BIODIVERSITY BUILDING BLOCKS FOR POLICY

M24 Design of impact indicator workflow

28/11/2023

Author(s): Sabrina Kumschick, Sandra MacFadyen, Hanno Seebens, Cang Hui, Quentin Groom

Funded by the European Union

This project receives funding from the European Union's Horizon Europe Research and Innovation Programme (ID No 101059592). Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the EU nor the EC can be held responsible for them.

Table of contents

1.Summary

This report provides a summary of the discussions held at the online workshop of 13 September 2023 on “Indicators of impacts of biological invasions”, as well as the results of a literature search conducted leading up to the discussions on suggested workflows for selected indicators.

From the literature review, three main types of indicators were identified for discussion which capture the impacts of biological invasions. The first type focuses on the impacted system or species (e.g., impacted habitats, threatened species) and assesses to what extent the entities of interest are impacted by biological invasions (called “impacted species or habitat indicator” hereafter). The second type deals with the impacting taxa, incorporating their impacts and distributions (called “impacting taxa indicator” hereafter). The third type uses relative numbers (e.g., abundance or richness) of alien vs native taxa as a proxy for the pressure on native systems (called “pressure indicator” hereafter).

The main aim of the workshop was to identify the most prominent indicators of impact of biological invasions, the variables needed to calculate them, and data sources available. After a brief presentation on the main indicators of impact suggested in the literature, and the three impact types selected, the workshop participants were asked to split into three groups, one for each indicator type. For the first breakout session, they were asked to discuss input variables needed for the respective impact indicators, and name possible data sources for the variables. In a second breakout session, participants discussed the accessibility of data, including whether it was FAIR, as well as data gaps and how they could be filled.

Based on the discussions in the workshop and a survey that was conducted afterwards among the workshop participants, three indicators, one from each type, were selected for further elaboration within B-cubed. We provide possible data sources and skeleton workflows for the three indicator types. These workflows will need to be completed, tested and refined for a selection of which indicators are actually feasible to implement in automated dashboards under the B-cubed project.

2.List of abbreviations

EU	European Union
EC	European Commission
EICAT	Environmental Impact Classification for Alien Taxa
SEICAT	Socio-Economic Impact Classification for Alien Taxa
IUCN	International Union for the Conservation of Nature
FAIR data	Findable, Accessible, Interoperable and Reusable data
GISD	Global Invasive Species Database
CBD	Convention for Biological Diversity

3. Background

3.1. What is impact of biological invasions?

Organisms get moved around the globe and establish outside their native range at an ever-increasing rate (Seebens et al. 2017). Species are identified as alien when they are transported by human activity to areas outside their indigenous range, allowing them to surpass natural biogeographical dispersal barriers (Blackburn et al. 2014). Some of these alien species establish where they are introduced and even spread rapidly, in which case we refer to these populations as invasive (Blackburn et al. 2011). Alien species can interact with the recipient ecosystem, native biota, society and the economy in several ways, some of which are beneficial to the recipient systems and some which are harmful (e.g., Jeschke et al. 2014). This interaction is commonly referred to as impact. In this report, we mainly focus on negative impact, i.e., impact which is harmful to the recipient system.

Impacts of alien species can happen at various scales, through different mechanisms and cause harm at varying magnitudes (e.g., Blackburn et al. 2014, Bacher et al. 2018). Consequently, they have been measured using a large variety of methods (e.g., Kumschick et al. 2015). This results in very heterogeneous data on impacts of alien species and makes impacts difficult to compare between taxa, habitats and regions. Several attempts have been made to standardise impact measures and categorising impacts to enable comparisons. Most recently, the IUCN adopted a Standard to classify impacts of alien taxa, the Environmental Impact Classification for Alien Taxa (EICAT) (IUCN 2020) to this end. EICAT has been applied to various taxonomic groups in different regions (e.g., Jansen & Kumschick 2022, Evans et al. 2018, Kumschick et al. 2017).

Similarly, the Red List of Threatened Species (IUCN 2012) lists pressures on the threatened species, which includes information on alien species. Such information has been used to compare impacts of different invasions (e.g., Bellard et al. 2016).

3.2. Policy relevance of indicators

Indicators for policy making need to adhere to several standards in order to be useful. They need to be policy relevant, as well as scientifically valid. Important considerations include whether the indicator is spatially explicit, applicable at different scales, temporal (can be calculated at different times to show trends) and taxon specific (should be applicable for different taxa) (see Vicente et al. 2022). They furthermore need to include a measure of uncertainty and be reproducible, meaning the data necessary to populate the indicator need to be readily available. These factors ensure the indicators are empirically supported and easy to articulate to stakeholders.

Optimal workflows for biodiversity or invasion indicators should be rooted in Open Data, with all contributing data strictly complying with the FAIR Data Principles as outlined by Wilkinson et al. (2016) (Groom et al. 2017, Groom et al. 2019) To produce reliable and repeatable biodiversity metrics, it is essential to employ Open Data workflows that consistently convert raw data into coherent, detailed, and replicable indicators of biodiversity, as emphasized by Boyd et al.

(2023), Groom et al. (2019), and Seebens et al. (2020). Adherence to the FAIR Data Principles in both inputs and outputs is crucial for maintaining transparency, reusability, and long-term viability. Adopting an Open Data and Open Source methodology permits the community to rigorously examine and repurpose workflows, significantly improving the ability for users to maintain, refine, and enhance the datasets.

Generally, indicators used to assess biodiversity focus on its current status as well as the pressures and threats it faces (Heink & Kowarik 2010), with biological invasions being one such threat.The harmful impacts of alien species are often the main (if not only) reason to regulate and manage these species. Therefore, it is important to understand the impacts, and to be able to monitor impact over time to enable the derivation of management strategies and tracking progress their implementation. Several international policy frameworks also deal with the threat of biological invasions. For example, Target 6 of the CBD Kunming-Montreal Global Biodiversity Framework (CBD/COP/DEC/15/4, 19 December 2022) invites governments to “eliminate, reduce and/or mitigate the negative impacts of alien species on biodiversity and ecosystem services by identifying and managing pathways of the introduction of alien species, preventing the introduction and establishment of priority species, reducing the rates of introduction and establishment of other known or potential invasive alien species by at least 50 per cent by 2030, and eradicating or controlling alien species especially in priority sites, such as islands”. Similarly, the Sustainable Development Goal (SDG) number 15.8 states that governments need to “introduce measures to prevent the introduction and significantly reduce the impact of invasive alien species on land and water ecosystems, and control or eradicate the priority species”.
To track progress on these and other relevant targets, as well as management actions in general, we need indicators that are comparable across regions and over time. Several indicator frameworks for biological invasions have been developed to this end (e.g., McGeoch et al. 2006, McGeoch et al 2010). The proposed indicators cover all aspects of biological invasions from alien species richness, their impacts, pathways of introduction and management.

3.3.Indicators for invasive alien species

Often, indicator frameworks are designed to fit a specific purpose, but they might be more broadly applicable and adaptable to different regions, taxa and purposes. Here we showcase a few of the indicator frameworks developed.

For tracking progress on the CBD targets, an aggregated indicator was proposed which can be used at national or global scales (McGeoch et al. 2006). The three components of the indicator, namely number of alien and invasive species, pathways, and management, can also be assessed separately (McGeoch et al. 2006). A refined indicator following the Pressure-State-Response framework included the number of alien and invasive species, number of impact types, number of national policies and international agreements on biological invasions and their level of adoption (McGeoch et al. 2010). Most recently, the sTWIST project has developed indicators within the Pressure-State-Response framework to monitor biological invasions, such as the spread rate and impact of invasive alien species and the quality of information available to inform policy effectiveness. These efforts are documented in the literature, including works by McGeoch et al. (2021), which focus on policy-relevant indicators for invasive species assessment.

Rabitsch et al. (2016) developed indicators at a European scale to track the efficacy of the EU regulations on invasive species (Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species). They proposed six indicators:

- Combined index of invasion trends;
- Indicator on pathways of invasions;
- The Red List Index of invasive alien species;
- Indicator of invasive alien species impacts on ecosystem services;
- Trends in incidence of livestock diseases;
- and Indicator on costs for alien species management and research.

