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REVIEW

Existing indicators do not adequately monitor progress toward meeting invasive alien species targets

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Abstract

Monitoring the progress parties have made toward meeting global biodiversity targets requires appropriate indicators. The recognition of invasive alien species (IAS) as a biodiversity threat has led to the development of specific targets aiming at reducing their prevalence and impact. However, indicators for adequately monitoring and reporting on the status of biological invasions have been slow to emerge, with those that exist being arguably insufficient. We performed a systematic review of the peer-reviewed literature to assess the adequacy of existing IAS indicators against a range of policy-relevant and scientifically valid properties. We found that very few indicators have most of the desirable properties and that existing indicators are unevenly spread across the components of the Driver-Pressure-State-Response and Theory of Change frameworks. We provide three possible reasons for this: (i) inadequate attention paid to the requirements of an effective IAS indicator, (ii) insufficient data required to populate and inform policy-relevant, scientifically robust indicators, or (iii) deficient investment in the development and maintenance of IAS indicators. This review includes an analysis of where current inadequacies in IAS indicators exist and provides a roadmap for the future development of indicators capable of measuring progress made toward mitigating and halting biological invasions.

KEYWORDS
biodiversity, biological invasions, environmental policy, essential biodiversity variables, global environmental change

1 | INTRODUCTION

Current declines in biodiversity are primarily the result of a number of large-scale key drivers of environmental change, one of which is the impact of invasive alien species (IPBES, 2019; Stoett et al., 2019). With a changing climate and an increasingly connected world, the number of introduced (and therefore also potential invasive) species, already in the tens of thousands, is predicted to grow (Seebens et al., 2017). The recognition of the impacts and costs of invasive alien species has placed biological invasions on the agenda of major global political initiatives: from the 1992 CBD (Convention on Biological Diversity; Article 8 h) to the 2030 Agenda for Sustainable Development of the United Nations (Target 15.8). Specific to invasions, the Aichi Target 9 from the CBD's Strategic Plan for Biodiversity 2011–2020, stipulated that *"by 2020, invasive alien species and pathways are identified and prioritised, priority species are controlled or eradicated, and measures are in place to manage pathways to prevent their introduction and establishment*." However, as with many other biodiversity targets (Tittensor et al., 2014), and in spite of some progress, these invasion policy targets were unmet (CBD, 2020b).

Two important reasons for slow progress are the inadequate implementation of the interventions needed to slow the spread, reduce the negative impacts and to measure the success of invasive alien species (IAS) management (IPBES, 2019; Pyšek et al., 2020b). However, also under question is the adequacy of both available information and the indicators used to assess and monitor progress toward the CBD agenda (McGeoch & Jetz, 2019). Much has been said in the literature about the desirable properties of biodiversity policy indicators and underlying variables (Collen & Nicholson, 2014; Jetz et al., 2019; Mace & Baillie, 2007; McQuatters-Gollop et al., 2019; Noss, 1990). In essence, such indicators of conservation targets require two dimensions: (1) political relevance, that is, clearly address a relevant policy goal and enable reporting against a policy target, including reporting in all relevant contexts, and at all levels and scales at which the policy applies and (2) scientific validity, that is, accurately represent (taxonomically, spatially and temporally) the status and trend in the environmental property or process of interest in an integrated and harmonized way (Collen & Nicholson, 2014; Jetz et al., 2019; McQuatters-Gollop et al., 2019). This includes indicators being easy to interpret and understand (not prone to being misinterpreted), which requires that they are reproducible and convey information on the uncertainty and limits of the measured status or trend.

Multiple indicators for monitoring biological invasions have been developed and implemented at various spatial scales, including global, continental and national (Genovesi et al., 2013). Compared with indicators for monitoring other aspects of biodiversity policy (such as social-ecological resilience, environmental degradation, climate change mitigation, and the contribution of biodiversity to carbon stocks), invasion targets (specifically Aichi Target 9) are one of the few to have associated indicators deemed adequate for monitoring progress (Mcowen et al., 2016). This finding, however, contradicts the view that available evidence is insufficient for quantifying progress against invasion targets at a global scale (McGeoch & Jetz, 2019). The apparent contradiction arises from indicators assessed either primarily for their policy relevance or against scientific validity criteria, while both are necessary for effective indicators.

Monitoring the status of biological invasions is a global imperative given their persistent presence and threat to biodiversity (Seebens et al., 2020). A detailed analysis of existing invasion indicators, including their strengths and weaknesses for reporting progress against policy targets, is lacking. Insights obtained from such a review would strategically pave the way for further indicator development and application. There is a pressing need for such information, given the approaching conclusion of COP-15 where the details of the Post-2020 Global Biodiversity Framework are to be agreed on (CBD, 2020a), and the development of the IPBES Thematic assessment on invasive alien species and their control. For example, the outcome of the IPBES IAS assessment will inform invasion policies and management strategies in more than 130 countries, for whom information on effectiveness and adequacy of current invasion indicators will help inform future action (Stoett et al., 2019).

Here we evaluate the extent to which existing indicators are adequate for monitoring and reporting on progress toward meeting targets, established to reduce the prevalence and impact of biological invasions. We performed a systematic literature review to identify existing invasion indicators, and subsequently evaluated their properties for assessing and reporting on progress against reaching global

