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# Is invasion science moving towards agreed standards? The influence of selected frameworks

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## Abstract

The need to understand and manage biological invasions has driven the development of frameworks to circumscribe, classify, and elucidate aspects of the phenomenon. But how influential have these frameworks really been? To test this, we evaluated the impact of a pathway classification framework, a framework focussing on the introduction-naturalisation-invasion continuum, and two papers that outline an impact classification framework. We analysed how these framework papers are cited and by whom, conducted a survey to determine why people have cited the frameworks, and explored the degree to which the frameworks are implemented. The four papers outlining these frameworks are amongst the most-cited in their respective journals, are highly regarded in the field, and are already seen as citation classics (although citations are overwhelmingly within the field of invasion science). The number of citations to the frameworks has increased over time, and, while a significant proportion of these are self-citations (20–40%), this rate is decreasing. The frameworks were cited by studies conducted and authored by researchers from across the world. However, relative to a previous citation analysis of invasion science as a whole, the frameworks are particularly used in Europe and South Africa and less so in North America. There is an increasing number of examples of uptake into invasion policy and management (e.g., the pathway classification framework has been adapted and adopted into EU legislation and CBD targets, and the impact classification framework has been adopted by the IUCN).

However, we found that few of the citing papers (6–8%) specifically implemented or interrogated the frameworks; roughly half of all citations might be viewed as frivolous ("citation fluff"); there were several clear cases of erroneous citation; and some survey respondents felt that they have not been rigorously tested yet.
Although our analyses suggest that invasion science is moving towards a more systematic and standardised approach to recording invasions and their impacts, it appears that the proposed standards are still not applied consistently. For this to be achieved, we argue that frameworks in invasion science need to be revised or adapted to particular contexts in response to the needs and experiences of users (e.g., so they are relevant to pathologists, plant ecologists, and practitioners), the standards should be easier to apply in practice (e.g., through the development of guidelines for management), and there should be incentives for their usage (e.g., recognition for completing an EICAT assessment).

**Keywords**
Biological invasions, EICAT, introduction pathways, invasion science, Pathway Classification, Unified Framework

## Introduction

The field of invasion science has grown rapidly (Pyšek et al. 2006; Richardson and Pyšek 2008). However, despite major advances on many fronts, there are ongoing debates about how the phenomenon of biological invasions should be circumscribed and classified (Latombe et al. 2019). Such differences in definitions hamper our ability to develop robust generalisations, consistently monitor the phenomenon across different scales, and report on it to multiple stakeholders. To facilitate generalisations, and to improve the link between science, policy, and management, numerous frameworks have been developed in an attempt to unify different concepts and definitions. For these frameworks to allow for generalisations and to have value in decision-making, they need to be applicable across taxonomic groups and environments and be accepted by different end users.

These issues were discussed as part of a workshop on "Frameworks in Invasion Science" in November 2019 (Wilson et al. 2020). As background to this workshop, and to understand the role of frameworks in invasion science generally, this paper explores the degree to which existing frameworks have been accepted and adopted. For this purpose, we selected three of what we consider amongst the most influential recent frameworks in invasion science: the pathway classification framework first outlined by Hulme et al. (2008); the proposed Unified Framework for Biological Invasions describing the introduction-naturalisation-invasion continuum (Blackburn et al. 2011); and the Environmental Impact Classification for Alien Taxa [the rationale was introduced by Blackburn et al. 2014; and guidance as to how to apply it in practice (with slight modification) was provided by Hawkins et al. 2015]. These are hereafter referred to as the "Pathway Classification", the "Unified Framework", and "EICAT", respectively (and where data are presented for all three frameworks, they are presented in this order, with a combined/single figure for the two papers that outline EICAT). This is a biased selection. Many more frameworks have been proposed, some of which are very similar to those selected (Catford et al. 2009; Leung et al. 2012; Wilson et al. 2020), and several others paved the way for the frameworks selected here (Nentwig et al. 2010; Rich-

ardson et al. 2000; Williamson and Fitter 1996). However, we selected these frameworks as they capture the phenomenon of invasion in its entirety (i.e., introduction dynamics, establishment, spread, and impact) and they were all explicitly designed to be generalisable across taxa and contexts. They are also amongst the most widespread and widely adopted frameworks, for example, the Pathway Classification has been modified and adopted into EU regulations and by the Convention on Biological Diversity (Scalera et al. 2016), and EICAT was adopted by the IUCN (IUCN 2020). Both the Unified Framework and the Pathway Classification have been proposed for use in international biodiversity standards, and EICAT is under consideration for a future proposal (Groom et al. 2019). Therefore, they arguably represent the frameworks that are closest to being standards in invasion science, and see Box 1 for how they have been adopted policy and management settings in South Africa as an example.

**Box 1.** How the frameworks have influenced policy and management in South Africa.

All three frameworks–the Pathway Classification (Hulme et al. 2008), the Unified Framework (Blackburn et al. 2011), and EICAT (Blackburn et al. 2014; modified by Hawkins et al. 2015)–have been implemented to different degrees in South Africa. While these frameworks are not formally part of South African legislation, they are incorporated into national reporting on biological invasions and in a recently-developed risk analysis framework (see details below). There is, therefore, an incentive for South African researchers to explicitly use the coding of the frameworks.

*Status report on biological invasion in South Africa*

South African regulations on biological invasions require that, every three years, a report on the status of biological invasions and the effectiveness of control measures and regulations is produced. The primary aim of the status report is to strengthen the links between basic research, policy, and management by detailing the current status and providing support to decision-makers. The first report was released in October 2018 and it was the first effort globally to report on the status of biological invasion at a national level (van Wilgen and Wilson 2018). The report is based around 20 indicators covering pathways, species, sites, and interventions (Wilson et al. 2018). Of these, six indicators require the direct application of the invasion frameworks, and a further two are related to the frameworks.

*Risk analysis framework*

The South African regulatory lists (Department of Environmental Affairs 2014a; b) were initially developed through a series of stakeholder engagements and expert panel meetings (Kumschick et al. 2020-b). However, this has been contested in some cases. In response to the need for transparent and repeatable evidence to underpin the list, a risk analysis framework was developed. (Kumschick et al. 2020-c) As with the status report, the framework explicitly tries to align with the proposed frameworks.

Due to the way we selected the three frameworks, our analysis is somewhat circular. For example, the frameworks were selected on the basis that there has been some uptake into policy, so it is unsurprising that we found some uptake by policy-makers. However, we feel it is important to: (i) establish whether these frameworks are used broadly by people interested in invasion science or used just by a subset (e.g., only researchers based in Europe or only people studying marine invasions); (ii) determine whether the frameworks are being used as they were intended or only used to justify working on biological invasions; (iii) to assess how users perceive the frameworks; and (iv) to draw insights on how the field could move forward.

## Methods

To evaluate the impact of the frameworks, we conducted an analysis of the citations of the papers, surveyed the authors of citing papers, and explored the extent to which the frameworks have been used in policy and management documents.

### Citation analysis

The impact of a research publication is often measured by where it is published and how often it is cited (Biagioli 2016). By aggregating across publications, metrics have been developed to provide a measure of the impact of individual scientists and institutions (Hirsch 2005) that is incorporated into decisions around recruitment, promotions, and research funding (Hicks et al. 2015). While such metrics are simple and transparent, they create perverse incentives. For example, researchers, in an attempt to increase their h-scores, might inappropriately or egregiously promote their own work when reviewing or editing other people's manuscripts (Biagioli 2016; Zaggl 2017). Nonetheless, and acknowledging that impact as measured by citations is a different concept from research quality (Bornmann and Haunschild 2017), citations are a useful starting point to evaluate impact.

We explored four main aspects. First, we assessed the proportion of self-citations to gauge the degree to which the frameworks were only used by those who constructed them. Second, we evaluated whether the geographic and taxonomic biases apparent in the scientific literature in general (cf. Wilson et al. 2007; Wuestman et al. 2019) and invasion science in particular (Pyšek et al. 2006; Pyšek et al. 2008) were also apparent in the papers citing the frameworks. Our expectation was that the selected frameworks would be used across taxa as they were designed to be generally applicable. For example, an explicit rationale for the development of the Unified Framework was to merge a scheme predominately used by zoologists (Williamson and Fitter 1996) with a scheme used predominately by botanists (Richardson et al. 2000). Third, we wanted to explore whether the citing papers actually implemented the frameworks or simply cited the papers to back up general comments about biological invasions. And finally, we wanted to assess the degree to which the citations were from studies focussing on biological invasions or whether the frameworks had impact beyond their originally-intended field of study.

We downloaded bibliographic information from the ISI Web of Science Core Collection (https://www.webofknowledge.com) on 1 July 2019 for all the publications listed as citing one of the four papers considered here (Blackburn et al. 2014; Blackburn et al. 2011; Hawkins et al. 2015; Hulme et al. 2008), and obtained copies of the citing publications if possible (books and book chapters were omitted if a digital copy could not be readily obtained – 3.2, 1.6, 2.8% of cases for the Pathway Classification, the Unified Framework, and EICAT respectively; Suppl. material 1). We developed an initial protocol to score the articles according to set criteria. Ten of the authors scored 10 papers to look at consistency in scoring (i.e., inter-rater reliability). For most categories, it was found to be consistent, but in a few cases (e.g., the discipline), we found there was some disagreement that could be reduced by refining the protocol. However, when attempting to score papers in terms of the degree of influence the frameworks had on the paper there was substantial disagreement, even after discussion to refine the categories [Fleiss' Kappa of 0.179 in R package irr (Gamer et al. 2019)]. As a result, the extent of influence of each framework was scored by only one person for consistency (JRUW scored the Pathway Classification and SK scored the Unified Framework and EICAT, after discussing and aligning the scoring categories, see Suppl. material 2: Table S2.1). Most authors did some scoring of the other sections. We then adapted the protocol (see Suppl. material 2.1) and scored each paper accordingly (see Table 1 for details of the data extracted). It took 2–10 minutes to score each paper once it was downloaded.

The list of journals that cited each framework was extracted. To determine whether the frameworks had impact beyond their originally-intended field of study, we assigned each citing journal to one of three categories – those that explicitly included biological invasions as a subject area; those that published other aspects of ecology or were more general in scope; and those that did not include ecology as a subject area.

To evaluate geographic biases in the papers citing the frameworks, we used the results of a previous analysis of the geographic pattern of invasion science as a whole (Pyšek et al. 2008) as a point of comparison. We identified the corresponding author of studies that had cited the frameworks and assigned their primary affiliation to a geographic region as per the regions used by Pyšek et al. (2008). We then compared the number of studies in each region relative to the number of studies noted in Pyšek et al. (2008) against the expectation based on the rest of the world. After adjusting for multiple comparisons, regions that tended to have cited one of the frameworks either more often or less often than expected were identified (see Suppl. material 2.5).

## Survey of citing authors

Because it was difficult to be sure how the frameworks had influenced publications, we surveyed the corresponding authors of papers that cited any one of the four papers. The survey was conducted under ethical clearance (SU project number: 14445) issued by Stellenbosch University.

The questionnaire (Suppl. material 2.2) was structured to assess how the frameworks are viewed and why they were cited in the authors' works. We used structured questions

that were adopted and modified from a framework that has been applied to survey authors in citation analyses (Case and Higgins 2000; Harwood 2008; Prabha 1983; Shadish et al. 1995). The questionnaire consisted of 35 questions in four sections: eight proximity questions that assess the relationship between the person who cited a publication and any authors of that publication; 21 questions that seek reasons why authors might cite a paper; four semi-structured questions to gauge whether the frameworks are used in research or to implement policy and management strategies; and two questions that provided an opportunity to list any suggestions for or proposed improvements to the frameworks (Suppl. material 2.2). The questions that elicit reasons why authors might cite a paper can be grouped into five broad citation categories – classic citations, negative citations, creative citations, personal influence citations, and supportive citations – and the results were interpreted in the context of these groupings. A cover letter and a link to the questionnaire were emailed to a total of 958 corresponding authors, with a reminder sent to non-responders after one week. The survey ran for three weeks, from 13 March to 6 April 2020.

### Influence on policy and management

Policy papers and strategies, unlike journal articles, often do not have a comprehensive list of references, are not indexed by academic databases, and many are published in languages other than English. Therefore, we read a selection of national and international policy documents. These documents included national strategies, status reports, national and international guidelines, and documents published by the Convention on Biological Diversity, International Union for Conservation of Nature, and the European Union. We then qualitatively assessed the degree to which the documents explicitly or implicitly referred to or implemented the frameworks. For this purpose, we only considered documents dated more recently than 2008, i.e., after the Pathway Classification was published.

## Results

### Citation analysis

The results of the citation analysis are summarised in Table 1. As of 1 July 2019, the Pathway Classification had 436 citations recorded on the ISI Web of Science database, the Unified Framework 729 citations, and the two papers that present and refine EICAT 249 citations. This puts them in the top ten most cited papers in their respective journals amongst articles published in the same year or more recently. The vast majority of these citations are from papers that can be classified as invasion science. In fact, about a third of all papers published in the journal Biological Invasions in 2018 cite the Unified Framework. The numbers of citations are increasing annually, with no indication of any plateaus (Figure 1). The number of self-citations has also increased over time, but their relative proportion has declined. Twelve percent of the papers cited more than one of the frameworks (Suppl. material 2.3).