To track the status of biological invasions in South Africa, Wilson et al. (2018) developed an indicator framework for the National Status Report (van Wilgen and Wilson, 2018; Zengeya and Wilson, 2020). This framework suggests four high level indicators with twenty detailed indicators.

Vicente et al. (2022) recently reviewed indicators for biological invasions and noted that many indicators are based on occupancy of alien species, such as the number of alien species. This seems to be the data most readily available and most easily accessible. However, they also note that indicators on impacts are scarce and relatively underdeveloped. This possibly has to do with the context dependent nature of impacts of alien and invasive species, and the inherent difficulties linked with measuring them (e.g., Pysek et al. 2020, Measey et al. 2020).

3.4.Currently used impact indicators

One of the most commonly implemented indicators on impacts of biological invasions has been the Red List Index (e.g., Butchart 2008) which is set out to track the extinction probability (i.e., Red List status) of species threatened by biological invasions (Table 1; Fig. 1b). Recently, an IUCN scheme was put forward to serve as a standard to classify impacts of alien taxa, namely the Environmental Impact Classification of Alien Taxa - EICAT (IUCN 2020a, b). It has been proposed as an indicator to track the impacts of alien species (Wilson et al. 2018, Latombe et al. 2017) (Fig. 1a). Furthermore, the relative abundance of alien vs native species has been used to express the potential pressure on native biodiversity (Fig. 1c; Wilson et al. 2018; Delavaux et al. 2023). This indicator is not directly based on species interactions and impacts, but more related to potential impacts due to the presence of alien species.

We are particularly interested in exploring the suitability of impact indicators that can be calculated using biodiversity occupancy cubes (Oldoni et al. 2020). These cubes aggregate biodiversity data, offering a multi-dimensional perspective that encapsulates species presence across different spatial and temporal scales, and improve interoperability of these data with other environmental data. Our objective is to identify indicators that not only align with the unique data structure of these cubes but also leverage their potential to provide policy-relevant assessments of biodiversity patterns and trends.

4. Online workshop

An online workshop was held on 13 September 2023 on “Indicators of impacts of biological invasions”. Fourteen participants from eight organisations in six countries were present (Appendix 2). The aim of the workshop was to “identify the most prominent indicators of impact of biological invasions, the variables needed to calculate them, and data sources available”. Firstly, a short presentation outlining currently used impact indicators was provided, which summarised in Table 1 here. Indicators were grouped into three types for discussions in groups, dubbed here as “impacting taxa indicator”, “impacted species or habitat indicator”, and “pressure indicator” (Fig. 1). Each group tackled one indicator type and was tasked to assess which variables would be required for its calculation, and note possible data sources. In a second session after feedback to the whole group, they discussed whether the data are available in a FAIR manner, what data gaps remain, and how to tackle them (see Table 1). The workshop participants were asked to fill in a survey to prioritise which indicator would be most feasible and most useful (Appendix 4).

5.Indicators selected for the workshop

For discussions in the workshop, we collated indicators of biological invasions which contain an impact component. These can be related to sites, or species (cf. McGeoch et al. 2016; no impact indicators on pathways were found) and have mainly been classified as state (e.g., number of impacted native species) or pressure (e.g., number of high impacting alien species) in the Driver-Pressure-State-Response framework (cf. Vicente et al. 2022).

5.1.Additional suggested indicators on impacts

As outlined above and in Fig. 1, there are several broad classes of indicators on impacts of biological invasions. These include impacts of specific alien species (i.e., how impacting is a species?) and impacts caused by invasions on specific sites. There can be different variants of each indicator using different parts of a dataset and calculating and amalgamating variables in different ways. We did not look at each variant of an indicator here, as the data needs and sources will be similar. Table S5 shows a selection of some of the most relevant indicators discussed at the workshop. Some of these are identical or overlap with the indicators presented in Table 1.

5.2.Possible issues with data availability

One major issue for the development of impact indicators in general is that we lack data on the impacts of most alien species in most situations. Although in an ideal situation there would be site specific impact data for each alien species, we do not have data on each alien or invasive population of a certain species and in each possible context. This makes us reliant on using data about impacts caused elsewhere and inferring impact in places where it is not measured. However, we know that impacts are a combination of the species’ traits, the recipient ecosystem including the native and other alien biota, and environmental conditions (e.g., Pysek et al. 2020). Assigning an alien species a certain impact value based on impacts caused elsewhere in its range can therefore be misleading (see also Kumschick et al. in press Conservation Biology). However, our understanding of the specific circumstances that lead to impacts is still limited, and we are just starting to attempt predictions of potential future impacts. Therefore, we rely on those data that are available for the development of indicators on impacts and need to disclose the shortcomings and uncertainties rather than delay decisions (Kumschick et al. in press). Ideally, with the collection of more data on impacts, increased availability of such data, and enhanced predictive modelling, the development of impact indicators for biological invasions could be significantly strengthened.

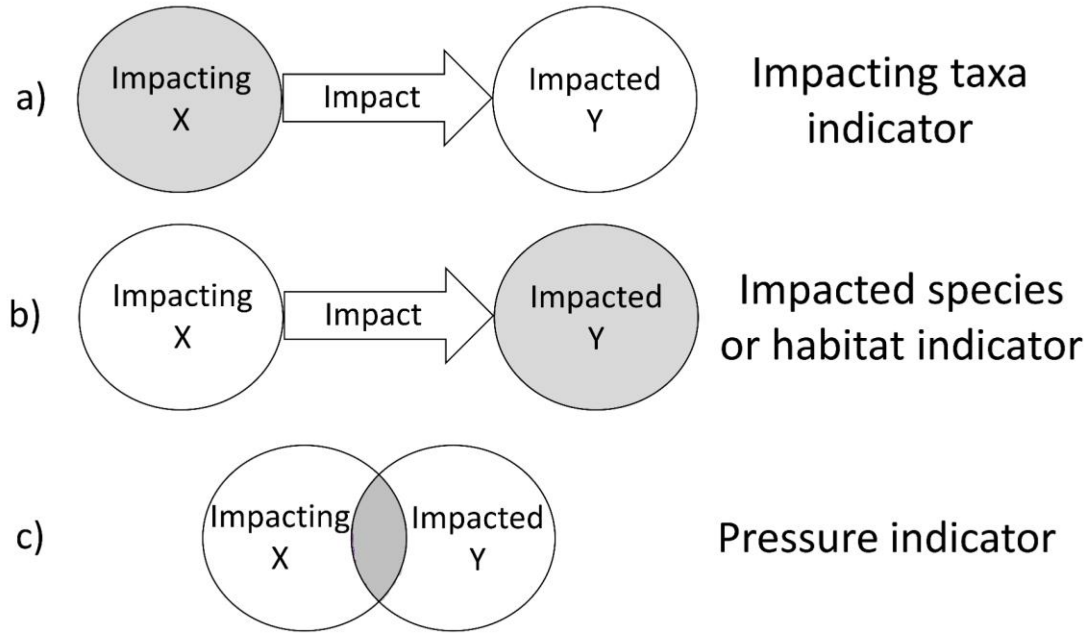


Figure 1: Three different types of impact indicators for biological invasions: a) The "impacting taxa indicator" includes indicators which focus on the impacting species, in our case the alien species or population; b) the "impacted species or habitat indicator" shows a situation where the focus is on the impacted species or commodity (e.g., threatened native species, a habitat of interest, protected areas, etc). Both of these typically include data on the impacts as well. This is in contrast to the "pressure indicator" c), which looks at co-occurrence, or relative numbers of impacted and impacting, however without specifically including a measure of impact in the indicator.

Table 1: Currently used indicators on impact of biological invasions, based on literature. This was collated before the workshop and used as a baseline for discussions.

