D5.3 Indicators on Impacts of Alien Taxa

30/04/2025

Author(s): Mukhtar Muhammed Yahaya, Sabrina Kumschick, Sandra MacFadyen, Pietro Landi, John Ross Wilson, Langeraert Ward, Emma Cartuyvels, Cang Hui

Funded by the European Union

Prepared under contract from the European Commission
Grant agreement No. 101059592
EU Horizon Europe Research and Innovation Action

Project acronym:	**B3**
Project full title:	**Biodiversity Building Blocks for policy**
Project duration:	01.03.2023 – 31.08.2026 (42 months)
Project coordinator:	Dr. Quentin Groom, Agentschap Plantentuin Meise (MeiseBG)
Call:	HORIZON-CL6-2021-GOVERNANCE-01
Deliverable title:	[INDICATORS ON IMPACT OF ALIEN TAXA]
Deliverable n°:	[D5.3]
WP responsible:	[WP5]
Nature of the deliverable:	[Report]
Dissemination level:	[Public]
Licence of use:	[Creative Commons Attribution 4.0 International]
Lead partner:	[SUN]
Recommended citation:	Yahaya, M.M., Kumschick, S., MacFadyen, S., Landi P., Wilson, J.R., Langeraert, W., Cartuyvels, E. & Hui C. (2025). ***Indicators on Impact of Alien Taxa***. B3 project deliverable D5.3.
Due date of deliverable:	Month n26°
Actual submission date:	Month n26°

Deliverable status:

Version	Status	Date	Author(s)
1.0	Final	30 April 2025	Yahaya Mukhtar Muhammed (SUN), Kumschick Sabrina (SUN), MacFadyen Sandra (SUN), Landi Pietro (SUN), Wilson John Ross (SANBI), Ward Langeraert (INBO), Cartuyvels Emma (INBO), Hui Cang (SUN)

Table of contents

Key takeaway messages

- The negative impact of alien species is recognised as a major threat to biodiversity. However, in the absence of generic evidence-based impact indicators that follow the Findable, Accessible, Interoperable, and Reusable (FAIR) Data Principles with standardised workflows, the impacts of alien species are not systematically estimated over time, a major gap for policy.
- The Environmental Impact Classification of Alien Taxa (EICAT) recently adopted by the International Union for Conservation of Nature (IUCN) fits to serve as standard evidence of alien species' impact on biodiversity.
- We designed a workflow to compute impact indicators of alien species by combining their distribution and impact magnitude.
- We developed an R package to seamlessly allow users to compute and visualise the impact indicators.

Executive summary

This report introduces a new, open-source workflow for computing impact indicators of alien species, combining occurrence data from the Global Biodiversity Information Facility (GBIF) with Environmental Impact Classification for Alien Taxa (EICAT) assessments. By uniting standard approaches to combining distribution data with qualitative impact categories, it provides a reproducible and policy-relevant tool for estimating how the ecological consequences of biological invasions change spatially and temporally.

To operationalise the developed workflow, the **`impIndicator`** R package translates EICAT categories into numerical values and integrates them with distribution of alien species to estimate which species are likely to be most impactful and where impacts are most likely to occur. Its flexible methods allow computation of impact indicators for species-level analyses, site-level comparisons, and overall regional assessments.

By packaging these steps into a coherent, FAIR data-compliant workflow, this tool offers an approach that can inform both ecological research and management responses. Policy frameworks such as the Convention on Biological Diversity Kunming-Montreal Global Biodiversity Framework Target 6 and the Sustainable Development Goals will benefit from timely and accurate insights into where alien species pose the greatest threats and whether current interventions are effectively mitigating those threats. With ongoing expansion of EICAT databases and the potential integration of advanced species distribution models, this workflow stands poised to become a cornerstone for monitoring and guiding management strategies related to biological invasions.

This workflow has been demonstrated using *Acacia* species in South Africa, showcasing the spatiotemporal dynamics of their impacts and highlighting sites with higher impact risk. The results displayed dependency on sampling efforts of the occurrences data, therefore, we suggest flexibility in the workflow to allow use of local occurrences data with high sampling efforts.

Non-technical summary

This deliverable presents a straightforward method for estimating the harm caused by alien (non-native) species, using freely available data and a clear, step-by-step process. As non-native species spread and multiply, they can seriously affect local plants, animals, and entire ecosystems. By combining information about where these alien species occur (from online databases) with the evaluations of their ecological effects (from an international standardised process that gathers information on impacts and collates them into a standard score), we developed a practical tool that gives an "impact value." This value reflects both how widespread a species is and how serious its negative effects can be. Researchers, conservationists, and policymakers can use these values to identify which non-native species are likely to be problematic, allowing managers to address the urgent future problems. This method thus helps guide actions to protect biodiversity and maintain healthy ecosystems into the future.

List of abbreviations

EU	European Union
EICAT	Environmental Classification of Alien Taxa
IUCN	International Union for Conservation of Nature
RLI	Red List Index
GBIF	Global Biodiversity Information Facility
CBD	Convention on Biological Diversity
SDG	Sustainable Development Goal
GISD	Global Invasive Species Database

1. Introduction

1.1. Impact indicator for alien species

The negative impact of alien species is one of the leading causes of biodiversity loss (Bacher et al., 2023). A challenge to the appropriate management of such impact is the lack of sufficient evidence-based indicators for the impact caused by alien species that satisfy Findable, Accessible, Interoperable, and Reusable (FAIR) principles of data (Vicente et al., 2022). As there is growing information on distributions (GBIF, 2025), and standard assessments of the impact caused by alien species across different native ecosystems become available (e.g., Evans et al., 2016; Canavan et al., 2019; Volery et al., 2021; Jansen & Kumschick, 2022), there is room for a standard method to infer the impact of alien species as indicators from the combination of their occurrences and impact assessment. In terms of policy, the indicator will allow for the prioritisation of key species and sites, tracking the response of controls, and forecasting the impact under possible future scenarios (Kumschick et al., 2025).

