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Invasion trends: An interpretable measure of change is needed to support policy targets

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All authors designed the general idea, led by MMG and MW. YB, JB built the model and simulated the scenarios, EA built the country level scenarios. MMG, YB, JB wrote the first manuscript draft. All authors contributed to the writing.

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Abstract

The Kunming-Montreal Global Biodiversity Framework (GBF) calls for a 50% reduction in rates of invasive alien species establishment by 2030. However, estimating changes in rates of introduction and establishment is far from straightforward, particularly on a national scale. Variation in survey effort over time, the absence of data on survey effort, and aspects of the invasion process itself interact in ways that make rate estimates from naive models of invasion trends inaccurate. To support progress towards robust global and national reporting against the GBF invasions target, we illustrate this problem using a combination of simulations, and global and national scale case studies. We provide recommendations and a clear set of steps that are needed for progress. These include routine collection of survey effort data as part of surveillance and monitoring protocols and working closely with researchers to develop meaningful estimates of change in biological invasions. Better awareness of this challenge and investment in developing robust approaches will be required from Parties if progress on Target 6 of the GBF is to be tracked and achieved.

KEYWORDS

Invasive alien species, Convention on Biological Diversity, Global Biodiversity Monitoring Framework, Target 6, species populations data, Essential Biodiversity Variables, survey effort, rate of establishment, EU's biodiversity strategy 2030

1 | WHY A PERSISTENT FOCUS ON INVASION TRENDS?

The documented numbers of alien species in new locations have continued to increase over recent decades (Seebens et al. 2017). Evidence of known drivers, patterns, and pathways of invasion has also grown significantly (e.g., Capinha et al. 2023), adding impetus to the message that this invasion load (numbers of invasive alien species (IAS) (**Table 1**(1)) and populations) and associated risks of socioeconomic and environmental impacts continue to increase (Diagne et al. 2020). Target 6 of the recently adopted Kunming-Montreal Global Biodiversity Framework (GBF) of the Convention on Biological Diversity (CBD) specifies, *inter alia*, reducing the rate of introduction and establishment of IAS by at least 50% by 2030 (CBD/COP/DEC/15/4). The associated headline indicator is 'Rate of invasive alien species establishment' (CBD/COP/DEC/15/5), pointing to a policy-driven need to quantify and estimate introduction (**Table 1**(2)) rates. To report on this biodiversity target, authorities need robust indicators that track invasion trends (**Table 1**(3)), and derived estimates of IAS introduction rate (**Table 1**(4)).

Trends in the observed number of IAS in an area (expressed per unit time or cumulatively), from which rates of introduction are estimated, are among the most long-standing and frequently referred-to indicators of biological invasions (Butchart et al. 2010; Tittensor et al. 2014; Seebens et al. 2017). Such time series are an intuitive way to visualize and interpret the increase in biological invasions (e.g., Mormul et al. 2022). However, investment in IAS surveillance and monitoring (referred to as 'survey effort' here (**Table 1**(5)) is spatially and temporally variable and the true number of introduced species is different from the observed number, i.e., the process by which IAS are introduced is unobservable) (Solow and Costello 2004). Furthermore, the GBF specifically calls for investment in updating and maintaining IAS data, and for better data standards, although it does not refer specifically to data on survey effort. As we demonstrate here, trends of observed numbers of introductions are, on their own, almost certainly misleading. This widely underappreciated problem must be addressed if estimates of introduction rates are to inform the GBF and decision-making on IAS in the coming years.

2 | HOW INTRODUCTION RATES BASED ON OBSERVATION DATA MISLEAD

High and increasing rates of IAS introduction are a reason for concern at all spatial scales. They suggest that prevention and control measures have not been sufficient. On the contrary, low or declining introduction rates suggest that prevention efforts are succeeding. However, the difficulty of accurately estimating such invasion trends, first raised two decades ago (e.g., Solow and Costello 2004), remains largely underappreciated in both scientific and indicator selection and development communities. The problem arises from the fact that the observed number of new IAS (**Table 1**(6)) over time is a function of both (1) the true rates of introduction of new alien species (i.e., the invasion process) and (2) the survey effort. As we show here, temporally and spatially variable survey effort can have a substantial effect on the form and slope of invasion trends and therefore on estimates of the introduction rate.

Inferring IAS introduction rates directly from the raw numbers of newly observed introductions neglects the fact that survey effort influences the counts of IAS (Solow and Costello 2004; Belmaker et al. 2009). Simulating different patterns of variation in the survey effort over time shows how a range of invasion trends result (**Fig. 1B**) even when the true number of introductions per unit time is constant (**Fig. 1A**). Both the true numbers of newly introduced IAS (i.e., all species, observed and not observed) and survey effort are likely to vary over time. Even when species introductions and survey effort are constant over time (**Fig. 1,** black line), the numbers of new species observations can still appear to be accelerating (e.g., **Fig. 1**, green dashed line). This is because with inadequate survey effort the number of unobserved IAS accumulate through time, and as a result even a constant survey effort over time with the same baseline introduction rate will appear to show an increasing number of IAS (Wonham and Pachepsky 2006). Therefore, variation in survey effort alone can produce strongly positive invasion trends and thus apparently positive invasion rates (Solow and Costello 2004; Wonham and Pachepsky 2006; Belmaker et al. 2009) (**Fig. 1**). This means that percentage reductions in introduction rate, such as the 50% called for by GBF Target 6, cannot naively be estimated from IAS observations alone, and the inferences from trends in IAS observations are likely to be wrong if survey effort is not considered.

Many different potential scenarios exist for: 1) the impact of survey effort on observed invasion trends; 2) the implication of each of these scenarios for understanding how invasion is changing; and 3) levels of certainty about national and multinational policy success (**Fig. 2**). Interpretations range from a high risk of underestimating new introductions (left column, scenarios 1, 4 and 7, **Fig. 2**), to high and increasingly certain evidence that the success of prevention efforts is being accurately evaluated (right column, scenarios 3 and 6, **Fig. 2**). However, there is currently no available and comparable data on survey effort at national scales.