Type	Indicator	Values	Data needs	Data accessibility	Gaps in data	Reference
impacting taxa indicator	Impact of alien species	Category of impact	Primary literature to classify impact, or ICAT assessments	Low; GISD for species which have EICAT assessments, but not FAIR	Many taxa not assessed for impacts; many alien species have no data on impacts (are Data Deficient)	Latombe et al. 2017; Wilson et al. 2018; Bacher et al. 2018; IUCN 2020; Streftaris & Zenetos 2006

This project receives funding from the European Union's Horizon Europe Research and Innovation Programme (ID No 101059592). Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the EU nor the EC can be held responsible for them.

Type	Indicator	Values	Data needs	Data accessibility	Gaps in data	Reference
impacting taxa indicator	Impact risk	Cumulative impact based on distribution of species and impact magnitude	Impact assessments, species distribution data, species alien status	See above for impact data; lists of alien species available through GRIIS and some national lists and other databases	Many taxa not assessed for impacts; alien species list quality varies among regions	Katsanevakis et al. 2016; McGeoch et al. 2021
impacting taxa indicator	Number of invasive and transformer species	Number of invasive and transformer species	List of alien species and their impacts	Lists of alien species available through GRIIS and some national lists and other databases; invasion status on GRIIS and GBIF (is invasive)	What constitutes an "invasive" or "transformer" species not consistently applied and not always clear; alien species list quality varies among regions	McGeoch et al. 2006
impacted species or habitat indicator	Red List Index	Number of native species threatened by aliens	Native species with Red List assessments with threats	Many taxa assessed globally (IUCN Red List of Threatened Species database) or regionally (e.g., national red list assessments)	Pressures/threats not captured consistently; some taxa and regions not assessed; assessments largely based on expert opinion and not repeatable; mostly assessments not repeated over time	Butchart 2008; McGeoch et al. 2010; McGeoch et al. 2015; Genovesi et al. 2012; Rabitsch et al. 2016;
pressure indicator	Percentage of alien species	Number of native species; number of alien species	Native and alien species lists	Field collections, GBIF	Good for some taxonomic groups and regions, lacking for others	Bowers & Boutin 2008

Type	Indicator	Values	Data needs	Data accessibility	Gaps in data	Reference
pressure indicator	Relative invasive abundance	e.g., biomass, number of individuals	native and alien species abundance/biomass/number of individuals	field surveys	Data on abundance often not collected	Wilson et al. 2018; Delavaux et al. 2023
Other (Socio-economic impact)	Trends in incidence of livestock disease	Occurrence of selected livestock diseases over time	Information on which livestock diseases are important for the region; information on occurrence of diseases	Animal health databases such as Animal Disease Notification System (ADNS)	Good databases for some regions, lacking for others	Rabitsch et al. 2016
Other (Socio-economic impact)	Impact of invasion on ecosystem services	Number of ecosystem services affected by alien species	Ecosystem services affected by alien species	DAISIE, meta-analyses	Gaps in taxa assessed, no standardised classification of ecosystem services	Rabitsch et al. 2016; Wilson et al. 2018
Other (Costs)	Costs of management and research	Money spent on research and management of biological invasions	$$	Invacost database	Much cost data not readily available, though invacost database has improved accessibility; many impacts on biodiversity difficult to monetize	Rabitsch et al. 2016

5.3.Prioritised indicators for further development

Based on the indicators presented in Table 1 and 2 and the considerations captured, we selected three indicators for further consideration. For those, we will outline their data requirements in more detail and suggest possible data sources which can aid the development of exemplar workflows. We selected one indicator for each of the three indicator types presented in Fig.1.

Although there are some major issues with data availability and accessibility for most of the indicators collated here, there is an urgent need to better capture impacts in the monitoring and reporting on biological invasions. There was no clear preference for any of the indicators proposed by the workshop participants, as indicated by the survey results in Appendix 3 and 4. Furthermore, as the three impact types have different objectives and are based on different data sources, we provide possible data sources for each, and recommend how certain data gaps could be filled.

This project receives funding from the European Union's Horizon Europe Research and Innovation Programme (ID No 101059592). Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the EU nor the EC can be held responsible for them.

6.Data sources for indicator workflows

6.1. Impacting taxa indicator: Impact based on distribution of alien species

The first indicator selected for further development is that on cumulative impact as described in Table 1. This indicator is based on the distribution of alien taxa and it fits into the impacting taxa indicator depicted in Fig. 1a). It requires data on the alien species present in the area of interest (occupancy), a measure of their impacts (including magnitude, if possible), as well as their distribution. This indicator can be calculated at different levels and as different variants based on the need and interest: a) if the interest is in one specific alien species, no aggregation across species needs to be done; b) if the focus is on a certain site (e.g., a country), aggregation across all alien species, or a specific set of species of interest is done; c) using suitability cubes (modelled occurrence of predicted suitable habitat) instead of occupancy cubes could provide an indication of potentially occupied and impacted sites. For all of these variants, the same basic data are needed, as outlined in Table 3.1.1

Table 3.1.1: The variables needed to populate an indicator on the impact based on the distribution of alien species. Some of the steps could be skipped by directly starting with a list of alien species, which is available for some regions.

Variable	Description	Data sources	Gaps in data
Species occurrence	A list of species occurring at site of interest.	GBIF	Different regions have different data coverage
Native/alien status	Focus is on alien species. One can also directly start off with a list of alien species for the region.	GBIF, GRIIS	Datasets incomplete for some countries, native/alien status of some species unknown
Impact	Standardised impact measure	EICAT data on GISD	Many alien species not yet assessed with standardised systems; Data on impacts for many alien species lacking; No site specific impacts available for all sites, but just where records of impacts are available in global alien range; Global coverage patchy as only literature in English considered.

6.2. Impacted species or habitat indicator: Native species impacted by biological invasions

This indicator is based on Fig. 1b) and focuses on native species impacted by biological invasions. It therefore requires information on native species and their threatened status, as well as information on the threats as we want to disentangle the threat posed by biological invasions from other threats, if possible.

Table 3.2.1: The variables needed to populate an indicator on native species impacted by biological invasions. Some of the steps could be skipped by directly starting with a list of threatened native species, which is available for some regions.

Variable	Description	Data sources	Gaps in data
Species occurrence	Species occurring at site of interest	GBIF	Different regions have different data coverage Intentional data protection on occurrence of endangered native species can create biases
Native/alien status	Focus is on native species; Can also start with a list of threatened species in the site of interest directly.	GBIF, GRIIS	Datasets incomplete for some countries, native/alien status of some species unknown
Threatened status	Threatened status of native species	Red List of Threatened Species	Many species not assessed; Assessments based on expert opinion and evidence underlying assessments not available, therefore not repeatable; Assessments done at very coarse temporal intervals (e.g., every 10 years), many not done multiple times at all
Threats on threatened species	Need to identify which species are threatened by biological invasions, or alien species	Red List of Threatened Species	Threats not provided for many species, or at very coarse resolution; Data based on expert opinion and evidence for threat identification not provided; Information on threatening alien species rarely provided at species level

A major shortcoming of this indicator was identified to be the lack of consistent assessments across time, and the general lack of evidence underpinning the Red List of Threatened Species. Although the Red List is a well-established framework, there is currently no standardised way in which impacts of biological invasions are assessed under that framework (e.g., van der Colff et al. 2020).

6.3. Pressure indicator: Alien vs. native species richness

Based on Fig. 1c), this indicator does not directly include a measure of impact or threat, but only considers native and alien species occupancy and distribution. This indicator has received some criticism as its relevance for assessing impacts of biological invasions is debatable (Stohlgren et al. 2003, Wilson et al. 2018). Relative abundance has been suggested as being of more relevance (e.g., Wilson et al. 2018), however, data for abundance of alien and native species is rarely available (but see Living Planet Index; also, Delavaux et al. 2023). Therefore, we focus here on relative richness, noting that if the data become available, relative abundance should rather be calculated.

Table 3.3.1: The variables needed to populate an indicator on relative richness of alien vs native species.

