instruments, these are mostly done at the supranational scale or when no scale is applicable (20.63 and 21.67%, respectively). Implementation, outreach, and enforcement are a minority for all scales but are more prominent on the supranational (3.17%) and subnational scale (2.42%) (Fig 8b).

The four records that reported training and capacity built are all done at the national scale (Fig. 8b).

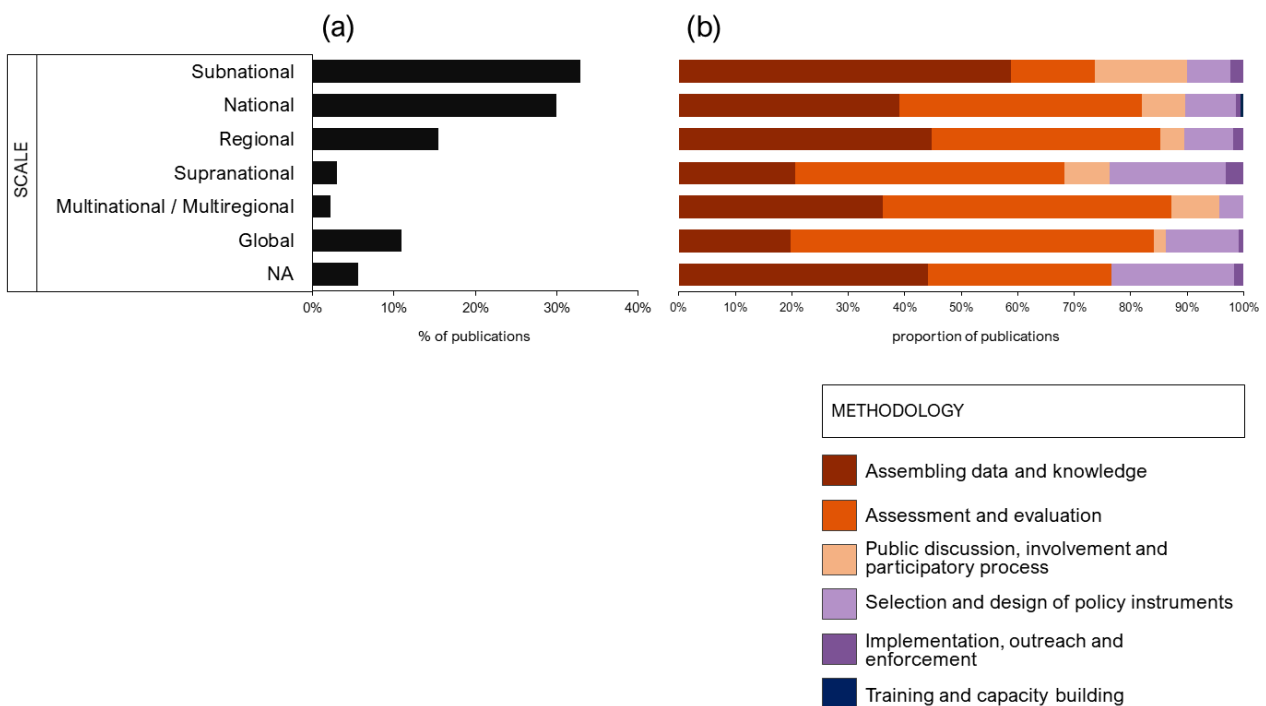


Figure 8. Percentage of publications performed at each scale (a) and proportion of records in each methodological category for each scale (b).

As for geographical regions, Europe has the most studies (27.92%), followed by Northern America (23.09%; Fig. 8). Excluding Antarctica, that has 30 records in total (1.41 %), Latin America and the Caribbean is the geographical region with less policy-oriented research (Fig. 8).

Within Europe, the UK, Italy, and Spain are the countries with the most publications, followed by Germany and Portugal (Fig. 9). It should be noted that 32 out of 44 countries of this region have at least one publication. Globally, the United States is the country with the greatest number of studies (Fig 9).

In the Oceania and the Pacific region, almost every national or subnational scale record is from Australia or New Zealand. In Asia, India and China are the countries with more publications. As for Africa and Latin America, South Africa and Brazil are, respectively, the countries with by far the greatest number of policy-oriented publications (Fig 9).

Europe, Northern America and Latin America and the Caribbean have a bigger proportion of studies done at subnational scale, while the Oceania and the Pacific, Asia and Africa have more studies done at the national scale (Fig. 8). Europe is the region with a bigger percentage of studies done at a regional scale (26.01%), followed by Northern America (17.44%) (Fig. 8).

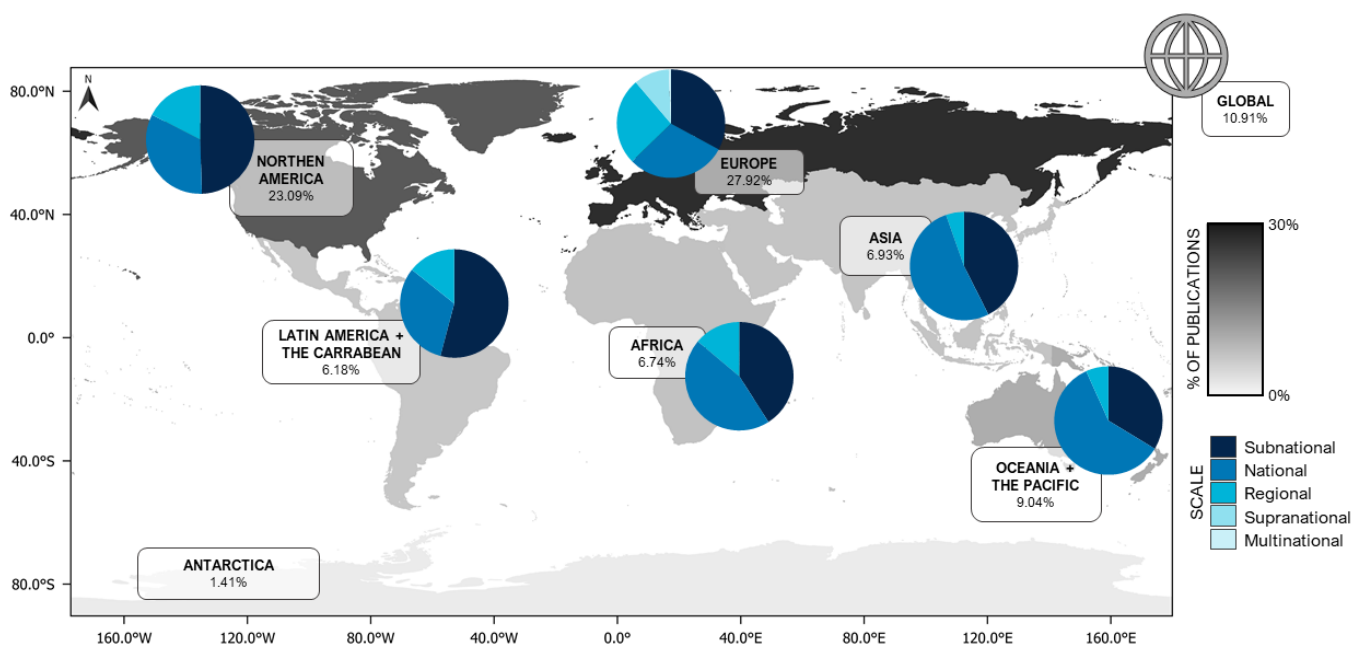


Figure 9. Percentage of studies done in each geographical region. The proportion of publications done at each scale for each geographical region is also represented.

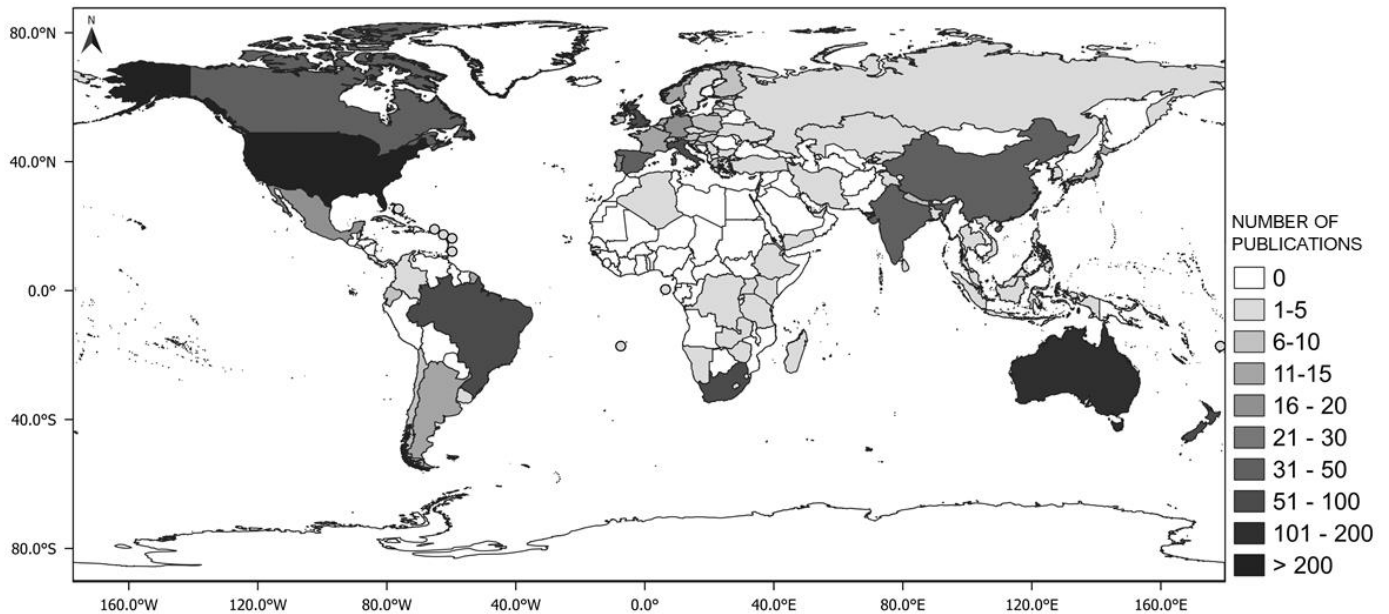


Figure 10. Number of publications by country (includes subnational and national studies).

When analysing taxonomic focus by region, studies mostly relate to animals, except for Africa, where most studies relate to plants (Fig. 10). Oceania and the Pacific has a higher proportion of studies directed towards terrestrial animals (with mammals being the studied group; Fig. 11), while Europe, Africa, Asia and Latin America have a bigger proportion of articles directed towards aquatic animals (Fig. 10). Fish is the most studied group in all regions, but in Europe and Asia crustaceans, molluscs and other invertebrates are also prominent (Fig. 11).