The simulated example (**Fig. 1**), and the alternative possible scenarios for the impact of survey effort on interpreting invasion trends (**Fig. 2**), demonstrate the challenge of using IAS introduction rates as indicators for biodiversity policy reporting. Below, we outline data solutions and analytical options for countries to address this challenge. We also outline the research needs for enabling confident reporting on progress to achieve Target 6 of the GBF, supported by an up-to-date and sustainable flow of necessary information on IAS (*sensu* McGeoch and Jetz 2019).

3 | DATA SOLUTIONS

The most powerful and instrumental solution to this challenge is to invest in collecting data on explicit measurement of IAS survey effort, the identities, timing of introductions, and distributions of IAS. This data provides the information critical for estimating robust invasion rates (**Fig. 3**). Significant progress has been made in making IAS occurrence data available for countries over the last decade, for example, through the Alien Species First Records Database (Seebens et al. 2021). Baseline, multi-taxon, and openly available country checklists are also available (Pagad et al. 2022). Efficient and pragmatic approaches to improving this essential IAS data have been proposed (Latombe et al. 2017; van Rees et al. 2022), and potential financial benefits of doing so have also been shown (Cheney et al. 2018). This suggests advances on the collection and delivery of survey effort data are similarly possible.

Data on survey effort are nonetheless much less readily available than data on IAS per se. Standard approaches and tools for measuring and recording survey effort are currently not developed and harmonized guidelines will be needed. Examples of relevant data on the survey effort include measures such as hectares surveyed for IAS per assessment period (Cheney et al. 2018), numbers of inspections of high-risk establishment sites (Lovell et al. 2021), volume of cargo inspected (Miralles et al. 2021), time spent searching for a specific species (Mehta et al. 2007), number of high conservation value areas surveyed for IAS (Keet et al. 2022) and proportion of cells with expected presences that have relevant observations, the metric underpinning the Species Information Index (Oliver et al. 2021). New monitoring technologies are increasingly available, such as remotely sensed products (e.g., UAV, satellite, camera traps) or eDNA approaches, which through fixed elements of deployment protocols (e.g., area surveyed, number of traps or samples) provide quantifiable, efficient and effective ways to survey a subset of IAS for rapid and systematic observations (van Rees et al. 2022). These methods could in future provide repeatable quantification and reporting on survey effort. We strongly suggest collecting data on survey effort and routinely incorporating this into species monitoring protocols.

Without comparable information on survey effort for IAS, more readily available proxies could be used. For example, we used the number of IAS occurrences in the GBIF database as a proxy for survey effort (for eight countries, recorded over the last ~ 50 years), to show how the scenarios in Figure 2 are plausible (Supporting Information, Methods S1 and Figure S1). Although biases in such data are well recognized, approaches to reducing these biases are increasingly available (Meyer et al. 2016; Arlé et al. 2021), and the steps outlined in this Perspective will improve the quality of information required for assessment and reporting (**Fig. 3**). Other possible proxies of survey effort include the number of new biodiversity occurrence records per area per reporting period, correlations between the number of native and nonnative occurrence records, numbers of publications on IAS for a region, effort invested in monitoring for other environmental purposes, as well as the respective survey effort for those species, and qualitative scoring of how proactive countries are perceived to be with recording early invasions (e.g., Visser et al. 2016; Larson et al. 2020; Capinha et al. 2023). Such proxies are commonly used (e.g., Bonnamour et al. 2021) and provide a useful independent assessment that can indirectly inform on IAS observation probability based on the assumption that during the collection of general occurrence records, IAS are likely to be observed.

An alternative that could be useful, especially in cases of geographic progression of invasions over larger land masses rather than ‘jump’ introductions, would be model-based, Essential Biodiversity Variable (EBV) style predictions (McGeoch and Jetz 2019). Integration of varied, relevant data types and sources (e.g., individual occurrences, inventory, and expert elicitation on IAS distributions) can reduce data gaps, along with environmental information and appropriate modeling, and increase the resolution of information on the redistribution of IAS (McGeoch and Jetz 2019). Species population EBVs, along with increasing and ongoing data collection on IAS (e.g., including government, research and citizen science contributions), and on survey effort, can begin to provide reliable predictions of IAS in near real time and at spatial resolutions useful for management and reporting. Drawing on and contributing to occurrence records in GBIF, maintaining GRIIS country checklists (see Pagad et al. 2022) and investing in EBV production are the backbone of this process (McGeoch and Jetz 2019).

The steps to build the information needed to adequately estimate invasion trends and inform on the success of policy interventions are clear (**Fig. 3**; **Supporting Information, Table S1**). Importantly, the information benefits of such data are wide-ranging and relevant beyond the estimation of introduction trends (right-hand text in **Fig. 3**). Temporally explicit data on the identity and distribution of IAS populations provide the evidence base for species, site, and pathway prioritization and management, risk assessment, resource allocation planning, and evaluations of management effectiveness (Cheney et al. 2018; van Rees et al. 2022). There is therefore a strong incentive for sustained investment in keeping such data up to date. Although proxies can provide an interim solution, survey effort data are so foundational for assessing, maintaining, and interpreting information on IAS that we recommend collecting and collating such data as a strategic priority for countries and researchers (**Fig. 3**, **Supporting Information, Table S1**) (OECD 2019, Leadley et al. 2022; Vicente et al. 2022).

Building a sustainable pipeline of ongoing new data from which introduction rates can be estimated and reported based on ongoing updates of IAS observations is essential (Fig. 3, Supporting Information, Table S1). Where countries lack national information platforms to support these data, GBIF and the Global Register of Introduced and Invasive Species (GRIIS, Pagad et al. 2022) provide tools to collate and publish IAS occurrences, first record, and checklist information (data steps 1 and 2, Fig. 3). Some countries could substantially enhance their data by digitizing relevant information from gray literature (e.g., government reports) (Groom 2015). Importantly, routine and timely capture of information on new introductions is key to ongoing reporting on invasion trends.