Variable	Description	Data sources	Gaps in data
Species occurrence	Species occurring at site of interest	GBIF	Different regions have different data coverage
Native/alien status	Determine native/alien status of each species present at the site	GRIIS	Datasets incomplete for some countries, native/alien status of some species unknown
Number of records	Number of records per species pre site	GBIF	Different regions have different data coverage

Different variations of this indicator are suggested: a) occurrence cubes could be used to calculate the relative number of species per site; b) the number of occurrence records per species per site could give a rough indication of abundance of the species based on statistical models, and c) suitability cubes could be used to assess a relative probability of occurrence.

7. Conclusions and way forward

The indicators selected for this project represent a balance between data availability and the specificity of the indicators to impacts of biological invasions. There are several issues limiting our ability to generate indicators of impact. Some of the indicators selected here do not (yet) have the data available in the format necessary to ensure automated workflows (e.g., machine readable), and some data is costly and labour intensive to collect and might not become available in the volume needed to effectively implement some indicators. Indeed, a recent review by Vicente et al. (2022) identified data scarcity as one of the three primary reasons for the inadequacy of current indicators used in monitoring biological invasions, a problem that is not easily or quickly resolved..

7.1. Data coverage

Generally, data available on biological invasions are patchy at best, with biases regarding regions and taxa studied (e.g., Pysek et al. 2008). Significant data gaps, particularly in the distribution, impact and ecology of invasive species, hinder the ability to predict and manage invasive species effectively. Comprehensive data are crucial for assessing risks and developing mitigation strategies. Understanding the life history, adaptability, and interaction of alien species with native biodiversity is essential, but often, such data are incomplete or entirely lacking, leading to challenges in conservation and management efforts. Information on impacts is specifically scarce, often limited to certain taxonomic groups. For example, EICAT assessments are usually conducted for a specific taxonomic group, as for example for birds (Evans et al. 2018), amphibians (Kumschick et al. 2017), Australian acacias (Kumschick & Jansen 2023), and ungulates (Volery et al. 2021). Many taxonomic gaps remain. Therefore, there needs to be a concerted effort to collate data for different taxonomic groups in the standardised frameworks such as EICAT (IUCN 2020a, b) and SEICAT (Bacher et al. 2018) to fill the taxonomic gaps. Furthermore, such data need to be made available in a computer readable format (Groom et al. 2017).

Similarly, data are often only collected in English, and regions which do not publish their findings in that language are therefore potentially under-represented in such databases (Amano et al. 2016). Understudied regions should be assessed whenever possible to fill regional data gaps. Often, data are only available for one specific time window and not available across different time periods (e.g. Red List assessments). However, such information is needed to be able to assess trends over time. Therefore, Red List assessments should be updated after a number of years and pressures identified. If possible, if the threat includes biological invasions, the alien species should be identified to species level. Ideally, EICAT and Red list assessments should complement each other and feed into each other whenever feasible (van der Colff et al. 2020). Furthermore, if the Red List is to be repeatable, which is a requirement for data underpinning indicators, it needs to include evidence in the assessments underpinning the data/assessments provided.

7.2. FAIR data

Data on impacts of the alien taxa are crucial for several of the indicators identified with development potential. Although there is currently a concerted effort to collate and standardise data on impacts using the IUCN EICAT Standard (e.g., Kumschick et al. 2020), as well as making the data publicly available, the data are not easily findable nor in a machine-readable format and are therefore of limited use when creating automated workflows. FAIR data are imperative if we are to move towards automated workflows and real-time dashboards of indicators (Groom et al. 2024 submitted). The only indicator in the selection of indicators assessed here which relies solely on FAIR data is the indicator on relative species richness. However, this indicator does not include a direct measure of impacts and can be seen as a proxy. Furthermore, more work is needed to understand the meaning of equating richness of different taxonomic and functional groups.

7.3. Steps to create an indicator workflow

To develop an exemplar workflow for biodiversity or invasion risk assessments that adheres to Open Data and FAIR Data Principles, the following steps can be outlined:

❶ **Define the Scope**: Establish clear objectives for biodiversity or invasion indicators. Determine the spatial and temporal scales and target species or ecosystems.

❷ **Data Collection Phase**: Gather data from reliable sources ensuring all data are Open Data. Ensure all collected data complies with the FAIR Data Principles: Findability, Accessibility, Interoperability, and Reusability. Document the data sources and collection methods for transparency.

❸ **Data Transformation Phase**: Convert the raw data into structured formats suitable for analysis. Cleanse and filter the data to remove errors or inconsistencies. Standardize the data to enable interoperability across various datasets and systems.

❹ **Biodiversity Metrics Generation**: Employ statistical and computational methods to analyze the structured data. Generate biodiversity or invasion indicators, ensuring they are coherent, detailed, and replicable. Validate the generated metrics with experts or through peer review.

❺ **Transparency and Reusability Emphasis**: Maintain detailed documentation of the methodologies and algorithms used in the analysis. Use open-source tools and software for the analysis to ensure that the workflow is transparent, cost-effective, sustainable and reproducible. Share the data and findings in a manner that allows for reusability and further research by the community.

❻ **Open Data and Open Source Integration**: Integrate the workflow into an open-source platform to allow community contributions. Enable continuous improvement by incorporating community feedback and peer suggestions. Support the maintenance, refinement, and enhancement of the datasets and workflows.

❼ **Quality Assurance and Validation**: Implement regular checks and validation steps to ensure the quality and reliability of the data and metrics. Compare results with established benchmarks or through collaborative efforts with other researchers.

❽ **Final Outcome**: Summarize the findings in a report or through scientific papers. Provide actionable insights and recommendations based on the generated indicators. Ensure that the final outcomes are accessible and can be utilized by policymakers, scientists, and conservationists.

❾ **Dissemination and Communication**: Communicate the results to stakeholders, policymakers, and the scientific community. Use visualizations and infographics to make the findings understandable and engaging.

❿ **Feedback and Iteration**: Gather feedback from the community and stakeholders. Iterate on the workflow to refine and improve upon the methodologies and outcomes based on the feedback received.

8. Acknowledgements

B^3 (Biodiversity Building Blocks for policy) receives funding from the European Union’s Horizon Europe Research and Innovation Programme (ID No 101059592). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the EU nor the EC can be held responsible for them. We would like to thank Andrew Rodrigues, Cristina Preda, Emily McCulloch-Jones, Heliana Texeira, John Wilson, Laura Abraham, Louise Hendrickx, Tim

Adriaens, Yanina Sica, Shawn Dove and Tanushri Govender for their inputs and participation in the workshop.

9. References

Amano T, González-Varo JP, Sutherland WJ, 2016. Languages are still a major barrier to global science. PLoS Biol 14(12): e2000933.

Bacher S, Blackburn TM, Essl F, Genovesi P, Heikkilä J, Jeschke JM, Jones G, Keller R, Kenis M, Kueffer C, Martinou AF, Nentwig W, Pergl J, Pyšek P, Rabitsch W, Richardson DM, Roy HE, Saul W-C, Scalera R, Vilà M, Wilson JRU & Kumschick S (2018) Socio-economic impact classification of alien taxa (SEICAT). Methods in Ecology and Evolution 9: 159-168

Bellard, C., Cassey, P. and Blackburn, T.M., 2016. Alien species as a driver of recent extinctions. Biology letters, 12(2), p.20150623.

Blackburn TM, Essl F, Evans T, Hulme PE, Jeschke JM, Kühn I, Kumschick S, Mrugała A, Marková Z, Nentwig W, Pergl J, Pyšek P, Rabitsch W, Ricciardi A, Richardson DM, Sendek A, Vilà 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(5): e1001850. DOI: 10.1371/journal.pbio.1001850

Blackburn, T.M., Pyšek, P., Bacher, S., Carlton, J.T., Duncan, R.P., Jarošík, V., Wilson, J.R. and Richardson, D.M., 2011. A proposed unified framework for biological invasions. Trends in ecology & evolution, 26(7), pp.333-339.

Bowers, K. and Boutin, C., 2008. Evaluating the relationship between floristic quality and measures of plant biodiversity along stream bank habitats. Ecological indicators, 8(5), pp.466-475.