Various indicators have been proposed to be used to track invasions over time (Vicente et al., 2022; Wilson et al., 2018). Indicators focussing on the occurrence of the alien species include the cumulative number of established alien species (Henriksen et al., 2024) and the relative abundance of alien species (Delavaux et al., 2023; Wilson et al., 2018). While indicators based on species occurrence provide trends of invasion generally, they do not necessarily depict the trend of the impact on the ecosystem. Also, they do not capture the variability of the magnitude of the impact caused by the alien species. This occurrence-based indicator can be advanced by incorporating impact variability between species to account for these limitations.

The Red List Index (RLI) of alien species is an impact indicator that uses the change in extinction risk of native species caused by alien species as evidence of impact on the ecosystem (Butchart, 2008; Butchart et al., 2007; Rabitsch et al., 2016). The RLI is based on the IUCN Red List of Threatened Species which categorises species into a status between the range of Least Concern to Extinct. Changes in Red List categories can be attributed to factors such as alien species. Because of this, these changes can serve as a useful proxy for gauging the magnitude of alien species' impacts on native biodiversity (Rabitsch et al., 2016). Although the RLI reflects variation in how alien species affect native species, it does not fully capture the specific magnitude of impacts or the mechanisms by which alien species exert those impacts on the broader ecosystem. These species' impact magnitude and mechanisms coupled with alien species distribution can provide a better representation of alien species impact on the recipient ecosystem. Moreover, the RLI is not an evidence based classification and relies heavily on expert opinion, which makes comparison across timescales difficult.

The Environmental Impact Classification for Alien Taxa (EICAT), recently adopted by the IUCN, offers information about the impact of alien species and mechanisms thereof (IUCN, 2020a). Alien species are categorised from Minimal to Massive levels of concern, depending on the magnitude of impact reported on native species (Blackburn et al., 2014; IUCN, 2020b). Combining the impact of alien species and their occurrence can give the representation of the alien species in a particular region (Latombe et al., 2017). The combination of data on impacts and occurrences has been proposed as an indicator of the impact of invasions (e.g., Wilson et al. 2018), but there has been no standardised methodology to achieve this in practice. Recent research has seen significant practical developments to address this shortcoming. For example, Kumschick et al., (2025) used EICAT and species distribution to map the impact of *Acacia* species in South Africa. The authors transformed the EICAT categories into numerical values and computed the impact score for each site. Building on their approach, we now derive species-specific impact values over time to produce more refined impact indicators. In doing so, we expand the methods of Kumschick et al. (2025) and Boulesnane-Genguant et al. (submitted) by integrating open-source EICAT assessments and species occurrence data, making the impact indicators taxonomically, spatially, and temporally explicit. As part of the B3 project (https://b-cubed.eu/), we developed a workflow to calculate the impact indicator which visualises the impact of alien species over time and across space. The workflow is embedded in an R package following a standard software development guide (Huybrechts et al., 2024). The workflow produces three main products which include (i) a species impact indicator, (ii) a site impact indicator and (iii) an overall impact indicator.

1.2. Policy relevance

Alien species can have detrimental impacts on ecosystems, threatening the functioning of ecosystems for human well-being. To address these impacts, governments and organisations worldwide are developing and implementing policies to prevent the introduction of new invasive species, control the spread of existing ones, and restore affected ecosystems (IPBES 2023; Roy et al., 2023). These policies require evidence-based decision tools with standard workflows, such as impact indicators to monitor the trend of impact, assess the spread, and evaluate the effectiveness of control measures (Grêt-Regamey et al., 2017). Impact indicators can be used to forecast the spread and impact of alien species to enable appropriate preventative measures.

For an indicator to be useful for policy, it should comply with the FAIR Data Principles (Groom et al., 2017; Groom et al., 2019). To produce reliable and repeatable impact indicators, it is essential to employ an Open Data workflow that consistently converts raw data into coherent, detailed, and replicable indicators (Boyd et al., 2023; Groom et al., 2019; Seebens et al., 2020). Adherence to the FAIR Data Principles in both inputs and outputs is important for maintaining transparency, reusability, and long-term viability. Furthermore, to ensure the comprehensiveness and versatility of the indicator, it must be applicable to different spatial, temporal and taxonomic scales. Also, indicators must include uncertainty measures in the output to express the confidence level of the output to ensure end-users are not given false confidence when interpreting outputs.

The policy-relevant impact indicator will be an important decision-support tool for some current policy frameworks, such as Target 6 of the Convention on Biological Diversity (CBD) Kunming-Montreal Global Biodiversity Framework (UNEP, 2022) which aims 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 percent 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”.