4 | ANALYTICAL SOLUTIONS

Analytical methods exist for modeling invasion trends without data on survey effort. As outlined above, estimates of introduction rates should account for the effects of underlying survey effort on IAS observation probabilities. Observation probabilities vary over time and space because of both survey effort and properties of the invasion process (e.g., increase in abundance after introduction; Solow and Smith, 2005). Modeling solutions can bridge the gaps in data availability to arrive at estimates of underlying introduction rates, with associated measures of confidence, and thus survey effort-informed estimates of species introduction rates.

One simple method that accounts for IAS observation probability (in other words assuming that observations are affected by survey effort), is the Solow and Costello (2004) model (SC model). The SC model is based on a time series that describes the number of observed species in each time period, and estimates the rate of introduction of new species from these IAS observations (see **Supporting Information, Methods S1**). The observed number of IAS is the product of the number of introductions and the observation probability of the introduced species. Observation probability is allowed to change over time, as might happen with increasing survey effort or growing IAS populations. Once the model has been applied, the key indicator is the parameter of the model that estimates the (exponential) change in the introduction rate over time (β_1). Positive values indicate accelerating introduction rates, while negative values indicate decelerating rates (**Fig. 4**). The SC model has the advantage that it does not require data on survey effort and uses data commonly available, i.e., IAS observations and first records (although more complex versions of the model are possible, e.g., Belmaker et al. (2009)).

We applied the Solow and Costello model (Solow and Costello 2004) to a global data set of first country-level records of invasive alien plants (**Supporting Information, Methods S1**). The SC model of the cumulative number of invasive alien plants at new locations between 1800 and 2000 fits the empirical data well (**Fig. 4A**). However, the comparison of the rates calculated from observations (new species records per year, 1970-2014) with the SC model estimates of introduction rates shows clearly that accounting for survey effort (in this case through the model structure) influences the introduction rate (**Fig. 4B**). For example, this analysis suggests that in the year 2000, the global rate of plant introductions is lower than the observed rate (**Fig. 4B**). Conversely, in 1960 the introduction rates were likely higher than the observation rate suggests. This example demonstrates the importance of considering survey effort before inferring and reporting on IAS introduction rates. Applying this SC model to data for a selection of individual countries also shows that, rather than increasing across the board, introduction rates are likely to vary as either accelerating, stable or decelerating (**Fig. 4C**).

While a model like this that compensates for survey effort has clear advantages, its usefulness depends on the degree to which the model assumptions are met. For example, the SC model assumes that the underlying IAS introduction rate increases or decreases exponentially with time, and that the survey effort changes monotonically with time. Neither assumption holds across the board, deviations from them are hard to estimate, and violations will affect the estimated introduction rate. More complex models can be used to account for survey effort when additional information on survey processes is available, such as models with an additional term that relies on independent data to estimate survey effort (e.g., Belmaker et al., 2009). However, currently all available models need rigorous quantification of their data requirements, performance, and sensitivity to deviation from model assumptions. In the interim, we recommend making information available on both observed trends and modeled estimates of introduction rate that consider observation probabilities when reporting on introduction rates (as in **Fig. 4**). Despite their drawbacks, with no or limited direct data on survey effort, modeling approaches represent a best-practice solution to estimate robust IAS introduction rates. Further research is needed on modeling methods that accommodate observation probability and/or survey effort data when estimating introduction rates.

5 | CONCLUSION

Is it possible to estimate the rate of change in establishment for a 50% reduction to be met, as called for by Target 6 of the Global Biodiversity Framework? This is a question that all countries must answer soon. As shown here, the 50% target value aimed for could assume very different, and not necessarily meaningful, numbers under different scenarios of survey effort. Confident comparisons in percentage-reduction targets are difficult to achieve at present because IAS survey effort data are not available, have varied over time, and between taxa, countries, and regions; and because the effects of survey effort are largely unaccounted for in existing trend estimations. However, within individual countries, it is both possible and valuable to identify locally relevant introduction-survey effort scenarios and to build the data needed to provide robust and meaningful estimates. The steps to do so are outlined here (**Fig. 3**, **Supporting Information, Table S1**), provide clear direction and will deliver multiple information benefits for IAS management and international reporting obligations. These steps will bring about significant progress on several of the recommendations agreed to at the 15th Conference of Parties of the Convention on Biological Diversity. Strong international partnerships and data infrastructures, including the Global Biodiversity Information Facility, Group on Earth Observations Biodiversity Observation Network, and the Invasive Species Specialist Group of the IUCN, are in place to support countries as they progress towards 2030 reporting on this foundational element of Target 6. Close collaboration between researchers and implementation and reporting agencies will be necessary.

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DATA AVAILABILITY STATEMENT

Details of the data used to illustrate the points made in this perspective are available in the Supporting Information of this article.

ETHICS STATEMENT

There are no ethical concerns associated with this work.

CONFLICTS OF INTEREST

The authors have no competing interests to declare.

SUPPORTING INFORMATION

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

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TABLE 1 Clarifications needed when estimating invasion trends and introduction rates

	Concept	Application
1	Delimitation of the intended species pool	Here we use the definition under the Convention of Biological Diversity (https://www.cbd.int/invasive/WhatareIAS.shtml), and do not make a distinction between 'alien' species and 'invasive alien species' (IAS). The latter represent a subset of alien species and the argument in his paper applies in either instance.
2	Introduced versus established species	Here the term introduction encompasses the introduction, establishment and spread stages of the invasion process. These stages of the invasion process are in the main not possible to disaggregate for the purpose of empirical invasion trend modeling.
3	Invasion trend	A time series showing the change in the number of IAS in an ecosystem, country, region or globally.
4	Introduction rate	The rate at which new species are introduced over a particular time period and for a particular region (sub-national to global), calculated from the invasion trend.
5	Survey effort	Investment in surveillance and monitoring activities to observe (and document/report) newly introduced and established species. We assume for argument's sake here that 'effort' constitutes effective and efficient surveys. Here 'survey effort' is synonymous with the term 'discovery process' in Solow and Costello (2004).
6	Observed IAS	Detected and documented new IAS, recognizing that some IAS go undetected and unrecorded (synonymous with the term 'discovery' in Solow and Costello (2004)).