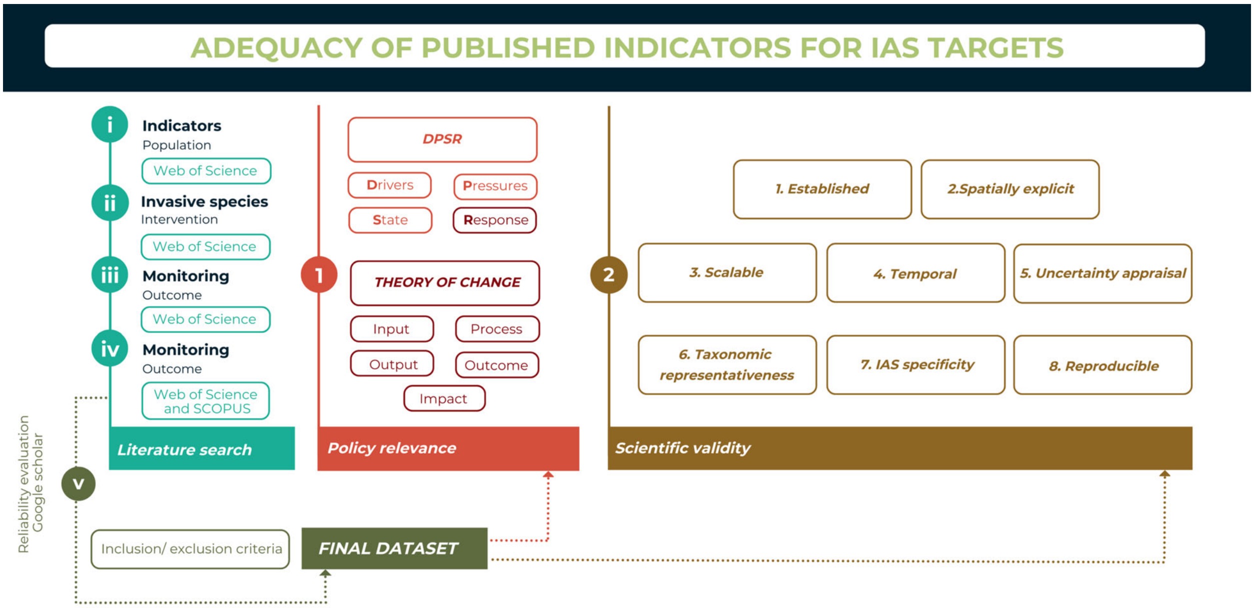

FIGURE 1 Approach to evaluating the adequacy of published indicators for reporting on invasive alien species (IAS) targets. The approach started (left of figure) with a literature search of published IAS indicators. (1) These indicators were reviewed to determine their policy-relevance classified according to their ability to inform on each dimension of the DPSR model (Driver-Pressure-State-Response) and the Theory of Change framework (as Input, Process, Output, Outcome, or Impact indicators). (2) The properties of each indicator were then assessed against eight criteria determining their scientific validity

IAS policy targets. Finally, we provide guidance on the type and properties of indicators that are still needed to inform global environmental policies on IAS, particularly the Post-2020 Global Biodiversity Framework.

2 | METHODS

2.1 | Approach and data collection

A three-step approach was taken to evaluate the extent to which existing indicators are adequate for monitoring progress toward meeting invasion goals and targets (Figure 1). First, we conducted a systematic literature search to identify published indicators in the peer-reviewed invasion science literature (Section 2.2). We followed protocols and guidelines for systematic literature reviews (O'Dea et al., 2021), including keywords from well-established literature on invasion science, environmental indicators, and biodiversity monitoring (Table S1). To minimize linguistic uncertainty, a common feature in invasion science (McGeoch et al., 2012), we included known synonyms for alien species and invasion-related terms. As a result, our search string included a broad set of relevant keywords, combined with relevant Boolean operators and characters. The literature search was conducted in June 2020 using ISI Web of Science (ISI WoS; http://webofknowledge.com/), Scopus (https://www.scopus.com/), and Google Scholar (http://scholar.google.com) search engines. Records retrieved from these databases were combined, resulting in a total of 501 unduplicated records. We did not consider indicators that had not been peer-reviewed, that is, from gray literature including government and other agency reports, as we consider peer-review to be the minimum essential criterion for an indicator to be used in monitoring and policy reporting.

Each record was subjected to an inclusion/exclusion procedure to remove unsuitable records (e.g., records on topics such as aliens/invaders from outer space; see supporting information S1 for details). Only papers that demonstrated the application of the indicators mentioned, using data (empirical or simulated). were included, that is, publications that simply suggested or listed desirable indicators were excluded. The final set included 27 relevant peer reviewed journal publications that contained one or more invasion-related indicators. Each indicator was then classified according to their policy relevance and scientific validity using a set of criteria (Section 2.2.2). Finally, we grouped and ranked the performance of indicators, against this set of desirable properties (Table 1), to assess and measure progress toward IAS policy targets, particularly those of the Convention on Biological Diversity and Sustainable Development Goals (Section 2.3). Importantly, our purpose here was to evaluate indicators against a set

TABLE 1 Eight properties used to assess and classify the policy relevance and scientific validity of each indicator monitoring the status of IAS

Rational	Review categories
1. Established	
Information derived from an indicator, which has already been tested and applied in a range of situations and contexts, will be in principle more reliable than that from an indicator, which has been proposed but not yet validated.	*Established: the indicator has been proposed, tested, and applied to inform on range of situations.
	Not established: the indicator is being proposed and defined for the first time and had not been yet tested or applied to any situation.
2. Spatially explicit	
Spatially explicit information enables an increasingly space-conscious capture of IAS trends and provides critical spatial sensitivity and flexibility for monitoring of IAS numbers, distributions, and impacts. Linking the data that underpin indicators to specific places—fine or course grain as possible—makes an indicator more valuable to local, national, or regional management, and possible to disaggregate to application at finer scales.	*Spatially explicit: the indicator provides information that can be linked to a specific spatial location (e.g., a site, region, and country) so that its features can be associated with that location.
	Not spatially explicit: the indicator does not provide information that can be linked to a spatial location.
3. Scalable	
Scalability enables the application of the indicator at the relevant spatial extent, a robust indicator should hence be reproducible at multiple, distinct spatial scales. Scalability allows data collected for indicators at national scale to be meaningfully aggregated for use at international scales (and vice versa).	*Scalable: the indicator is calculated through a hierarchy of nested spatial grains, i.e., scalable up or down.
	Not scalable: the indicator is not calculated over different spatial grains and does not provide clear indication on how to calculate it beyond the scale for which it was created.
4. Temporal	
The availability of temporal information that is timed and of a duration relevant to informing on the status and trends of IAS. The indicator should be designed so that it can be recalculated over time to support the monitoring of IAS-relevant change.	*Temporal: the indicator includes a temporal dimension (is expressed as a trend), being calculated for a particular time, and is periodically updated.
	Somewhat temporal: the indicator is not specifically designed to have a temporal dimension (be expressed as a trend), but it provides clear indication that it can be repeated in future if data is collected for this purpose.
	Not temporal: the indicator is not designed to be recalculated in future nor does it provide clear indication that would allow calculation of a trend.
5. Uncertainty appraisal	
The presentation of measurements of uncertainty for informing on IAS trends and status represents a key aspect of any evaluation approach, with implications for implementation and reproducibility. This provides scientists and decision makers with information on the degree of confidence in the indicator message.	*Quantitative uncertainty: the indicator reports a quantitative measure of uncertainty.