Boyd, R.J., August, T.A., Cooke, R., Logie, M., Mancini, F., Powney, G.D., Roy, D.B., Turvey, K. and Isaac, N.J., 2023. An operational workflow for producing periodic estimates of species occupancy at national scales. Biological Reviews.

Butchart, S. H. M. (2008). Red List Indices to measure the sustainability of species use and impacts of invasive alien species. Bird Conservation International, 18, S245–S262.

Delavaux CS, Crowther TW, Zohner CM, et al. (2023). Native diversity buffers against severity of non-native tree invasions. Nature 621: 773-781.

Evans T, Kumschick S, Sekercioglu CH & Blackburn TM (2018) Identifying the factors that determine the magnitude and type of alien bird impacts. Diversity and Distributions 24: 800-810. https://doi.org/10.1111/ddi.12721

Genovesi, P., Carnevali, L., Alonzi, A. and Scalera, R., 2012. Alien mammals in Europe: updated numbers and trends, and assessment of the effects on biodiversity. Integrative zoology, 7(3), pp.247-253.

Groom et al. 2024 submitted

Groom, Q., Strubbe, D., Adriaens, T., Davis, A.J.S., Desmet, P., Oldoni, D., Reyserhove, L., Roy, H.E. and Vanderhoeven, S., 2019. Empowering Citizens to Inform Decision-Making as a Way Forward to Support Invasive Alien Species Policy. Citizen Science: Theory and Practice, 4(1), p.33.DOI: https://doi.org/10.5334/cstp.238

Groom QJ, Adriaens T, Desmet P, Simpson A, De Wever A, Bazos I, Cardoso AC, Charles L, Christopoulou A, Gazda A, Helmisaari H, Hobern D, Josefsson M, Lucy F, Marisavljevic D, Oszako T, Pergl J, Petrovic-Obradovic O, Prévot C, Ravn HP, Richards G, Roques A, Roy

HE, Rozenberg M-AA, Scalera R, Tricarico E, Trichkova T, Vercayie D, Zenetos A and Vanderhoeven S (2017) Seven Recommendations to Make Your Invasive Alien Species Data More Useful. Front. Appl. Math. Stat. 3:13. doi: 10.3389/fams.2017.00013

Heink, U. and Kowarik, I., 2010. What are indicators? On the definition of indicators in ecology and environmental planning. Ecological indicators, 10(3), pp.584-593.

Helm, A., Zobel, M., Moles, A.T., Szava-Kovats, R. and Pärtel, M., 2015. Characteristic and derived diversity: implementing the species pool concept to quantify conservation condition of habitats. Diversity and Distributions, 21(6), pp.711-721.

IUCN (2020a) IUCN EICAT Categories and Criteria. The Environmental Impact Classification for Alien Taxa (EICAT) First edition. IUCN, Gland, Switzerland and Cambridge, UK. IUCN. https://doi.org/10.2305/IUCN.CH.2020.05.enIUCN 2020

IUCN (2020b) Guidelines for using the IUCN Environmental Impact Classification for Alien Taxa (EICAT) Categories and Criteria: First edition. Version 1.1. Gland, Switzerland and Cambridge, UK. IUCN.

Jansen C, Kumschick S (2022) A global impact assessment of Acacia species introduced to South Africa. Biological Invasions 24: 175-187. https://doi.org/10.1007/s10530-021-02642-0

Jeschke JM, Bacher S, Blackburn TM, Dick JTA, Essl F, Evans T, Gaertner M, Hulme PE, Kühn I, Mrugała A, Pergl J, Pyšek P, Rabitsch W, Ricciardi A, Richardson DM, Sendek A, Vilà M, Winter M & Kumschick S (2014) Defining the impact of non-native species. Conservation Biology 28: 1188-1194. DOI: 10.1111/cobi.12299.

Katsanevakis, S., Tempera, F. and Teixeira, H., 2016. Mapping the impact of alien species on marine ecosystems: the Mediterranean Sea case study. Diversity and Distributions, 22(6), pp.694-707.

Kumschick S, Bacher S, Bertolino S, Blackburn TM, Evans T, Roy HE, Smith K (2020) Appropriate uses of EICAT protocol, data and classifications. NeoBiota 62: 193–212. doi.org/10.3897/neobiota.62.51574

Kumschick S, Gaertner M, Vilà M, Essl F, Jeschke JM, Pyšek P, Bacher S, Blackburn TM, Dick JTA, Evans T, Hulme PE, Kühn I, Mrugała A, Pergl J, Rabitsch W, Ricciardi A, Richardson DM, Sendek A & Winter M (2015) Ecological impacts of alien species: quantification, scope, caveats and recommendations. BioScience 65: 55–63. DOI: 10.1093/biosci/biu193

Kumschick S & Jansen C (2023) Evidence-based impact assessment for naturalized and invasive Australian Acacia species. Wattles: Australian Acacia species around the world (eds. D.M. Richardson, J.J. Le Roux & E.M. Marchante). CABI, Wallingford, pp. 359-381.

Kumschick S, Measey GJ, Vimercati G, de Villiers FA, Mokhatla MM, Davies SJ, Thorp CJ, Rebelo AD, Blackburn TM & Kraus F (2017) How repeatable is the Environmental Impact Classification of Alien Taxa (EICAT)? Comparing independent global impact assessments of amphibians. Ecology and Evolution 7: 2661-2670

Latombe, G., Pyšek, P., Jeschke, J.M., Blackburn, T.M., Bacher, S., Capinha, C., Costello, M.J., Fernández, M., Gregory, R.D., Hobern, D. and Hui, C., 2017. A vision for global monitoring of biological invasions. Biological Conservation, 213, pp.295-308.

McGeoch M.A., Chown, S.L. and Kalwij, J.M., 2006. A global indicator for biological invasion. Conservation Biology, 20(6), pp.1635-1646.

McGeoch, M.A., Butchart, S.H., Spear, D., Marais, E., Kleynhans, E.J., Symes, A., Chanson, J. and Hoffmann, M., 2010. Global indicators of biological invasion: species numbers, biodiversity impact and policy responses. Diversity and Distributions, 16(1), pp.95-108.

McGeoch, M. A., Shaw, J. D., Terauds, A., Lee, J. E., & Chown, S. L. (2015). Monitoring biological invasion across the broader Antarctic: A baseline and indicator framework. Global Environmental Change, 32, 108–125.

McGeoch, M.A., Genovesi, P., Bellingham, P.J., Costello, M.J., McGrannachan, C. and Sheppard, A., 2016. Prioritizing species, pathways, and sites to achieve conservation targets for biological invasion. Biological Invasions, 18, pp.299-314.

McGeoch, M.A., Arlé, E., Belmaker, J., Buba, Y., Clarke, D.A., Essl, F., García-Berthou, E., Groom, Q., Henriksen, M.V., Jetz, W., Kühn, I., et al. 2021. Policy-relevant indicators for invasive alien species assessment and reporting. bioRxiv, pp.2021-08.

Measey, J., Wagener, C., Mohanty, N.P., Baxter-Gilbert, J. and Pienaar, E.F., 2020. The cost and complexity of assessing impact. NeoBiota, 62, pp.279-299.

Mitchell, S.N., et al., 2022. FAIRdata pipeline: provenance-driven data management for traceable scientific workflows. Phil.Trans.R.Soc. A380: 20210300.https://doi.org/10.1098/rsta.2021.0300

Oldoni, D., Groom, Q., Adriaens, T., Davis, A. J., Reyserhove, L., Strubbe, D., ... & Desmet, P. (2020). Occurrence cubes: a new paradigm for aggregating species occurrence data. bioRxiv, 2020-03.

Pyšek, P., Bacher, S., Kühn, I., Novoa, A., Catford, J. A., Hulme, P. E., Pergl, J., Richardson, D. M., Wilson, J. R. U., & Blackburn, T. M. (2020). MAcroecological Framework for Invasive Aliens (MAFIA): Disentangling large-scale context dependence in biological invasions. NeoBiota, 62, 407–461.