**Table 1.** Summary of the results of the citation analysis of frameworks in invasion science. Where numbers are given, they are for the Pathway Classification framework (Hulme et al. 2008), the Unified Framework (Blackburn et al. 2011), and EICAT (Blackburn et al. 2014; Hawkins et al. 2015) in that order.

| Variable | Type | Description | Expectation | Results |
|---|---|---|---|---|
| *Discipline* | Factor with three levels (invasion, ecology, other) | A rough indication of what the topic of the paper is. | No specific expectation, but provides an indication of the extent to which the frameworks have been used beyond invasion science. | The vast majority of citing papers were directly related to biological invasions (96, 93, 92%), but all of the frameworks were cited by some broader ecological (or evolutionary) papers (4, 6, 7%), and a handful of papers in other disciplines (< 1% in each case, including some in journals with apparently no link to ecology, for example, the *American Journal of Roentgenology*). |
| *Extent of influence* | Ordered factor with four levels (general, definition, broad, specific) | An interpretation of how the citation is actually used (i.e., the degree to which the paper implements the framework). This provided a response variable for testing other variables against. | Papers citing the frameworks should tend to implement specific aspects of the proposed frameworks, although they might also be used to make general points about biological invasions. | The level of frivolous citations was surprisingly high ~ 50% of all citations were classed as general (i.e. "citation fluff"), with only 6–8% of citing papers actually implementing the frameworks. This pattern was similar across the frameworks studied here. (see Figure 2, cf. the bar widths from left to right). |
| *Self-citation* | Factor with two levels (TRUE, FALSE) | Whether authors of the original paper were also authors of the citing article. | There should be a significant number of self-citations, but this should decline over-time as other people start using the framework. Authors of the framework would be more likely to specifically utilise the framework. | Confirmed (Figure 1)<br>There were a large number of self-citations, (25, 22, 39%), but the relative proportion of self-citation is declining over time (generalised linear model with binomial errors, with year as an explanatory variable and whether a reference was a self-citation as the response using Chi-squared test of the change of variance: $p = 0.02$; $p < 0.01$; $p = 0.11$).<br>Self-citations were more likely to implement the frameworks in detail than use them as "citation fluff" (analysis based on an ordered factor of the *extent of influence* versus *self-citation*: $F_{3,417} = 6.1$, $p < 0.01$; $F_{3,708} = 4.0$, $p < 0.01$; $F_{3,240} = 4.8$, $p < 0.01$). |
| *Realm* | Factor with six levels (freshwater, marine, terrestrial, other, multiple, NA) | The scope of the paper in terms of the environment. For laboratory-based studies, this is based on the taxa used. | A core rationale for the development of the frameworks was to make them generalisable across different environments (cf. Ojaveer et al. 2018). As such, the expectation was the frameworks are used consistently across realms. | Largely confirmed, but with notable biases (Figure 2).<br>All three frameworks are cited by studies across different realms and taxa, though most were terrestrial studies and most on animals. However, it is notable that, when implemented in detail, the Pathway Classification was particularly used for comparisons across taxa and realms (i.e. multiple), while the Unified Framework tended to focus on particular realms (freshwater or terrestrial) and particular taxa (animals or plants) rather than for comparisons. |
| *Taxon* | Factor with five levels (animals, plants, other, multiple, NA) | The taxonomic scope of the organisms studied in the paper. | A core rationale for the development of the frameworks was to make them generalisable across different taxa. As such, the expectation was the frameworks are used consistently across taxa. | Largely confirmed, but with notable biases (Figure 2).<br>See results for realms above. Studies on animals that cited EICAT tended to have implemented the framework more than other studies and there were no fungal or microbial studies as yet. |
| *Number of citations* | Integer | The number of times the framework is cited in the paper. | Papers that cite a framework multiple times would be more influenced by those frameworks. | Confirmed, but there is a large amount of variation.<br>The extent of influence tended to increase with number of citations, but this factor on its own did not explain much of the variance in number of citations (31, 23, 30%); and some papers that specifically implemented the frameworks only cited the frameworks once, while other papers that used the frameworks as "citation fluff" still had numerous citations (maximums of 4, 9, 5). In conclusion, the amount of variance explained was not enough to suggest that the number of times the framework is cited in text is a reliable proxy for the extent of influence of the framework on a paper. |

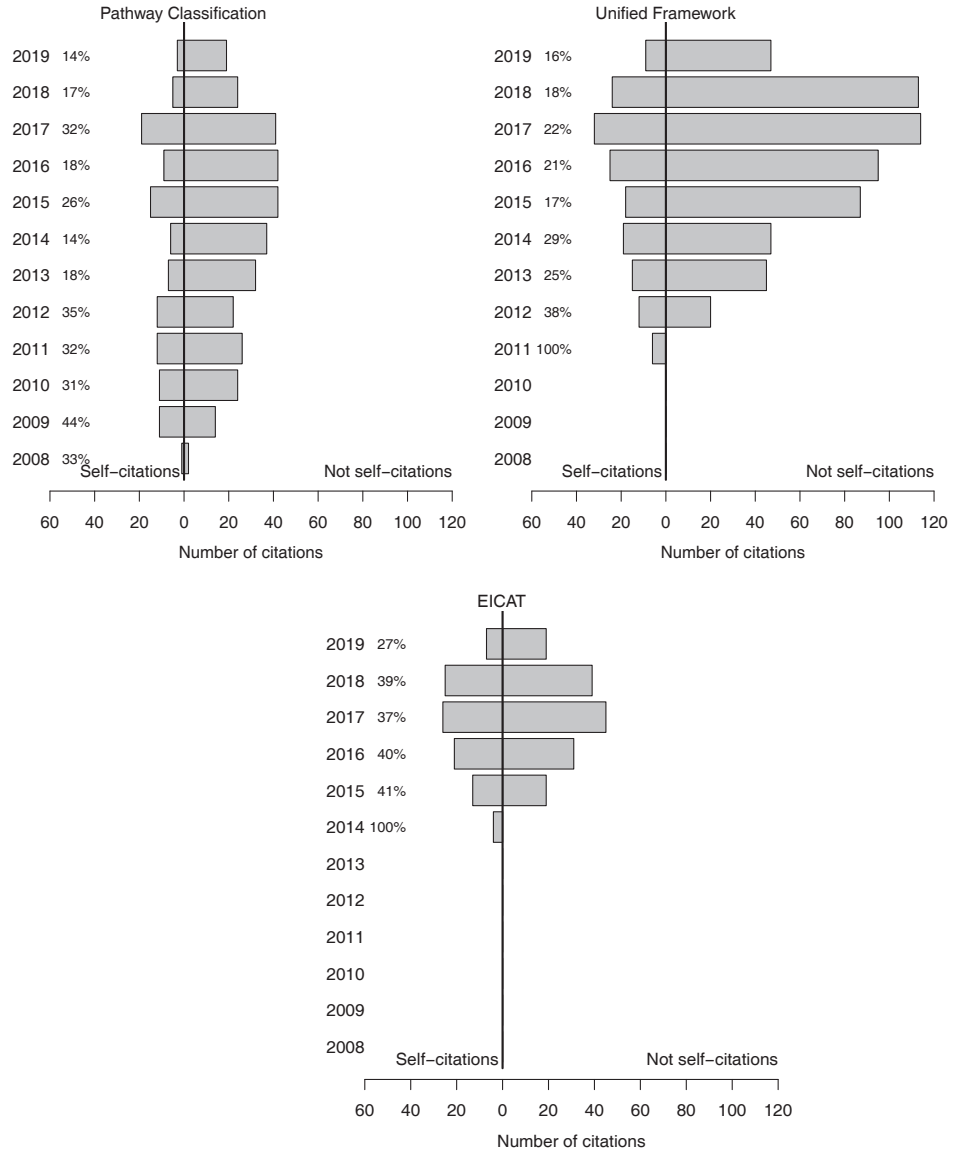


**Figure 1.** The number of times each framework paper was cited since publication until 1 July 2019. The frameworks are the Pathway Classification (Hulme et al. 2008), the Unified Framework (Blackburn et al. 2011), and EICAT (\Blackburn et al. 2014; Hawkins et al. 2015). Values from 2019 only include a portion of the year and even the number of citations by articles published in 2018 is a slight underestimate as it has also increased in the time since July 2019. Each framework has shown a general increase in citations per year since publication, and a decrease in the proportion of self-citations (Table 1).

Almost half of the citing papers only cited the frameworks to justify general comments about biological invasions. Importantly, however, the citing papers covered a wide range of realms and taxa, and the frameworks were implemented in detail in a similar wide range of studies (Figure 2).

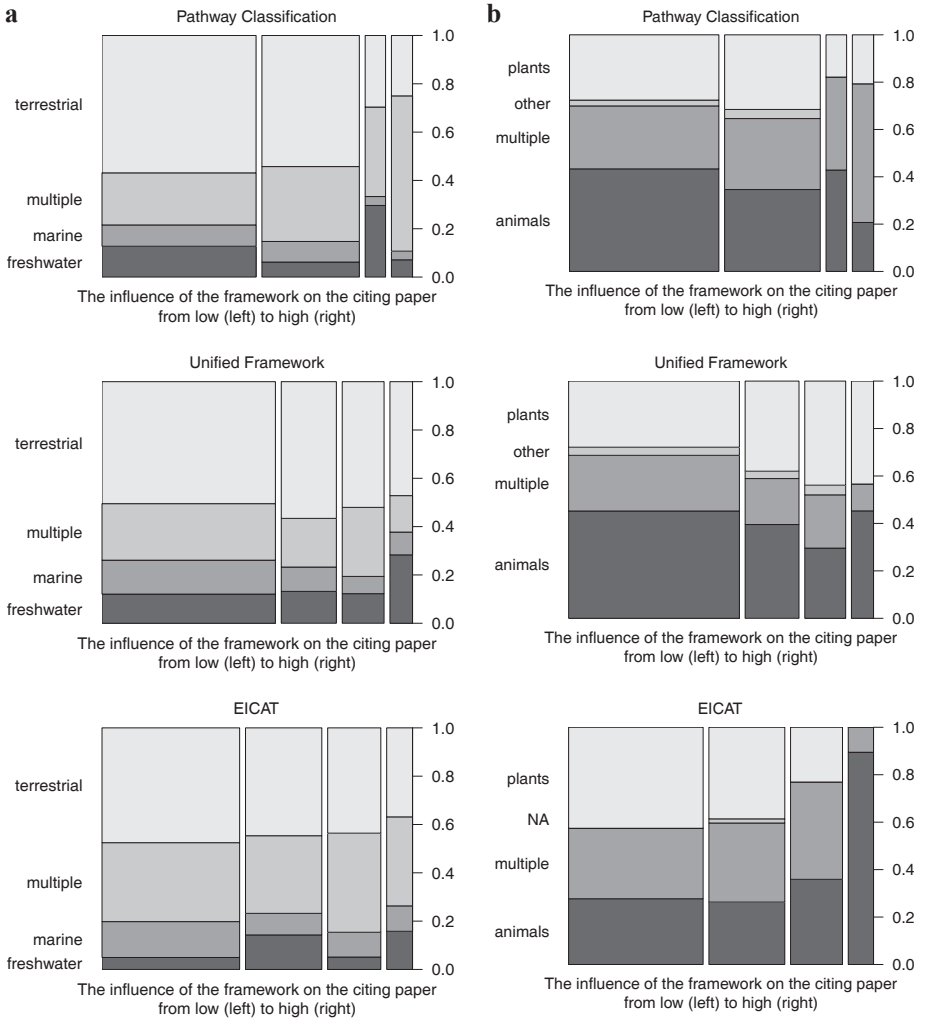


**Figure 2.** The extent to which the frameworks have influenced citing papers broken down by (**a**) environment and (**b**) taxonomic groups. The frameworks are the Pathway Classification (Hulme et al. 2008), the Unified Framework (Blackburn et al. 2011), and EICAT (Blackburn et al. 2014; Hawkins et al. 2015). The widths of the bars are proportional to the number of citations. The degree to which the framework was used in the citing paper increases from left to right on each figure [from general, to definition, to broad (application), to specific (application)]. The data are in Suppl. material 1, and the methodology used for scoring in Suppl. material 2.1.

The frameworks were cited by articles published in a wide range of journals (151, 223, and 108 journals, see Suppl. material 2.4). Unsurprisingly, the majority of these journals (70, 68, and 79%) have invasions as one of or their main subject area. Similarly, the majority of articles citing each framework (83, 85, and 87%) were explicitly on invasion science. All three frameworks have a global reach and have been cited by authors from around the world working on invasions in a similar global range of sites (Suppl.

material 2.5). However, when compared with the analysis of citation patterns in invasion biology (Pyšek et al. 2008), all the frameworks are more frequently cited by researchers based in Europe or South Africa and less often by those based in North America [49, 44, and 52% of all citations to the respective frameworks were from research led by European based authors vs. 22% of all studies in Pyšek et al. (2008); for South Africa: 9, 16, 18% vs. 2%; for North America: 20, 17, 12% vs. 50%; (the probability from a Chi-squared test was < 0.01 in all these cases)]. See Suppl. material 2.5 for the full details.

## Survey of citing authors

We received responses from 84 people contacted (~ 9% of the 905 e-mails that did not bounce) from 20 countries (including 14 responses from North America, a slight over-representation). Responses were split fairly evenly across the frameworks (20 of 256; 51 of 589, and 13 of 113 respectively). The statement that respondents tended to most agree with was "This reference is authored by recognized authorities in the field" followed by "This is a classic reference in the field". The most common reason for citing the frameworks was that they are "classic citations" (Fig. 3, Shadish et al. 1995). Importantly, of the six statements that suggest a paper is viewed as a "classic citation", the two questions that were not widely supported (in fact more respondents disagreed than agreed) were "There have been substantial efforts to show that the framework is wrong" and "The framework has withstood many efforts to show that it is wrong". Therefore, while the papers are undoubtedly viewed and used as classic citations, there is a general feeling that the frameworks have not been adequately investigated. This was borne out by various suggestions of how the frameworks could (and in some cases have) been modified or where other frameworks are more appropriate (Suppl. material 2.6).