Northern America has the same percentage of studies directed at terrestrial and aquatic animals (17.65%) (Fig. 10), with fish and insects being the most studied groups (Fig. 11). Herpetofauna and birds are low studied groups across all regions (Fig. 11).

Studies at the global scale or without scale were mostly done for multiple groups of species or IAS in general (multiple groups or no specific taxonomy group) (see Appendix, Fig. A2).

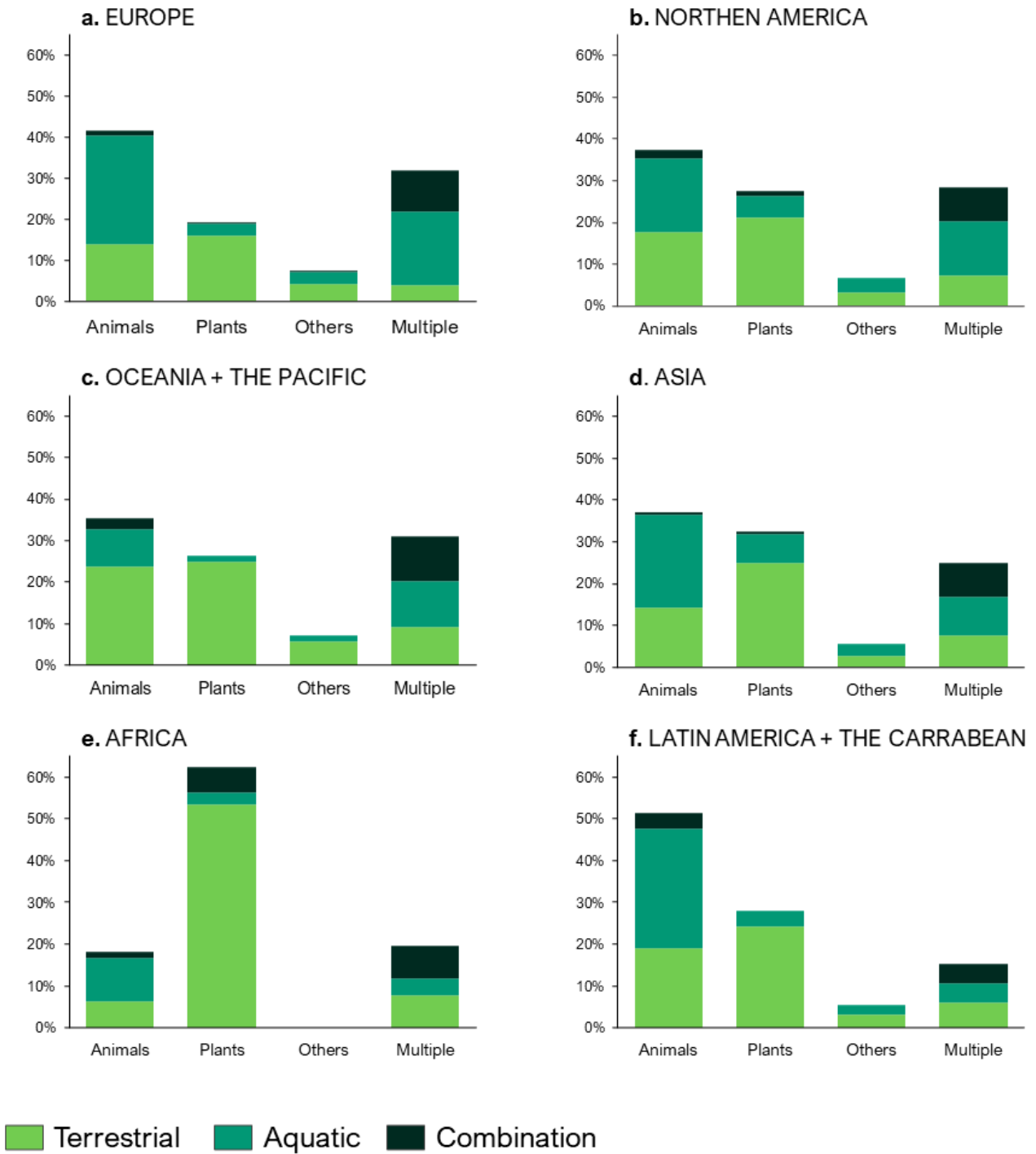


Figure 11. Percentage of publications directed at each taxonomical group, and environment, per geographical region.

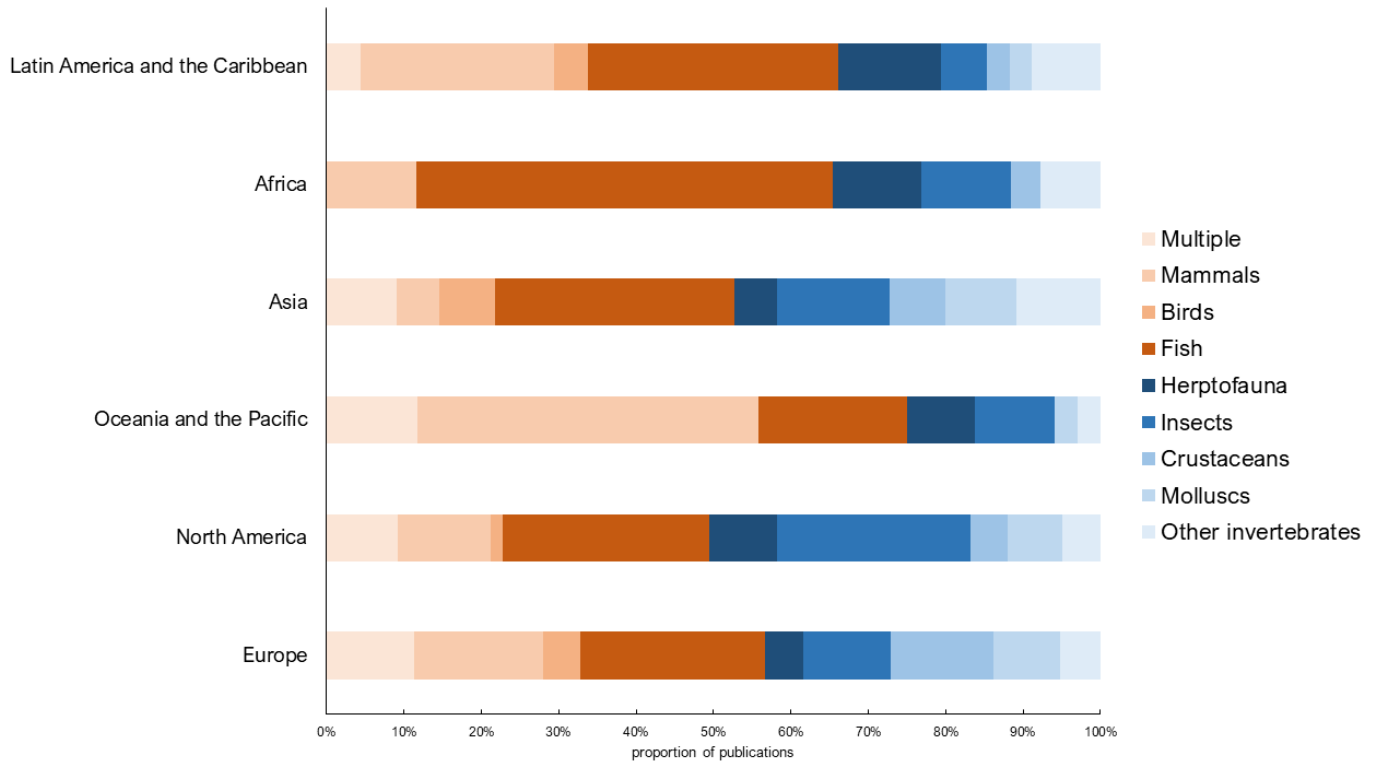


Figure 12. Proportion of records directed to each animal taxonomic group for each geographical region.

3.4. Policy instruments

The policy-related theme of most publications is Biodiversity and Environment (55.88%). Sectors and Pathways ranks second (11.05%) and Security and Safety last (4.59%) (Fig. 12). Since this a non-exclusive category, some studies fit into two or all categories (BE+SP – 15.46%; BE+SS – 1.41%; SP+SS – 10.63%; All – 1.08%)

Policywise, most records present policy instruments in both the context and as recommendations (42.25% of total records). Records that only mention policy instruments in the context rank second (34.80%), and records that only mentioned policy instruments as recommendations are last (22.95%).

When considering that publications in the category “both” can be included in both categories (context and recommendations), then about 77% of publications mention policy instruments in context while 65% mention them as recommendations. This approach will be used for further analyses. In this way, it is possible to evaluate and quantify differences and similarities between instruments used to contextualize research studies and instruments that are recommended by science to inform policymaking or to achieve policy objectives.