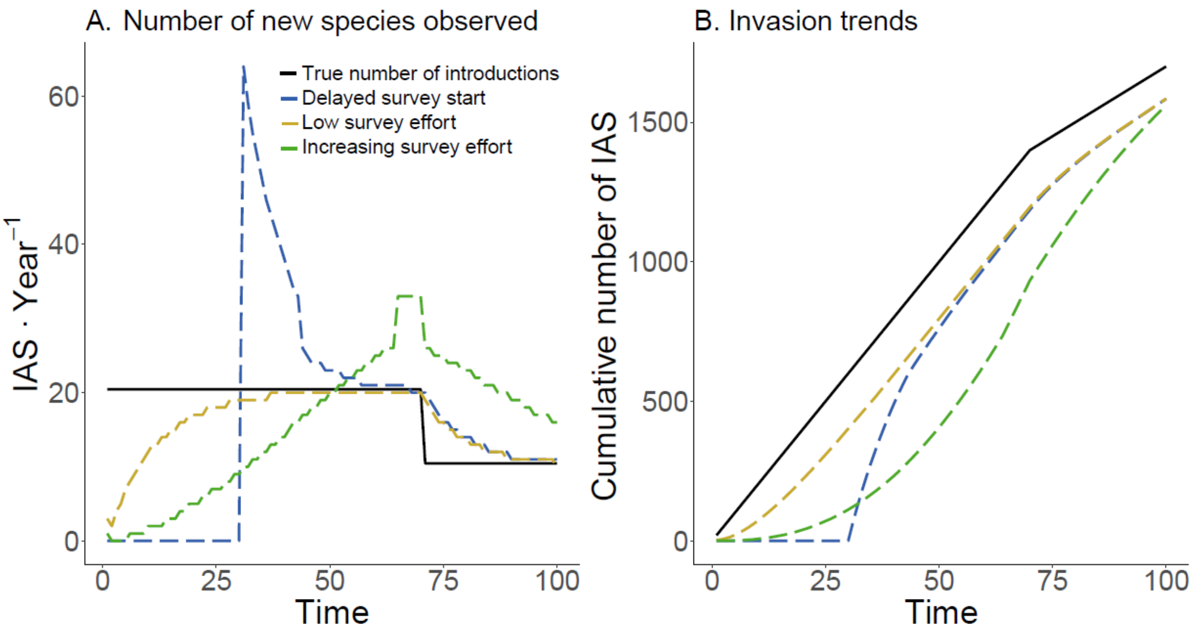

FIGURE 1. Simulation showing how varying survey effort for invasive alien species (IAS) produces different patterns of new species observations (A, number per year), and invasion trends (B, cumulative introductions). All curves in (**A**) and (**B**) are based on the same 'true', constant introduction rate of 20 species per year until year 75, and a decrease of 50% to 10 species per year over the last 30 years. Curve colors and dash types in (**A**) correspond to those in (**B**). The **true number of IAS introductions** (solid black line) (**A**) produces the trend in (**B**) if all IAS are detected as soon as they are introduced (i.e., the survey effort is high enough to achieve this). The dashed-line cases in A and B show scenarios of varying survey effort over time (delayed, low or increasing): **Delayed sampling** (blue) assumes here that recording of IAS starts 25 years after the first introduction, after which 10% of IAS are detected each year; **Low sampling effort** (gold) assumes that a set portion (e.g. 10%) of IAS are observed each year; **Increasing sampling effort** (green) assumes that survey effort increases with time (the sudden drop with increasing survey effort ~ 75 years results from the sudden 50% drop in the true number of introduced species per year (solid black line). (**B**) shows (i) how there is routine underestimation of IAS numbers, particularly during earlier stages of invasion (dashed lines lie below solid black line), and (ii) if observations of new introductions are not complete and instantaneous, the 50% drop in true introduction rate in the final 30 years is not clearly visible from the observation record (i.e., the success of an intervention that reduces introduction rates would not be discernible from trends in observed numbers of IAS). This implies that an indicator based solely on observed numbers of IAS over time can be misleading.