In terms of the link between the citing authors and the authors of the frameworks, over half have spoken to one of the authors (64, 51, 95%) and a substantial number of these consider one of the authors a personal friend (35, 13, 41%). While the respondents often recommended the citation to others during review (40, 27, 46%), it was not suggested to them often (5, 6, 0%). Of course, the respondents are a small section of the invasion science community who have actively cited the framework and who were willing to respond to a survey concerning the framework.

## Influence on policy and management

All three frameworks seem to have had some impact on policy and management (Suppl. material 2.6 and 2.7; Box 1). The Pathway Classification framework has arguably had the most impact. The CBD's Aichi Biodiversity Target 9 specifies (amongst other things) the need to identify and prioritise pathways by 2020 and a modification of the pathway framework was proposed for use by the CBD itself (Scalera et al. 2016). Other examples of its adoption include the guidelines for invasive species planning

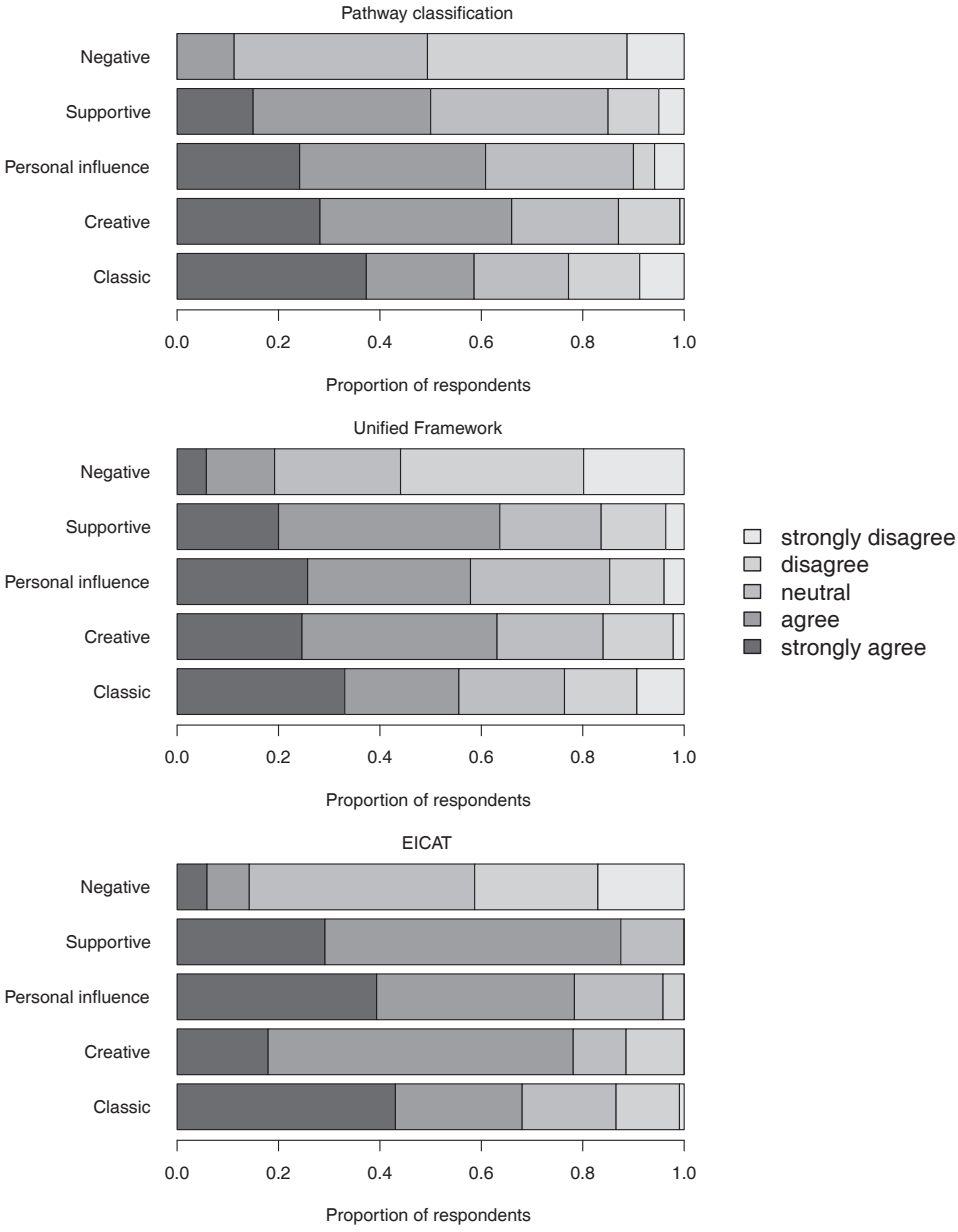


**Figure 3.** Reasons for citing the frameworks based on the response to a questionnaire sent to corresponding authors. The frameworks are the Pathway Classification (Hulme et al. 2008), the Unified Framework (Blackburn et al. 2011), and EICAT (Blackburn et al. 2014; Hawkins et al. 2015). The categories Negative, Supportive, Personal Influence, Creative, and Classic are based on Shadish et al. (1995). See Suppl. material 2.2 for a copy of the questionnaire and Suppl. material 2.6 for the full results and how the questions map on to different categories.

and management on islands published by IUCN and the European Union Regulation on the prevention and management of the introduction and spread of invasive alien species. More recently, EICAT has been adopted as an IUCN standard (IUCN 2020) and is anticipated to play an important role in future biodiversity targets and as part of an indicator to track impact (Essl et al. 2020; GEO BON 2015; Latombe et al. 2017). By contrast, we found little evidence that the Unified Framework (the most cited framework investigated here) has been used in policy and management. This could in part be due to differences in how the phenomenon of biological invasions is defined (Wilson et al. 2016). Policy-orientated definitions of invasive organisms often include the impact of the organism, while the biogeographic definition also represented in the Unified Framework (Richardson et al. 2000) seems to be more common in science.

Importantly, once a scientific framework has been widely accepted by an international body like the CBD or the IUCN, it is very likely that the original references are no longer cited. Therefore, caution must be observed in interpreting the policy influence of scientific documents.

## Discussion

We found that the invasion frameworks assessed here are widely cited by studies focussing on different realms and taxa, and from many different parts of the world. While many citations might be viewed as frivolous ("citation fluff"), there is a substantial number where the frameworks have been implemented in detail. There are different possible explanations for these trends. Invasion science might be coalescing temporarily; it might be settling down to adopt standard and widely-agreed practices; a particular 'school' of invasion science that uses particular frameworks might be emerging; or there might always be a suite of papers that are core papers for citing, but that do not actually influence the direction of the field. We discuss some of these issues here.

### Frameworks are temporary, concepts are permanent, but where ideas come from can have long-lasting effects

The Unified Framework and EICAT owe substantial intellectual debts to previous papers and frameworks. Indeed, some of the original frameworks are arguably still more influential. The Unified Framework is based partly on a framework for plants outlined by Richardson et al. (2000), and this earlier paper still tends to be more widely cited. Richardson et al. (2000) had a huge effect on the study of biological invasions. By creating standards that were widely adopted by the research community, data on biological invasions have been increasingly based on a common set of criteria, and are therefore directly comparable. This has facilitated a wide range of comparative analyses [e.g., the Global Naturalized Alien Flora (GloNAF) project (Pyšek et al. 2017)].

Frameworks also evolve and develop over time and in some cases are superseded. The Pathway Classification has been expanded and subcategories developed as part of its proposed uptake by the CBD (Harrower et al. 2017; Scalera et al. 2016). It is noticeable that some more recent journal articles and policy documents implement the CBD pathway classification scheme without citing the original paper on which it is based. This might be quite typical, i.e., once a framework is adopted into a policy or adapted into a guideline, there is a step-change in the impact it has, but conversely, the original paper might no longer be cited. Papers applying EICAT often use it in combination with the Generic Impact Scoring System (GISS; Nentwig et al. 2016; Nentwig et al. 2010) upon which EICAT is based or they use a modification using aspects of both schemes. GISS has probably been more often applied to date and to a wider taxonomic range than EICAT (e.g., Kumschick et al. 2015), but due to EICAT's adoption as an IUCN Standard, EICAT is rapidly gaining momentum.

Frameworks often need to be adapted in light of practical experience. For example, several adaptations to the Unified Framework have been proposed based on experiences of implementing it in Europe (Groom et al. 2019), Hawaii (Brock and Daehler 2020), and South Africa (Wilson et al. 2018). Similarly, Pergl et al. (2020) and Faulkner et al. (2020) provide proposals to refine the CBD pathway classification scheme based on applying it in different contexts, and Volery et al. (2020) document changes made to EICAT after stakeholder consultation. All three frameworks have, to different extents, been incorporated in developing biodiversity data standards, and this will provide a more formalised process for revising them.

Importantly, however, our results show that the extent of influence of the frameworks is still somewhat affected by how they were originally developed. There is, unsurprisingly, a high level of self-citations, and this likely explains part of the apparent European and South African bias in uptake (cf. Fig. 1 and Suppl. material 2.5). The Pathway Classification was a direct product of the European Union Funded ALARM project (Settele et al. 2005); the idea to develop the Unified Framework arose at a workshop in Switzerland and was further elaborated at a meeting in South Africa; and EICAT resulted from a workshop in Germany. Moreover, of the 33 original authors of the frameworks, 26 are based in Europe, three in South Africa, and one each in Australia, Canada, New Zealand, and the USA. In this context, the global influence of the frameworks has been impressive, but it will be important for the utility of the frameworks to be assessed in more depth and in different contexts. For example, introduction pathways have changed over time (Faulkner et al. 2016; Hulme 2009), and the importance of different pathways varies across the world. Faulkner et al. (2020) highlight one such case, where the trade in traditional medicines is a potentially important introduction pathway in Africa, but is not considered explicitly in the current (arguably Eurocentric) Pathway Classification. Similarly, the Unified Framework originated from combing zoological and botanical frameworks, and there are several practical issues applying both it and the Pathway Classification to fungi and microbes (Paap et al. 2020).

Nonetheless we believe that our results provide some indication that invasion science is beginning to coalesce around systematic schema for classification and understanding that are applicable across taxa and realms.

## Comparisons with other frameworks?

Given the lack of points of comparison, it is difficult to gauge whether the results seen here are surprising or not. Ideally, we would have looked at the uptake of other important frameworks in invasion science (including historical and more contemporary schemes) and compared with highly-cited framework papers from related disciplines. Unfortunately, the methodology we developed was time-consuming. We found no reasonable proxy for a manual analysis of the extent of influence of the frameworks on the citing papers. There was a broad correlation between our manual scoring of the extent of influence and the number of times a framework was cited, but there were many exceptions (Table 1). Similarly, simply noting whether a citation was in the methods, discussion, or introduction provided some indication of whether the frameworks were used, but not enough to reliably predict that the frameworks were actually implemented (results not shown, but data presented in Suppl. material 1). We concluded that conducting such a citation analysis requires careful examination of at least the sentences that include the citation, and often an evaluation of the whole manuscript. Machine-learning techniques might offer a solution to this issue in future.

We did, however, identify some comparisons that would be particularly interesting and some important research gaps. As mentioned previously, most of the frameworks presented here had progenitors [for example, the Unified Framework explicitly built upon Williamson and Fitter (1996) and Richardson et al. (2000)], an explicit evaluation of how these have been used over time would provide a benchmark against which our results could be assessed. Similarly, while the frameworks chosen reflect pathways, species, and impacts, it would be important to consider frameworks centred around sites of invasion or the effectiveness of interventions (McGeoch et al. 2016; Wilson et al. 2018), or to consider how invasion hypotheses are cited (Catford et al. 2009; Jeschke and Heger 2018). Finally, it might be instructive to track recent frameworks [e.g., SEICAT, the socio-economic impact classification of alien taxa scheme (Bacher et al. 2018), although there has not been much time for uptake].

## Insights into citation practices

Our research did not primarily set out to evaluate citation practices, but several insights were apparent. Many of the citations were what we considered frivolous (and informally dubbed "citation fluff"). The introduction of most papers starts with a generic catch-all statement about invasions, and the frameworks were often used to support these, often inappropriately [e.g., citing the Unified Framework as evidence that invasions have impact, or EICAT as a risk assessment protocol (Kumschick et al. 2020-a)]. Arguably "citation fluff" provides an indication of influence, i.e., the frameworks are not directly and explicitly used, but play a role in shaping the overall mental model of the processes at play. However, there were many errors in the way in which the frameworks are cited (see Suppl. material 2.3). Should there be a greater onus on authors, reviewers, and editors to purge "citation fluff" or at least to ensure such references really support the general statements made?

The fact that 20–40% of all citations are self-citations is not necessarily indicative of nepotistic or insular research practices (Seeber et al. 2019). The frameworks were the products of highly productive scientists with the intention of producing seminal papers in a research field in which they were amongst the research leaders. The rapid uptake and declining proportion of self-citations are arguably, healthy signs, as is the geographic spread of the citations. This is borne out by the respondents to the survey where the authors were considered well respected, and the framework papers were, by and large, considered classic papers in the field.

However, the papers analysed and the people surveyed were very biased. The results are, therefore, consistent with the notion of a distinct school of thought amongst certain (particularly European and South African) invasion scientists for whom these frameworks are valuable (cf. the MAFIA framework of Pyšek et al. 2020). A study of researchers who did not cite or use these frameworks despite the framework being relevant to (or even designed to assist) their research would do much to further our understanding of the limitations of the frameworks. As an analogue, it is difficult to understand why some invasions are successful if we lack data on failed invasions (Zenni and Nuñez 2013).

### A suggestion to journals – avoid numbered citations

Finally, as a side note, in our experience papers with numeric citations are harder to read, comment on as editors and reviewers, and make analyses, like the one here, much more cumbersome. It is not clear to us why online-only publishers (e.g. the Public Library of Science) persist with this format (cf. https://svpow.com/2011/01/07/an-open-letter-to-plos-one-a-pox-on-your-numbered-references/).