2. Method

2.1. Occurrences data

The workflow uses the Global Biodiversity Information Facility (GBIF) occurrence data (https://www.gbif.org/). GBIF is the largest database for biodiversity information that adheres to FAIR Data Principles and is the most widely used for scientific purposes, demonstrating its reliability. The workflow uses an occurrence cube - a data format which aggregates occurrences along spatial, taxonomical and temporal scale - suitable for modelling and computational analysis (Oldoni et al., 2020). The GBIF provides options for spatial resolution for aggregating occurrences, such as the European Environmental Agency (EEA) or the Extended Quarter Degree Grid Cells (QDGC) commonly employed in South African atlas projects (Harrison et al., 1997). The downloaded GBIF occurrence cube is then processed using the **`b3gbi`** R package (Dove, 2025). This ensures standardised input data for further analysis and verifies that the data format is correct. Alternatively, an occurrence cube with customised site resolution and code can be built from GBIF occurrence data within the workflow. To correct for sampling bias, all computations convert multiple species occurrences at each site per year into binary presence (1) or absence (0) values.

2.2. Impact data

The workflow uses EICAT impact assessments which categorise the impact of an alien species into minimal concern (MC), minor (MN), moderate (MO), major (MR), or massive (MV) based on the severity of the species’ negative impact caused on the native species of the recipient community (IUCN 2020a, b). Specifically, a species is assigned
MC - if there is no reduction in the performance of individuals of a native species
MN - if the performance of individuals is reduced, but there is no decrease in native species population size
MO - if the native species’ population reduces
MR - if impact led to species’ local extinction but naturally reversible
MV - if impact led to naturally irreversible extirpation or extinction.

The impacts are also classified based on the 12 mechanisms described by the IUCN which include competition, predation, hybridisation, transmission of disease, parasitism, poisoning/toxicity, bio-fouling or other direct physical disturbance, grazing/herbivory/browsing, chemical impact on ecosystem, physical impact on ecosystem, structural impact on ecosystem, indirect impact through interactions with other species. Additional information such as the location of the impact is also reported (see IUCN, 2020a).

The data collection process for EICAT assessments involves several key steps. First, raw impact records for the alien species are gathered through an established search protocol using scientific literature, databases, and other relevant sources. These impacts are then categorised according to EICAT criteria. Each assessment undergoes a rigorous review by the EICAT Authority, comprising experts from diverse taxonomic groups and geographic regions, to ensure accuracy and consistency. Once validated, assessments are published on the IUCN Global Invasive Species Database (GISD), making them accessible to scientists, conservation practitioners, and policymakers for prioritising management actions and developing preventive or mitigation measures (IUCN, 2020b). Currently, EICAT assessments in the GISD are not fully open or FAIR, although efforts to address this are underway (personal communication, P Genovesi). Available EICAT data can presently be downloaded from https://www.iucngisd.org/gisd/. For species lacking published assessments, users can independently conduct assessments within the workflow.

2.2.1. Transforming EICAT impact categories to numerical values

The EICAT categories are semi-quantitative (ordinal) data which need to be transformed into numerical values to enable computation. The transformation depends on the assumptions of the relationship between the impact categories (e.g., linear) and the interpretation of the minimal concern (e.g., zero impact). The transformation

- **MC = 0, MN = 1, MO = 2, MR = 3 and MV = 4** assumes the categories have a linear relationship and minimal impact implies zero impact since no impact was found on the native species (e.g., Hagen & Kumschick 2018).
- **MC = 1, MN = 2, MO = 3, MR = 4 and MV = 5** assumes a linear relationship with minimal concern implying some concern even if no impact was found on the native species' individual (e.g., Jansen & Kumschick 2022).
- **MC = 0, MN = 10, MO = 100, MR = 1000 and MV = 10000** assumes impact categories have an exponential relationship and minimal concern is equal to zero impact (e.g., Rumlerová et al., 2016).

2.3. Species impact indicator

Species are often reported to have multiple impact categories specific to different study locations and mechanisms through which they exert the impact. For example, *Acacia dealbata* has been categorised as MR in Drakensberg, South Africa through structural impact but MN in Biobio region, Chile (see dataset of Jansen & Kumschick 2022). To get an estimate of a likely impact category which could apply more broadly, we aggregate the multiple impact scores per species into one impact score per species. Aggregation methods include, overall maximum, sum across maximum mechanism and overall mean. Additional statistics will be included in future updates.

- maximum: The maximum method assigns a species the maximum impact across all records of the species (Blackburn et al., 2014; IUCN, 2020a; Kumschick et al., 2024). It is best for precautionary approaches. Also, the assumption is that the management of the highest impact can cover for the lower impact caused by a species and can be the best when there is low confidence in the multiple impacts of species of interest. However, the maximum method can overestimate the impact of a species especially when the highest impact requires specific or rare conditions and many lower impacts were recorded.
- sum across maximum mechanism: Assigns a species the summation of the maximum impact per mechanism (Nentwig et al., 2010). The assumption is that species with many mechanisms of impact have a higher potential to cause impact.
- mean: Assigns a species the mean impact of all the species impact. This method computes the expected impact of the species considering all species impact without

differentiating between impacts (D'hondt et al., 2015). This method is adequate when there are many impact records per species.

Finally, to compensate for regions (spatial areas or ranges of occurrence data) with many sites (grid cells covering a region) having higher overall impact value, we divide the impact value of each by the number of sites occupied in the region.