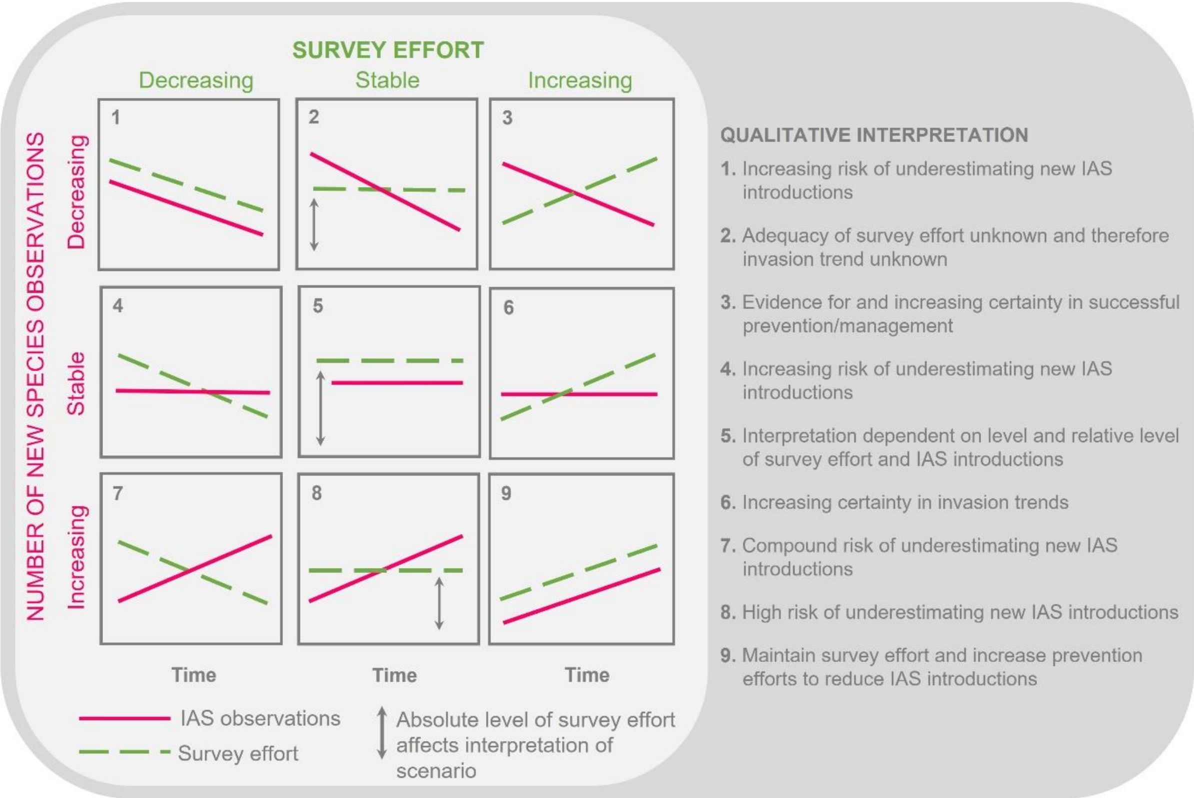

FIGURE 2. Introduction-survey effort scenarios showing how different combinations of trends in survey effort (dashed line, green) and observed numbers of new invasive alien species (IAS) (solid line, dark pink) have different implications. Each of these scenarios has a different potential interpretation and associated relative level of confidence (see 'Qualitative Interpretation' to right). For example, in scenario 1, both the survey effort and numbers of new IAS observed are declining. With the decline in survey effort, it is not possible to tell if the true numbers of new IAS are actually declining or simply not being observed because of declining survey effort. By contrast, in scenario 6, even though survey effort is increasing over time, the number of new species being observed is constant. Over time there is therefore increasing confidence that the number of new species observed is an accurate reflection of the true number of new introductions. Note (i) that the range of scenarios shown are simplified and relative for illustration, and (ii) that the initial and absolute levels of survey effort and IAS observations will affect the interpretation (see also **Supplementary Information Figure S1** that uses country examples and proxy survey effort data to demonstrate the plausibility of these scenarios).

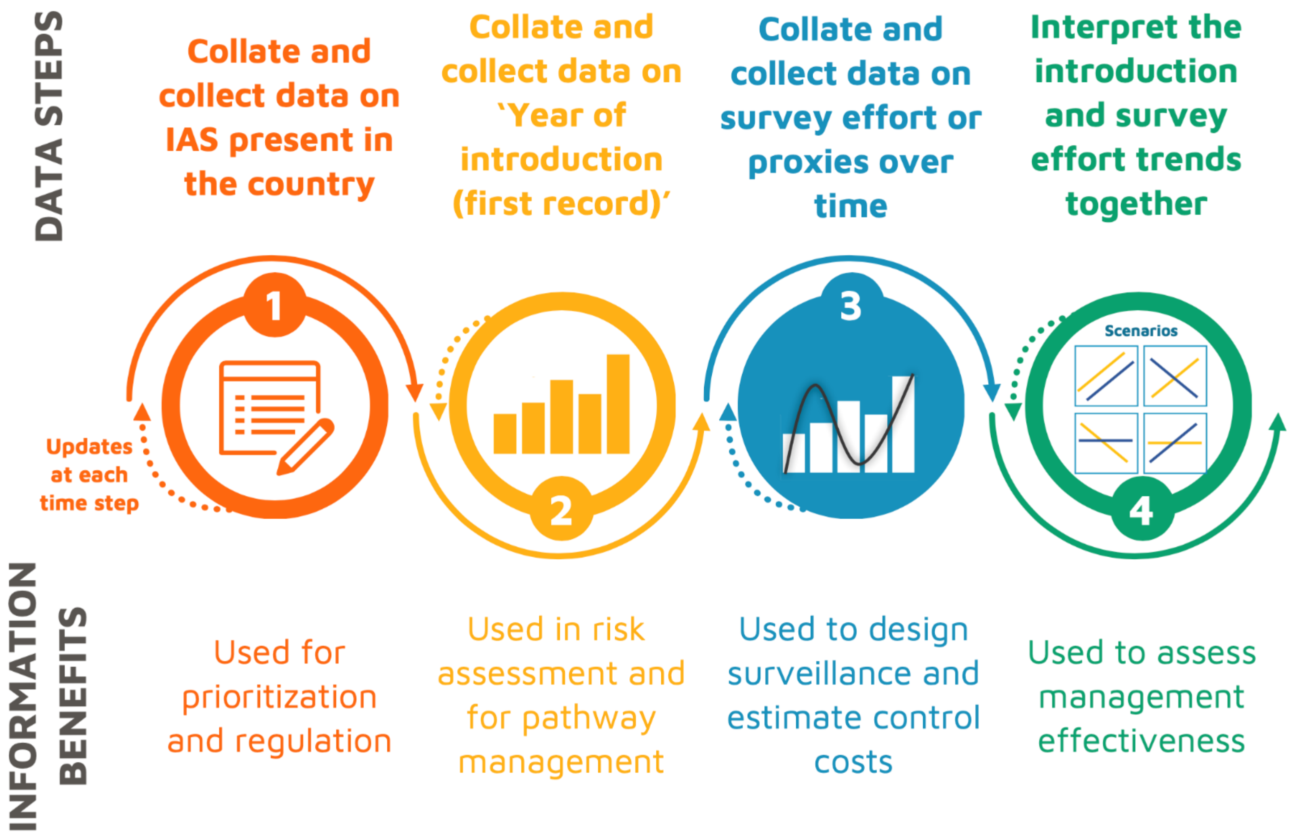

FIGURE 3. Governments and institutions responsible for assessing invasive alien species at the national level can follow steps (1-4) to build the data needed to estimate rates of invasive alien species (IAS) introductions (above) (for recommendation details see **Supporting Information, Table S1**). These data contribute to building an indicator of trends in IAS within and across countries, and importantly include the collection of data on survey effort. These steps also deliver several other key information benefits (below) for policy and management.