(Continues)

TABLE 1 (Continued)

Rational	Review categories
	Qualitative uncertainty: the indicator reports a qualitative measure of uncertainty.
	No uncertainty: no uncertainty measure is reported with the indicator.
6. Taxonomic representativeness	
To address a range of policy or decision-support requirements, the information provided by an indicator should be applicable to a range of IAS taxonomic groups.	*Representative: the indicator is presented as a general indicator that can be, by design, applied to any taxa.
	Somewhat representative: the indicator is designed or applied to a particular species or taxon but provides clear indication that it can be transferred to other taxa.
	Not representative: the indicator is specifically designed for a particular species or taxon and it does not clearly indicate whether it can be transferred to other taxa.
7. Invasive alien species (IAS) specificity	
Sound measurement of progress toward preventing and controlling IAS requires indicators that use (IAS) species data (Note: this property is not applicable to some indicator types).	*IAS specific: the indicator has been calculated using IAS specific data and not proxy data that can be used to infer on IAS. This property is particularly relevant for Pressure indicators.
	Not specific: the indicator is proposed and calculated using proxy data on IAS.
8. Reproducible	
Reproducibility is essential for any communication, scientific and political goal, as it allows availability, repeatability, standardization, and archiving in support of information harmonization, integration, use, and transparency.	*Reproducible: the data necessary to populate the indicator are accessible and available for public use and indications on how to calculate the indicator are provided.
	Somewhat reproducible: data necessary to populate the indicator is not explicitly indicated as accessible, yet indications on how to calculate the indicator and get the necessary data are provided.
	Not reproducible: the data are not available for public use nor they contain explicit instructions to calculate it.

*Properties that are most desirable of an adequate IAS indicator.

of relevance and scientific properties for the purpose of national to global reporting, and was not an evaluation of the performance of the indicator in the original content within which it was published.

2.2 | Review categories

2.2.1 | Policy relevance: invasion goals, targets, and indicators in multinational agreements

In its 2011–2020 Biodiversity Framework, the CBD described seven "Generic Indicators" for monitoring progress toward meeting Aichi Target 9. In short, these indicators provide information on the identification, number, distribution and impact of IAS, as well as the implementation of policy responses (CBD, 2016; McGeoch & Jetz, 2019). The Post-2020 Biodiversity Framework proposes the use of the Driver-Pressure-State-Response (DPSR) and Theory of Change (ToC) frameworks in the design of informative indicators (OECD, 2019). In the context of IAS, the DPSR framework distinguishes individual invasion indicators based on the underlying pathways for IAS (Drivers; e.g., trade or transport), indicators of IAS change (Pressure; e.g., number or abundance of IAS), biophysical conditions or state as a consequence of IAS impacts (State; e.g., number of impacted native species), and societal responses to IAS (Response; e.g., actions to control IAS) (McGeoch et al., 2010, 2015). Response indicators can be further compartmentalized, according to the Theory of Change (ToC) framework, into indicators of inputs (i.e., resources needed for a response, e.g., budget or staff), processes (i.e., progress of the response that uses inputs; e.g., committees or actions), outputs (i.e., measure of the amount and quality of the response results; e.g., research, reports or policy instruments), outcomes (i.e., IAS changes resulting from the response action; e.g., number or abundance of IAS taxa), and impacts (i.e., measures of the improved condition of the invaded site). While the particular wording and scope of invasion-related goals, targets, and indicators in multinational agreements change across reporting cycles, the DPSR and ToC frameworks provide stable, sustainable frameworks for formulating and assessing the indicators needed to monitor and bring about change (see McGeoch & Jetz, 2019) and were therefore used here for assessing the policy relevance of existing IAS indicators.

2.2.2 | Scientific properties of indicators to inform and monitor ecological change

Fundamental properties for the design of environmental indicators, including those focused on biological invasions, should include their scientific validity and the extent to which they can be efficiently communicated (i.e., readily communicated, not prone to misinterpretation, and with clear quantification and communication of uncertainty; Jetz et al., 2019; OECD, 2019). Grounded on this premise, we used eight properties (Table 1) to assess and represent the degree to which an indicator is scientifically valid and communicable (Balmford et al., 2005; Collen & Nicholson, 2014; Jetz et al., 2019). Some properties may not be relevant to particular indicators, although most will be essential to any indicator, and the more of these properties an indicator has the more informative and effective it is likely to be (Table 1).

2.3 | Indicator classification and ranking

Each indicator identified in the systematic review was subjected to three types of information extraction and subsequent classification. First, information was extracted on: (a) the spatial extent and region of focus (e.g., particular country, continent, region, or global); (b) the temporal range of the assessment (e.g., at a particular point in time, or through a temporal range); (c) the main type of ecosystem under analysis (i.e., terrestrial, marine or freshwater); and (d) the targeted IAS taxa (e.g., plants, mammals, and birds). Second, we categorized each indicator according to which of the DPSR and Theory of Change components was most relevant (Section 2.2.1). Third, we recorded how well each indicator aligned with the eight properties of scientific validity in Table 1.

We ranked each indicator, using equally weighted scoring, in which a value of one was attributed whenever the indicator met the desirable property. An effective and informative indicator of IAS should have as many of the suite of desirable properties for indicators described in Table 1 as relevant (see also Balmford et al., 2005; Collen & Nicholson, 2014; Jetz et al., 2019). The property being IAS-specific (i.e., not using proxy data) (Table 1 [7]) will not be relevant to all indicators, and indicators that summed to either seven or eight were therefore considered most scientifically valid compared to those with fewer desirable properties (Table 1).