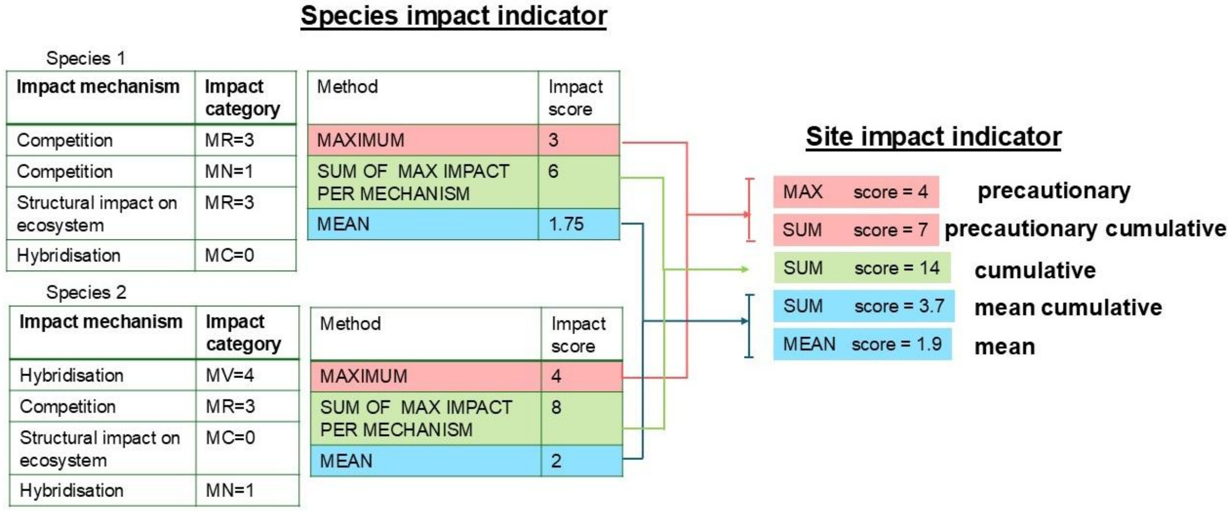

Figure 1: Methods for computing Species and Site impact indicator. The figure is adapted from Boulesnane-Guengant et al., (Submitted).

2.4. Site impact indicator

Multiple alien species can co-occur in a site. To get information on how sites are affected by alien species (i.e. site impact), we aggregate the different impacts per species in each site using one of five methods proposed by Boulesnane-Genguant et al. (submitted). These methods are precautionary, precautionary cumulative, mean, mean cumulative, and cumulative which depend on the combinations of aggregation within species and across species (Fig. 1).

- precautionary: This method uses the maximum method to aggregate each species' impact and then compute the maximum impact across species in each site.
- precautionary cumulative: Uses the maximum method to aggregate each species' impact and then compute the summation of all impacts in each site. The precautionary cumulative method provides the highest impact score possible for each species but considers the number of co-occurring species in each site.
- mean: Uses the mean method to aggregate each species' impact and then computes the mean of all species in each site. The mean provides the expected impact within individual species and across all species in each site.
- mean cumulative: Uses the mean method to aggregate each species' impact and then computes the summation of all impact scores in each site. The mean cumulative provides the expected impact score within individual species but adds co-occurring species' impact scores in each site.
- cumulative: Uses the sum across maximum mechanism method to aggregate each species' impact and then computes the summation of all species' impacts per site. The cumulative method provides a comprehensive view of the overall impact while considering the impact and mechanisms of multiple species.

2.5. Overall impact indicator

Furthermore, to estimate the impacts of all the species in a study area, we sum the impact values of all the sites for each year. Also, to compensate for regions with many sites having higher overall impact value, we divide the impact value of each by the number of sites occupied in the region. Hence, the impact score I_i

$$I_i = \frac{\sum S_i}{N}$$

Where i represents the year, S is the sum of site impact, $S = \{s_1, s_2, \ldots, s_n\}$ and s_n is the site score for the site n. N is the number of sites occupied throughout the year included in the analysis. The overall impact indicator has the same methods as the site impact indicator (Fig. 1)

2.6.Software description

We developed an R package called **`impIndicator`** (Yahaya et al., 2025) which implemented the workflow outlined in section 2.1 – 2.5 above (Fig. 2). The source code is freely available on the B3 GitHub repository (https://github.com/b-cubed-eu/impIndicator). The latest version of the package is automatically deposited on Zenodo (https://doi.org/10.5281/zenodo.15052675)