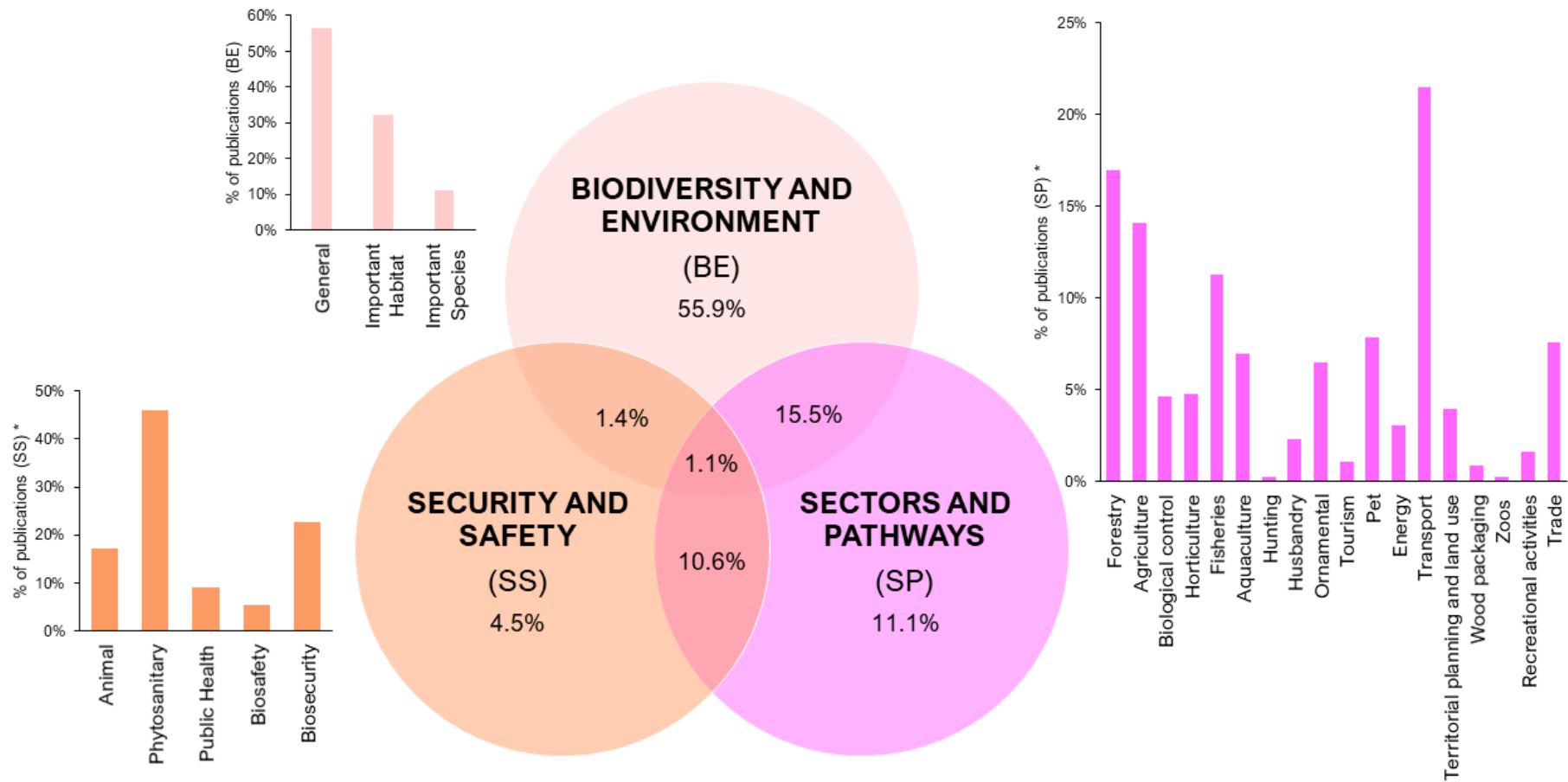


Figure 13. Venn diagram representing the percentage of publications that have each thematical group as main theme (considering some publications could fit into two or all categories). For each thematical group the percentage of publications in each subclass is also represented. * These subclasses are also non-exclusive.

In both context and as recommendations, planning instruments rank as the most mentioned category (this category includes the subcategories “IAS management plans”, “conservation strategies” and “local management plans”) (Fig. 13). Therefore, excluding planning instruments, the types of policy instruments that are more mentioned in the context of the study are legislative (e.g., “conventions” and “national legislation”) and regulative (e.g., “bans”, “listing”, “standards” and “licenses”) ones (Fig. 13). Recommendations more often pertain to information (e.g., “education” and “labeling”), cooperative (e.g., “codes of conduct” and “cooperation”), and knowledge instruments (e.g., “research” and “public participation”) (Fig. 13). Economic and financial instruments (e.g., “taxes”, “subsidies” and “funding”) are the less mentioned category of policy instruments, in both context and recommendations, however, they are still more prominent in the recommendations than in the context of the study (Fig. 13).

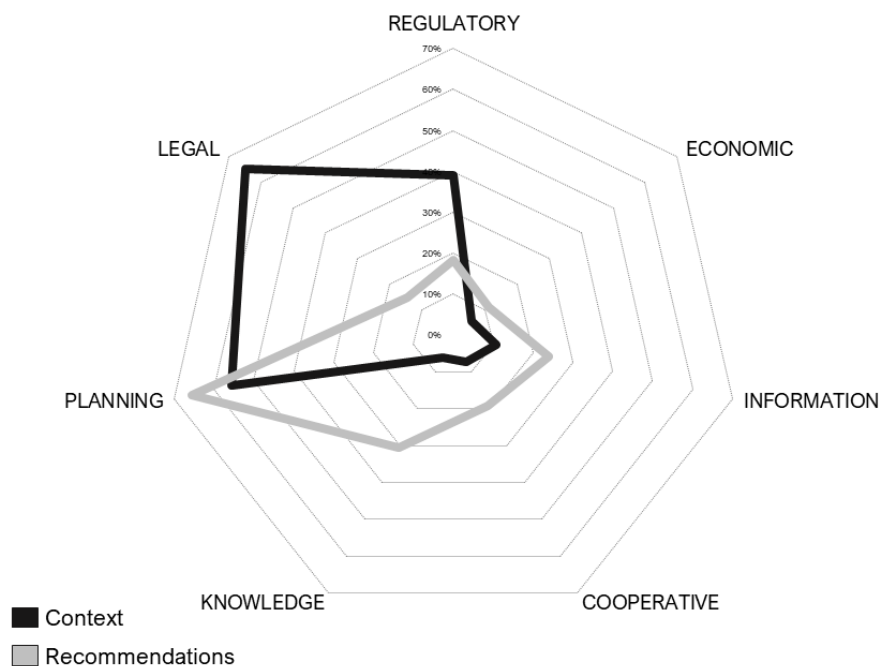


Figure 14. Radar plot representing the percentage of articles that mention each category of policy instruments. The black line represents the percentage of publications that mention each category of policy instruments in the context from the total number of articles that mention policy instruments in the context. The grey line represents the percentage of publications that mention each category of policy instruments in as recommendations from the total number of articles that mention policy instruments as recommendations.

The most mentioned types of legislative instruments are international agreements and national legislation, in the context, and law enforcement, when analysing the recommendations (Table 4).

As for regulative instruments, the most mentioned in the context of studies are bans/prohibitions, standards, lists and protection status (local), while the ones most mentioned in recommendations were bans/prohibitions and lists (Table 4)

As for economic instruments, funds/grants were the most mentioned type of instrument in both categories. Additionally, the majority of economic instruments were more mentioned as recommendations than in context, with the exceptions being taxes, tradable permits, bonds, and deposit-refund systems (Table 4).

The type of information instrument more mentioned in the context was guidelines while as recommendations it was education (Table 4).

In the cooperative instruments category, codes of conduct and cooperation are the subcategories more mentioned in the context, while as recommendations the most mentioned ones are cooperation followed by coordination. Despite being top2 in both contexts, cooperation is substantially more mentioned in the recommendations (Table 4).

As for knowledge and capacity building instruments, the one more mentioned in context was research. As recommendations research, followed by public participation and technical innovation.

As for planning instruments, “IAS management plans” is the instrument more mentioned in both cases. When IAS management plans are recommended, Control and Monitoring are the most mentioned management actions (Appendix, Fig. A3). The percentage of publications that mention Local management plans is also relevant, especially in the recommendations category.

Table 4. Percentage of publications that mention each subcategory of policy instruments. Percentages are expressed in percentage from the total number of publications that mention policy instruments in the context (a) and percentage from the total number of publications that mention policy instruments as recommendations (b). Yellow bars represent the subcategories that are more relevant in the context, red bars represent subcategories that are more relevant as recommendations and grey lines represent subcategories that are relevant in both the context and as recommendations.

CATEGORY	SUBCATEGORY	% OF PUBLICATIONS (a. CONTEXT)	% OF PUBLICATIONS (b. RECOMMENDATIONS)
LEGAL	L1	32,16	/
	L2	4,62	/
	L3	19,21	/
	L4	26,20	/
	L5	3,28	/
	L6	/	4,60
	L7	/	4,53

	L8	/	5,89
	L9	/	0,29
	R1	8,75	4,45
	R2	0,36	0,07
	R3	2,74	0,65
	R4	8,33	0,72
	R5	7,60	3,45
REGULATORY	R6	3,65	2,23
	R7	6,81	3,16
	R8	4,19	2,95
	R9	3,59	0,65
	R10	7,48	3,02
	R11	0	0,57
	R12	0,30	1,01
	E1	1,34	1,15
	E2	0,97	1,65
	E3	1,03	2,80
	E4	1,58	2,66
	E5	0,49	0,57
	E6	0,30	0,14
ECONOMIC	E7	0,36	0,36
	E8	1,76	5,03
	E9	0,12	0,07
	E10	0,06	0
	E11	0,06	0,22
	E12	0,18	0,57
	E13	0	0,07
	I1	3,95	20,62
INFORMATION	I2	1,40	0,86
	I3	6,26	1,94
	I4	0,55	2,95
	C1	3,53	0,86
COOPERATION	C2	3,53	15,37
	C3	1,03	5,03
	K1	3,04	18,53
KNOWLEDGE	K2	2,13	9,41
	K3	1,70	7,40
	P1	8,45	9,55
PLANNING	P2	14,16	21,91
	P3	40,36	46,70

4. Discussion

4.1. The road so far: Evolution of policy-oriented research in invasion science

As in other fields from the natural sciences, the scientific interest in biological invasions has grown substantially since the last two decades (Vaz et al. 2017). The presented systematic literature review also indicates a similar increasing interest in IAS policy-oriented research (cf. Fig. 3). At the time of our search (October 2020), results that included policy-related keywords represented ca. 5% of search results related to biological invasions. Esler et al. (2010) reported about 2% of search hits including the term “policy” in a literature search on invasion ecology. Our results may therefore suggest that within one decade, the interest in policy-oriented studies in invasion research grew.

The first publications of policy-oriented research captured by our search are from the 1970s, and focused mostly on animal health concerns, and the impacts of industry-related activities. Specifically, they focus on reviewing existing Australian plans for the control of alien animal diseases (Gee and Whitem 1973) and the recognition of alien species as impacts of inshore coastal aquaculture (Odum 1974). Our results are in line with wider trends during the 1970s, time during which the spread of alien species becomes a subject of concern, both in the scientific and policy community, due to the ability of alien species to work as vectors of diseases and pests in natural and production ecosystems (Krebs 2001; Stork et al. 2014).

The late 1990s and early 2000s mark the beginning of an exponential increase in the scientific interest of IAS policy. It was also around this period that policy-oriented research became more focused on sectors (i.e., industries) and IAS pathways (e.g., Rouget et al. 2002; Schuppli and Fraser 2000). At the 6th Conference of Parties of the CBD, in 2002, guiding principles for the implementation of Article 8(h) were defined. One 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).

Therefore, the increasing interest on IAS policy-oriented research may well surge as a consequence of the SCOPE research program, a major (and first) international research initiative on biological invasions (Drake et al. 1989), as well as a response to the political institutionalisation of IAS, e.g., through legislation such as the Convention on Biological Diversity (global), the Bern Convention (regional), US Executive Orders (national) and

EU regulations (supranational) (Johnson, Crafton, and Upton 2017; Secretariat of the Convention on Biological Diversity 2001; Shine et al. 2010).

In the early 2010s, there was a notable and prominent peak in the publication of policy-oriented studies. In fact, it was during this time that the 10th Conference of the Parties of the CBD adopted the Strategic Plan for Biodiversity 2011–2020. Within the 20 targets (Aichi Targets) assumed in the plan, one (Aichi Target 9) was explicitly focused on IAS: “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”. The last decade has been a landmark in invasion science during which the interest in policy has laid the foundations for further research on the topic.