3 | RESULTS

3.1 | General characterization of IAS indicators

We identified a total of 61 indicators from 27 publications (Tables S2 and S3), with publication dates ranging from 2005 to 2019. Most indicators were produced at a national (~31%) or continental (~31%) scale. Indicators expressed at a subnational region (e.g., protected area or natural region) or at the global scale each contributed ~18% of the data set. Most of the reviewed IAS indicators have been either tested in, or applied to, European countries (~28%) or South Africa (~23%), with 20% global in scope (Figure 2). Other regions with IAS indicator development were Antarctica (~11%) and North America (i.e., the United States and Canada; ~8%), with remaining small proportions in Australia, Asia (i.e., China and India; ~3%), South America (i.e., Brazil), and the Mediterranean Sea (~2%; Figure 2). Many indicators were relevant to multiple environments ($n = 24$), or were either terrestrial ($n = 26$), marine ($n = 5$), or freshwater specific ($n = 5$). Most indicators covered multiple IAS taxa ($n = 26$) with some plant ($n = 17$) or animal ($n = 8$) focused. For the latter, and when specified, indicators focused on birds ($n = 3$), fishes ($n = 2$), or mammals ($n = 2$).

3.2 | Representation of DPSR and Theory of Change across indicators

In general, Pressure indicators were most common, accounting for ~46% of the indicators identified, followed by Response (~25%), State (~18%), and Driver (~12%) categories (Figures 2 and 3). IAS change measurements (i.e., Pressures) included the number, frequency, abundance, density, cover or area of introduced, established or invasive alien species. Indicators on IAS pathways (i.e., Drivers) were quantified as the number of species vectors (e.g.,

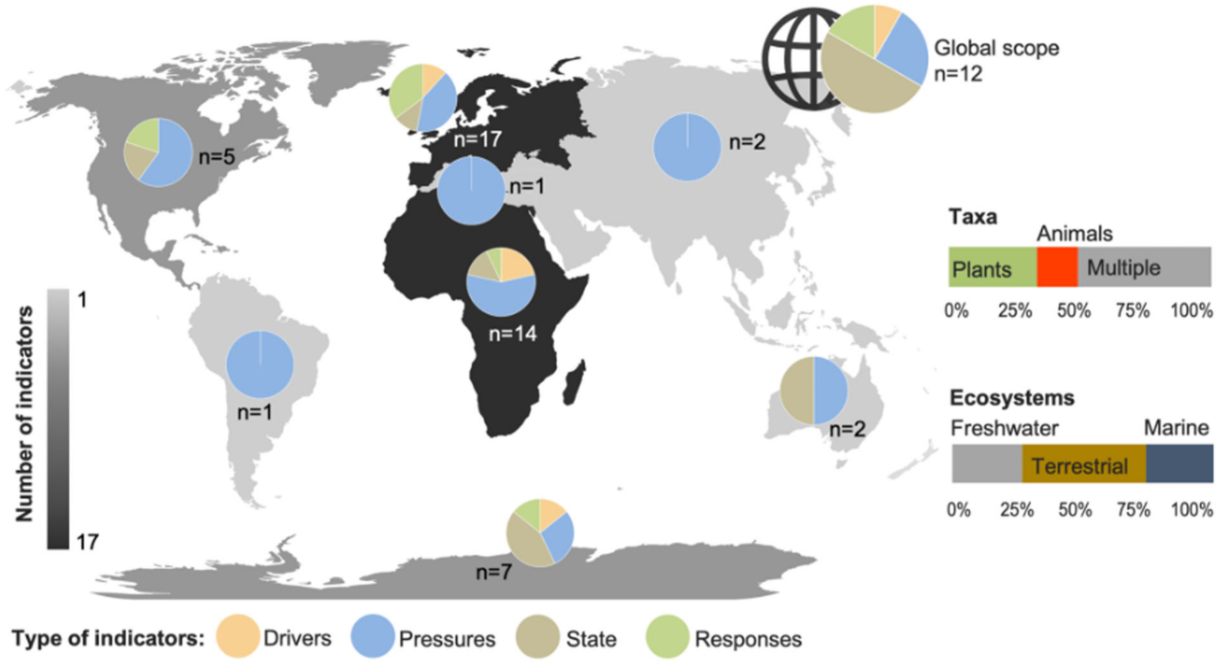

FIGURE 2 Left panel: Number of indicators found per continent and their classification into each DPSR category: Drivers, Pressures, State, and Responses, as well as 12 with a global scope. Right panel: The proportion of indicators applied to particular taxa (plants, animals, or multiple taxa) (right) and environments (i.e., terrestrial, marine, and freshwater)