## Conclusion

The selected frameworks are influential and widely cited. They are being used to provide information about explicit efforts at monitoring and reporting biological invasions and the development of internationally-agreed data standards. Nonetheless, they are not yet widely implemented as they were originally formulated. We believe that our ability to understand and manage biological invasions will improve as we move increasingly towards agreed standards in the field (Wilson et al. 2020). Invasion frameworks will need to both provide information about such change and be flexible, so they can be modified in the light of the experience and needs of users.

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## Supplementary material 1

**Data used in a citation analysis of frameworks in invasion science**

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Data type: Excel spreadsheet

Explanation note: Information on the papers that cited the three frameworks under investigation here (see Suppl. Material 2 for details).



Link: https://doi.org/10.3897/neobiota.62.53243.suppl1

## Supplementary material 2

**Supplementary material to a citation analysis of frameworks in invasion science**

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Data type: explanatory text and additional analyses

Explanation note: **2.1** The protocol used to score publications that had cited the selected invasion framework papers (including **Table S2.1.** An ordinal categorical four point-scale used to score the extent to which the papers were directly or indirectly influenced by or applied the invasion frameworks). **2.2** The questionnaire used to evaluate the opinion of invasion scientists as to how fundamental the frameworks have been to invasion science, policy, and management. **2.3** Citations to the frameworks as at 1 July 2019 showing frequency with which papers shared citations. **2.4** The journals in which papers citing the invasions framework were published, and number of citing papers published in each. **2.5** The location of the corresponding authors when they completed their study (i.e. their primary address) of papers that cited each framework compared to the number of studies reported from different geographical regions by Pyšek et al. (2008). **2.6** The results of the survey of corresponding authors of papers who have cited one of the papers that outline the Pathway Classification framework; the Unified Framework or EICAT. **2.7** Examples of documents showing the influence of the selected framework papers beyond scientific audience.



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**Wilson JRU, Datta A, Hirsch H, Keet J-H, Mbobo T, Nkuna KV, Nsikani MM, Pyšek P, Richardson DM, Zengeya TA, Kumschick S (2020) Is invasion science moving towards agreed standards? The influence of selected frameworks. Supplementary Material 2[1], NeoBiota.**

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[1] Supplementary Material 1, the database of papers used in the citation analysis, is available in a separate spreadsheet

**2.1 The protocol used to score publications that had cited the selected invasion framework papers.**

1. Web of Science was searched for publications citing the framework (Blackburn et al. 2014; Blackburn et al. 2011; Hawkins et al. 2015; Hulme et al. 2008), and details downloaded into a spreadsheet
2. A digital copy of the publication was obtained. To reduce the complexity of the task supplementary material were not considered.
3. Results were entered on a shared online spreadsheet, with the citing publications scored according to steps 4–10 below.
4. Whether any of the authors of the framework paper were an author of the citing publication (i.e. ~self-citations) was noted. This was automated in part by using lookup with surnames, although, as formatting of names might differ, and people might share surnames, this was checked manually, and several errors corrected.
5. The discipline of the citing publication was scored as "invasion" if the topic of the citing publication was biological invasions (as defined by the Unified Framework). If the topic of the citing publication was not related directly to the introduction-naturalisation-invasion continuum or its outcome(s), then it was scored as "ecology" if the topic were biological in a broad sense (including evolutionary biology as well as molecular, genetic, taxonomic and conservation biology studies). If the citing publication did not fall within this broad definition (e.g. the focus was medicine or physics) it was scored as "other". While the presence of "invasion" in the title, abstract, or keywords was usually indicative that the topic was invasion science, it was important to manually confirm this (e.g. the term invasion might be referring to weeds or pests that are native or processes related to ecological dominance without any crossing of a biogeographic barrier).
6. The scope of the paper in terms of the realm investigated was noted (marine, freshwater, terrestrial, other, multiple, NA). Laboratory studies were scored according to the taxa used.
7. The scope of the paper in terms of the taxa investigated was noted (animals, plants, others (microbes, fungi etc.), multiple, NA).
8. Citing publications were then searched for the citations (e.g. CTRL+F in Adobe), with using either the lead author's surname "e.g., *Blackburn*" or if references were numeric in text the corresponding reference number in the bibliography was used "e.g., *14*" noting that the reference might be in a numeric range "e.g., *[11–15]*". The number of citations was noted, and the citing text copied and pasted into the spreadsheet. This was usually just the sentence itself, but if more context was needed to facilitate scoring the surrounding sentences were also extracted or some notes made.
9. The citing text / citing publication was then evaluated in terms of the purpose of the citations as:

a) scene setting (usually in the introduction) (T or F);
b) a description of what and how it was done (usually material and methods) (T or F);
c) used in interpretation (usually results / discussion / conclusion / recommendations) (T or F).

10. Any issues or observations were added to the final column.
11. Papers were then evaluated by one person (for consistency) using specific categories of the extent to which the frameworks had a direct or indirect impact on the work conducted. This was based on the sentences extracted from the paper above, and if necessary, an evaluation of the paper itself. See Table S2.1 below for details.

Note: We discussed whether to add a question on "Which type of paper it is? (review / opinion; or paper that producing original data)" but decided it would complicate things, and it was not clear how to analyse the data (too many grey areas).

**Table S2.1: An ordinal categorical four point-scale used to score the extent to which the papers were directly or indirectly influenced by or applied the invasion frameworks.**

The frameworks are the Pathway Classification framework (Hulme et al. 2008); the Unified Framework (Blackburn et al. 2011); and EICAT (i.e., the impact classification framework, Blackburn et al. 2014; Hawkins et al. 2015). For practical purposes, it was decided to use slightly different interpretations for the different frameworks. The frequency of mis-citations was not explicitly scored, as it was not clear where a line could be drawn. However, there were a range of clear mistakes: in at least two cases Blackburn et al. 2011 was referenced in the bibliography but is not cited in the text; in another case Blackburn et al. 2011 was referenced in the text as Blackwell et al. 2011, though this was corrected by Web of Science; and in another case Blackburn et al. 2011 was used to support the statement "Its [the web-site www.xeno-canto.org] main goal is to improve knowledge of bird sounds by increasing accessibility and diffusion of bird sound recordings from across the globe", presumably a different publication by Tim Blackburn was intended to be cited). Mis-citations would all be scored as level 1, i.e. general.

| Level | Application to the Pathway Classification | Application to the Unified Framework | Application to EICAT |
|---|---|---|---|
| 1 (General)—Little to no direct influence. This was informally dubbed by us as "citation fluff" | Used as a general reference (e.g. to state that invasive species are introduced along pathways) | The framework is not applied, but cited to underpin some general statements about invasions. | Used as a general reference (e.g. that invasions have impacts) |
| 2 (Definition)—the framework is referenced explicitly, but not clearly implemented. | There is a link to the need to look at different pathways, and some definitions are used, but these do not underpin the work | The framework is cited to underpin the definition of terms (invasion, alien, etc), but it is not applied | The categories of mechanisms are used in some way, or it is used to indicate there is the need for consistent scoring of impacts |
| 3 (Broad application)—Some evidence that at least part of the framework actually implemented | There is some classification of pathways that is influenced by the classification scheme. | The framework is applied, but only in a broad sense. i.e., populations/species are classified according to the framework, but not in the specific language nor with the specific descriptions/definitions provided in that framework. Other frameworks might have been used instead | An indication of EICAT levels is given with reference to specific mechanisms at specific operation levels, though it is not clear that the methodology has been followed as intended. |
| 4 (Specific application)—Specifics of the framework are implemented | The paper specifically scores the pathways using the proposed classification (or sub-categories) | The framework is applied, and populations/species are classified according to the specific descriptions/definitions and terminology outlined in the framework (e.g. A–E scheme). No other framework was used in preference | Impacts are scored using the EICAT methodology |

## 2.2 The questionnaire used to evaluate the opinion of invasion scientists as to how fundamental the frameworks have been to invasion science, policy, and management.

**"Introduction**

You are kindly asked to complete a questionnaire as part of research entitled "An evaluation of the influence of selected invasion frameworks on invasion science and management". This is research conducted through Stellenbosch University. You are asked to participate because of your experience in invasion science.

**Purpose of the study:** The aim of this survey is to collect data from researchers to investigate the influence of invasion frameworks in the field of invasion science.

**Your responsibilities:** We are inviting you to participate in an on-line survey that is composed of a series of questions about three selected invasion frameworks. We estimate the survey will take no longer than fifteen minutes.

**Payment:** Participants are not paid nor charged a fee to participate.

**Confidentiality:** All data collected during this survey will be anonymised and stored at the Centre for Invasion Biology, Stellenbosch in password protected files at least until the study is published. Only the group members working on this research article will have access to the data. No personal identifiers (e.g. name, surname, or any form of identification or contact details) will be requested, nor there any information collected that will enable the identity of participants to be determined.

**Participation and withdrawal:** You have the right to choose whether to be in this study or not. You may refuse to answer any questions you do not want to answer and remain in the study, and you may skip questions you do not wish to answer. However, given all replies will be anonymised, once data has been submitted it will not be possible to identify who is responsible for a particular entry.

**Identification of investigators:** If you have any questions or concerns about the research, please contact: Ms. Tumeka Mbobo, 021 808 2834 or Prof. John Wilson, South African National Biodiversity Institute / Centre for Invasion Biology, Stellenbosch University, jrwilson@sun.ac.za.

**Introduction to the three frameworks:**

- a pathway classification framework (Hulme et al. 2008 *Journal of Applied Ecology*);
- the proposed Unified Framework for Biological Invasions (Blackburn et al. 2011 *Trends in Ecology & Evolution*); and
- the Environmental Impact Classification of Alien Taxa Scheme (Blackburn et al. 2014 *PLoS Biology*; modified by Hawkins et al. 2015 *Diversity and Distributions*).

The questionnaire consists of four subheadings; (1) background, (2) description of the frameworks, (3) their use in management and policy reporting, and (4) any suggestions or proposed improvements. The same questionnaire is used for all three frameworks being evaluated in this study.

**Where to find all frameworks**

1. Have you used any of the above-mentioned frameworks in your research? Yes/No.

If you have used Blackburn et al. 2011 please follow this link

https://docs.google.com/forms/d/e/1FAIpQLSch_tOLNJDEncx08DZxXWf_d1iDkkndc2fdk4-0YICyVEXNJw/viewform?usp=sf_link If you have used Hulme et al. 2008 please follow this link

https://docs.google.com/forms/d/e/1FAIpQLSdQftFdRx43s453amFvHL4U2MqFSW7ujEFtWW7bgi4TrBjsHA/viewform?usp=sf_link

If you have used Blackburn et al. 2014 please follow this link

https://docs.google.com/forms/d/e/1FAIpQLSeiHRwYKFAfDwGf9jDdnLG8cYY0N5tVVMT_yi2PU_0C9o0Otw/viewform?usp=sf_link

If you have used Hawkins et al. 2015 please follow this link

https://docs.google.com/forms/d/e/1FAIpQLSePB0fh9D5MFKuGKX4z_bEuNrNURrnYzSFHAhPHPfLiNA2PQ/viewform?usp=sf_link

**1. Background**

Please answer the following questions with yes or no.

1. Have you ever cited this reference in your publications?

2. Do you currently possess a copy of this reference?

3. Have you ever spoken directly to one of the authors of this citation (i.e. not just over the email)?

4. Would you consider the author a personal friend?

5. Is the author a colleague at your institution?

6. Did the author work at an institution where you have studied / worked?

7. Have you ever recommended this particular reference as a reviewer or editor?

8. Has a journal referee/reviewer asked you to include this particular reference during the review process?

**2. How would you describe the framework?**

The following questions are based on the modified schemes of Case & Higgins (2000) https://doi.org/10.1002/(SICI)1097-4571(2000)51:7<635::AID-ASI6>3.0.CO;2-H and:

Shadish et al. (1995) https://doi.org/10.1177/030631295025003003

*Note: these questions were answered on a five-point scale (1 strongly agree, 2 agree, 3 neither agree nor disagree; 4 disagree; 5 strongly disagree)*

1. There are problems with the framework?

2. This reference illustrates your perspective or finding that contradicts a perspective or findings.

3. This reference strongly influenced your thinking on the topic.

4. This reference was a major source of inspiration for your work.

5. This reference helps justify central argument in invasion science.

6. This reference is similar to your own work.

7. This reference reviews prior work in this area.

8. This study used a method or theoretical perspective that you think is currently unusual or especially innovative.

9. This reference bridges a gap between two subfields.

10. This reference helps to reconcile contrasting viewpoints or findings in the field.

11. This reference illustrates possible avenues for future research.

12. This reference solves an important conceptual or practical problem in the field.

13. More so than most, this reference advances our ability to address an important social or human problem.

14. This is a classic reference in the field.

15. This reference is authored by recognized authorities in the field.

16. This reference has generated much novel and successful research or scholarship.

17. There have been substantial efforts to show that the framework is wrong.

18. The framework has withstood many efforts to show that it is wrong.

19. This reference helps establish the legitimacy of the topic of your work.

20. This reference reports what you consider to be an exceptionally high-quality piece of science.

21. This reference documents the sources of a method or design feature used in your study.

**3. The use of the framework in management and policy/monitoring and reporting.**

1. Are you aware of instances where the framework was used to guide management? Yes/No. If yes, please provide details.

2. How important is the framework for management?

*Note: answered on a five-point scale*

3. Are you aware of instances where the framework was used to guide policy/monitoring and reporting? Yes/No. If yes, please provide details.