4.2. Where we stand: Current status of IAS policy-oriented research

International policy provides institutional support for research and innovation, increasing scientific and public motivation, and promoting the funding of scientific consortia (Bruyninckx 2005; Liao and Liu 2021). As such, it is expected that international policy instruments driving focus toward IAS (e.g., SCOPE and CBD) also drive additional impetus for IAS policy-oriented research. Nevertheless, when analysing the results from our literature review, we see that the positive feedbacks detected between international agreements and policy-oriented research may become less obvious at a regional or national scale.

For instance, it has been shown that Canada has more legislation relevant to IAS than the USA (Turbelin, Malamud, and Francis 2017); however, our literature review shows that the USA has substantially more policy-oriented research compared to any other Northern American country (cf. Fig. 10). Similarly, most South American countries have legal instruments entirely dedicated to IAS and are signatory of a substantial number of international treaties mentioning IAS (Turbelin et al. 2017), yet the amount of published papers found for this region through our search suggests a low incidence of policy-oriented studies (cf. Fig. 9 and Fig. 10). Finally, Brazil, India, South Africa, and China showed a great number of published papers in IAS policy-oriented research; still, only South Africa and Brazil have legal instruments entirely dedicated to IAS (Turbelin et al. 2017) (cf. Figure 10). Accordingly, other factors besides legislation, appear to explain the different geographical focus patterns of policy-oriented research. Such factors may well be justified by economic motivations, including research and management funding,

which can reflect research interest and/or capacity (Leydesdorff and Wagner 2009). The economies of the United States of America, India, China and Brazil are among the most damaged by IAS (Diagne et al. 2021), suggesting that economic factors (either financial capability that impulses science or economic costs that drive political interest) can serve as main drivers of the interest in policy-oriented research.

Most IAS policy-oriented studies considered in our literature review are performed at either subnational or national scales (cf. Fig. 13). While a global, international, setting can be extremely important for driving the interest in policy-oriented research, the application of said research to more local scales is favoured by the fact that each place has specific characteristic ecological, economic and sociocultural aspects, which allows the adaptation of policy mechanisms to local circumstances and needs (Sovacool and Brown 2010).

Our review highlights that Oceania has the highest amount of policy-oriented studies at the national scale (cf. Figure 9). Since all countries in the region are islands, and, therefore, geographically isolated territories, it makes sense that research goals follow a view on policy application that has a more national perspective, especially when related to biosecurity (Whittington and Chong 2007). Additionally, the most studied animal group was mammals. Australia and New Zealand are the regions where mammal alien richness is higher (Dawson et al. 2017), and, being (big) islands (with rich diversity of endemic native species), the impacts of invasive alien mammals can be devastating for native flora and fauna (Krull et al. 2014).

In 2016, New Zealand implemented a programme that committed to eradicate, by 2050, the most damaging introduced predators that have severe impacts on native biodiversity, the economy and primary sector (“Predator Free 2050”; Department of Conservation New Zealand 2020). Therefore, in Australia and New Zealand, policy-oriented research seems to be hand-in-hand with most policy priorities.

Additionally, one of the records that was related to training and capacity building, was a paper that introduced the first Master’s program directed at biosecurity, in Australia (Bayliss 2015), demonstrating how the importance of managing IAS is being translated into education and capacity building (technical training).

Interestingly, in all other regions, fish are the most studied animal group (cf. Fig. 12). However, in a general sense, fish are neither the taxonomic group with more richness nor with more impacts (Dawson et al. 2017; Kumschick et al. 2015). Therefore, the prominence of the study of alien fish in policy-oriented science can be more related to the fact that fisheries are highly associated with the deliberate introduction of alien

species (Cambray 2003) and has specific sectorial legislation addressing IAS (e.g., Fisheries Act) as well as several industry codes of conduct (Secretariat of the Convention on Biological Diversity 2001).

Additionally, the 10 alien taxa with highest economic costs worldwide are either insects or mammals (Diagne et al. 2021), which might explain the focus on insects in policy-oriented research in Northern America.

As such, it seems that the taxonomical focus of policy-oriented research can be driven by several factors including ecological and biological impacts (e.g., mammals in Australia), economic impacts (e.g., mammals in Australia and insects in Northern America) and sectorial and industry-related concerns (e.g., fishes in many regions), depending on the specific contexts and policy priorities of regions and nations.

4.3. The road ahead: The need for solid governance and complementary policy approaches

While in the past the most common instrument to deal with environmental issues was regulations (Schout, Jordan, and Twena 2010), cooperative, participative and knowledge-building instruments are gaining space in the environmental policy arena (Schout et al. 2010). This is further supported by our study, which demonstrated that scientific researchers recommend these types of policy instruments for the purpose of achieving IAS management goals more often (cf. Fig. 14).

In fact, the mere existence of legislation does not guarantee effectiveness. Most countries have legislation that deals with IAS to some extent. However, in most cases, there is no coordination, thus leading to reactive and fragmented responses, which in turn can lead to ineffective management (Smith, Bazely, and Yan 2013).

Policy-mixes where legislative, regulatory, and planning instruments are applied and are complemented with other types of instruments, associated with more flexible, networking, and participative types of governance seems to be the way forward for better achieving policy goals, especially in environmental contexts, where target group heterogeneity can be high (OECD 2007; Pedersen, Nielsen, and Daugbjerg 2020).

For instance, trade-related risks and pathways for the introduction of IAS require effective trade regulations, but also global coordination and cooperation in the design and application of said regulations (Perrings et al. 2010).

IAS research also benefits from the cooperative action between different actors, and it has been widely suggested that biodiversity managers and researchers should work together from the beginning of the scientific process, even developing research questions together (Saunders et al. 2021).

Cooperative IAS programmes between researchers and local citizens have also proven to be successful in reporting and tracking IAS (Wallace et al. 2016). In fact, citizens play a crucial role in supporting local environmental management plans, either through volunteer participation in control or eradication actions, that guarantee long-term management with low funding (Dechoum et al. 2018), or in monitoring IAS, which results in a more cost-effective management as well as in an allocation of human resources that allows the coverage of a spatial and temporal extent which would not be possible otherwise (Theobald et al. 2015). Other potential benefits of Citizen Science (CS) initiatives include the increase of public awareness and knowledge, the democratization of science, the development of mutual trust between scientists and citizens, and the incorporation of local, traditional, or indigenous knowledge in scientific assessments (Pedersen et al. 2020).

Additionally, citizen science (CS) can be considered a knowledge and capacity building policy instrument (i.e., involves the combination of research, public participation, and technical innovation), which only underlines its importance, and, therefore, should be supported both by policymakers when designing policies, and by researchers when designing research experiments (Groom et al. 2019).

However, for CS initiatives to work more effectively, efforts should also be mobilized to improve data sharing (cooperation) and data standardization (coordination) (Johnson et al. 2020), once again underlining the interest and importance for cooperative actions between researchers.

Additionally, education and technical training of citizens (e.g., capacity to distinguish between native and invasive alien species) can also be important for the success of CS initiatives (Roche et al. 2020).

The optimal policy mix application can vary depending on the context and goals, the pathway that is being managed or the target groups (Ayoo 2008). For instance, invasions caused by the intentional release of alien pets can be dealt with by applying a mix of regulatory instruments with information and communication ones, specifically through education campaigns directed towards would-be owners for awareness building, tagging animals so they can be associated with owners and the obligation of potential owners to

seek accreditation schemes (that guarantee that they have the ability to house pets) (Maceda-Veiga et al. 2019).

In fact, using information and communication instruments is important not only for owners, but also for sellers, as education campaigns in pet stores have been associated with higher rates of compliance with IAS regulations (Oele et al. 2015). Again, legislation and associated regulations might not be effective by themselves, as illegal IAS trade still happens despite prohibitions (Signorile et al. 2016).

As for the ornamental and horticulture industry, it has been suggested that policy instrument mixes that include government-industry agreements (cooperative instruments) to fund (economic) effective pre- and post-border weed risk assessments (knowledge-based) and are supported by industry codes of conduct (cooperative) and complemented by labelling and public education (information) should be the most effective way to deal with this particular pathway (Maceda-Veiga et al. 2019).

In theory, economic instruments should be an interesting tool in managing the introduction of IAS related to sectors and activities, since they have the capacity to correct the effects of externalities, as well as other market failures (Ayoo 2008; Ekpe 2013). For instance, it has been suggested that economic policy instruments (e.g., penalties or fines) are useful to incentivize invasive plant management on private property (McDermott et al. 2013). Even if the incentive doesn't work, these financial instruments could be used to raise funds for the implementation of IAS management programs (Ayoo 2008). And yet, economic and fiscal instruments were the least mentioned, both in the context of the studies and as recommendations (cf. Table 4).

Most people don't like to pay extra, even preferring restrictive types of policies, which might explain the low relevance given to economic instruments in policy-oriented research science. In a study of the horticultural industry in North America, it was concluded that all stakeholders preferred policies related to screening and banning all newly imported exotic species with a high likelihood of invasion, as a means of controlling and reducing its spread, then those market-based (e.g., variable tax application or annual licence fee) (Barbier et al. 2013).

New visions of governance, and, consequently, policy design and application, based on **policy mixes that include cooperation among involved actors and public participation, are taking form, and revealing themselves to be the best way to deal with complex environmental and biodiversity challenges** (OECD 2007).

The EU regulation on IAS (Regulation No 1143/2014) is considered by many to be an innovative piece of legislation (Genovesi et al. 2014), since its design accounted for the inclusion of different types of policy instruments. In fact, it regulates activities (e.g., by use of regulatory instruments like permits, licences, or lists), implements economic instruments in case of non-compliance (e.g., sanctions or penalties) while also promoting research and innovation, and developing public participation strategies. Cooperation is also part of the equation since all member-states must follow these rules in a coordinated manner. Funding from the EU for IAS management, research and other initiatives is also quite significant (Scalera 2009). The existence of this specific legislation may explain why policy-oriented research at the supranational scale (European union scale) includes, in greater percentages, the selection and design of policy instruments, as well as the reporting of implementation, outreach, and enforcement (e.g., design or evaluation of management plans (cf. Fig. 8).

In regions where legislation is already operating under a more cooperative and participative governance mode, like the EU, these types of policy tools are already included in policy frameworks (e.g., Regulation (EU) No 1143/2014 on Invasive Alien Species). For instance, the EU regulation on IAS does mention citizen science as part of their surveillance plan. This might explain the higher amount of CS initiatives in this region, demonstrating that policy support is extremely important when considering funding for these types of initiatives (Roy et al. 2018).