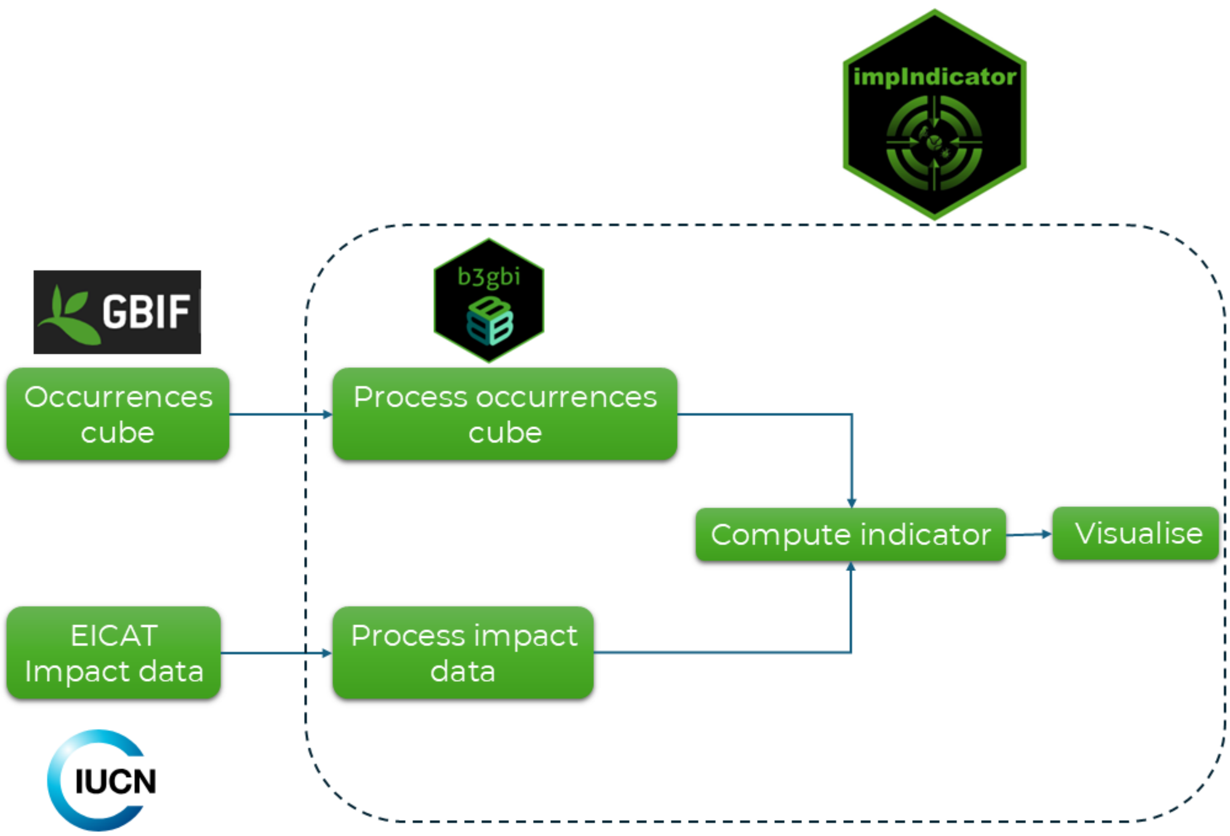

Figure 2: The diagrammatic representation of the workflow embedded in **impIndicator** to compute and visualise impact indicators of alien species https://github.com/b-cubed-eu/impIndicator.

3. Demonstration of workflow using *Acacia* species in South Africa

We demonstrate the workflow using *Acacia* species in South Africa. We used *Acacia* species alien to South Africa as a case study as data on impacts for this taxon is available on GISD. Furthermore, this taxon is among the most harmful and invasive in South Africa and other introduced regions and therefore provides a relevant case study (Richardson et al., 2023; Lusizi et al., 2024). We produce the impact indicator per individual species (species impact indicator), the impact indicator per site (site impact indicator) and the overall impact indicator of *Acacia* in South Africa.

Firstly, the **`impIndicator`** can be installed from the B3 r-universe repository (https://b-cubed-eu.r-universe.dev/builds).

```
# install impIndicator in R
install.package("impIndicator", repos = "https://b-cubed-eu.r-universe.dev")

# Load packages
library(impIndicator)
```

The *Acacia* occurrence downloaded from GBIF can be processed using the `taxa_cube()`. The occurrences data is named `taxa_Acacia` in the package. The `taxa_cube()` can download the occurrences data directly from the database, but we used the pre downloaded data in the package which saves downloading time. The `southAfrica_sf` is the shapefile of a map of South Africa. Alternatively, the a cube downloaded from the GBIF, with users selecting desired taxonomic, temporal, and/or spatial dimensions from pre-set options and optionally customising the SQL query before downloading (see https://www.gbif.org/en/occurrence-cubes for more info).

```
# Process cube from GBIF occurrence data in the R studio environment

acacia_cube <- taxa_cube(
  taxa = taxa_Acacia,
  region = southAfrica_sf,
  first_year = 2010
)

acacia_cube
#>
#> Simulated data cube for calculating biodiversity indicators
#>
#> Date Range: 2010 - 2024
#> Number of cells: 398
#> Grid reference system: custom
#> Coordinate range:
#>      xmin      xmax      ymin      ymax
#>  16.60833  31.60833 -34.69700 -22.94701
```

```
#>
#> Total number of observations: 6252
#> Number of species represented: 29
#> Number of families represented: Data not present
#>
#> Kingdoms represented: Data not present
#>
#> First 10 rows of data (use n = to show more):
#>
#> # A tibble: 6,252 × 8
#>    scientificName   taxonKey minCoordinateUncerta…¹  year cellCode xcoord ycoord
#>    <chr>               <dbl>                  <dbl> <dbl> <chr>     <dbl>  <dbl>
#>  1 Acacia mearnsii   2979775                      8  2010 1376       30.4  -29.7
#>  2 Acacia saligna    2978552                      1  2010 206        18.4  -33.9
#>  3 Acacia implexa    2979232                      1  2010 206        18.4  -33.9
#>  4 Acacia pycnantha  2978604                      1  2010 206        18.4  -33.9
#>  5 Acacia cyclops    2980425                    122  2010 668        18.4  -32.2
#>  6 Acacia mearnsii   2979775                      1  2010 215        20.6  -33.9
#>  7 Acacia mearnsii   2979775                    110  2010 215        20.6  -33.9
#>  8 Acacia saligna    2978552                      1  2011 206        18.4  -33.9
#>  9 Acacia saligna    2978552                      1  2011 144        19.4  -34.2
#> 10 Acacia melanoxy…  2979000                      1  2011 206        18.4  -33.9
#> # ℹ 6,242 more rows
#> # ℹ abbreviated name: ¹minCoordinateUncertaintyInMeters
#> # ℹ 1 more variable: obs <dbl>
```