4. How important is the framework for policy?

*Note: answered on a five-point scale*

**4. Proposed improvements**

1. If the framework was to be revised, how would you revise it?

2. Do you also use a different framework instead of the one mentioned here? If yes, please give details.

**2.3 Citations to the frameworks as at 1 July 2019 showing frequency with which papers shared citations.**

The frameworks are the Pathway Classification framework (Hulme et al. 2008); the Unified Framework (Blackburn et al. 2011); and EICAT (i.e., the impact classification framework, Blackburn et al. 2014; Hawkins et al. 2015). Both the total number of citations, and citations from 2016–2019 (i.e. citations where it was possible to have cited Hawkins *et al*. 2015) are shown

| | Total number of citations | Citations 2016–2019 |
|---|---|---|
| Pathways classification | 436 | 162 |
| Unified Framework | 729 | 460 |
| EICAT (Blackburn) | 237 | 201 |
| EICAT (Hawkins) | 49 | 48 |
| EICAT (Blackburn OR Hawkins) | 249 | 213 |
| EICAT (Blackburn AND Hawkins) | 37 | 36 |
| Pathways + Unified | 82 | 44 |
| Pathways + EICAT (Blackburn) | 27 | 22 |
| Pathways + EICAT (Hawkins) | 7 | 7 |
| Pathways + EICAT (Blackburn OR Hawkins) | 27 | 22 |
| Pathways + EICAT (Blackburn AND Hawkins) | 7 | 7 |
| Unified + EICAT (Blackburn) | 69 | 61 |
| Unified + EICAT (Hawkins) | 16 | 16 |
| Unified + EICAT (Blackburn OR Hawkins) | 72 | 64 |
| Unified + EICAT (Blackburn AND Hawkins) | 15 | 15 |
| Pathways+Unified+EICAT(Blackburn) | 14 | 11 |
| Pathways+Unified+EICAT(Hawkins) | 2 | 2 |
| Pathways+Unified+EICAT(Blackburn OR Hawkins) | 17 | 13 |
| Pathways+Unified+EICAT(Blackburn AND Hawkins) | 3 | 3 |

The number of papers that cited more than one of the frameworks is given by (Pathways + Unified) + (Pathways + EICAT (Blackburn OR Hawkins)) + (Unified + EICAT (Blackburn OR Hawkins)) – (Pathways+Unified+EICAT(Blackburn OR Hawkins)) = 82 + 27 + 72 – 17 = 164. So proportion is 164/(436+729+237) = 11.7%

## 2.4 The journals in which papers citing the invasions framework were published, and number of citing papers published in each.

The subject areas were scored as: (1) invasion (journal publishes articles on invasion science); (2) ecology (journal publishes articles on ecology but biological invasions are not specifically mentioned as a subject areas); and (3) other (invasions or ecology are not subject areas of the journal). Pathway is the Pathway Classification framework; Unified is the Unified Framework; EICAT is the Environmental Impact Classification of Alien Taxa.

| Journal | Subject | Pathway | Unified | EICAT |
|---|---|---|---|---|
| Acta Botanica Brasilica | Invasion | 0 | 0 | 1 |
| Acta Botanica Croatica | Invasion | 0 | 0 | 1 |
| Acta Botanica Mexicana | Invasion | 0 | 2 | 0 |
| Acta Oecologica-International Journal of Ecology | Invasion | 0 | 2 | 0 |
| Acta Societatis Botanicorum Poloniae | Invasion | 0 | 1 | 1 |
| Acta Zoologica Bulgarica | Invasion | 0 | 0 | 1 |
| African Entomology | Invasion | 1 | 2 | 0 |
| African Journal of Aquatic Science | Invasion | 0 | 3 | 1 |
| African Journal of Marine Science | Invasion | 0 | 2 | 2 |
| African Journal of Range and Forage Science | Invasion | 0 | 1 | 0 |
| African Zoology | Invasion | 1 | 4 | 0 |
| Agriculture Ecosystems and Environment | Invasion | 0 | 0 | 1 |
| Agroecology and Sustainable Food Systems | Invasion | 1 | 1 | 0 |
| Ambio | Invasion | 2 | 3 | 0 |
| American Journal of Botany | Invasion | 0 | 2 | 0 |
| American Journal of Roentgenology | Other | 0 | 1 | 0 |
| American Naturalist | Invasion | 1 | 3 | 0 |
| Amphibia-Reptilia | Invasion | 1 | 0 | 0 |
| Anales Del Jardin Botanico De Madrid | Invasion | 1 | 0 | 0 |
| Animal Conservation | Invasion | 1 | 1 | 1 |
| Annals of Applied Biology | Invasion | 0 | 1 | 0 |
| Annals of Botany | Invasion | 0 | 2 | 0 |
| Annals of Forest Science | Invasion | 0 | 0 | 1 |
| Annals of Operations Research | Other | 0 | 1 | 0 |
| AOB Plants | Invasion | 0 | 12 | 3 |
| Applied Animal Behaviour Science | Invasion | 0 | 0 | 1 |
| Applied Entomology and Zoology | Invasion | 1 | 0 | 0 |
| Applied Vegetation Science | Invasion | 0 | 1 | 0 |
| Aquatic Biology | Invasion | 1 | 0 | 0 |
| Aquatic Conservation-Marine and Freshwater Ecosystems | Invasion | 0 | 2 | 0 |
| Aquatic Ecology | Invasion | 0 | 1 | 0 |
| Aquatic Ecosystem Health and Management | Invasion | 1 | 3 | 0 |
| Aquatic Invasions | Invasion | 6 | 11 | 1 |
| Arctic | Invasion | 0 | 0 | 1 |
| Asian Herpetological Research | Invasion | 1 | 0 | 0 |
| Austral Ecology | Invasion | 0 | 6 | 2 |
| Australian Journal of Botany | Invasion | 1 | 0 | 0 |
| Avian Research | Invasion | 0 | 1 | 0 |
| Basic and Applied Ecology | Invasion | 1 | 1 | 0 |
| Behavioral Ecology | Invasion | 0 | 1 | 0 |
| Behavioral Ecology and Sociobiology | Invasion | 0 | 2 | 0 |
| Belgian Journal of Zoology | Invasion | 1 | 0 | 0 |
| Biocontrol | Invasion | 2 | 0 | 0 |
| Biodiversity and Conservation | Invasion | 1 | 7 | 2 |
| Bioenergy Research | Other | 1 | 0 | 0 |
| Biofouling | Invasion | 0 | 1 | 0 |
| Bioinvasions Records | Invasion | 0 | 11 | 1 |
| Biologia | Ecology | 1 | 1 | 0 |
| Biological Bulletin of Bogdan Chmelnitskiy Melitopol State Pedagogical University | Invasion | 0 | 1 | 1 |
| Biological Conservation | Invasion | 8 | 9 | 3 |
| Biological Invasions | Invasion | 47 | 86 | 31 |
| Biological Journal of the Linnean Society | Ecology | 1 | 1 | 0 |
| Biological Reviews | Invasion | 3 | 1 | 1 |
| Biology and Environment-Proceedings of the Royal Irish Academy | Invasion | 1 | 1 | 1 |
| Biology and Philosophy | Ecology | 0 | 1 | 0 |
| Biology Letters | Invasion | 1 | 3 | 0 |
| Bioscience | Invasion | 2 | 6 | 4 |
| Biosystems Diversity | Invasion | 0 | 0 | 1 |
| Biotropica | Invasion | 1 | 0 | 0 |
| Bird Conservation International | Invasion | 0 | 1 | 1 |
| Blumea | Invasion | 0 | 1 | 0 |
| BMC Ecology | Invasion | 0 | 0 | 1 |
| BMC Evolutionary Biology | Ecology | 0 | 1 | 0 |
| Botanica Marina | Invasion | 0 | 0 | 1 |
| Botany Letters | Invasion | 0 | 2 | 0 |
| Bothalia | Invasion | 2 | 15 | 6 |
| Brazilian Journal of Biology | Invasion | 0 | 2 | 0 |
| Bulletin of Entomological Research | Invasion | 1 | 0 | 0 |
| Bulletin of Insectology | Invasion | 1 | 0 | 0 |
| Canadian Journal of Fisheries and Aquatic Sciences | Invasion | 0 | 1 | 0 |
| Canadian Journal of Zoology | Invasion | 0 | 0 | 1 |
| Central European Journal of Biology | Invasion | 1 | 0 | 0 |
| Chiang Mai Journal of Science | Ecology | 0 | 0 | 1 |
| Climatic Change | Ecology | 1 | 0 | 0 |
| Conservation Biology | Invasion | 4 | 3 | 0 |
| Conservation Genetics | Ecology | 0 | 1 | 0 |
| Conservation Genetics Resources | Ecology | 1 | 0 | 0 |
| Conservation Letters | Invasion | 3 | 3 | 2 |
| Critical Reviews in Plant Sciences | Invasion | 0 | 1 | 0 |
| Crop Protection | Invasion | 1 | 0 | 0 |
| Current Biology | Invasion | 0 | 1 | 0 |
| Current Forestry Reports | Ecology | 0 | 1 | 0 |
| Current Opinion in Behavioral Sciences | Other | 0 | 1 | 0 |
| Current Opinion in Insect Science | Invasion | 1 | 0 | 1 |
| Current Zoology | Invasion | 2 | 4 | 1 |
| Diversity and Distributions | Invasion | 19 | 30 | 11 |
| Ecography | Invasion | 4 | 2 | 2 |
| Ecohealth | Invasion | 0 | 1 | 0 |
| Ecological Applications | Invasion | 2 | 2 | 0 |
| Ecological Complexity | Invasion | 0 | 1 | 0 |
| Ecological Economics | Other | 5 | 1 | 2 |
| Ecological Engineering | Invasion | 0 | 1 | 0 |
| Ecological Entomology | Invasion | 0 | 1 | 0 |
| Ecological Indicators | Invasion | 1 | 1 | 1 |
| Ecological Informatics | Invasion | 1 | 0 | 0 |
| Ecological Modelling | Invasion | 1 | 1 | 2 |
| Ecological Monographs | Invasion | 0 | 1 | 0 |
| Ecological Research | Invasion | 0 | 1 | 0 |
| Ecology | Invasion | 2 | 6 | 1 |
| Ecology and Evolution | Invasion | 1 | 10 | 5 |
| Ecology Letters | Invasion | 4 | 10 | 1 |
| Ecology of Freshwater Fish | Invasion | 1 | 4 | 0 |
| Ecosistemas | Invasion | 0 | 1 | 0 |
| Ecosphere | Invasion | 2 | 3 | 4 |
| Ecosystems | Invasion | 0 | 0 | 1 |
| Emerging Microbes and Infections | Other | 0 | 1 | 0 |
| Emu | Invasion | 0 | 1 | 0 |
| Entomologia Experimentalis Et Applicata | Invasion | 1 | 1 | 0 |
| Environment International | Other | 1 | 1 | 0 |
| Environmental and Planning Law Journal | Other | 1 | 0 | 0 |
| Environmental Conservation | Invasion | 1 | 1 | 0 |
| Environmental Evidence | Invasion | 2 | 2 | 1 |
| Environmental Management | Invasion | 1 | 2 | 1 |
| Environmental Monitoring and Assessment | Other | 0 | 4 | 2 |
| Environmental Science and Policy | Invasion | 0 | 1 | 1 |
| Environmental Science and Technology | Invasion | 2 | 0 | 0 |
| Environmental Sciences Europe | Invasion | 0 | 0 | 1 |
| Estuaries and Coasts | Invasion | 0 | 1 | 0 |
| Estuarine Coastal and Shelf Science | Invasion | 0 | 3 | 0 |
| Ethology | Ecology | 0 | 1 | 0 |
| Ethology Ecology and Evolution | Ecology | 1 | 2 | 0 |
| European Journal of Entomology | Invasion | 0 | 1 | 0 |
| European Journal of Forest Research | Ecology | 0 | 1 | 0 |
| European Journal of Plant Pathology | Ecology | 0 | 1 | 0 |
| Evolutionary Applications | Ecology | 2 | 6 | 2 |
| Evolutionary Ecology | Ecology | 0 | 1 | 1 |
| Fish and Fisheries | Ecology | 0 | 1 | 1 |
| Fisheries Management and Ecology | Ecology | 1 | 0 | 0 |
| Flora | Invasion | 2 | 0 | 2 |
| Folia Geobotanica | Invasion | 0 | 1 | 0 |
| Forest Ecosystems | Invasion | 0 | 1 | 0 |
| Forestry | Ecology | 1 | 0 | 0 |
| Forestry Chronicle | Ecology | 0 | 1 | 0 |
| Forests | Invasion | 1 | 1 | 1 |
| Freshwater Biology | Invasion | 2 | 0 | 2 |
| Frontiers in Ecology and Evolution | Invasion | 1 | 2 | 1 |
| Frontiers in Ecology and the Environment | Invasion | 4 | 7 | 1 |
| Frontiers in Immunology | Other | 0 | 1 | 0 |
| Frontiers in Marine Science | Invasion | 1 | 1 | 3 |
| Frontiers in Plant Science | Invasion | 0 | 1 | 3 |
| Functional Ecology | Invasion | 2 | 3 | 0 |
| Fungal Ecology | Ecology | 0 | 2 | 0 |
| Gayana Botanica | Invasion | 1 | 0 | 0 |
| Genetica | Ecology | 0 | 1 | 0 |
| Genetics and Molecular Biology | Ecology | 0 | 1 | 0 |
| Genome Biology and Evolution | Ecology | 0 | 1 | 0 |
| Geographia Cassoviensis | Other | 0 | 1 | 0 |
| Geographia Polonica | Other | 0 | 1 | 0 |
| Global Change Biology | Invasion | 4 | 8 | 3 |
| Global Ecology and Biogeography | Invasion | 9 | 16 | 3 |