Pyšek, P., Richardson, D.M., Pergl, J., Jarošík, V., Sixtová, Z. and Weber, E., 2008. Geographical and taxonomic biases in invasion ecology. Trends in ecology & evolution, 23(5), pp.237-244.

Rabitsch, W., Genovesi, P., Scalera, R., Biała, K., Josefsson, M., & Essl, F. (2016). Developing and testing alien species indicators for Europe. Journal for Nature Conservation, 29, 89-96.

Seebens, H., Blackburn, T. M., Dyer, E. E., Genovesi, P., Hulme, P. E., Jeschke, J. M., Pagad, S., Pyšek, P., Winter, M., Arianoutsou, M., Bacher, S., Blasius, B., Brundu, G., Capinha, C., Celesti-Grapow, L., Dawson, W., Dullinger, S., Fuentes, N., Jäger, H., ... Essl, F. (2017). No saturation in the accumulation of alien species worldwide. Nature Communication, 8, 14435.

Seebens, H., Clarke, D.A., Groom, Q., Wilson, J.R., García-Berthou, E., Kühn, I., Roigé, M., Pagad, S., Essl, F., Vicente, J. and Winter, M., 2020. A workflow for standardising and integrating alien species distribution data. NeoBiota, 59, pp.39-59.

Stohlgren TJ, Barnett DT, Kartesz JT (2003) The rich get richer: patterns of plant invasion in the United States. Frontiers in Ecology and the Environment 1: 11–14

Streftaris, N. and Zenetos, A., 2006. Alien marine species in the Mediterranean-the 100 'Worst Invasives' and their impact. Mediterranean Marine Science, 7(1), pp.87-118.

Van der Colff D, Kumschick S, Foden W, Wilson JRU (2020) Comparing the IUCN's EICAT and Red List to improve assessments of the impact of biological invasions. NeoBiota 62: 509–523. https://doi.org/10.1098/rsbl.2015.0623.

van Wilgen, B.W., Wilson, J.R., 2018. The status of biological invasions and their management in South Africa 2017. In: South African National Biodiversity Institute and DST-NRF Centre of Excellence for Invasion Biology, Kirstenbosch and Stellenbosch.

Volery, L., Jatavallabhula, D., Scillitani, L., Bertolino, S. and Bacher, S., 2021. Ranking alien species based on their risks of causing environmental impacts: A global assessment of alien ungulates. Global Change Biology, 27(5), pp.1003-1016.

Wilkinson, M.D., Dumontier, M., Aalbersberg, I.J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.W., da Silva Santos, L.B., Bourne, P.E. and Bouwman, J., 2016. The FAIR Guiding Principles for scientific data management and stewardship. Scientific data, 3(1), pp.1-9.

Wilson, J.R., Faulkner, K.T., Rahlao, S.J., Richardson, D.M., Zengeya, T.A. and Van Wilgen, B.W., 2018. Indicators for monitoring biological invasions at a national level. Journal of Applied Ecology, 55(6), pp.2612-2620.

Zengeya, T.A., Wilson, J.R., 2020. The status of biological invasions and their management in South Africa in 2019. In: South African National Biodiversity Institute and DSI-NRF Centre for Invasion Biology, Kirstenbosch and Stellenbosch.

10. Supplementary Material

Appendix 1: Workshop agenda

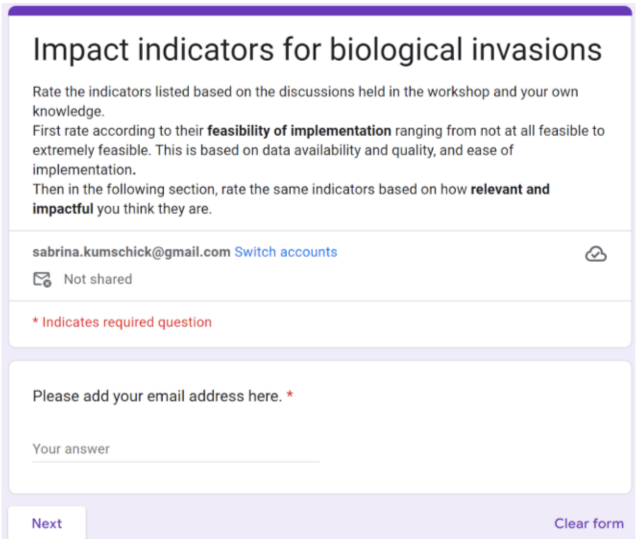
Schedule

Time	Item	Responsibility
9:00 am	Welcome and introductions	All
9:20 am	Aim of the workshop	SK
9:30 am	Overview of impact indicators	SK
9:50 am	Selection of impact indicators	All
10:00 am	Group work on 3 main indicators (e.g., Red List Index, Impact Risk, Alien vs Native abundance): - What are the input variables needed? - Possible data sources	All
11:30 am	Group feedback	All
12:30 am	Lunch break	All
1:15 pm	Group work: - Accessibility of data for indicators - Data gaps and how they could be filled	All
2:15 pm	Feedback on group work	All
3:15 pm	Tea break	All
3:45 pm	Brain storming: possible impact indicators OR Workflows for indicators	All
4:30 pm	Wrap up and way forward	SK
5:00 pm	Close	SK

Appendix 2: List of workshop participants

Name	Organisation	Country	email
Sabrina Kumschick	SU	South Africa	sabrinakumschick@sun.ac.za
Andrew Rodrigues	GBIF	Denmark	arodrigues@gbif.org
Cristina Preda	UOC	Romania	cristina.preda2008@gmail.com
Emily McCulloch-Jones	SANBI	South Africa	emcjones@sun.ac.za
Hanno Seebens	JLU	Germany	hanno.seebens@senckenberg.de
Heliana Texeira	UAVR	Portugal	heliana.teixeira@ua.pt
John Wilson	SANBI	South Africa	jrwilson@sun.ac.za
Laura Abraham	Meise	Belgium	laura.abraham@plantentuinmeise.be
Louise Hendrickx	Meise	Belgium	louise.hendrickx@plantentuinmeise.be
Quentin Groom	Meise	Belgium	quentin.groom@plantentuinmeise.be
Tim Adriaens	INBO	Belgium	tim.adriaens@inbo.be
Yanina Sica	JLU	Germany	yanina.sica@gmail.com
Shawn Dove	JLU	Germany	shawn.dove@hotmail.com
Tanushri Govender	SUN	South Africa	tanushrigovender@sun.ac.za

Appendix 3: Survey to select indicators for further development
Survey available on
https://docs.google.com/forms/d/e/1FAIpQLSc3xUK_Eg9AfMN4__OAiEeLJARM7wkRJjcdxXJrJNUVyq4Vig/viewform?usp=sf_link


Impact indicators for biological invasions

Rate the indicators listed based on the discussions held in the workshop and your own knowledge.
First rate according to their **feasibility of implementation** ranging from not at all feasible to extremely feasible. This is based on data availability and quality, and ease of implementation.
Then in the following section, rate the same indicators based on how **relevant and impactful** you think they are.