4.4. Methodological constraints and the way forward

The main limitations of this study were those related to the methodological choices. For instance, the analysed records were those that mentioned “policy” (or related used keywords) in the title, abstract or keywords. There can be policy-oriented research that just does not mention it in these fields, and, therefore, wasn’t considered in the analysis.

Additionally, the search was performed in English, which can geographically bias the results. Nevertheless, a language bias analysis was performed, guaranteeing, to some extent, that this bias should not be significant considering the extensive amount of analysed literature.

The broad nature of the research questions contributed to an extensive final database, which included 2135 records. This factor, combined with the high number of categories, imposed a trade-off, in which some relationships between variables, that would be

interesting to analyse, were not included in order to decrease complexity and redundancy.

Through the literature review, some gaps in policy-oriented research were identified. Geographically, there is more policy-oriented research being performed in Europe, Northern America, and Oceania, compared to other regions, and even in those regions, studies are mostly performed in specific countries (e.g., China and India in Asia, South America in Africa and Brazil in Latin America and the Caribbean).

Some studies have already demonstrated that the amount of applied research in invasion science (i.e., that can inform challenges associated with invasion detection, control, and management) is still lagging behind the body of research representing the “spectator” approach (i.e., basic research) (Esler et al. 2010).

Interestingly, even in policy-oriented research, there is a methodological tendency towards studies that contribute to the assembly of data and knowledge and that perform assessments and reviews, while studies that involve public discussions, that develop frameworks or that report/evaluate management and capacity building programmes are lacking (cf. Fig. 8b)

As for the main lessons, in a general way, policy-oriented research in invasion science seems to be driven by international conventions relevant to IAS. As such, an international convention on IAS could be beneficial for driving additional policy-oriented research globally.

It was also found that in regions where economic impacts are high and legal instruments are abundant, the amount of policy-oriented research is high (e.g., Europe, Australia, and New Zealand, and Northern America) and in places where the first are high but the latter is scarce, the quantity of policy-oriented research is also high (e.g., China and India). On the other hand, some countries/regions can have abundant and relevant legal instruments in relation to IAS and that does not necessarily translate into high quantities of policy-oriented research (e.g., South America). Therefore, it is expected that policy-oriented research in invasion science will continue to grow, especially in places where the economic impacts of IAS continue to increase.

Finally, our study further supports the idea that policy-mixes, that include legislative and regulative policy instruments, complemented by cooperative and knowledge-building ones, should be the most effective way to deal with complex socioecological problems, including IAS.

Science can support policy design and implementation (through the construction of knowledge and the design of policy tools) and policy can support science (through incentives and funding), demonstrating how these two dimensions need to work in a collaborative and cooperative manner. Scientific policy tools, like risk assessment, ecological modelling, cost-benefit analysis, and citizen science, among others, are proving to be an effective and innovative way of dealing with invasive alien species.

5. Conclusions

This thesis has contributed to the broaden the knowledge about policy-oriented research in invasion science, as well as better understanding the relationship between these two dimensions. Opportunities and gaps were identified.

The main conclusions are:

- (1) Following the identified effect related to high number of publications in the periods surrounding important conventions, a global convention on IAS is expected to drive additional policy-oriented research.
- (2) Policy-oriented research in invasion science has geographical and methodological gaps that should be addressed.
- (3) Economic instruments were the least mentioned type of policy instrument in policy-oriented invasion science, despite most economic literature suggesting them as a viable solution for biodiversity-related policy issues.
- (4) When dealing with environmental challenges, including IAS, policymakers should design policies that combine the application of novel types of policy instruments, related with cooperation, public participation, and knowledge-building, to complement legislative and regulatory approaches.
- (5) Governance, especially related to complex socioecological problems, can benefit from a more networking, participative and community-based approach.
- (6) The development and implementation of scientific-based policy tools (e.g., citizen science, cost-benefit analysis, and risk assessment) should be supported by policy, as a means to achieve policy objectives.

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APPENDIX

Fig. A1. The number of records retrieved by the literature search considering only invasive alien species keywords (dark grey) and invasive alien species and policy keywords (light grey). Searches were performed on SCOPUS database on October 2020.

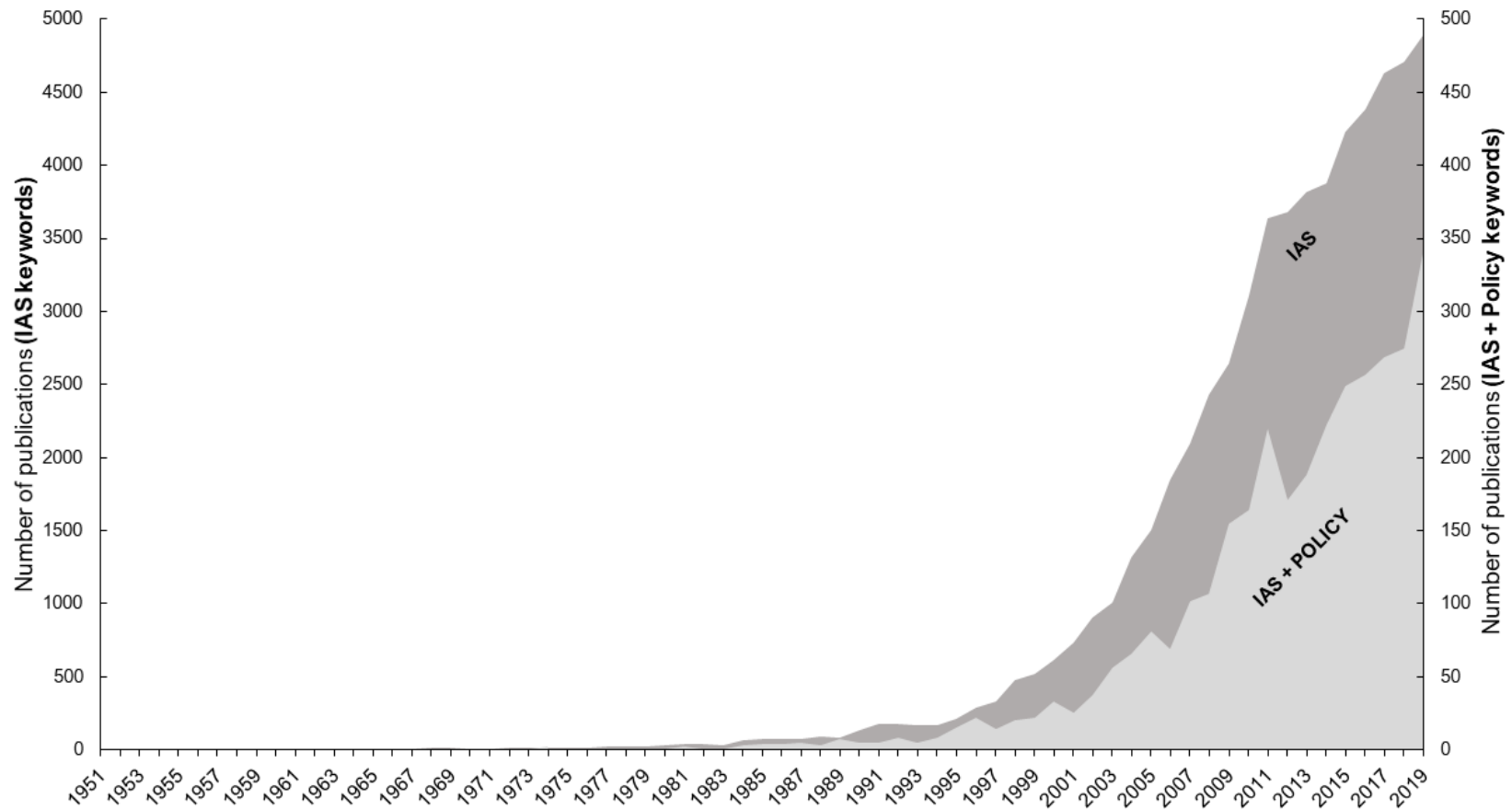


Fig. A2. Proportion of publications directed to each taxonomical group at each scale.

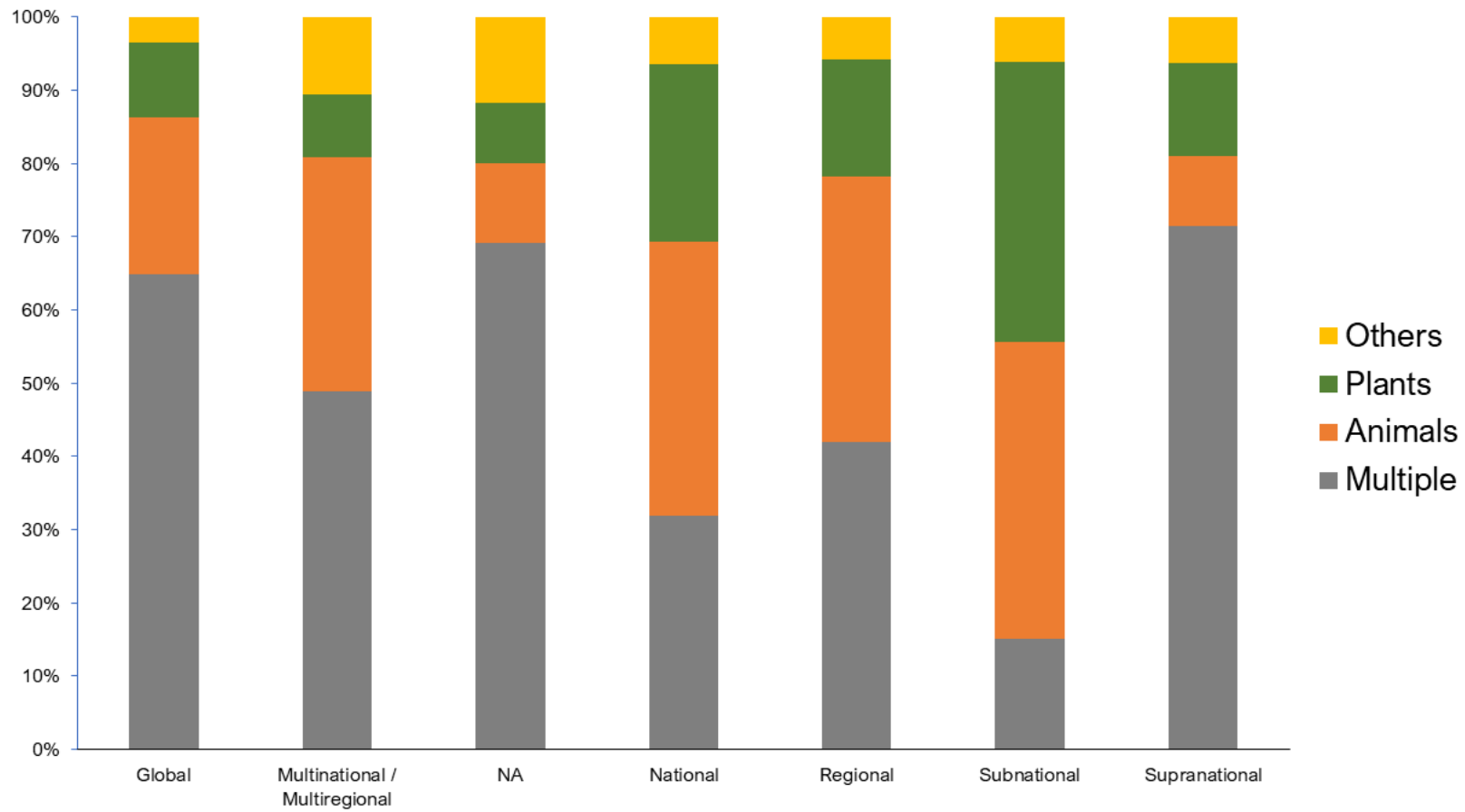


Fig. A3. Proportion of mentioned management actions when “IAS management plans” was recommended.