We used the EICAT assessments from Jansen et al. (2022). The list provides the acacia species name, categories and mechanism of the impact reported in each source. Here is the view of the first ten rows.

```
# view EICAT data
head(eicat_acacia, 10)
#> # A tibble: 10 × 3
#>    scientific_name   impact_category impact_mechanism
#>    <chr>             <chr>           <chr>
#>  1 Acacia saligna    MC              (1) Competition
#>  2 Acacia saligna    MC              (12) Indirect impacts through interaction …
#>  3 Acacia saligna    MC              (1) Competition
#>  4 Acacia saligna    MC              (1) Competition; (9) Chemical impact on th…
#>  5 Acacia mearnsii   MC              (6) Poisoning/toxicity
#>  6 Acacia longifolia MC              (9) Chemical impact on ecosystems
#>  7 Acacia dealbata   MC              (9) Chemical impact on ecosystems
#>  8 Acacia dealbata   MC              (9) Chemical impact on ecosystems
#>  9 Acacia saligna    MC              (9) Chemical impact on ecosystems
#> 10 Acacia dealbata   MC              (12) Indirect impacts through interaction …
```

3.1.Species impact indicator of *Acacia* species in South Africa

The `compute_impact_per_species()` computes the impact indicator per species using the given method (e.g., mean). We used the default arguments for transformation MC = 0, MN = 1, MO = 2, MR = 3 and MV = 4 and site resolution of 0.25 degree. The `plot()` function creates the graph of the impact indicator.

```
#  impact indicator per species
species_value <- compute_impact_per_species(
  cube = acacia_cube,
  impact_data = eicat_acacia,
  method = "mean"
)

# visualise species impact
plot(species_value)
```

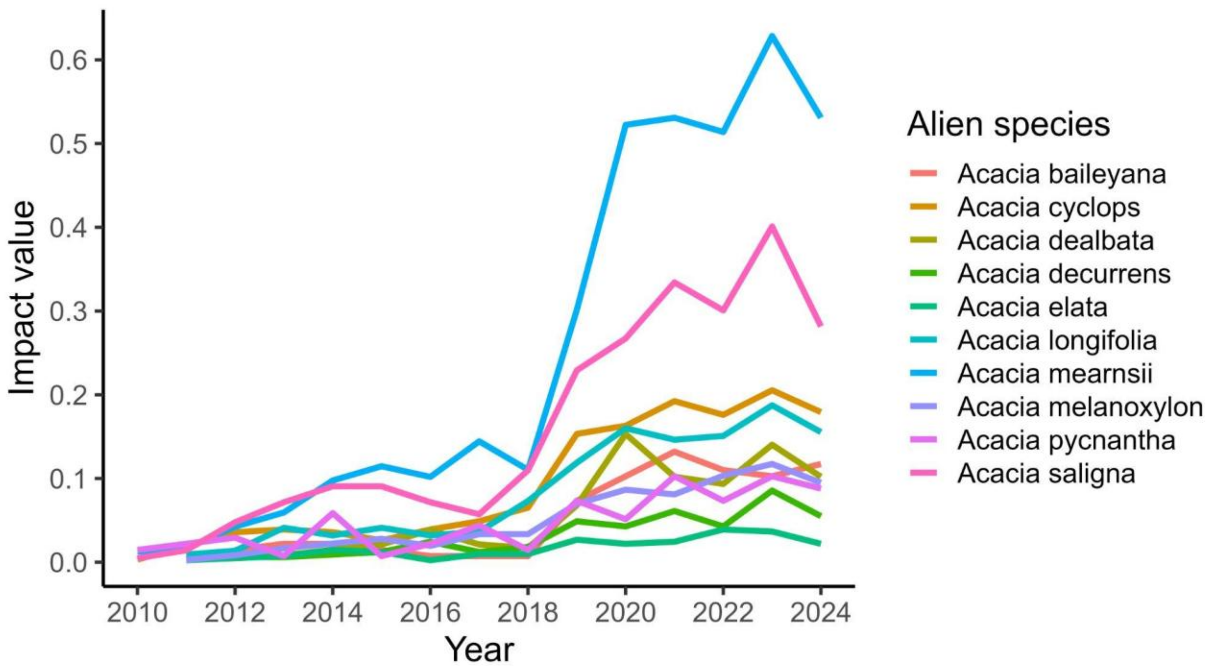

Figure 3: Species impact indicator per *Acacia* species over time, showing an increase in impact value corresponding primarily to the growing number of occupied grid cells, likely reflecting both species spread and intensified sampling efforts. Each species' impact value is calculated using the mean impact score of its records multiplied by the total sites occupied by the species, thereafter, normalised by the total number of sites occupied by all species in the dataset. Plans are underway to incorporate **`dubicube`** functionality (https://b-cubed-eu.github.io/dubicube/) for calculating indicator uncertainty using bootstrapping.