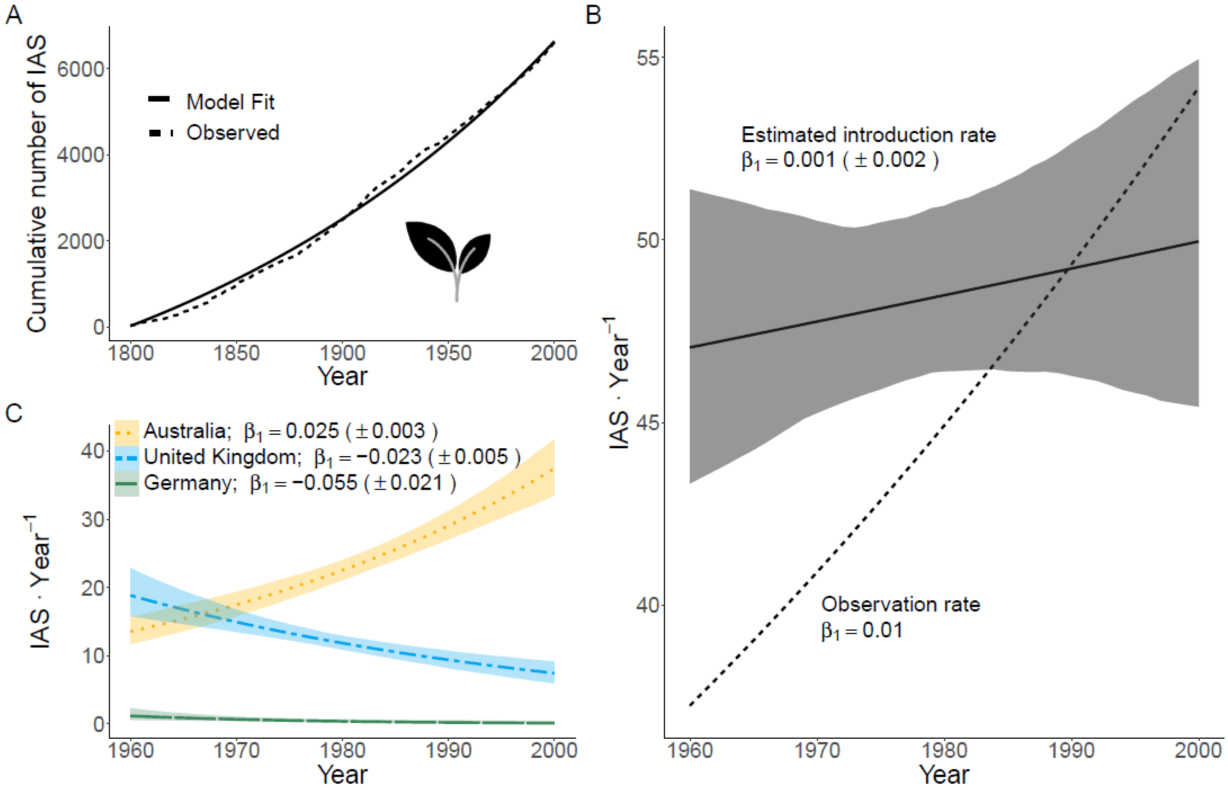

FIGURE 4. Case study examples of estimating alien species introduction rates. (A) Vascular plant species at a global scale: Cumulative observed number of new invasive alien plants globally (records of species in new localities) since 1800 (dashed line) and the fit of the Solow and Costello (2004) model (SC model, solid line). (B) Comparison between the observed (naïve, dashed line) and estimated (SC model, solid line) introduction rates from (A). The rates are estimated for the period 1960-2000; shaded area denotes 95% confidence intervals. The annual change in rate parameter (β_1 ± s.e.) represents the rate of change in IAS introductions; and the two β_1 values are clearly very different for the observed (naive) versus modeled with assumption about survey effort (SC model). Both show that the rate of global plant invasions is increasing (positive β_1 values), but at a slower rate when modeled to consider survey effort. (C) Country case studies used to show that the generally expected increase in introduction rates does not always hold. Using the SC model, the rate of change in invasive alien plant introductions (β_1) for Australia (orange; dotted), United Kingdom (blue; dash-dotted), and Germany (gray, dashed) are shown with 95% confidence intervals. Australia has an accelerating introduction rate of invasive alien plants (β_1 is positive), whereas the rate in the United Kingdom is slowing (β_1 is negative). Germany has a comparatively low number of IAS introductions per year and a largely stable, yet slowing, rate of invasive alien species introductions (β_1 is negative).

SUPPORTING INFORMATION

Invasion trends: An interpretable measure of change is needed to support policy targets

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Supporting information includes Methods S1 (including Data S1, Data S2), Table S1, Figure S1 and References.

METHODS S1

1. Data

Data used in Figure S1:

Data S1. First_records.csv has the information of the number of first records (vascular plants) for each region in each 5-year period, representing invasive alien species (IAS) introductions (primary data from Seebens et al. 2021; extracted using the workflow in Seebens et al. (2020), including species subset filtering using the Global Register of Introduced and Invasive Species (Pagad et al. 2022)).

Data S2. Average_occurrences.csv includes the mean number of records collected in each 5-year period for all the IAS introduced in each region up to that point, as a proxy for survey effort (primary data from GBIF 2023). The relevant species subset was determined using the workflow in Seebens et al. (2020), using the Global Register of Introduced and Invasive Species (Pagad et al. 2022).

Data used in Figure 4:

Plants (151 countries) were used as the example in Fig. 4 (GBIF 2020a). The dataset of taxonomic occurrences and first records was generated by integrating databases of IAS occurrences at country scales with first records of discovery using open-source data and a workflow published for this purpose (Seebens et al. 2020), to provide the backbone of country-level locality and introduction event data (Seebens et al. 2021) for the species subset of IAS (see Seebens et al. 2020). The workflow was used to harmonize i) taxon names according to the backbone taxonomy of the Global Biodiversity Information Facility (GBIF 2020b), ii) the Darwin Core terminology of occurrence status and means of establishment (Groom et al. 2019), and iii) the presentation of first records in countries as single years (Seebens et al. 2021). Multiple forms of uncertainty are associated with assigning alien and IAS status to populations and species. To ensure appropriate interpretation of trends and their repeatability it is essential that their production is underpinned by systematic decisions that operationalize the definition of species included and excluded and the use of data in the indicators (McGeoch et al. 2012).