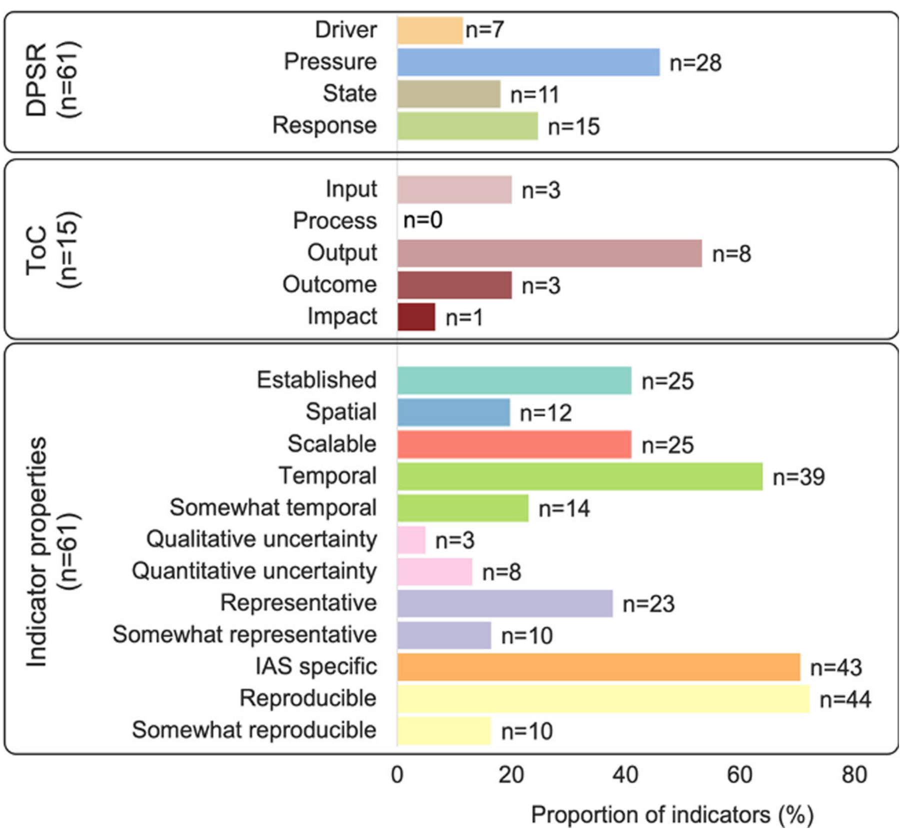

FIGURE 3 The proportion of indicators of policy relevance (DPSR and Theory of Change: ToC) and with desirable scientific validity properties (Table 1) of the 61 reviewed indicators (n, number of indicators)

vessels), activities associated with invasion risk (e.g., tourism), or the use of socioeconomic indices as proxies for drivers of invasion risk (e.g., Gross Domestic Product, GDP; Human Development Index, HDI; McGeoch et al., 2010). IAS impacts (i.e., State) were expressed by changes in the Red List Index, ecosystem services, or relative proportion of alien to native taxa.

Response indicators in the five Theory of Change categories primarily expressed the Output ($n = 8$) of societal responses to IAS, evaluated as the number of relevant policies, agreements, or management plans for IAS (Figure 3). Response indicators on Inputs ($n = 3$) mostly captured the expenditures and costs of management actions, whereas indicators of Outcomes ($n = 3$) measured changes in the number or abundance of IAS taxa in response to management actions. Only one Response indicator focused on Impacts, measured as improved condition in a freshwater system (a blue-green algal index) after removal of invasive carp (indicator R1 in Table S3). No Process-oriented Response indicators were identified.

3.3 | Properties of IAS indicators

Overall, ~41% of all indicators were classified as established, that is, had already been tested and applied for the purpose of management or policy reporting (Figure 3). Only 20% of indicators were spatially explicit. Most indicators (~59%) were not scalable; that is, they could not be generalized upward or downward through a hierarchy of spatial grains. In ~64% of cases, the indicator was specifically designed to have a temporal dimension, or at least be repeatedly calculated in the future (~23%) (Figure 3). Most indicators (~75%) had no associated measure of uncertainty, while comparatively few were associated a quantitative (~13%) or qualitative (~5%) measure of uncertainty. Most indicators (~37%) could potentially be applied to multiple IAS taxonomic groups (~16%), and the majority (~70%) of indicators were developed using IAS-specific (rather than proxy) information. Finally, ~72% of the indicators were considered reproducible, in the sense that the data necessary to populate the indicator were accessible and available, and clear instructions on how to calculate the indicator were provided. For ~16% of indicators, clear instructions were provided on how to obtain the data or compute the indicator; however, the data were not clearly indicated as accessible (Figure 3).

3.4 | Individual indicator performance

Assessed against the desirable properties of an ideal indicator, the most complete indicators of IAS Drivers included five of the eight desirable properties (D1, D4, D6; Figure 4). Two of these indicators focused on the pathways of introduction and spread of alien or invasive species at the continental (D1) or national scale (D6), being considered established, replicable, reproducible, IAS specific and with a temporal dimension. The remaining Driver indicator reported on socioeconomic drivers of invasions (e.g., GDP, HDI) at the global scope, being considered replicable, reproducible, IAS specific and temporal, and providing a quantification of uncertainty (Table 2).

One pressure indicator met the eight desirable properties (P5) and two met seven, either not being spatial explicit (P3) or reporting on uncertainty (P23). These indicators measured the number or richness of alien or invasive alien taxa, applied to marine (P3), freshwater (P5), and terrestrial systems (P23), in the Mediterranean Sea, the United States, and South Africa, respectively.

State indicators achieved a maximum of five desirable properties. All these applied to Europe and were replicable, reproducible, scalable, and temporal. Only one of these indicators was established, but not IAS specific (S1). The remaining two, although not established, were IAS-specific (S2, S3). State indicators reported on the number of outbreaks or diseases associated with IAS (S3), the number of ecosystem services affected by IAS (S2), and included the Red List Index of IAS (S1; Figure 4). The most complete indicator in the Response component reported on the number of IAS eradications in Antarctica (in the Outcome category) and included seven desirable properties, failing to report uncertainty in the assessment (R6; Figure 4).

4 | DISCUSSION

Most existing, peer-reviewed invasion indicators were found to be inadequate when assessed against the desirable properties for measuring and/or reporting on progress toward reaching global biodiversity targets that are aimed at reducing the effects of IAS. Existing indicators do align well with policy relevant dimensions (see also Mcowen et al., 2016), and the Driver, Pressure and State indicator categories are represented by multiple indicators (Table 2). However, we found that the very category of indicator that has been identified as instrumental to bringing about the progress needed toward global biodiversity goals and targets post 2020 were sparsely represented by existing indicators, i.e. the Response indicators (OECD, 2019). In particular, the "process," "outcomes," and "impacts" of actions to prevent and control IAS are poorly covered by existing indicators. Commonly missing properties of existing indicators were measures of uncertainty and the inclusion of spatially explicit information.