3.2. Site impact indicator of *Acacia* species in South Africa

The `compute_impact_per_site()` computes the impact score per site using the given method (e.g., mean cumulative). We used the default arguments for transformation MC = 0, MN = 1, MO = 2, MR = 3 and MV = 4 and site resolution of 0.25 degree. The `plot()` creates a map of impact indicators overlayed on the target region (South Africa in our case; `southAfrica_sf`) map. We visualise four maps of the site impact indicator for the map to be big enough to read (Fig. 4).

```r
# compute impact per site

siteImpact <- compute_impact_per_site(
  cube = acacia_cube,
  impact_data = eicat_acacia,
  method = "mean_cum"
)

# impact map
# visualise last four years for the map to be big enough to read
plot(x = siteImpact, region = southAfrica_sf, first_year = 2021)
```

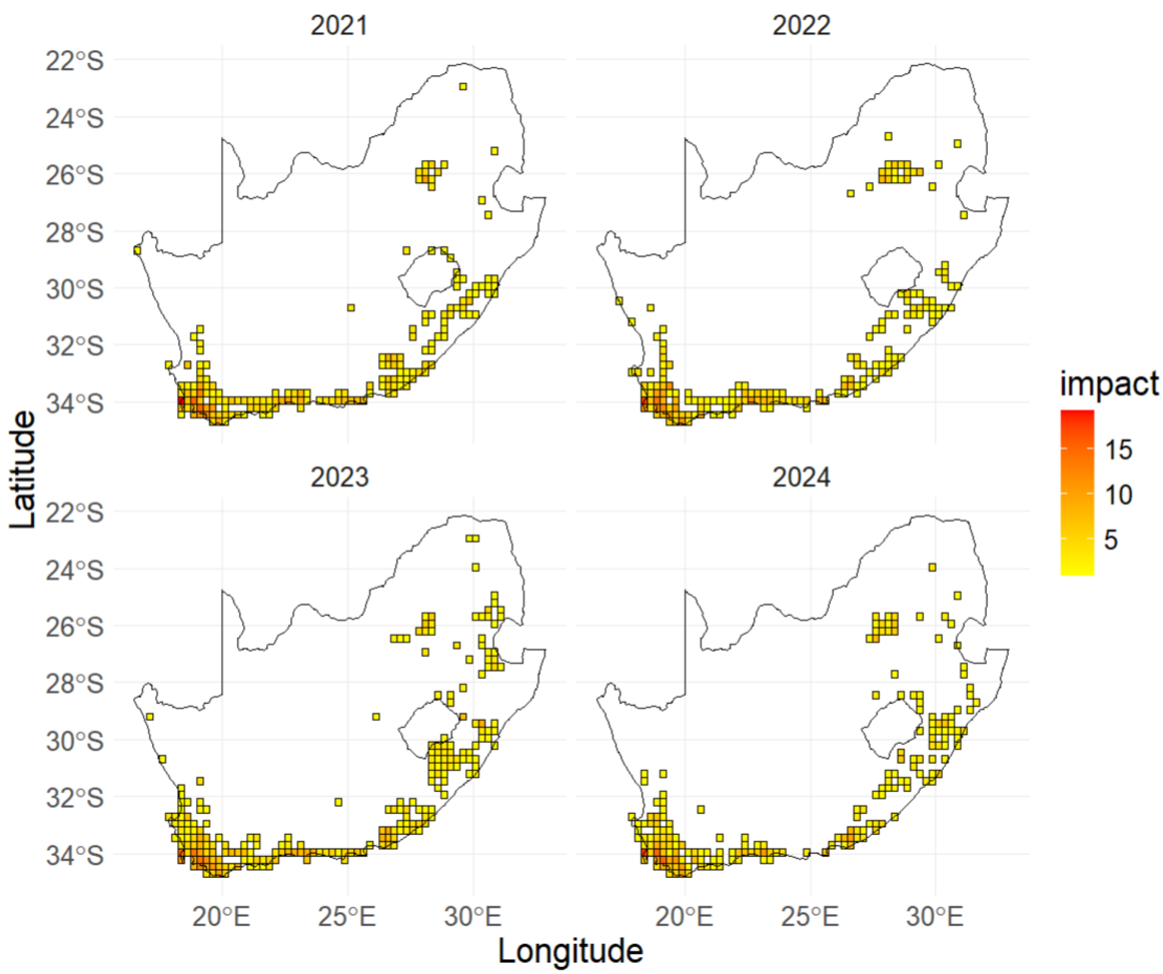

Figure 4: Site impact indicator of *Acacia* species in South Africa from 2021–2024. The site impact indicator represents the mean cumulative magnitude of impact across all *Acacia* species at each site. It is calculated by assigning each species the average impact score of all its recorded impacts and summing these values per site (Fig. 1) i.e. a spatial view of Fig. 3 summed per grid cell. Note that disappearing coloured grid cells do not necessarily indicate

species disappearance; rather, they may reflect instances where species observations were not repeated in subsequent surveys.