2. Model

Figure 4 was produced by fitting the model described in Solow and Costello (2004) to the time series of first records of IAS in each country. This model finds the maximum-likelihood (ML) estimates of five parameters used in two dependent functions, the first (μ_t) describing the mean annual introduction rate, and the second (Π_{st}), an inverse-logit function describing the probability of discovery of species in year t (see Solow and Costello 2004) for full model description):

(i) $$\mu_t = exp\ (\beta_0 + \beta_1 t)$$

(ii) $$\Pi_{st} = \frac{exp\ [\gamma_0+\gamma_1+\gamma_2(t-s)]}{1+exp\ [\gamma_0+\gamma_1+\gamma_2(t-s)]}$$

We then focused on the parameter β_1 – the mean annual change in the rate of new species introductions. We used equation (i) to visualize the underlying introduction rates (new IAS · year-1; Fig. 4 B,C). Confidence intervals were produced by resampling the parameters based on the variance and covariance of their ML estimates and calculating μ_t based on the resampled β_0 and β_1. We compared this to the discovery rate (new IAS records · year-1) estimated from an exponential model fit to the annual number of new IAS observations.

TABLE S1. Guidance to countries on information needs and the foundations for constructing indicators of invasive alien species (IAS) introduction. Sharing data and code from all the steps below by contributing to open global data sources (such as the Global Biodiversity Information Facility (GBIF) and Global Register of Introduced and Invasive Species (GRIIS)), and publishing data and code in appropriate repositories will strengthen benefits and support rapid progress across levels of invasion policy and management (see fig. 3 in main paper for a schematic representation).

Step	Benefit	Example global data sources	Technical notes
Collate and collect data on invasive alien species present in the country.	Knowledge of which invasive alien species are introduced and established in a country, and those that are not yet established, provides the foundation for prioritizing prevention and control efforts (Costello et al. 2007; McGeoch et al. 2012, 2016; Uchida et al. 2016; Wilson et al. 2018). It also informs the Global Biodiversity Framework (GBF) (Essl et al. 2020), Target 6, which requires preventing 'priority' invasive alien species (CBD/COP/15/DEC/05).	Country Checklists of the Global Register of Introduced and Invasive Species (GRIIS) (Pagad et al. 2018; Pagad et al. 2022).	• The data needed here include those species for which there is evidence of negative impact, where such data are available. • These species are all those tagged as 'isInvasive' in GRIIS, i.e. if a species is present in the target country AND has evidence of impact somewhere in the world (not necessarily in the target country) then it is included in the country checklist of IAS. • Countries can update their data and checklists based on recent establishments, new evidence of in-country impact and/or newly collated evidence. • Distinguish established from casual (i.e. introduced but not established) where possible. • Collection of spatially explicit information, locality, habitat, bioregion, protected area for example alongside the above data will contribute to sub-national prioritization once available, and efficient and cost-effective approaches are possible (e.g. Berec et al. 2015; Liu et al. 2021).
Collate and collect data on 'Year of observation (first record)'.	To understand general trends in introduction success. With this information it also becomes possible to track the	First Records Database (Seebens et al. 2021).	• From around 1970 is a suggested, policy-relevant first year of introduction (Butchart et al. 2010). • The total number of IAS pre-1970 could be considered as the baseline. • Countries can update the first record information (e.g.,

	effectiveness of early discovery and rapid response programs, e.g., the time between first discovery and eradication. Repeated introduction information is also essential for knowing if populations of particular species are being repeatedly introduced (potentially increasing genetic heterogeneity and fitness).		Seebens et al. 2021) available based on recent establishments or newly collated evidence. • Collection and reporting of temporal data on an annual or 5-yearly basis, however reporting can be done over longer periods until data is available.
Plot the number of new introductions per year (or per 5-year period) from at least 1970.	This enables a quick first approximation for both how well prevention measures have been working, plus the level of potential threat of new establishments.	First Records Database (Seebens et al. 2021).	• Data can be shown by major taxonomic groups (e.g., plants, birds, mammals, fish, insects etc). • Data can be displayed separately for discrete biogeographical regions (e.g., oceanic islands). • View both annual and cumulative numbers of species per time step to aid interpretation.
Collate and collect data on survey effort or proxies of survey effort over time.	This information is an integral part of the response data that are recommended to bring about transformative change to meeting policy goals and targets (OECD 2019).		• Suggest using from at least 1970 as the policy relevant baseline year (Butchart et al. 2010). • A range of proxies are possible (see main text) and could include ‘input’ or ‘process’ response variables (Theory of Change; OECD 2019). • Research is required on optimal and standardized measures for survey effort. This is critical for interpreting IAS trends as we show here. • Investment in surveillance and early discovery activities.
Simultaneously plot the number of new	This provides information on the association between		

introductions, and a measure of survey effort, per year or relevant time period.	new introductions and survey effort.		
Interpret the introduction and survey effort trends together, within the context of understanding the country's investment in surveillance, monitoring and recording (survey) effort.	This information provides a foundation for and early indicators of rate of invasive alien species spread at a country scale.		• We consider this to be a minimal achievable step for the majority of countries and to be an informative contribution to reporting on GBF Target 6. • See **Fig. 2** and **Figure S1** as an example of how introduction-survey effort scenarios may be interpreted.
Combine IAS trends and survey effort to model true underlying introduction rates.	Helps to understand patterns in the true introduction rates that are obscured by IAS observation trends. Provides higher confidence and richer understanding compared to qualitative estimates obtained from step 4 (**Fig. 3**).		• Data limitations means that it will not always be possible to accurately model underlying trends. • Robustness of the models to violation in assumptions and data limitation not clear. For example, introductions might be sporadic and based on a few notable events rather than a continuous gradually changing introduction rates. In such situations socio-historical narratives can be incorporated into the predictions. • Models can be performed on sub-regions and taxa for which the data are adequate for modeling purposes. • Models to estimate the introduction rates from IAS observation data (Solow and Costello 2004) or using auxiliary survey effort proxies (Belmaker et al. 2009) (as for example in **Fig. 4**).