TABLE 2 Alignment of policy targets and policy-identified indicators with the most relevant and complete (meeting most of the scientific validity properties)

Policy target	Target element	Suggested policy indicator	Most relevant and complete peer-reviewed indicators (indicator review number in brackets)*
DRIVER category (DPSR Framework)			
Aichi Target 9	Invasive alien species pathways identified and prioritized	None	• Pathways of invasions (D1)[1] • Socioeconomic drivers of invasion (D4)[2] • Number of taxa introduced via different pathways (D6)[3]
SDG 15.8	Introduce measures to prevent the introduction	None	
GBF Target 6	Manage pathways for the introduction of invasive alien species (5.1)	Identification, control, and management of pathways for introduction of invasive alien species	
PRESSURE category (DPSR Framework)			
Aichi Target 9	Invasive alien species identified and prioritized	Trends in number of invasive alien species	• Numbers of alien species in the Mediterranean by taxonomic group (P3)[4] • Aquatic invasive alien species richness (P5)[5] • Invasive alien plant species richness (P23)[3]
GBF Target 6	Effective detection, identification, prioritization, and monitoring of invasive alien species (5.2)	• Numbers of invasive alien species introduction events (5.1.1) • An established an alert system for prevention and control of IAS (5.1.2) • Number of invasive alien species in national lists as per the Global Register of Introduced and Invasive Species (t5.1) • Proportion of countries adopting relevant national legislation and adequately resourcing the prevention or control of invasive alien species (t5.2)	

(Continues)

TABLE 2 (Continued)

Policy target	Target element	Suggested policy indicator	Most relevant and complete peer-reviewed indicators (indicator review number in brackets)*
GBF Target 6	Prevent or reduce their rate of introduction and establishment	Rate of invasive alien species spread	
STATE category (DPSR Framework)			
Aichi Target 9	*No directly linked element*	Trends in the impact of invasive alien species on extinction risk trends	• The Red List Index of Invasive Alien Species (S1, S7, S8)[1,8,9] • An indicator of IAS impacts on ecosystem services (S2)[1] • Trends in incidence of livestock diseases (S3)[1]
SDG 15.8	Significantly reduce the impact of invasive alien species on land and water ecosystems	None (although reports on Trends in the impact of invasive alien species on extinction risk trends)	
GBF Target 6	Eliminate or reduce the impacts of invasive alien species (5.4)	Rate of invasive alien species impact	
RESPONSE category (DPSR Framework) [ToC subcategory]			
SDG 15.8	*No directly linked element*	Proportion of countries adequately resourcing the prevention or control of invasive alien species **[Input]**	
SDG 15.8	*No directly linked element*	Proportion of countries adopting relevant national legislation **[Process]**	
GBF Target 6	Establishment of measures for eradication, control, and management of invasive alien species (5.3)	Rate of invasive alien species eradication by species type (5.3.1) **[Process]**	

(Continues)

TABLE 2 (Continued)

Policy target	Target element	Suggested policy indicator	Most relevant and complete peer-reviewed indicators (indicator review number in brackets)*
Aichi Target 9	Priority species controlled or eradicated	None	• Trends in invasive alien species eradications (R6)[6]
SDG 15.8	Control or eradicate the priority species	None	
GBF Target 6	Eradicate, control or management of invasive alien species in priority sites (5.5)	Proportion of key biodiversity areas threatened by invasive alien species (5.5.1) **[Outcome]**	
GBF Target 6	Eliminated or reduced impacts of invasive alien species (5.4)	• Rate of invasive alien species impact (5.0.2) • Red List Index (impacts of invasive alien species) (5.4.1) **[Impact]**	• The Red List Index of Invasive Alien Species (S1, S7, S8)[1,8,9]

*Listing of peer-reviewed indicators here (right column) does not imply that the indicator is necessarily perfectly suited to reporting on the policy target and its elements, rather simply that this indicator came closest to being most relevant and having the most desirable properties. In addition, as outlined in the text, single indicators in some instances are relevant to multiple categories and target elements.

SDG, Sustainable Development Goals; GBF, Post-2020 Global Biodiversity Framework (as proposed, CBD/SBSTTA/24/3Add.1); DPSR, Driver, Pressure, State, Response Framework; ToC, Theory of Change.

[1]Rabitsch et al. (2016).
[2]Sharma et al. (2010).
[3]Wilson et al. (2018).
[4]Zenetos et al. (2017).
[5]Shaker et al. (2017).
[6]McGeoch et al. (2015).
[8]Butchart (2008).
[9]McGeoch et al. (2010).