sabrina.kumschick@gmail.com Switch accounts
Not shared

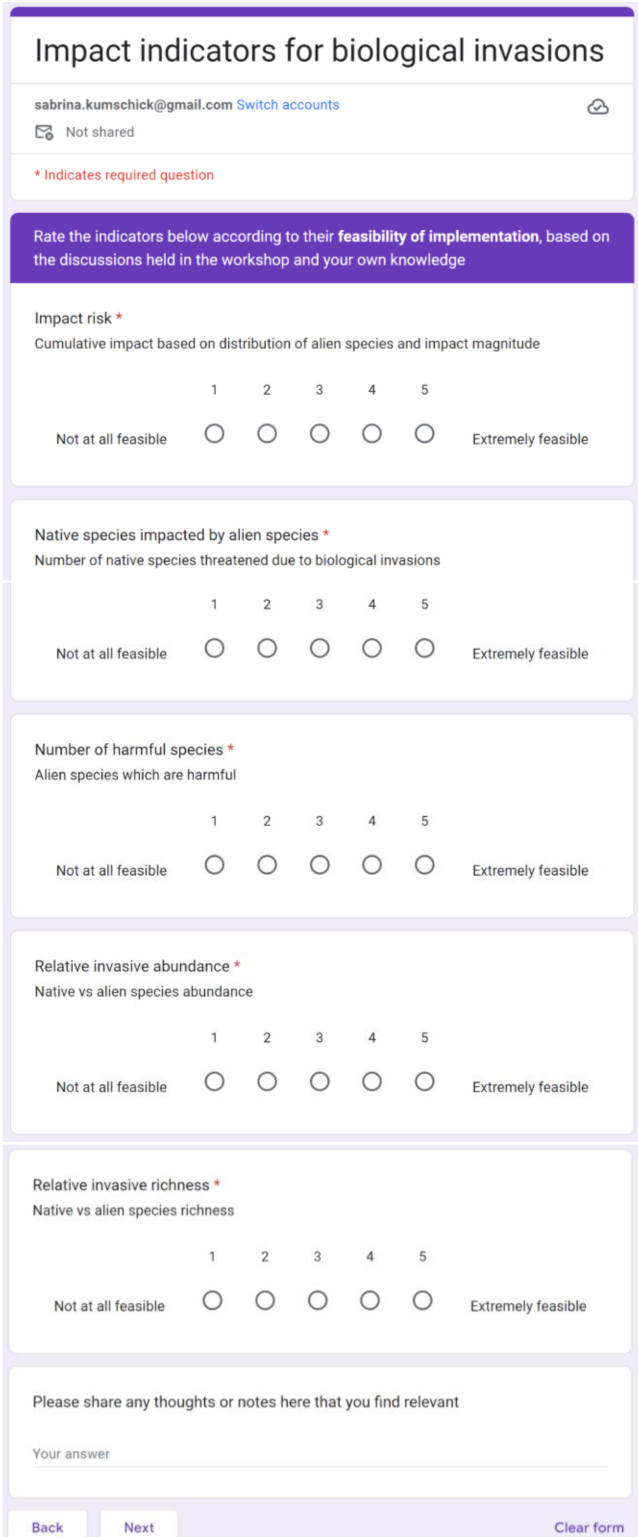
* Indicates required question

Please add your email address here. *

Your answer

Next

Clear form



Impact indicators for biological invasions

sabrina.kumschick@gmail.com Switch accounts

Not shared

* Indicates required question

Rate the indicators below according to their **feasibility of implementation**, based on the discussions held in the workshop and your own knowledge

Impact risk *

Cumulative impact based on distribution of alien species and impact magnitude

	1	2	3	4	5	
Not at all feasible	○	○	○	○	○	Extremely feasible

Native species impacted by alien species *

Number of native species threatened due to biological invasions

	1	2	3	4	5	
Not at all feasible	○	○	○	○	○	Extremely feasible

Number of harmful species *

Alien species which are harmful

	1	2	3	4	5	
Not at all feasible	○	○	○	○	○	Extremely feasible

Relative invasive abundance *

Native vs alien species abundance

	1	2	3	4	5	
Not at all feasible	○	○	○	○	○	Extremely feasible

Relative invasive richness *

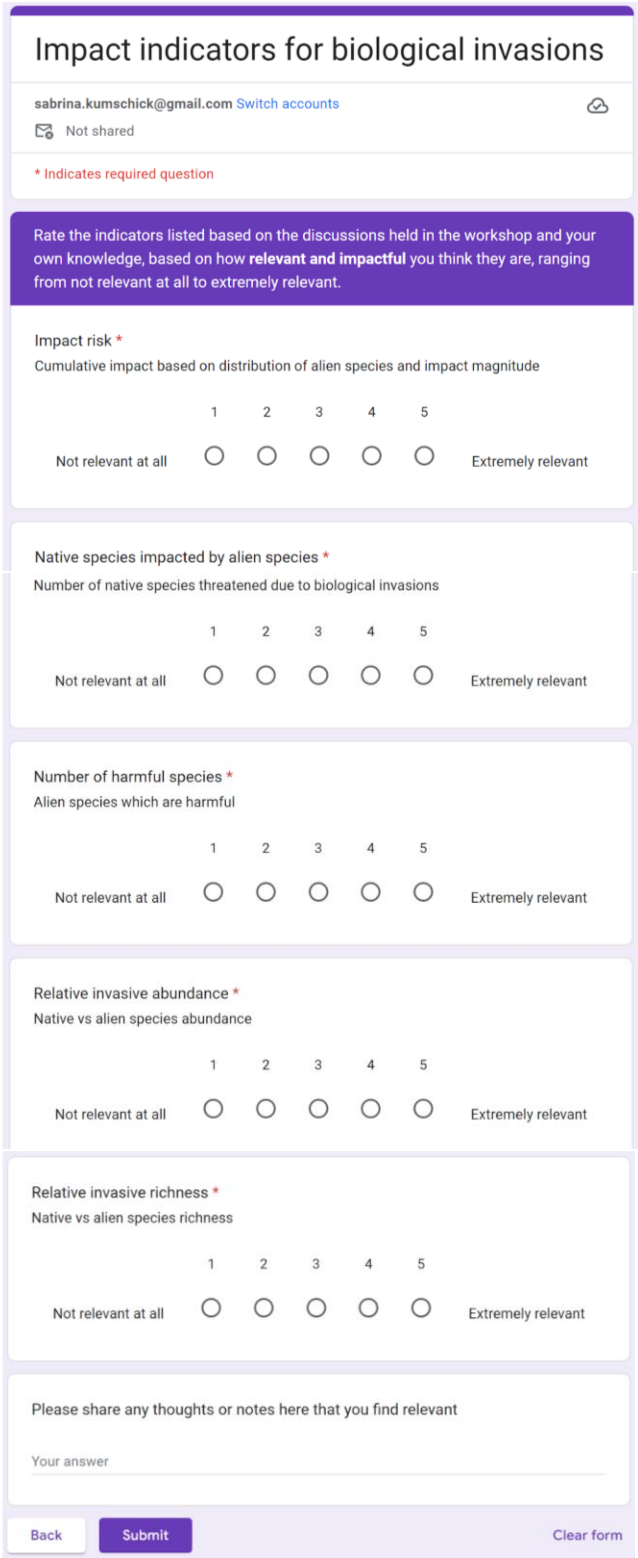
Native vs alien species richness

	1	2	3	4	5	
Not at all feasible	○	○	○	○	○	Extremely feasible

Please share any thoughts or notes here that you find relevant

Your answer

Back Next Clear form



Impact indicators for biological invasions

sabrina.kumschick@gmail.com Switch accounts

Not shared

* Indicates required question

Rate the indicators listed based on the discussions held in the workshop and your own knowledge, based on how **relevant and impactful** you think they are, ranging from not relevant at all to extremely relevant.

Impact risk *

Cumulative impact based on distribution of alien species and impact magnitude

	1	2	3	4	5	
Not relevant at all	○	○	○	○	○	Extremely relevant

Native species impacted by alien species *

Number of native species threatened due to biological invasions

	1	2	3	4	5	
Not relevant at all	○	○	○	○	○	Extremely relevant

Number of harmful species *

Alien species which are harmful

	1	2	3	4	5	
Not relevant at all	○	○	○	○	○	Extremely relevant

Relative invasive abundance *

Native vs alien species abundance

	1	2	3	4	5	
Not relevant at all	○	○	○	○	○	Extremely relevant

Relative invasive richness *

Native vs alien species richness

	1	2	3	4	5	
Not relevant at all	○	○	○	○	○	Extremely relevant

Please share any thoughts or notes here that you find relevant

Your answer

Back Submit Clear form

Appendix 4: Results of survey on indicators of impact

This project receives funding from the European Union's Horizon Europe Research and Innovation Programme (ID No 101059592). Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the EU nor the EC can be held responsible for them.