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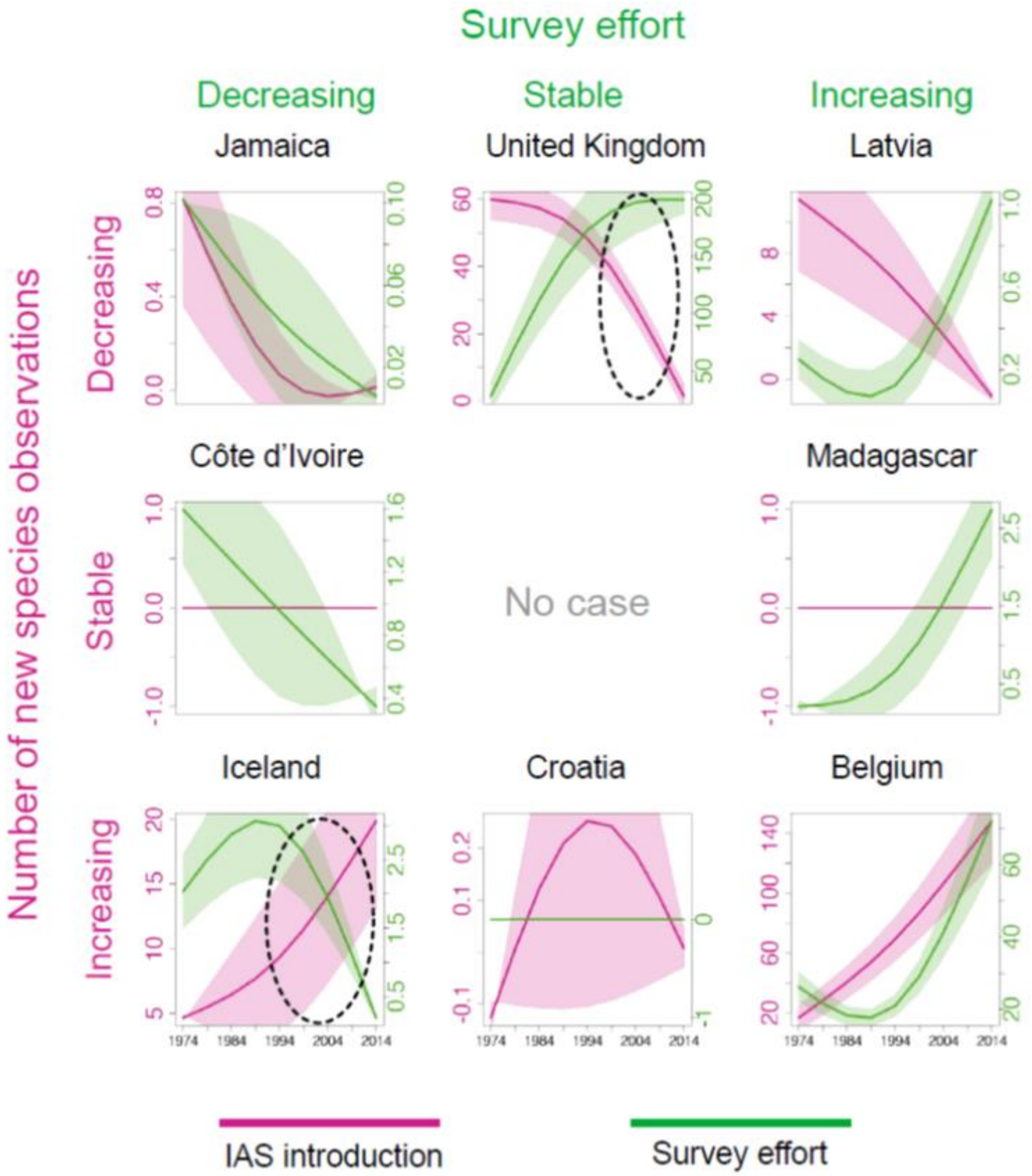

FIGURE S1. Country-level examples of introduction-survey effort scenarios matching those in Fig. 2 and using country data on invasive alien species (IAS) and proxy data for suvey effort. These examples show how the scenarios in Fig. 2, could be relevant across countries. The proxy data for national survey effort used is the number of occurrence records in the Global Biodiversity Information Facility (GBIF) of all IAS present in a country per time period. IAS observation data are used alongside this for each country, along with national first records (i.e., documented year of first observation of IAS per country (see Seebens et al. 2017). The dark pink line shows the number of new invasive alien species (IAS) observations per 5-years in the Alien Species First Record Database (Seebens et al. 2017, 2021); the green line shows the proxy used here for survey effort, i.e. the average number of GBIF records for all the IAS recorded with first records for that country (Supporting Information, Methods S1)). Dashed circles show relevant parts of the time series for that scenario. Y-axes: (left) - mean number of new IAS per 5-year period, with low values a result of low observed total numbers of species; (right) - mean number of occurrence records in GBIF per 5-year period for the IAS listed in the region until that point in time.

Interpretation: In Jamaica, for example, survey effort is declining and so is the number of observed new IAS, suggesting that it is currently not possible to infer the number of IAS or the introduction rate from IAS observations. In Latvia, survey effort has been increasing and the number of new IAS observed declining, suggesting that current data provide an adequate estimate of the number of IAS for the country. Note that the initial and absolute levels of survey effort and IAS observations will affect the interpretation. For example, in the United Kingdom case, historical increases in survey effort and declines in numbers of new observations result in an interpretation different to scenario 2 in Figure 2 (main paper).

Calculation: The proxy is calculated as the number of records in GBIF accumulated in a 5-year period for all IAS, and the total number of IAS with first records up to and including each time step. Both lines were smoothed fitting a Generalized Additive Model, with two degrees of freedom (hence the apparent negative value on the number of new species observations for Croatia).

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