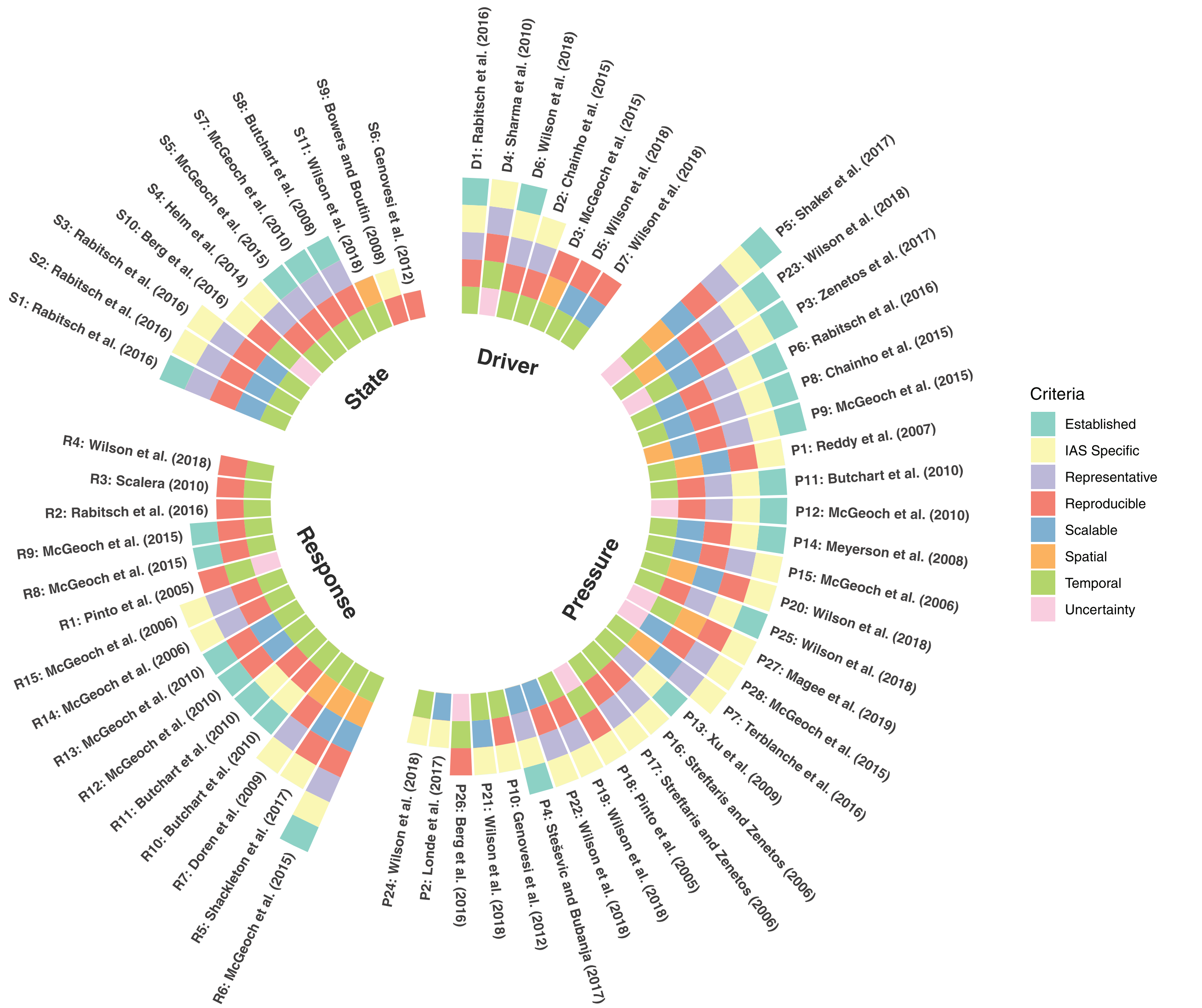

FIGURE 4 The distribution of desirable properties (criteria) for reporting on IAS goals and targets across existing indicators of invasion drivers, pressures, state and response. The taller the bar, the more desired properties the indicator has (Indicator numbers (D1, S1, etc.) and details are provided in Table S3 and Figure S1). The eight desired indicator properties are outlined in Table 1 (note that IAS-specific is particularly desirable for Pressure indicators). The indicators are ordered from more complete (taller bars) to less complete indicators (shorter)

Despite variation in the terminology used to frame invasion-related goals and targets, both within and across multinational agreements and policy reporting cycles, the essential variables required to monitor progress remain unchanged (Latombe et al., 2017; McGeoch & Jetz, 2019). CBD and SDG goals and targets to date, including the current first draft Post-2020 Global Biodiversity Framework (CBD Secretariat, 2021), have variously included pathway identification and prioritization (Drivers); the identification, prioritization, and trends in IAS and their impacts (Pressure); the mechanisms and severity of IAS impacts to threatened species and priority sites and ecosystems (State); and a range of responses from managing pathways and priority species, allocation of resources, legislation, and the adoption of relevant policies, preventing introduction and spread, and controlling and eradicating species (Response; Essl et al., 2020; McGeoch et al., 2010) (Table 2). The DPSR model and its ToC expansion are likely to remain relevant for framing invasion indicators for the foreseeable future, both in terms of policy relevance and in terms of existing investment in indicator research. Sustained investment in invasion indicators for national and global reporting within the DPSR and ToC frameworks would therefore maintain their policy alignment, and further development within these would strengthen their policy relevance.

4.1 | Driver indicators

Identification of invasion pathways was the most common Driver indicator, although few had many of the desirable properties. For example, four pathway metrics have been proposed for South Africa, including information on pathway size, introduction rates, within country prominence and within country dispersal rate (Wilson et al., 2018). However, the information required to populate this indicator for all countries, and at a global scale, is unlikely to be currently available across taxa. An alternative, albeit less comprehensive, indicator is the cumulative numbers of alien arthropods introduced by each pathway category (Horticulture/Ornamentals, Stored product pests, Biological control, Forestry, Unknown) (Rabitsch et al., 2016). However, spatial information at the necessary grain would need to be collated and made available to calculate a spatially explicit pathway indicator of this type. Progress collating data on a standard suite of invasion pathways used across invasive alien taxa (Harrower et al., 2018), in addition to the incorporation of pathway information in Darwin Core (Groom et al., 2019), are steps toward future development and adoption of an invasion pathways indicator (Faulkner et al., 2020; Galanidi & Zenetos, 2022; McGrannachan et al., 2021; Pergl et al., 2020).

4.2 | Pressure indicators

Indicators for reporting on "Trends in the distributions and populations of IAS" were more frequent than other framework components, with many deemed largely adequate (Sharma et al., 2010; Zenetos et al., 2017; Wilson et al., 2018). However, although meeting at most five of the seven desirable features, most were neither spatially explicit, nor were designed to provide trend (temporal) information. Likewise, for indicators to report on the spread and population expansion of invasive alien species, long-term data on species distributions across taxa needs to be collected, curated, easily accessible, and gathered from dedicated long-term monitoring. A "whole of knowledge-system" approach, supported by Essential Biodiversity Variables (EBV) for species populations (Jetz et al., 2019) and approaches to develop and support country-level data generation (Latombe et al., 2017), has been proposed for the sustainable delivery of invasive alien species information for policy and management (McGeoch & Jetz, 2019). The EBV approach includes the pipeline from raw data from multiple sources to the production of indicators based on modeled species distribution and abundance data; although abundance-based indicators are likely to most feasible and relevant at selected and local management scales (Jetz et al., 2019; Staehr et al., 2020). Modeling solutions are needed to overcome data biases and produce robust metrics that can be used to infer establishment events over time. For example, the Global Register of Introduced and Invasive Species (GRIIS) provides species checklists that are available as a baseline and mechanism for tracking species numbers at a country scale and global scope (Pagad et al., 2018, 2022). Countries participating in GRIIS have committed to regularly update their IAS data in this database. Additionally, recently developed supportive tools (e.g., Arlé et al., 2021; Seebens et al., 2020) could help to improve data integration and minimize uncertainties in data underlying IAS indicators.