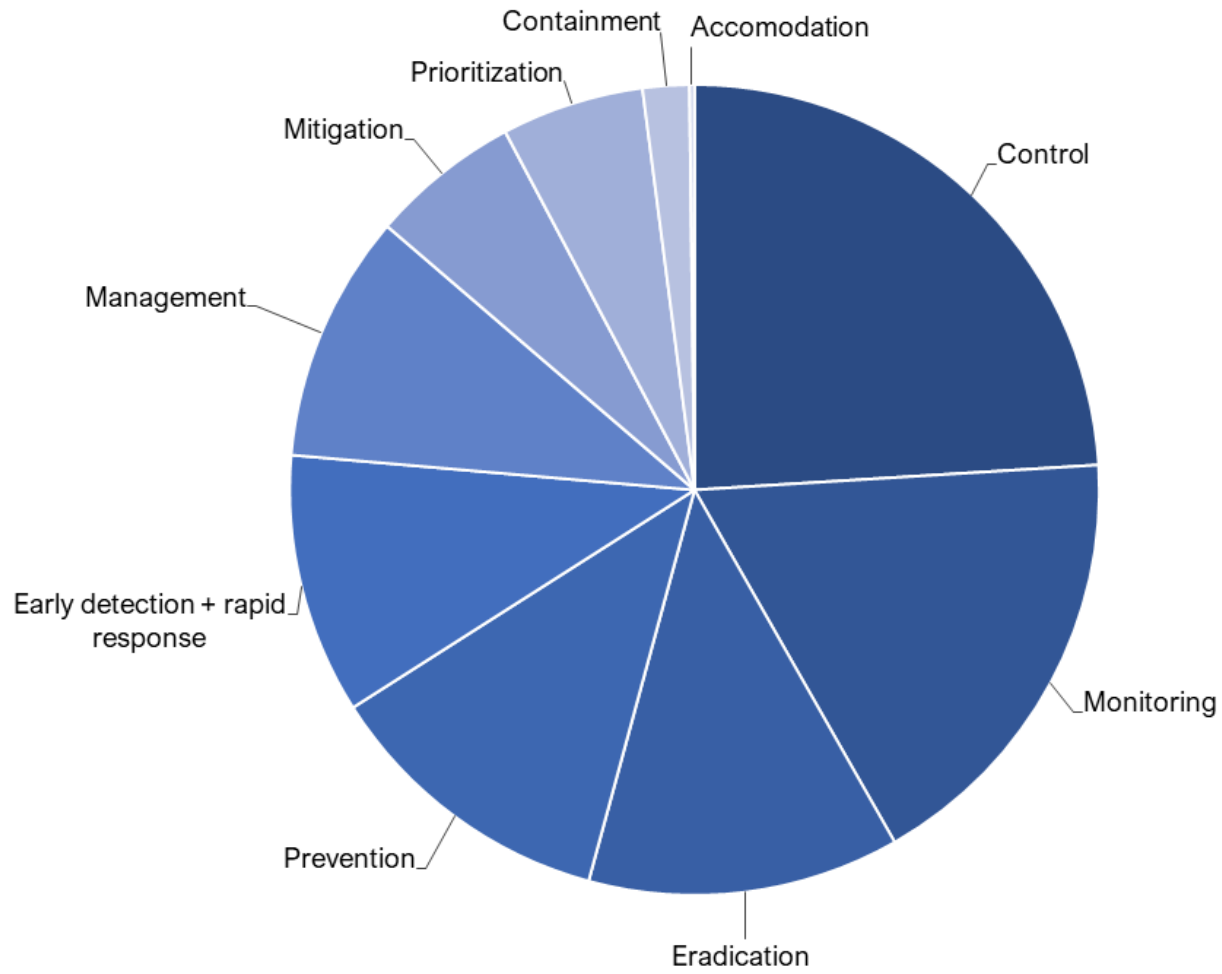


Table A1. Development of final keyword search string. Each term was added hierarchically, by apparent suitability, and for each term added, the first 10 references in the results were evaluated regarding the relevance for this study. Search conducted on SCOPUS on June 2020.

Keywords	Hits	Comments
First group: biological invasions		
"biological invasion"	15380	Add new term
"biological invasion" OR "ecological invasion"	15433	Add new term
"biological invasion" OR "ecological invasion" OR "invasion biology"	15864	Add new term
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology"	16160	Add new term
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species"	41578	Add new term
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive taxa"	41627	Discard new term due to irrelevant hits
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant"	43721	Add new term
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant" OR "invasive animal"	43814	Add new term
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant" OR "invasive animal" OR "alien species"	47433	Add new term
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant" OR "invasive animal" OR "alien species" OR "alien taxa"	47486	Add new term
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant" OR "invasive animal" OR "alien species" OR "alien taxa" OR "alien plant"	48165	Add new term
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant" OR "invasive animal" OR "alien species" OR "alien taxa" OR "alien plant" OR "alien animal"	48177	Discard new term due to irrelevant hits
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant" OR "invasive animal" OR "alien species" OR "alien taxa" OR "alien plant" OR "exotic species"	53243	Add new term
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant" OR "invasive animal" OR "alien species" OR "alien taxa" OR "alien plant" OR "exotic species" OR "exotic taxa"	53329	Discard new term due to irrelevant hits
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant" OR "invasive animal" OR "alien species" OR "alien taxa" OR "alien plant" OR "exotic species" OR "exotic plant"	54176	Add new term
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant" OR "invasive animal" OR "alien species" OR "alien taxa" OR "alien plant" OR "exotic species" OR "exotic plant" OR "exotic animal"	54948	Add new term
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant" OR "invasive animal" OR "alien species" OR "alien taxa" OR "alien plant" OR "exotic species" OR "exotic plant" OR "exotic animal" OR "non native species"	56635	Add new term
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant" OR "invasive animal" OR "alien species" OR "alien taxa" OR "alien plant" OR "exotic species" OR "exotic plant" OR "exotic animal" OR "non native species" OR "exotic taxa"	56667	Discard new term due to irrelevant hits

plant" OR "exotic animal" OR "non native species" OR "non native plant" OR "non native animal" OR "introduced species" OR "introduced plant" OR "introduced animal" OR "non indigenous species" OR "non indigenous plant" OR "allochthonous species" OR "invasive vegetation" OR "invader"		
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant" OR "invasive animal" OR "alien species" OR "alien taxa" OR "alien plant" OR "exotic species" OR "exotic plant" OR "exotic animal" OR "non native species" OR "non native plant" OR "non native animal" OR "introduced species" OR "introduced plant" OR "introduced animal" OR "non indigenous species" OR "non indigenous plant" OR "allochthonous species" OR "invasive vegetation" OR "invasive"	545369	Discard new term due to irrelevant hits (mostly medicine, immunology, biochemistry and social sciences)
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant" OR "invasive animal" OR "alien species" OR "alien taxa" OR "alien plant" OR "exotic species" OR "exotic plant" OR "exotic animal" OR "non native species" OR "non native plant" OR "non native animal" OR "introduced species" OR "introduced plant" OR "introduced animal" OR "non indigenous species" OR "non indigenous plant" OR "allochthonous species" OR "invasive vegetation" OR "invasive pests"	67030	Add new term
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant" OR "invasive animal" OR "alien species" OR "alien taxa" OR "alien plant" OR "exotic species" OR "exotic plant" OR "exotic animal" OR "non native species" OR "non native plant" OR "non native animal" OR "introduced species" OR "introduced plant" OR "introduced animal" OR "non indigenous species" OR "non indigenous plant" OR "allochthonous species" OR "invasive vegetation" OR "invasive pests" OR "alien pests"	67087	Add new term
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant" OR "invasive animal" OR "alien species" OR "alien taxa" OR "alien plant" OR "exotic species" OR "exotic plant" OR "exotic animal" OR "non native species" OR "non native plant" OR "non native animal" OR "introduced species" OR "introduced plant" OR "introduced animal" OR "non indigenous species" OR "non indigenous plant" OR "allochthonous species" OR "invasive vegetation" OR "invasive pests" OR "alien pests" OR "exotic pests"	67382	Add new term
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant" OR "invasive animal" OR "alien species" OR "alien taxa" OR "alien plant" OR "exotic species" OR "exotic plant" OR "exotic animal" OR "non native species" OR "non native plant" OR "non native animal" OR "introduced species" OR "introduced plant" OR "introduced animal" OR "non indigenous species" OR "non indigenous plant" OR "allochthonous species" OR "invasive vegetation" OR "invasive pests" OR "alien pests" OR "exotic pests" OR "non native pests"	67405	Add new term
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant" OR "invasive animal" OR "alien species" OR "alien taxa" OR "alien plant" OR "exotic species" OR "exotic plant" OR "exotic animal" OR "non native species" OR "non native plant" OR "non native animal" OR "introduced species" OR "introduced plant" OR "introduced animal" OR "non indigenous species" OR "non indigenous plant" OR "allochthonous species" OR "invasive vegetation" OR "invasive pests" OR "alien pests" OR "exotic pests" OR "non native pests" OR "introduced pests"	67576	Add new term
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant" OR "invasive animal" OR "alien species" OR "alien taxa" OR "alien plant" OR "exotic species" OR "exotic	67580	Discard new term due to irrelevant hits