| Journal | Subject | Pathway | Unified | EICAT |
|---|---|---|---|---|
| Global Ecology and Conservation | Invasion | 0 | 0 | 1 |
| Helgoland Marine Research | Invasion | 0 | 2 | 0 |
| Herpetological Conservation and Biology | Invasion | 0 | 0 | 1 |
| Human Ecology | Ecology | 1 | 0 | 0 |
| Hydrobiologia | Ecology | 7 | 11 | 4 |
| Hystrix-Italian Journal of Mammalogy | Ecology | 0 | 1 | 1 |
| Ibis | Ecology | 0 | 1 | 1 |
| Ices Journal of Marine Science | Invasion | 0 | 1 | 0 |
| Ichthyological Research | Ecology | 1 | 0 | 0 |
| Infection, Genetics and Evolution | Other | 1 | 0 | 0 |
| Insect Conservation and Diversity | Invasion | 0 | 0 | 1 |
| Insects | Ecology | 0 | 2 | 0 |
| Integrative Zoology | Ecology | 1 | 1 | 0 |
| International Journal for Parasitology-Parasites and Wildlife | Ecology | 0 | 1 | 0 |
| International Journal of Applied Earth Observation and Geoinformation | Other | 1 | 0 | 0 |
| International Journal of Biometeorology | Ecology | 1 | 0 | 0 |
| International Journal of Geographical Information Science | Other | 1 | 0 | 0 |
| International Journal of Pest Management | Invasion | 1 | 0 | 0 |
| Invasive Plant Science and Management | Invasion | 3 | 4 | 2 |
| ISME Journal | Ecology | 0 | 2 | 0 |
| ISPRS International Journal of Geo-Information | Other | 1 | 0 | 0 |
| Israel Journal of Ecology and Evolution | Ecology | 0 | 1 | 0 |
| Italian Journal of Zoology | Ecology | 1 | 0 | 0 |
| Journal for Nature Conservation | Invasion | 3 | 2 | 3 |
| Journal of Animal Ecology | Ecology | 0 | 1 | 1 |
| Journal of Applied Ecology | Invasion | 23 | 5 | 6 |
| Journal of Applied Ichthyology | Ecology | 2 | 0 | 0 |
| Journal of Applied Phycology | Other | 0 | 0 | 1 |
| Journal of Archaeological Research | Other | 0 | 1 | 0 |
| Journal of Arid Environments | Invasion | 0 | 1 | 0 |
| Journal of Avian Biology | Ecology | 0 | 0 | 1 |
| Journal of Biogeography | Invasion | 3 | 1 | 1 |
| Journal of Ecology | Invasion | 3 | 5 | 2 |
| Journal of Economic Entomology | Ecology | 7 | 0 | 0 |
| Journal of Environmental Management | Invasion | 7 | 3 | 1 |
| Journal of Evolutionary Biology | Ecology | 0 | 1 | 0 |
| Journal of Experimental Marine Biology and Ecology | Ecology | 0 | 2 | 0 |
| Journal of Fish Biology | Ecology | 0 | 2 | 0 |
| Journal of Insect Science | Ecology | 2 | 0 | 0 |
| Journal of Limnology | Ecology | 2 | 0 | 0 |
| Journal of Mammalogy | Ecology | 0 | 0 | 1 |
| Journal of Marine Systems | Ecology | 1 | 0 | 0 |
| Journal of Molluscan Studies | Ecology | 0 | 1 | 1 |
| Journal of Mountain Science | Invasion | 0 | 1 | 0 |
| Journal of Natural History | Ecology | 0 | 1 | 0 |
| Journal of Nematology | Ecology | 1 | 1 | 0 |
| Journal of Ornithology | Ecology | 0 | 1 | 0 |
| Journal of Pest Science | Ecology | 3 | 1 | 0 |
| Journal of Plant Ecology | Invasion | 0 | 2 | 0 |
| Journal of Sea Research | Ecology | 0 | 1 | 0 |
| Journal of Sustainable Forestry | Ecology | 0 | 1 | 0 |
| Journal of the Entomological Research Society | Ecology | 0 | 0 | 1 |
| Journal of the Royal Army Medical Corps | Other | 0 | 1 | 0 |
| Journal of the Royal Society of New Zealand | Invasion | 0 | 1 | 0 |
| Journal of Theoretical Biology | Invasion | 0 | 1 | 0 |
| Journal of Vegetation Science | Invasion | 0 | 2 | 0 |
| Journal of Zoology | Ecology | 1 | 0 | 0 |
| Knowledge and Management of Aquatic Ecosystems | Invasion | 1 | 0 | 0 |
| Koedoe | Invasion | 0 | 1 | 1 |
| Landscape and Urban Planning | Ecology | 1 | 0 | 0 |
| Landscape Ecology | Ecology | 2 | 1 | 0 |
| Latin American Journal of Aquatic Research | Ecology | 0 | 1 | 0 |
| Limnologica | Ecology | 0 | 0 | 1 |
| Limnology and Oceanography | Ecology | 1 | 1 | 0 |
| Mammal Review | Ecology | 0 | 1 | 1 |
| Management of Biological Invasions | Invasion | 5 | 5 | 4 |
| Marine and Freshwater Behaviour and Physiology | Ecology | 0 | 2 | 0 |
| Marine and Freshwater Research | Invasion | 0 | 2 | 0 |
| Marine Biology | Invasion | 1 | 9 | 1 |
| Marine Biology Research | Invasion | 0 | 1 | 0 |
| Marine Ecology Progress Series | Invasion | 0 | 2 | 0 |
| Marine Environmental Research | Invasion | 0 | 1 | 0 |
| Marine Policy | Ecology | 2 | 0 | 0 |
| Marine Pollution Bulletin | Ecology | 0 | 2 | 2 |
| Mathematical and Computational Forestry and Natural-Resource Sciences | Ecology | 0 | 1 | 0 |
| Mathematical Biosciences | Invasion | 0 | 1 | 0 |
| Mediterranean Marine Science | Ecology | 1 | 2 | 1 |
| Methods in Ecology and Evolution | Invasion | 0 | 1 | 1 |
| Mitochondrial DNA Part B-Resources | Ecology | 0 | 1 | 0 |
| Molecular Ecology | Invasion | 3 | 6 | 0 |
| Myrmecological News | Ecology | 0 | 1 | 0 |
| Natural Areas Journal | Invasion | 1 | 0 | 0 |

| Journal | Subject | Pathway | Unified | EICAT |
|---|---|---|---|---|
| Nature | Invasion | 0 | 1 | 0 |
| Nature Communications | Invasion | 3 | 6 | 1 |
| Nature Conservation-Bulgaria | Invasion | 0 | 1 | 0 |
| Nature Ecology and Evolution | Invasion | 0 | 2 | 0 |
| Natureza and Conservacao | Invasion | 1 | 0 | 0 |
| Naturwissenschaften | Invasion | 0 | 1 | 0 |
| Neobiota | Invasion | 8 | 21 | 20 |
| New Phytologist | Invasion | 5 | 3 | 1 |
| New Zealand Journal of Ecology | Invasion | 0 | 2 | 0 |
| Northwest Science | Invasion | 0 | 1 | 0 |
| Notulae Botanicae Horti Agrobotanici Cluj-Napoca | Ecology | 1 | 0 | 0 |
| Ocean and Coastal Management | Invasion | 1 | 0 | 0 |
| Ocean Yearbook | Ecology | 0 | 0 | 1 |
| Oecologia | Invasion | 1 | 2 | 0 |
| Oikos | Invasion | 1 | 2 | 0 |
| Pacific Science | Invasion | 1 | 0 | 0 |
| Parasites and Vectors | Ecology | 0 | 1 | 0 |
| Parasitology Research | Ecology | 0 | 1 | 0 |
| Peerj | Invasion | 4 | 8 | 8 |
| Perspectives in Ecology and Conservation | Invasion | 0 | 2 | 1 |
| Perspectives in Plant Ecology Evolution and Systematics | Invasion | 0 | 2 | 0 |
| Philosophical Transactions of the Royal Society B-Biological Sciences | Invasion | 1 | 3 | 0 |
| Phytopathology | Ecology | 1 | 0 | 0 |
| Plant and Soil | Invasion | 0 | 1 | 0 |
| Plant Biology | Invasion | 0 | 1 | 0 |
| Plant Biosystems | Invasion | 3 | 4 | 1 |
| Plant Ecology | Invasion | 2 | 1 | 0 |
| Plant Pathology | Ecology | 2 | 0 | 0 |
| Plant Protection Science | Ecology | 1 | 0 | 0 |
| Plos Biology | Invasion | 0 | 3 | 1 |
| PLoS One | Invasion | 17 | 29 | 6 |
| Polar Biology | Invasion | 2 | 4 | 0 |
| Polar Research | Invasion | 1 | 0 | 0 |
| Polish Journal of Ecology | Invasion | 0 | 1 | 0 |
| Population Ecology | Invasion | 1 | 1 | 0 |
| Preslia | Invasion | 8 | 8 | 1 |
| Proceedings of the National Academy of Sciences of the United States of America | Invasion | 6 | 7 | 0 |
| Proceedings of the Royal Society B-Biological Sciences | Invasion | 3 | 4 | 1 |
| Rangeland Ecology and Management | Ecology | 0 | 1 | 0 |
| Regional Environmental Change | Invasion | 0 | 1 | 0 |
| Regulatory Mechanisms in Biosystems | Ecology | 0 | 0 | 1 |
| Remote Sensing | Other | 0 | 1 | 0 |
| Rendiconti Lincei-Scienze Fisiche E Naturali | Invasion | 1 | 0 | 0 |
| Restoration Ecology | Invasion | 0 | 0 | 1 |
| Revista Brasileira De Entomologia | Ecology | 1 | 0 | 0 |
| Revista De Biologia Marina Y Oceanografia | Invasion | 0 | 1 | 0 |
| Revmar-Revista Ciencias Marinas Y Costeras | Invasion | 0 | 1 | 0 |
| Revue D Ecologie-La Terre Et La Vie | Invasion | 1 | 3 | 0 |
| Revue Scientifique Et Technique-Office International Des Epizooties | Ecology | 1 | 0 | 0 |
| Risk Analysis | Invasion | 2 | 3 | 0 |
| Royal Society Open Science | Invasion | 1 | 1 | 0 |
| Russian Journal of Biological Invasions | Invasion | 1 | 1 | 1 |
| Science | Invasion | 3 | 0 | 0 |
| Science of the Total Environment | Invasion | 4 | 3 | 0 |
| Scientia Marina | Invasion | 1 | 0 | 0 |
| Scientific Data | Invasion | 0 | 1 | 1 |
| Scientific Reports | Invasion | 4 | 3 | 2 |
| Silva Fennica | Invasion | 0 | 1 | 0 |
| South African Journal of Botany | Invasion | 1 | 10 | 2 |
| South African Journal of Science | Invasion | 0 | 2 | 1 |
| South American Journal of Herpetology | Ecology | 0 | 0 | 1 |
| Symbiosis | Ecology | 0 | 1 | 0 |
| Theoretical Ecology | Invasion | 1 | 0 | 0 |
| Transactions in GIS | Other | 0 | 0 | 1 |
| Tree Genetics and Genomes | Ecology | 0 | 1 | 0 |
| Trees-Structure and Function | Ecology | 0 | 1 | 0 |
| Trends in Ecology and Evolution | Invasion | 10 | 9 | 3 |
| Trends in Parasitology | Ecology | 0 | 1 | 0 |
| Tropical Ecology | Invasion | 0 | 1 | 0 |
| Tuexenia | Invasion | 2 | 0 | 0 |
| Turkish Journal of Botany | Invasion | 0 | 0 | 1 |
| Urban Ecosystems | Invasion | 1 | 0 | 0 |
| Urban Forestry and Urban Greening | Invasion | 1 | 0 | 1 |
| Water Resources Research | Ecology | 1 | 0 | 0 |
| Web Ecology | Invasion | 0 | 1 | 0 |
| Weed Biology and Management | Invasion | 0 | 1 | 0 |
| Weed Research | Invasion | 0 | 2 | 0 |
| Wildlife Research | Ecology | 0 | 2 | 0 |
| Wiley Interdisciplinary Reviews-Water | Ecology | 1 | 0 | 0 |
| Zookeys | Ecology | 1 | 3 | 0 |
| Zoological Studies | Ecology | 0 | 2 | 0 |
| Zootaxa | Ecology | 1 | 2 | 0 |
| Total | | 403 | 690 | 237 |

**2.5 The location of the corresponding authors when they completed their study (i.e. their primary address) of papers that cited each framework compared to the number of studies reported from different geographical regions by Pyšek et al. (2008).**

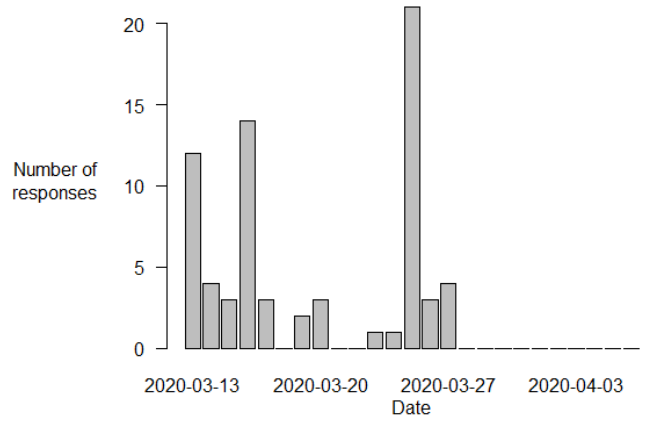
The geographic regions are as per those reported in Pyšek et al. (2008). The p-values shown are from Chi-squared tests comparing the number of studies conducted per region by Pyšek et al. (2008) to the number of papers authored by someone from that region who cited a particular framework against the number of studies and papers authored in all other regions. Unadjusted p-values are shown. Values that were significantly different at p=0.05 after adjusting p-values using the false discovery rate method using the function p.adjust in R, with all the p-values combined, are highlighted with ↗ indicating more studies using the framework than expected, ↘ fewer studies using the framework than expected, and ns is no significant different from the expectation.