4.3 | State indicators

Indicators developed for monitoring the consequences of IAS introductions encompass impacts on native species, communities, habitats, and ecosystems (Supporting Information S1). The IUCN Red List Index for species impacted by IAS is the most well-developed and regularly used (Butchart, 2008). Although some IAS impact indicators have been developed that focus on native communities or ecosystems, they are not well-established, lack most desirable properties, and thus provide opportunities for further indicator development. This is a particularly pressing research endeavor given that the "Rate of invasive alien species impacts" was originally proposed as one of the Headline Indicators for Target 6 in the draft Post-2020 Global Biodiversity Framework. One reason for the lack of adequate impact indicators is the complexity, inherent context dependence, and often idiosyncratic nature of environmental impacts (Pyšek et al., 2020a); thus generalizations to other geographic areas and spatial scales are difficult. In one attempt to overcome this, the IUCN has adopted the Environmental Impact Classification for Alien Taxa (EICAT) for classifying and quantifying the impacts of particular IAS (Hawkins et al., 2015). However, to date no indicators have yet been developed using this as an information source. More assessments that capture information on the taxonomic and geographic variability of environmental impacts are required for a suitable impact indicator to be populated.

4.4 | Response indicators

Recent advancements in policy-relevant indicators have recognized the importance of Response indicators for capturing the various types of interventions necessary for progress, using ToC to identify five essential response categories (OECD, 2019). While this is a significant step toward improving implementation of policy for IAS and directing transformative change, ToC indicators for IAS are particularly underdeveloped relative to the other DPSR categories. No indicators exist for tracking IAS prevention and control processes (Process Response indicators), such as mechanisms of implementation via working groups or committees responsible for overseeing the implementation of collaborative management programs. There were few Outcome- and Impact Response indicators for measuring the success of policy and management actions, and those found were local or regional in scale and mostly focused on individual species. A decline in pressure from IAS measured using Pressure indicators could be considered an option for tracking changes in IAS as a cumulative outcome of other responses to deal with IAS. In the same way, improvements in the conservation status of species threatened by IAS, tracked using the existing IUCN Red List Index for IAS (Butchart, 2008), could be considered an indicator for the Response Impacts ToC category. There were also only three indicators for tracking investment in IAS management and research (Input-Response), with one in Africa and two in Europe. The recent publication of a global data set on the costs of invasive alien species (Diagne et al., 2020) could potentially be used as a basis for an Input-Response indicator that meets more of the desirable properties for such an indicator.

The most prominent and established IAS Response indicator was "Trends in the adoption of relevant policy." Monitoring the adoption of both national and intergovernmental policies aimed at preventing and/or controlling IAS has been proposed at a range of administrative levels. However, the collation and provision of data on the implementation and success of management responses to IAS, at any administrative level, is lacking (Leadley et al., 2014). Few countries appear to have accessible data of this nature, although on-ground policy implementation via such management provides a more powerful indicator of likely progress than the intention to act implied by a country committing to a relevant policy instrument.

4.5 | Prospects for IAS indicator development

Relative to many other topics in invasion biology, 27 is a modest number of publications to have developed, demonstrated, tested, or reported on the results of IAS indicators. In addition, the number of publications and indicators are thinly spread across the multiple indicator categories, that is, across the DPSR and ToC frameworks. This is despite invasive alien species position among the top five threats to biodiversity and ecosystems (Díaz et al., 2019), and the clear policy requirements for such indicators identified by the goals and targets of the CBD's strategic plans and those of the Sustainable Development Goals. While it is not necessary and may even be undesirable to have many competing or noncomparable indicators for the same biodiversity change phenomenon, it is necessary to have robust and dynamic indicators, applicable across scales, environments, taxa, stages of invasion and of the policy to management response process.

Progress with policy-relevant data collation has been significant over the last decade and useful information sources continue to become available (e.g., Dyer et al., 2017; Pagad et al., 2022; van Kleunen et al., 2018). However, to ensure that the applied benefits of these data collation efforts are realized, policy relevant invasion indicators that use these data and that meet multiple criteria need to be developed, adopted, and supported. The Essential Biodiversity Variable approach provides a methodological avenue for achieving this (McGeoch & Jetz, 2019). In parallel, it is essential that the research community continue to increase and improve the quantity and quality of the data needed to populate these indicators.

A number of specific recommendations arise from the results of this review to improve the adequacy of indicators for measuring and reporting on progress toward reaching global biodiversity targets that are aimed at reducing the spread and effects of IAS.

- The policy relevance of invasion indicators would be strengthened by a sustained investment in indicators for national and global reporting, ensuring that key, persistent dimensions of the invasion problem are tracked consistently for long enough to assess the effectiveness of response interventions.
- Multiple indicators are needed to adequately track the threat of biological invasions, and the DPSR and ToC frameworks will remain relevant for framing invasion indicators for the foreseeable future, both in terms of policy relevance and in terms of existing investment in indicator research. When clearly linked to these frameworks and to the information cycle (see McGeoch & Jetz, 2019), single indicators can inform on multiple target elements. Properly designed this could lead to efficiencies and stability in policy reporting for IAS.
- Particular attention should be paid to including measures of uncertainty alongside indicators, such as confidence limits. As far as possible, spatially explicit information should also be captured so that indicators can be scaled across as many local to subnational scales as relevant.
- Solutions are needed to overcome data biases and produce robust metrics that can be used to infer establishment events over time. For example, the Global

Register of Introduced and Invasive Species—GRIIS—that provides species checklists is available as a baseline and mechanism for tracking species numbers at a country scale and global scope (Pagad et al., 2018, 2022). If countries participating in GRIIS commit to regularly updating their Country Checklists this resource could become a valuable basis for tracking the global spread of IAS.
- Rapid advances in biodiversity informatics and recently developed support tools (e.g., Arlé et al., 2021; McGeoch & Jetz, 2019; Seebens et al., 2020) can help to improve data integration and minimize uncertainties in data underlying IAS indicators.
- Research investment in quantifying the taxonomic and geographic variability of environmental impacts will benefit future indicators for tracking the impacts of IAS.
- Monitoring the adoption of both national and intergovernmental policies aimed at preventing and/or controlling IAS has been proposed at a range of administrative levels. However, the collation and provision of data on the implementation and success of management responses to IAS, at any administrative level, is a significant gap (Leadley et al., 2014). Few countries appear to have accessible data of this nature and investing in monitoring the effectiveness of interventions at local and national scales is a priority in line with the Theory of Change indicator framework.

The outcomes and directions provided by this review will, we hope, assist governments as they work to implement IAS policy and report on progress to reducing the impact and limiting the spread of alien species harmful to biodiversity and ecosystems.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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