plant" OR "exotic animal" OR "non native species" OR "non native plant" OR "non native animal" OR "introduced species" OR "introduced plant" OR "introduced animal" OR "non indigenous species" OR "non indigenous plant" OR "allochthonous species" OR "invasive vegetation" OR "invasive pests" OR "alien pests" OR "exotic pests" OR "non native pests" OR "introduced pests" OR "non indigenous pests"		
"biological invasion" OR "ecological invasion" OR "invasion biology" OR "invasion ecology" OR "invasive species" OR "invasive plant" OR "invasive animal" OR "alien species" OR "alien taxa" OR "alien plant" OR "exotic species" OR "exotic plant" OR "exotic animal" OR "non native species" OR "non native plant" OR "non native animal" OR "introduced species" OR "introduced plant" OR "introduced animal" OR "non indigenous species" OR "non indigenous plant" OR "allochthonous species" OR "invasive vegetation" OR "invasive pests" OR "alien pests" OR "exotic pests" OR "non native pests" OR "introduced pests" OR "allochthonous pests"	67576	Discard new term due to irrelevant hits
Second group: policy		
"policy"	2153	Add new term
"policy" OR "legislati*"	2655	Add new term
"policy" OR "legislati*" OR "convention"	2878	Add new term
"policy" OR "legislati*" OR "convention" OR "treaty"	2920	Add new term
"policy" OR "legislati*" OR "convention" OR "treaty" OR "**legal**"	3389	Add new term
"policy" OR "legislati*" OR "convention" OR "treaty" OR "**legal**" OR "law"	3665	Add new term
"policy" OR "legislati*" OR "convention" OR "treaty" OR "**legal**" OR "law" OR "politic**"	3947	Add new term
"policy" OR "legislati*" OR "convention" OR "treaty" OR "**legal**" OR "law" OR "politic**" OR "directive"	4106	Add new term
"policy" OR "legislati*" OR "convention" OR "treaty" OR "**legal**" OR "law" OR "politic**" OR "directive" OR "decree"	4108	Discard new term due to irrelevant hits
"policy" OR "legislati*" OR "convention" OR "treaty" OR "**legal**" OR "law" OR "politic**" OR "directive" OR "regulation"	5551	Discard new term due to irrelevant hits

Table A2. Main International Conventions (and Conferences of the Parties – COPs) that mention IAS.

Convention	Section(s) relevant to invasive alien species	Terminology used	Dates	References
<p>International Plant Protection Convention (IPPC)</p>	<p>Articles I.1, IV.2.c, VII.1, VII.4, IX.4.b and XI.2.a refer to introduced pests.</p> <p>“Pest” is broadly defined as “any species, strain or biotype, animal life or any pathogenic agent injurious or potentially injurious to plants or plant products”. Alien organisms that come within this definition are covered.</p>	<p>Introduced pests</p>	<p>1951 (adopted) 1952 (in force) 1997 (revised)</p>	<p>document (revised version 1997)</p>
<p>Convention on Biological Diversity (CBD)</p>	<p>Article 8(h) Prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats, and species.</p>	<p>Alien species</p>	<p>1992 (adopted) 1993 (in force)</p>	<p>document</p>
	<p>COP 6: Decision VI/23 Alien Species that Threaten Ecosystems, Habitats or Species</p>	<p>Invasive alien species</p>	<p>COP6 - 2002</p>	<p>COP6</p>
	<p>COP10: Decision X/2 Strategic Plan for Biodiversity 2011-2020 - Aichi Biodiversity Targets Target 9 – Invasive alien species and pathways</p>	<p>Invasive alien species</p>	<p>COP10 – 2010</p>	<p>COP10</p>

<p>Convention on Migratory Species of Wild Animals (CMW or Bonn Convention)</p>	<p>Exotic species are considered a threat to migratory species. Article III, 4c (...) prevent, reduce, or control factors that are endangering or are likely to further endanger the species, including strictly controlling the introduction of, or controlling or eliminating, already introduced exotic species. Article V, 5e (...) including strict control of the introduction of, or control of already introduced, exotic species detrimental to the migratory species.</p>	<p>Exotic species</p>	<p>1979 (adopted) 1983 (in force)</p>	<p>document</p>
<p>Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES or Washington Convention)</p>	<p>Article III, 4 Parties are required to prevent, reduce, and control the factors endangering migratory species, including “strictly controlling the introduction of, or controlling or eliminating already introduced exotic species”.</p>	<p>Introduced exotic species</p>	<p>1973 (adopted) 1975 (in force) 1979 (amended) 1983 (amended)</p>	<p>document</p>
	<p>COP10 Decision 10.54 (directed to the Parties) and Decision 10.76 (directed to the Animals Committee and Plants Committee)</p>	<p>Alien diseases Exotic species</p>	<p>COP10- 1997</p>	<p>Decision 10.54</p>
<p>Convention on Wetlands of International Importance (Ramsar Convention)</p>	<p>COP 7 Resolution VII/14 on Invasive species and wetlands: Address the environmental, economic, and social impact of invasive species on wetlands.</p>	<p>Invasive species</p>	<p>COP7 – 1999</p>	
	<p>COP 8 Resolution VIII/18: Invasive Species and Wetland.</p>	<p>Invasive species</p>	<p>COP8 – 2002</p>	

	<p style="text-align: center;">COP 10</p> <p>Resolution X/1 highlighted invasive alien species among “challenges that still require urgent attention in order to achieve wetland wise use under the Convention”.</p>	Invasive alien species	COP10 – 2008	
<p>Agreement on the Application of Sanitary and Phytosanitary Measures</p>	<p>There is no specific IAS content in the agreement, but it provides an international legal basis for all sanitary and phytosanitary measures that affect international trade.</p> <p>The focus is with pests, diseases, sanitary and phytosanitary issues, many of which are alien species.</p>	/	1994 (adopted) 1995 (in force)	text of the agreement
<p>International Convention for the Control and Management of Ship's Ballast Water and Sediments</p>	<p>They are mentioned in the general objectives.</p> <p>The rest of the document refers mostly to “harmful aquatic organisms” (that can be IAS).</p>	Invasive alien species	2004 (adopted) 2017 (in force)	document
<p>United Nations Convention on the Law of the Sea (UNCLOS)</p>	<p>Article 196: Use of technologies or introduction of alien or new species</p> <p>States shall take all measures necessary to prevent, reduce and control pollution of the marine environment resulting from the [...] intentional or accidental introduction of species, alien or new, to a particular part of the marine environment, which may cause significant and harmful changes thereto.</p>	Alien species	1982 (adopted) 1994 (in force)	document

<p>Agenda 2030 – Sustainable Development Goals SDG</p>	<p>Target 15.8: by 2020 introduce measures to prevent the introduction and significantly reduce the impact of invasive alien species on land and water ecosystems, and control or eradicate the priority species</p>	<p>Invasive alien species</p>	<p>2015 (adopted)</p>	<p>document</p>
<p>Millennium Ecosystem Assessment (MEA)</p>	<p>4.3.2 Invasive Alien Species (Anthropogenic Drivers)</p>	<p>Invasive alien species</p>	<p>2005 (published)</p>	<p>document</p>

Tabel A3. Categories with description and sources.

CATEGORIES		DESCRIPTION	SOURCE
PUBLICATION CHARACTERISTICS			
TEMPORAL	Year		
SCALE	Subnational	Studies at local scales. Regions / subregions of countries, either administrative or geographic. Includes studies done on Overseas Territories (e.g., British Overseas Territories).	(e.g., Foxcroft, Richardson, and Wilson 2007)
	National	Country-level studies.	(e.g., Van Wilgen, Richardson, and Baard 2008)
	Regional	Continental studies (e.g., Europe) or studies within one continent but in multiple countries (e.g., Iberian Peninsula, Great Lakes)	(e.g., Galil 2007)
	Supranational	Studies done at the level of multinational unions or associations in which member countries cede authority and sovereignty on at least some internal matters to the group, whose decisions are binding on its members (e.g., European Union).	(e.g., Scalera 2010)
	Multinational / Multiregional	Studies done in several countries or regions without geographical connection.	(e.g., Ervin 2003)
	Global	Studies done for the whole world / all countries. Global analysis on a theme.	(e.g., Endresen et al. 2004)

	NA	Not applied. Purely theoretical studies (e.g., ecological, or economic theory) or experimental designs (i.e., done in labs).	(e.g., Romero-Martínez et al. 2017)
TYPE OF STUDY	Assembling data and knowledge	Studies that address underlying knowledge gaps (i.e., experimental and observational research)	Based and adapted from the IPBES categorization of “Policy tools and methodologies”.
	Assessment and evaluation	Studies that revise and synthesise existing information (e.g., reviews)	
	Public discussion, involvement and participatory process	Studies with the participation of stakeholders or the general population to identify problems and opportunities, set goals and priorities or analyse public perception.	
	Selection and design of policy instruments	Studies that support the identification, evaluation and/or choice of potential policy tools or instruments (e.g., studies that present the development of a risk analysis framework).	
	Implementation, outreach and enforcement	Studies that present the development or evaluation programmes related to management and the application of policies.	
	Training and capacity building	Studies that present training or capacity building programmes.	
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		
	NA		
COUNTRY	Name country	Applicable to studies done at the national or subnational level.	Based on the United Nations Statistic Division categorization of Countries or Areas.
INVASIVE ALIEN SPECIES FEATURES			
TERMINOLOGY	Invasive alien species	Alien invasive species	
	Invasive species	Invaders	
	Exotic species		
	Introduced species		
	Alien species		
	Non-native species		
	Non-indigenous species		
	Allochthonous species		
ROLE	Subject	IAS are the subject of the study.	
	Threat	IAS are a threat to the main subject of the study (e.g., to another species, to an ecosystem or to a sector/activity).	
	Other	IAS are an indicator, driver or as part of study (not the main or only subject)	
TAXONOMY	ANIMALS	Mammals Birds	Taxonomic categorization was mainly based on Seebens et al., (2017). However, some categories were adapted

	Herpetofauna		(some groups were merged, and some groups were added).
	Fish		
	Insects		
	Crustaceans		
	Molluscs		
	Other invertebrates		
	Multiple / All		
	PLANTS	Includes vascular plants and bryophytes.	
	OTHERS	Includes algae, fungi, bacteria and protozoans, plankton, virus or when pests, parasites or diseases are mentioned without specifying which ones.	
	MULTIPLE	Includes various taxonomic groups or when invasive alien species are mentioned in general (no specific taxonomic group).	
ENVIRONMENT	Terrestrial		
	Aquatic	Includes freshwater, marine, coastal	Based on IPBES Units of Analysis.
	Combination		

POLICY FEATURES

THEMATICAL FOCUS	BIODIVERSITY AND ENVIRONMENT	General	Study has a focus on biodiversity conservation, in general, or invasive species management, in particular.	Categorization based and adapted from Shine (2000), McNeely (2001) and Secretariat of the Convention on Biological Diversity (2001).
		Important Habitat	Study has a focus on a specific habitat, ecosystem, or place.	
		Important Species	Study has a focus on an endangered, endemic, or native species.	
	SECURITY AND SAFETY	Phytosanitary	Study has a focus on phytosanitary issues (i.e., plant health).	Categorization based and adapted from Shine (2000), McNeely (2001) and Secretariat of the Convention on Biological Diversity (2001).
		Animal health	Study has a focus on animal health and well-being.	
		Public health	Study has a focus on public health (i.e., human health).	
		Biosecurity	Study has a focus on biosecurity.	
		Biosafety	Study has a focus on biosafety (e.g., hybridization).	
	SECTORS AND PATHWAYS	Forestry	Studies has a focus on forestry and forestry-related activities (e.g., timber harvesting).	Categorization based and adapted from McNeely (2001),Smith at al. (2014) and Faulkne et al. (2020).
		Agriculture	Study has a focus on agriculture.	
		Biological control	Study has a focus on biological control.	
		Horticulture	Study has a focus on horticulture or	
		Fisheries	Study has a focus on fisheries. Includes studies related to fish stocking and live-bait issues.	
		Aquaculture	Study has a focus on aquaculture.	
		Hunting	Study has a focus on hunting.	
Husbandry		Study has a focus on husbandry. Includes animal farming, fur farming, game farming.		