| Geographical region | Number of studies conducted per region by Pyšek et al. (2008) | Pathway Classification | | Unified Framework | | EICAT | |
|---|---|---|---|---|---|---|---|
| | | Number of papers authored | Trend (p-value) | Number of papers authored | Trend (p-value) | Number of papers authored | Trend (p-value) |
| Africa (excluding South Africa) | 24 | 0 | ns (0.10) | 3 | ns (0.32) | 1 | ns (0.68) |
| Asia (including Middle East) | 105 | 19 | ns (0.65) | 41 | ns (0.03) | 10 | ns (1.00) |
| Atlantic Islands (excluding the UK) | 16 | 0 | ns (0.22) | 1 | ns (0.22) | 0 | ns (0.46) |
| Australia, New Zealand, and Oceania | 209 | 69 | ↗ (<0.01) | 70 | ns (0.08) | 21 | ns (0.70) |
| Central America | 133 | 0 | ↘ (<0.01) | 1 | ↘ (<0.01) | 0 | ↘ (<0.01) |
| Hawaii | 50 | 1 | ↘ (0.03) | 2 | ↘ (<0.01) | 0 | ns (0.06) |
| Indian Ocean Islands | 31 | 0 | ns (0.05) | 0 | ↘ (<0.01) | 0 | ns (0.17) |
| North America | 1397 | 87 | ↘ (<0.01) | 126 | ↘ (<0.01) | 31 | ↘ (<0.01) |
| Northern Europe (including the UK) | 464 | 159 | ↗ (<0.01) | 239 | ↗ (<0.01) | 104 | ↗ (<0.01) |
| South Africa | 67 | 37 | ↗ (<0.01) | 117 | ↗ (<0.01) | 46 | ↗ (<0.01) |
| South America | 132 | 8 | ↘ (<0.01) | 49 | ns (0.04) | 10 | ns (0.71) |
| Southern Europe | 141 | 54 | ↗ (<0.01) | 77 | ↗ (<0.01) | 26 | ↗ (<0.01) |

**2.6 The results of the survey of corresponding authors of papers who have cited one of the papers that outline the Pathway Classification framework; the Unified Framework or EICAT.**

See Supplementary Material 2.2 for details of the survey. Out of the 958 people contacted, 53 email addresses returned with a message of "wrong address" and/or that "the email address is no longer on the server", of the remaining 905 e-mails, a total of 84 replies were received (20 of 256; 51 of 589, and 13 of 113 respectively). Respondents could fill in the questionnaire for multiple frameworks but this only happened in four instances when respondents completed the questionnaires for both Blackburn et al. 2014 and Hawkins et al. 2015. Two people declined to take part in the study, the first person because they use different frameworks (they provided some input that was consolidated in the suggestions section below). The second person stated that they couldn't be part of the study because they did not personally use the any of the frameworks even though they were corresponding authors on a paper that did. It was also noted that one question in the survey "This reference illustrates your perspective or finding that contradicts a perspective or findings" was not clear enough, this was reflected on the responses, as it was the only questions that was often left unanswered.

The most important reasons for citation across the frameworks were because "the reference is authored by recognized authorities in the field, it is a classic in the field and, it has generated much novel and successful research or scholarship" (Table 2). The results for proximity questions were similar between the three frameworks (Table 1). In terms of the use of frameworks in management, though just over half several the respondents (53%) stated that the Unified framework was important for management; less distinctive examples came up from the survey, with the exception of the national status report in South Africa. When asked how the unified framework should be revised, if at all, different responses came up i.e. "I would slightly modify it in order to allow its application to other invasive species presently badly fitting, remove "naturalized"; consider adding clarity around pre-border/post-border activities" (see Supplementary Material 2.6 for more responses for all the surveyed frameworks). When asked whether they use different frameworks, the CBD framework came up several times as the "revised and expanded version of the Pathway Classification framework.




**Supplementary Material 2 Figure 1 The date on which people responded to the questionnaire.** Respondents could fill in the questionnaire for each framework, but only one date is recorded per respondent here. The questionnaire was available on-line from 13 March to 6 April, with a reminder sent on 24 March (the second peak on the figure). No responses were received after 27 March 2020, although one request to complete the questionnaire was received after the closing date.

**Supplementary Material 2 Table 2 the results of the eight proximity questions (given the questionnaire was sent to people who had cited the framework the first two questions represent checks, though somewhat surprisingly at least two responses claimed to have not cited the paper)**

| Statement | Pathway classification | | Unified framework | | EICAT | |
|---|---|---|---|---|---|---|
| | yes | no | yes | no | yes | no |
| Have you ever cited this reference in your publications? | 18 | 2 | 55 | 0 | 13 | 0 |
| Do you currently possess a copy of this reference? | 19 | 1 | 54 | 1 | 13 | 0 |
| Have you ever spoken directly to one of the authors of this citation (i.e. not just over the email)? | 13 | 7 | 28 | 27 | 12 | 1 |
| Would you consider the author a personal friend? | 7 | 13 | 7 | 48 | 6 | 7 |
| Is the author a colleague at your institution? | 3 | 17 | 3 | 52 | 0 | 13 |
| Did the author work at an institution where you have studies/worked? | 5 | 15 | 7 | 48 | 4 | 9 |
| Have you ever recommended this particular reference as a reviewer or editor? | 8 | 12 | 15 | 40 | 8 | 5 |
| Has a journal referee/reviewer asked you to include this particular reference during the review process? | 1 | 19 | 3 | 52 | 0 | 13 |

**Supplementary Material 2 Table 3 the results of the questionnaire for the four publications on each of the 21 questions used to assess reasons for citing the frameworks from 1=strongly agree, 2=agree, 3=neutral, 4=disagree, 5=strongly disagree.**

| Category | Statement | Pathway classification | | | | | Unified framework | | | | | EICAT (Blackburn et al. 2014) | | | | | EICAT (Hawkins et al. 2015) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 |
| Negative | There are problems with the framework. | 0 | 2 | 4 | 12 | 2 | 2 | 5 | 12 | 21 | 14 | 1 | 3 | 1 | 2 | 2 | 0 | 0 | 1 | 3 | 0 |
| Negative | This reference illustrates your perspective or finding that contradicts a perspective or findings. | 0 | 2 | 9 | 3 | 2 | 4 | 9 | 14 | 17 | 7 | 1 | 0 | 6 | 0 | 1 | 0 | 0 | 2 | 0 | 1 |
| Personal influence | This reference strongly influenced your thinking on the topic. | 5 | 9 | 6 | 0 | 0 | 15 | 20 | 13 | 6 | 1 | 4 | 5 | 0 | 0 | 0 | 2 | 2 | 0 | 0 | 0 |
| Personal influence | This reference was a major source of inspiration for your work. | 4 | 4 | 8 | 1 | 3 | 8 | 16 | 21 | 7 | 3 | 5 | 4 | 0 | 0 | 0 | 2 | 0 | 2 | 0 | 0 |
| Classic | This reference helps justify a central argument in invasion science. | 8 | 6 | 4 | 0 | 0 | 21 | 22 | 8 | 2 | 2 | 2 | 5 | 2 | 0 | 0 | 2 | 2 | 0 | 0 | 0 |
| Personal influence | This reference is similar to your own work. | 3 | 10 | 3 | 2 | 2 | 6 | 15 | 20 | 7 | 7 | 2 | 5 | 2 | 0 | 0 | 2 | 2 | 0 | 0 | 0 |
| Personal influence | This reference reviews prior work in this area. | 7 | 6 | 6 | 1 | 0 | 27 | 18 | 8 | 1 | 0 | 2 | 5 | 1 | 0 | 0 | 0 | 2 | 1 | 1 | 0 |
| Creative | This study used a method or theoretical perspective that you think is currently unusual or especially innovative. | 2 | 7 | 8 | 5 | 0 | 1 | 16 | 25 | 10 | 2 | 1 | 4 | 1 | 2 | 0 | 0 | 2 | 2 | 0 | 0 |

| Category | Statement | Pathway classification | | | | | Unified framework | | | | | EICAT (Blackburn et al. 2014) | | | | | EICAT (Hawkins et al. 2015) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 |
| Creative | This reference bridges a gap between two subfields. | 2 | 8 | 5 | 4 | 1 | 10 | 21 | 11 | 11 | 2 | 3 | 2 | 2 | 1 | 0 | 0 | 1 | 1 | 2 | 0 |
| Creative | This reference helps to reconcile contrasting viewpoints or findings in the field. | 5 | 4 | 7 | 4 | 0 | 16 | 21 | 10 | 7 | 0 | 2 | 4 | 0 | 2 | 0 | 0 | 3 | 0 | 1 | 0 |
| Creative | This reference illustrates possible avenues for future research. | 7 | 11 | 1 | 1 | 0 | 19 | 26 | 3 | 5 | 1 | 4 | 3 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 |
| Creative | This reference solves an important conceptual or practical problem in the field. | 9 | 9 | 1 | 1 | 0 | 21 | 23 | 7 | 3 | 0 | 4 | 3 | 1 | 0 | 0 | 0 | 4 | 0 | 0 | 0 |
| Creative | More so than most, this reference advances our ability to address an important social or human problem. | 9 | 7 | 4 | 0 | 0 | 13 | 18 | 12 | 9 | 2 | 3 | 6 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 |
| Classic | This is a classic reference in the field. | 10 | 7 | 1 | 1 | 0 | 33 | 15 | 3 | 3 | 1 | 6 | 2 | 0 | 0 | 1 | 3 | 0 | 1 | 0 | 0 |
| Classic | This reference is authored by recognized authorities in the field. | 18 | 2 | 0 | 0 | 0 | 42 | 10 | 3 | 0 | 0 | 9 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 |
| Classic | This reference has generated much novel and successful research or scholarship. | 7 | 7 | 5 | 0 | 0 | 12 | 20 | 18 | 4 | 1 | 7 | 2 | 0 | 0 | 0 | 1 | 2 | 1 | 0 | 0 |
| Classic | There have been substantial efforts to show that the framework is wrong. | 0 | 0 | 4 | 8 | 7 | 0 | 3 | 13 | 23 | 16 | 0 | 1 | 3 | 4 | 0 | 0 | 1 | 1 | 2 | 0 |
| Classic | The framework has withstood many efforts to show that it is wrong. | 0 | 2 | 7 | 7 | 3 | 1 | 4 | 22 | 14 | 10 | 0 | 1 | 5 | 2 | 0 | 0 | 2 | 1 | 1 | 0 |
| Supportive | This reference helps establish the legitimacy of the topic of your work. | 3 | 7 | 7 | 2 | 1 | 11 | 24 | 11 | 7 | 2 | 3 | 6 | 0 | 0 | 0 | 1 | 2 | 1 | 0 | 0 |
| Personal influence | This reference reports what you consider to be an exceptionally high-quality piece of science. | 4 | 8 | 8 | 0 | 0 | 16 | 19 | 16 | 3 | 1 | 3 | 2 | 3 | 0 | 0 | 1 | 2 | 1 | 0 | 0 |
| Personal influence | This reference documents the sources of a method or design feature used in your study. | 6 | 7 | 4 | 1 | 2 | 12 | 17 | 12 | 11 | 1 | 5 | 2 | 1 | 0 | 0 | 2 | 0 | 1 | 1 | 0 |

**Supplementary Material 2.6 continued.** Responses to semi-structured questions on the use of biological invasions frameworks in management and, on any suggestions or proposed improvements of the frameworks

*Are you aware of instances where the framework was used to guide management? Yes/No. If yes, please provide details.*

the “Pathway Classification”

- Maybe the Ballast water convention
- Yes, adopted by Genovesi et al. for IUCN
- Yes, within IPBES invasive species sections
- National Strategy on IAS in Poland
- It was the basis for the development of the CBD pathways categorization, which is currently guiding management (e.g. the CBD classification is used for the implementation of the Regulation 1143/2014 of the EU and has been adopted by EASIN, which is the main tool supporting the implementation of the Regulation)
- Yes. Horizon Scanning and prioritisation processes use the ensuing CBD (2014) classification scheme for the assessed species. EU IAS Regulation (Risk Assessments and associated Management documents employ the scheme and/or extensions/modifications of it, e.g. IUCN (2017)).
- IUCN (2017). Guidance for interpretation of CBD categories on introduction pathways. Technical note prepared by IUCN for the European Commission.
- CBD classification of pathways categories and subcategories
- Yes - for example, the framework is important for management in the context the EU regulation on IAS

the “Unified Framework”

- Yes. I can remember an article, which I did not read, that use it specifically in the title. In the other hand, the framework explicitly removes "impact" from their definition of invasive, so I have to assume that it would incorrect to use it on an applied environment.
- Yes. Preventive measures to avert the spread of invasive species
- Stop IAS before they spread in a new range
- Yes, to motivate legislative treatment of invasive species and prioritization for management
- National Strategy on IAS in Poland
- Yes. Guidance on stages of invasion in NZ.
- Yes, for developing science/evidence-based government policy suggestions.
- Horizon scanning and species prioritisation
- Yes. Control of spread of invasive species.
- Yes. Management of invasive plants in South Africa.
- Yes, Gaertner M, Fisher JL, Sharma GP, Esler KJ (2012) Insights into invasion and restoration ecology: Time to collaborate towards a holistic approach to tackle biological invasions. NeoBiota 12: 57–75. doi: 10.3897/neobiota.12.2123
- Yes, as it allows to discriminate different management actions for different stages of the invasion process.