Table A4.1 Perceived relevance and impactfulness of selected impact indicators

	Relevance and impactfulness					
Respondent	Impact risk	Native species impacted by alien species	Number of harmful species	Relative invasive abundance	Relative invasive richness	Please share any thoughts or notes here that you find relevant
A	5	5	4	3	3	Impact risk: directly assesses the cumulative impact of alien species. can guide policy decisions by quantifying the overall impact Native species impacted by alien species: information on the extent of harm and threats. directly measures the impact of biological invasions Number of harmful species: identifying and quantifying harmful alien species Relative invasive abundance: insights into ecological impact of invasive species in relation to native species, but not very impactful in understanding the degree of disruption Relative invasive richness: relevant to assess the diversity of invasive species in comparison to native species, but not impactful in assessing changes in biodiversity and ecosystem composition.
B	2	3	4	5	1	
C	5	5	5	5	5	I think it would be great to know all of this, to make better informed decisions.
D	4	3	3	4	4	Not sure if this is useful - I wasn't in the workshop and not sure what was specifically discussed around each indicator (see note from previous page).
E	4	3	3	2	2	
F	4	3	5	2	5	The relevance and impact of these indicators imo entirely depends on what they are used for. At macro-level if they are used for IPBES assessments they could be impactful, it national levels they could too but "it depends".
G	4	3	5	4	2	The definition and list of 'native species' are ambiguous. Relative abundance could be important but relative richness does not have clear ecological meaning.
Average	4,00	3,57	4,14	3,57	3,14	
Median	4	3	4	4	3	
Min	2	3	3	2	1	
Max	5	5	5	5	5	

Table A4.2 Perceived feasibility of implementation of selected impact indicators

		Feasibility of implementation				
Respondent	Impact risk	Native species impacted by alien species	Number of harmful species	Relative invasive abundance	Relative invasive richness	Please share any thoughts or notes here that you find relevant
A	3	3	4	4	4	Impact risk: challenging on global scale due to unreliable/not available data/missing standardized framework on the distribution of alien species and their impact magnitude. But this data might be feasible for certain regions or taxa. The assessment of impact is not straightforward, and may require multiple dimensions, such as ecological, economic, and social impacts. Again standardized metric is needed for impact magnitude. Spatially the impact of alien species can vary from one location to another. Temporal scale, the impact of alien species can change over time due to climate change. Threshold values: what is a significant impact? Updating indicator continuously, as alien species distributions and impacts vary over time. Regular monitoring is maybe not possible. Native species impacted by alien species: We need access to reliable data on native species and the extent of their interactions with invasive species. Data quality can vary by region and taxonomic group. Assessing impact is difficult. Can range from predation and competition to more subtle ecological changes. Needs a reference point, assessing the situation before the introduction of invasive species. Number of harmful species: Gathering this data is achievable depending on the scope of the indicator (all taxa?). What is considered harmful, needs a definition, such as ecological disruption, economic damage or threats to human health. Relative invasive abundance: Feasibility depends on the availability and quality of data. useful in regions with good monitoring programs. How to measure abundance? Choice of metric and statistical methods. They need to be standardized to compare globally. Resource intensive Relevant?: assessing abundance alone may not fully capture the ecological consequences of invasive species Relative invasive richness: Feasibility depends on the availability and quality of data. useful in regions with good monitoring programs. How to measure richness? Choice of metric and statistical methods. They need to be standardized to compare globally. Resource intensive Relevant?: Impact can depend on interaction with native species and the ecosystem. Assessing richness alone may not capture the ecological consequences of invasive species.
B	3	3	4	2	4	feasibility is different from useful, can get species richness data but it is dodgy...

	Feasibility of implementation					
Respondent	Impact risk	Native species impacted by alien species	Number of harmful species	Relative invasive abundance	Relative invasive richness	Please share any thoughts or notes here that you find relevant
C	3	3	4	4	5	I guess it depends on the taxa analyzed and the level of confidence/accuracy...e.g. I think "Cumulative impact based on distribution of alien species" might be extremely feasible but less so if you have to associate impact magnitude to each alien species. Same with the number or abundance of species, it might be easier with trees but less so with insects (native or alien).
D	3	2	2	4	3	I didn't attend the workshop but the biggest limitation to using these indicators is the lack of data i.e. completeness of records or at least sampling effort or accuracy included. If this is a blue-sky scenario, then I would rate all of the above higher. Of course another limitation is we don't necessarily know what species will be impacted (unless we're using proxies e.g. trait overlap)?
E	3	3	4	3	2	
F	3	5	4	1	4	I think we should think of indices based on calculated trends (with occupancy modeling?) for high impact species (e.g. species from the Union List) based on distribution data or in groups of high impact species (for instance using groups of species with an EICAT categorisation). If we have a workflow and dashboard that, this could be very informative to a range of users. It is also lacking in EASIN, they have maps and registries, but nothing on trends. And gbif already have a built in tool for a sort of trend (tools>relative observation trend).
G	4	4	4	2	3	Impact magnitude needs to be provided for implementation; relative abundance and relative richness are dependent on the occurrence record quality, which can be poorly represented in some areas.
Average	3,14	3,29	3,71	2,86	3,57	
Median	3	3	4	3	4	
Min	3	2	2	1	2	
Max	4	5	4	4	5	

BIODIVERSITY BUILDING BLOCKS FOR POLICY

Appendix 5

Table S5: Suggested indicators on impact of biological invasions. This table is mainly based on discussions held at the online workshop on 13 September 2023.

Type	Indicator	Data needs	Databases	Data accessibility	Gaps in data	Way forward
Impacting	Number of harmful alien	- species occurring at site	GBIF; GRIIS	FAIR	EICAT for most taxa not yet	Collate data for more species in standardised manner (e.g.,

This project receives funding from the European Union's Horizon Europe Research and Innovation Programme (ID No 101059592). Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the EU nor the EC can be held responsible for them.

Type	Indicator	Data needs	Databases	Data accessibility	Gaps in data	Way forward
	species present at a site	- alien status of species	GRIIS; CABI	GRIIS data freely accessible, but some of CABI behind paywall	available; data not findable and machine readable CABI database not freely accessible	EICAT assessments) Improve FAIRness of data on impacts and database structure
		- EICAT category of alien species or other measure of harmful impact	GISD; CABI	Data for species assessed can be downloaded from GISD database, but not via API		
Impacting	Presence of certain high impacting species at a site	- Knowledge on species important for the site (indicator species)	Country lists of high impacting species; GBIF	Depending on the chosen taxon and region	See previous	See previous
		- possibly impact data for the species	GRIIS; GISD; CABI	See above		
Impacting	Occurrence range of some high impacting species	See previous	See previous	See previous	See previous	See previous
Impacting	Number of grid cells occupied by alien species and impact	See previous	See previous	See previous	See previous	See previous

Type	Indicator	Data needs	Databases	Data accessibility	Gaps in data	Way forward
Impacted	Number of threatened species present at a site impacted by alien species	- species occurring at a site - native status of each species - Red List threatened status of each native species - pressure on threatened species (invasion=TRUE)	Country lists of threatened species, National Red Lists, IUCN Red List of Threatened Species	Red List is well established globally	Many countries do not have national lists; data across time not available for most taxa	Red List assessments are not evidence based and it is recommended not to use this data as baseline as cannot be repeatable; see Table 1
Relative	Alien to native species richness	- Species richness of alien taxa - Species richness of native taxa	GBIF; GRIIS; national lists of native and alien species	Good	Some taxa and regions not as well studied as others and less complete	Meaning of indicator is questionable, but data largely available
Relative	Alien to native species abundance	Species lists of native and alien taxa as well as their abundances	none	Very poor, only in primary literature	Abundance data is generally very scarce and difficult to compare between taxa	Abundance data difficult to assess, not very practical for many taxa

BIODIVERSITY
BUILDING
BLOCKS FOR
POLICY

This project receives funding from the European Union's Horizon Europe Research and Innovation Programme (ID No 101059592). Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the EU nor the EC can be held responsible for them.