	Ornamental	Studies have a focus on ornamental-related activities like gardens, landscaping.		
	Tourism	Study has a focus on tourism.		
	Pet	Study has a focus on the pet industry.		
	Energy	Study has a focus on energy production.		
	Transport	Study has a focus on Includes ballast water and shipping-related issues but also air and land transport.		
	Territorial planning and land use	Study has a focus on urban planning, land use planning or other types of territorial planning.		
	Wood packaging	Study has a focus on wood packaging (for transport).		
	Zoos	Study has a focus on zoos.		
	Recreational activities	Study has a focus on recreational activities (e.g., boating, hiking)		
	Trade	Study a focus on trade in general (no specific sector mentioned).		
POLICY INSTRUMENTS – RELATION TO STUDY	Context	Policy instruments are mentioned to introduce the need for study / in context		
	Recommendations	Policy instruments are mentioned as recommendations of study results		
	Both			
TYPES OF POLICY INSTRUMENTS	LEGAL INSTRUMENTS (CONTEXT)	(L1) International agreements	International conventions and agreements (e.g., CBD,).	Based and adapted from Shine (2000), McNeely (2001) and Secretariat of the Convention on Biological Diversity (2001).
		(L2) Regional agreements	Regional conventions and agreements (e.g., CBD,).	

LEGAL INSTRUMENTS (RECOMMENDATIONS)	(L3) Supranational legislation	e.g., EU legislation (Directives; Regulations; Decisions).	
	(L4) National legislation	e.g., Decree; Act; (depends on country).	
	(L5) Subnational legislation	Legislation passed by states, municipalities or smaller regions (e.g., US States; Australian states; Canadian provinces; city-level legislation).	
	(L6) Update / Revise legislation	Amend and/or improve legislation (through stricter legislation, more proactive, integration harmonize)	
	(L7) New legislation	Create new legislation (national; international)	
	(L8) Law enforcement	Enforce existing legislation	
	(L9) Political engagement	Political acceptance, engagement, interest, accountability	
	(R1) Bans / Prohibitions		
	(R2) Licences	Government certifies competent professionals who can assist with compliance.	
(R3) Permits	For import or introduction; quotas		
REGULATORY INSTRUMENTS	(R4) Standards		Based and adapted from McNeely (2001), Gunningham, N. (2005), Knill et al., (2011), Taylor et al. (2012) and Bouwma et al. (2015).
	(R5) Listing		
	(R6) Inspections		
	(R7) Quarantine measures		
	(R8) Other import / export restrictions	Surveillance; screening; biosecurity measures; task force; pre-post border	

	(R9) Protection status (species)		
	(R10) Protection status (local)		
	(R11) Industry/activity- related regulations	Sales	
ECONOMIC AND FISCAL INSTRUMENTS	(E1) Taxes	Taxes on activities that pollute can be used to generate revenues to provide financial incentives for activities that do not pollute. Includes levies.	
	(E2) Penalties	Penalties are fines charged against violators. Includes sanctions, fines.	
	(E3) Tariffs		
	(E4) Subsidies	Includes tax allowances, tax relief, tax benefits, bonus scheme	
	(E5) Fees		
	(E6) Tradeable permits		
	(E7) Payment for ES		
	(E8) Funds / grants	Funds or grants with the purpose of funding IAS management activities or	
	(E9) Bonds		
	(E10) Deposit-Refund system		
	(E11) Offsetting		
	(E12) Liability rules	The threat". Includes mention to the "Polluter-pays"	

Based on Panayotou (1994), Knill et al. (2011), Taylor et al. (2012) and Bouwma et al. (2015).

	(E13) Property rights		
INFORMATION AND COMMUNICATION INSTRUMENTS	(I1) Education	Raising public awareness. educational campaigns Government informs the public about regulatory violations or dangers, causing a company negative public relation	
	(I2) Labelling / Certifications		Based and adapted from McNeely (2001), Gunningham, N. (2005), Knill et al., (2011), Taylor et al. (2012) and Bouwma et al. (2015).
	(I3) Guidelines		
	(I4) Technical training	Training of professionals to deal with IAS related issues (e.g., identification on border control).	
(C1) Codes of conduct / Codes of practice			
AGREEMENT-BASED OR COOPERATIVE INSTRUMENTS	(C2) Cooperation / Collaboration	Working together to achieve common goals. Between countries / states / administrative entities; or between policymakers and scientists, (...); partnerships; cooperative agreements; transboundary; between groups; public-private	Based and adapted from McNeely (2001), Gunningham, N. (2005), Knill et al., (2011), Taylor et al. (2012) and Bouwma et al. (2015).
	(C3) Coordination	Guided & coordinated action.	
	(K1) Research		
KNOWLEDGE AND INNOVATION INSTRUMENTS	(K2) Public participation	Public participation in policymaking or research (citizen science)	Based and adapted from McNeely (2001), Gunningham, N. (2005), Knill et al., (2011), Taylor et al. (2012) and Bouwma et al. (2015).
	(K3) Technical innovation		
	(P1) Conservation / biodiversity strategies	Biodiversity strategies (at all scales), conservation strategies for a specific species	
PLANNING AND POLICY SUPPORT INSTRUMENTS	(P2)	Park management plans, important area conservation plans	Based and adapted from McNeely (2001), Gunningham, N. (2005), Knill et al., (2011) and Taylor et al. (2012).

	Local management plans
	(P3)
	IAS management plans
TYPES OF RECOMMENDED ACTIONS	Accommodation
	Containment
	Control
	Early detection and rapid response
	Eradication
	Management (general)
	Mitigation
	Monitoring
	Prevention
	Prioritization

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Additional information

Figure A3. Percentage of publications directed to each IAS role (a), taxonomic group (b) and environment (c).

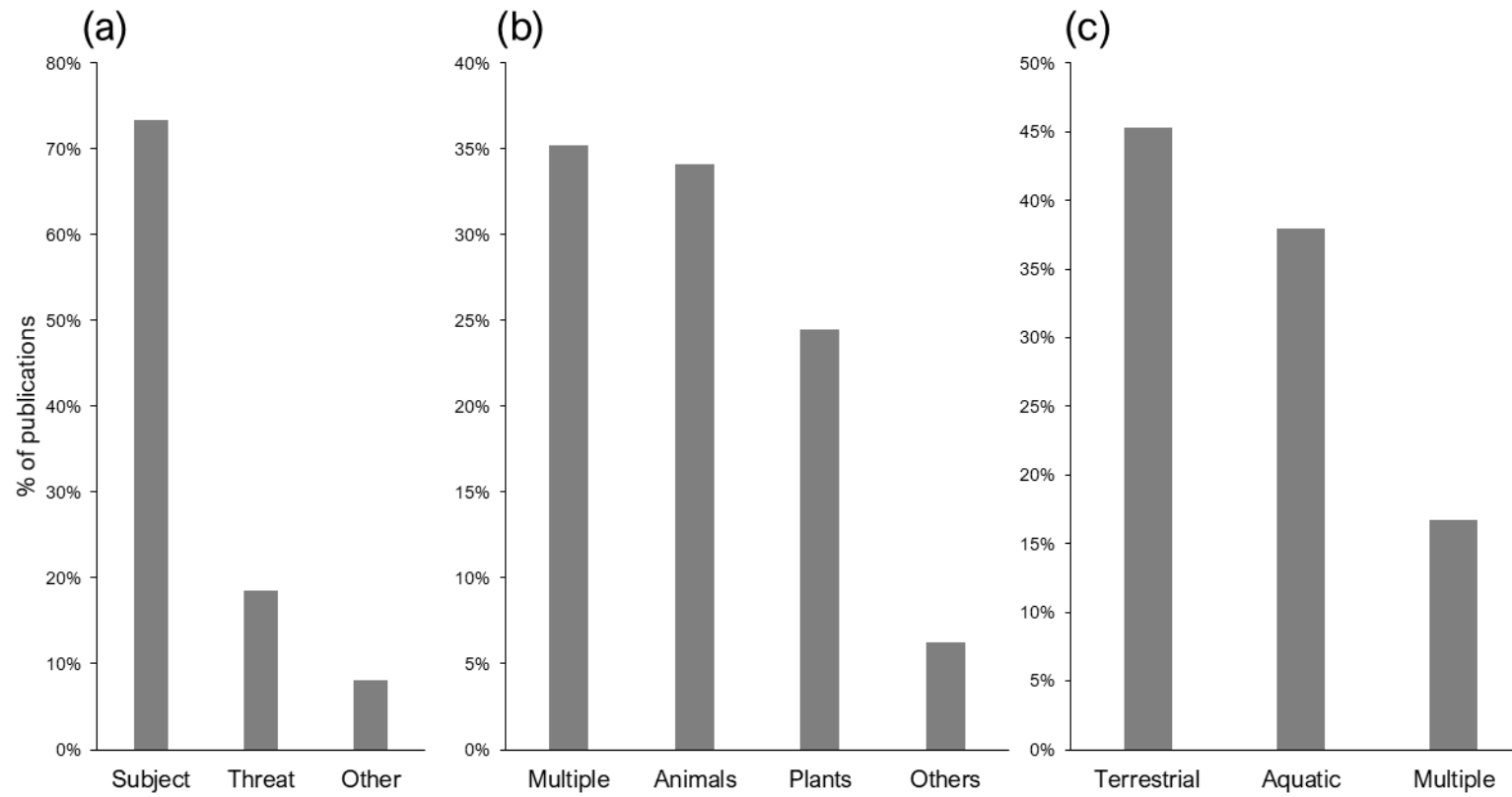


Fig. A4. Percentage of publications directed at taxonomic group, environment and role (S- Subject; T-Threat; O-Others).