EICAT

- Yes. The EICAT has five objectives. Among these objectives are including facilitate predictions of potential future impacts of taxa in the target region and elsewhere; aid in prioritisation of management actions, and aid in evaluation of management methods. In addition, the EICAT adopted as an official instrument of IUCN.
- Not the framework per se, but published literature on the impacts of particular species has been used in management decision making. For example, published

evidence of hybridization is used in various animal control projects such mallard ducks, guttural toads, goats.
- yes. I am working in a project (CONTAIN-LATAM) where we use this framework to identified outcomes of IS to design future potential management activities
- Yes, in Horizon Scanning exercises to score the risk of Impact of alien species
- National Strategy on IAS in Poland
- Prioritising alien species for management

*Are you aware of instances where the framework was used to guide policy/monitoring and reporting? Yes/No. If yes, please provide details.*

the “Pathway Classification”

- yes, national policy to regulate the pathways
- Yes. The CBD pathway classification (2014), used for purposes of MSFD reporting, as well as for the implementation of the EU IAS Regulation.
- It has been commonly used for classifying alien species by pathway of introduction in publications and reports (e.g. Katsanevakis S, Zenetos A, Belchior C, Cardoso AC, 2013. Invading European Seas: assessing pathways of introduction of marine aliens. Ocean and Coastal Management 76: 64–74). Its revised version (i.e. the CBD classification) is the standard for monitoring/reporting in Europe (e.g. reporting for the implementation of the Marine Strategy Framework Directive).
- Yes. CBD framework for prioritisation of pathways.
- Yes - for example, the framework has become the basis of the CBD scheme on IAS introduction pathways and is also important for the EU regulation on IAS.
- Linking to CBD Classification for Pathway Action Plans
- Considered in the action plan of Germany to manage introduction pathways
- National Strategy on IAS in Poland

the “Unified Framework”

- Not per se, but because the reference provides a method for classifying alien species, it is possible that it underpins legislation. Most of the policies I am aware of have to do with how to deal with alien species rather than how to classify them. Classification of aliens often takes place through iterative processes involving many people, some of whom undoubtedly use the reference to underpin their decisions.
- Yes, the proportion of species naturalizing and invading for Melaleuca influenced monitoring efforts
- Yes. Hard to evaluate, but underpins a great deal of the way we think about managing weeds
- yes, many alien species inventories now classify the species as casuals, naturalized or invasive
- Yes (South African national status report on biological invasions)
- Yes, as it allows to discriminate policy and monitoring for different stages of the invasion process.
- National Strategy on IAS in Poland
- Yes. Concept of barriers is relevant for almost all policies of invasive alien species.
- Yes, K Rana, N Goyal, Sharma GP (2018) Staging stewards of agro-ecosystems in the ecosystem services framework. Ecosystem Services, 33, 89-101
- Theoretically yes but not on a practical level.

EICAT

- Yes, it was used as a starting point for the Impact scoring scale currently used in the recommended Risk Assessment protocol developed and used to produce RAs for the EU IAS Regulation. It has been endorsed and applied by the IUCN.
- The EICAT form the technical and scientific basis for the IUCN-wide consultation on an IUCN standard classification of the impact of invasive alien taxa. IUCN, 2017. Consultation document. IUCN standard classification of the impact of invasive alien taxa. Version 1 May 2017.
- National Strategy on IAS in Poland
- Yes, there are efforts to use the framework in assessments of alien species impact nationally as part of risk analysis. However, one of the shortfalls is the requirement for published information on impacts, which while a sound gold standard, often results in the inability to classify a species impact.
- Yes, under the project LIFE INVASAQUA.
- Implemented in EU policy
- Yes, it has been used in many publications and reports, e.g. it has been used for reporting the cumulative impacts of marine invasive species in the Mediterranean Sea (Katsanevakis S, Tempera F, Teixeira H, 2016. Mapping the impact of alien species on marine ecosystems: the Mediterranean Sea case study. Diversity and Distributions 22: 694–707)

*Do you also use a different framework instead of the one mentioned here? If yes, please give details.*

the “Pathway Classification”

- PeST framework - developed using a multi-criteria approach considering Biology, Ecology and Pathways.
- Yes. In the marine environment, it is sometimes useful and informative to use categories of pathways of introduction defined on a human activity basis: ‘shipping’, ‘aquaculture’ ‘corridors’, ‘aquarium trade’ and ‘other’ (e.g. live food/bait trade; floating objects. etc.), as used in Katsanevakis et al. (2013). Katsanevakis, S., Zenetos, A., Belchior, C., Cardoso, A. C., 2013. Invading European Seas: assessing pathways of introduction of marine aliens. Ocean & Coastal Management, 76, 64-74.
- Since 2018, I have used the CBD framework, which is actually a revision of the Hulme et al. (2008) framework
- Yes, IPPC ISPM5
- Although not inclusive frameworks, I use the transport hub and stratified diffusion models to describe the movement of the invertebrates I study.
- I focus on the research of invasive aliens´ impacts - do not use any framework like this

the “Unified Framework”

- As many other theoretical frameworks, this was built with some particular examples that fit correctly into the framework. There are examples in the literature (understudied taxa, highly mobile vertebrate, inconspicuous organisms for which the precise way of arrival to a given area is impossible to determine) that are not good fit for the framework. The framework should be revised with those examples in mind.
- Richardson et al. (2000). Naturalization and invasion of alien plants: concepts and definitions
- Yes, The model of invasion steps and stages (INVASS): Heger, T. (2001) A model for interpreting the process of invasion: crucial situations favouring special characteristics of invasive species. Plant Invasions. Species Ecology and

Ecosystem Management (eds G. Brundu, J.H. Brock, I. Camarda, L.E. Child & P.M. Wade), pp. 3-10. Backhuys Publishers, Leiden. Heger, T. & Trepl, L. (2003) Predicting biological invasions. Biological Invasions, 5, 313-321. Heger, T. (2004) Zur Vorhersagbarkeit biologischer Invasionen. Entwicklung und Anwendung eines Modells zur Analyse der Invasion gebietsfremder Pflanzen. Technische Universität Berlin, Berlin.

- I find that it doesn't necessarily make sense to subscribe to a single framework. Each can be a useful tool/lens for interpreting patterns.
- Yes, open to considering all different views and trying to understand how they contribute to overall perspective.
- Yes, One Health
- yes, the framework on the different demographic dimensions of invasiveness (Catford et al. 2016 Journal of Ecology)
- Technically yes, depending on the research question. However, this is the usual framework that I find easier and more logical, especially for policy-wise and baseline research.
- Yes, GISS Nentwig et al
- I use Blackburn et al. (2011) and Jeschke et al. (2013, Ambio) which is similar, but more explicit about where impact is placed.
- yes: Catford et al. 2009
- Yes, I use others hypothesis in my work like as Hypothesis Invasion Meltdown (Simberloff and Von Holle 1999, Biological Invasions).
- Yes. Carlton 1985 was the original framework for stages of invasion

EICAT

- This reference is basically the same as Blackburn et al. 2015
- I used the Generic Impact Scoring System (GISS). Nentwig W, Bacher S, Pyšek P, Vilà M, Kumschick S (2016) The Generic Impact Scoring System (GISS): A standardized tool to quantify the impacts of alien species. Environmental Monitoring and Assessment 188: 315.
- Not yet, but I intend to use its revised version, i.e. EICAT (Hawkins et al. 2015) whenever needed in the future

**2.7 Examples of documents showing the influence of the selected framework papers in policy and management.**

These examples are from national and international level strategic documents, guidelines and recommendations that are aimed at bridging the gap between science and management.

| Type of document, scope, and country | Year | Unified Framework | Pathway Classification | Impact Classification | Reference |
|---|---|---|---|---|---|
| • Guidelines for prioritization<br>• All taxa<br>• India | 2017 | No | Mentions the need to identify pathways but does not refer to Hulme et al 2008. Instead refers to Aichi target 9. | The document aims to provide a guideline to prioritize invasive alien plants in India.<br>The document explicitly refers to the scheme proposed by Blackburn et al.2014 with minor modifications. However, it does refer to Blackburn et al.2014 but to SEICAT paper by Bacher et al. 2017 instead and to IUCN guidelines. | National Biodiversity Authority (not dated) Ministry of Environment Forests and Climate Change Government of India, Invasive Alien Species of India. Centre for Biodiversity Policy and Law (CEBPOL). |
| • Strategy<br>• Weeds<br>• Australia | 2017–2027 | No | Clearly mentions the need to identify pathways but does not refer to Hulme et al. 2008. Does not use exactly the same scheme for classifying pathways as proposed by Hulme et al 2008. | It says clearly underpins the need for impact assessment on the economy, environment and human health. However, does not use the EICAT scheme directly. | Invasive Plants and Animals Committee (2016) Australian Weeds Strategy 2017 to 2027, Australian Government Department of Agriculture and Water Resources, Canberra. |
| • Strategy<br>• All taxa<br>• Great Britain | 2015 | No | Detailed mention about pathways but does not explicitly use or refer to the framework proposed by Hulme et al. | Mentions the need to quantify the environmental, economic and social impacts. No explicit reference to EICAT or use of terms used in EICAT. | The Great Britain Non-native Species Secretariat Animal and Plant Health Agency (2015) The Great Britain Invasive Non-native Species Strategy |
| • Status Report<br>• All taxa<br>• South Africa | 2017 | Categorizing different stages of invasion. Follows the biogeographic definition. | Refers and uses pathways classification and sub-categories | Explicit and multiple references. While intention was to use the scheme, it was not implemented due to a lack of data. | van Wilgen, B.W. & Wilson, J.R. (Eds.). (2018). The status of biological invasions and their management in South Africa in 2017. South African National Biodiversity Institute, Kirstenbosch and DST-NRF Centre of Excellence for Invasion Biology, Stellenbosch |

| Type of document, scope, and country | Year | Unified Framework | Pathway Classification | Impact Classification | Reference |
|---|---|---|---|---|---|
| • Strategy<br>• Animals<br>• Australia | 2017–2027 | No explicit use of the framework. | Discusses issues closely related to Hulme et al.2008. For instance, it discusses issues related to release or escape of pets. But it does not provide explicit reference to the paper. | No explicit reference | Invasive Plants and Animals Committee (2016). Australian Pest Animal Strategy 2017 to 2027, Australian Government Department of Agriculture and Water Resources, Canberra. |
| • Recommendations on data standards<br>• All taxa<br>• International | 2016 | No explicit reference | Refers to more recent papers on pathways but does not refer to Hulme et al 2008. | Advocates the use of Blackburn et al. 2014 for impact assessment.<br>Also refers to another related paper by Hawkins et al 2015. | Conference of the parties to the convention on biological diversity. (2016). Invasive alien species: data access and use for research towards Achieving Aichi Biodiversity Target 9 (UNEP/CBD/COP/13/INF/38). Convention on biological diversity, UNEP. |
| • Recommendations<br>• All taxa<br>• International | 2018 | No explicit reference | No explicit reference | "Encourages Parties, other Governments and relevant expert organizations to promote data mobilization to, for example, the Global Register of Introduced and Invasive Species produced through the Global Invasive Alien Species Information Partnership, and by supporting the development of the Environmental Impact Classification of Alien Taxa by the International Union for Conservation of Nature" | Subsidiary body on scientific, technical and technological advice. (2018). Recommendation adopted by the subsidiary body on scientific, technical and technological advice (CBD/SBSTTA/REC/2/8). Convention on biological diversity, UNEP. |
| • Management guidelines<br>• All taxa<br>• Islands | 2018 | No explicit mention | Explicitly refers to Hulme et al 2008. Has adapted from the pathway scheme as proposed by Hulme et al 2008.<br>All the pathways proposed in the paper except unaided pathway has been used in the scheme. | No explicit reference | IUCN. (2018). Guidelines for invasive species planning and management on islands. Cambridge, UK and Gland, Switzerland: IUCN. viii + 40pp. |

| Type of document, scope, and country | Year | Unified Framework | Pathway Classification | Impact Classification | Reference |
|---|---|---|---|---|---|
| • Regulation<br>• All taxa<br>• European union | 2014 | No explicit mention but talks about stages in invasion in the context of eradication. | Although the entire document does not cite scientific papers explicitly, the issue of identifying and prioritising pathways has been repeatedly mentioned in different contexts. It appears that the document is strongly influenced by the pathway classification paper by Hulme et.al 2008. | The policy document was published prior to publication of the paper. | European Union. (2014). Regulation (EU) No 1143/2014 of the European Parliament and the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species. Official Journal of the European Union 317: 35–55. |
| • Consultation<br>• All taxa<br>• International | 2017 | No mention | Does not mention the pathway classification scheme. | The in this document the impact classification scheme (EICAT) has been directly adapted by IUCN and promoted for further use. | IUCN. (2017). Consultation document. IUCN standard classification of the impact of invasive alien taxa. Version 1 May 2017. |
| • Resolutions, recommendation, decisions<br>• All taxa<br>• International | 2016 | No mention | No direct mention, however, talks about identification and management of pathways. | Endorses the use of EICAT for impact assessment and considers it instrumental in achieving Aichi targets. | IUCN. (2016). IUCN Resolutions, Recommendations and other Decisions. Gland, Switzerland: IUCN. 106pp |

**Supplementary Material 2: Bibliogrpahy**


Blackburn TM, Essl F, Evans T, Hulme PE, Jeschke JM, Kühn I, Kumschick S, Marková Z, Mrugała A, Nentwig W, Pergl J, Pyšek P, Rabitsch W, Ricciardi A, Richardson DM, Sendek A, Vilá M, Wilson JRU, Winter M, Genovesi P, Bacher S (2014) A unified classification of alien species based on the magnitude of their environmental impacts. Plos Biology 12: e1001850, doi:1001810.1001371/journal.pbio.1001850. doi:10.1371/journal.pbio.1001850

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Pyšek P, Richardson DM, Pergl J, Jarošík V, Sixtová Z, Weber E (2008) Geographical and taxonomic biases in invasion ecology. Trends in Ecology & Evolution 23: 237-244. doi:10.1016/j.tree.2008.02.002