3.3. Overall impact indicator of *Acacia* species in South Africa

The `compute_impact_indicator()` function combines the acacia_cube and EICAT data using the given method (e.g., mean cumulative, Fig. 1) to compute the impact indicator of all species. We used the default arguments for transformation MC = 0, MN = 1, MO = 2, MR = 3 and MV = 4 and site resolution of 0.25 degree. The `plot()` creates the graph of the computed impact indicator.

```r
# compute impact indicator of all species
impactIndicator <- impact_indicator(
  cube = acacia_cube,
  impact_data = eicat_acacia,
  method = "mean_cum"
)


# visualise impact indicator
plot(impactIndicator)
```

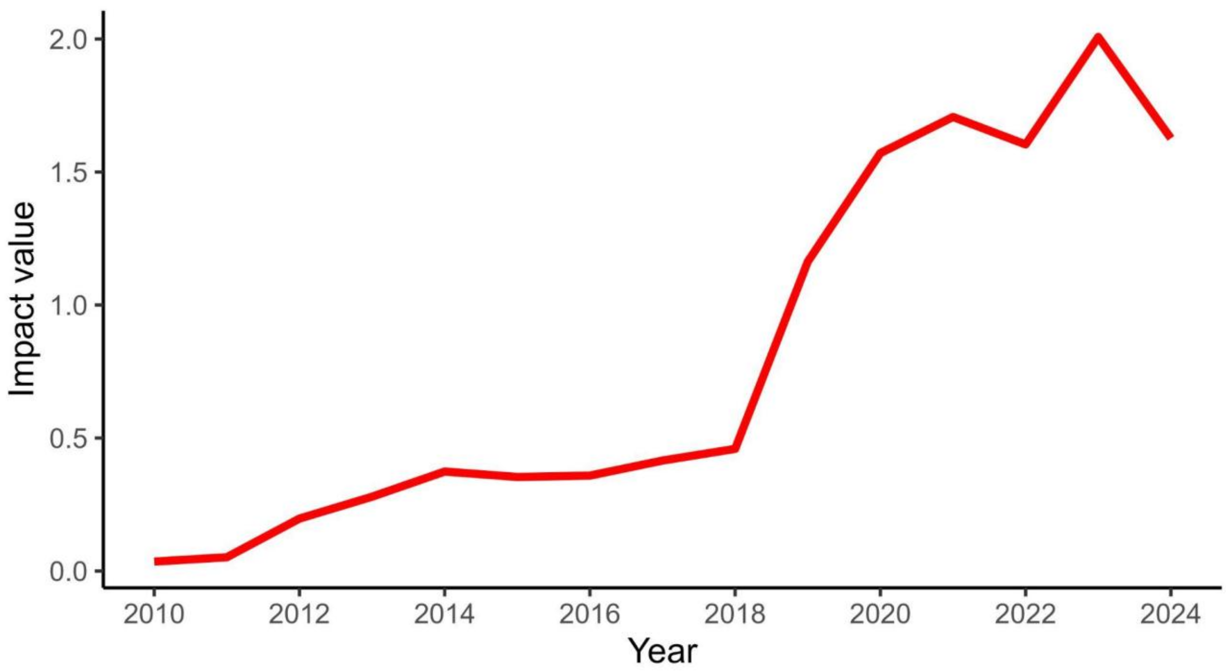

Figure 5: Impact indicator of *Acacia* species in South Africa, illustrating the cumulative impact value per year. The impact value is calculated using the "mean cumulative" method, where each species is assigned the average impact score based on all its impact records and summed across all sites for each year (Fig. 1), thereafter, normalised by the total number of sites occupied by all species in the dataset, i.e. summation of individual species displayed in Fig. 3. Note that the observed increases in impact likely reflect both genuine species spread and increased sampling effort, while the dip observed in 2022 may be an artefact resulting from observers not repeatedly recording previously identified plants or populations.

4. Discussion

Rapid and reliable monitoring information is required to enable appropriate management of the threats to biodiversity (UNEP, 2022). We developed a workflow to monitor the change in impact of alien species over time and space. The variability of the indicator in our workflow depends on the spread or restriction of the alien species in the area of study and their magnitude of impact. For example, the impact score increases in a year when an alien species spreads to a new site or when a new alien species arrives in the study area (Fig. 3)

Our workflow allows assigning a species the maximum impact score across all its impact records. This is the method IUCN uses to assign the final impact score to a species to suit a precautionary approach for biodiversity conservation. However, this was challenged in Cassini (2023), which argued that the maximum method does not fit some purposes and is a deviation from the classical central tendencies (e.g., mean) used in the field. The flexibility of our methods on assigning mean and sum across maximum mechanisms can address the concern of IUCN assigning maximum impact to an alien species (Cassini, 2023).

The product of our workflow can be used to enhance management and policy making for biological invasion. Specifically, the species impact indicator produces the trends of individual alien species, enabling a species-specific impact. This data supports comparisons of individual species' impacts, revealing their impact within the invaded area (Fig. 3). The species impact is invaluable for prioritising species-specific management efforts, informing control and eradication strategies, and advancing research on alien species' ecological roles and adaptation patterns (McGeoch et al., 2016; Carboneras et al., 2018).

Furthermore, the site impact indicator serves as a visual and analytical tool to represent the intensity of biological invasions across different parts of an area (e.g., Fig. 4). By enabling spatial comparisons, such as between provinces, states, or conservation areas, it highlights hotspots and areas at risk of impact caused by alien species. This spatial data is useful for prioritising management actions, coordinating restoration projects, and fostering cross-regional collaboration to address alien species impacts effectively (McGeoch et al., 2016; Potgieter et al., 2022).

Lastly, the overall impact indicator offers a nuanced representation of the trends of impacts of alien species on an area (local, regional, or global scales) (e.g., Fig. 5). By tracking the increase and decrease of ecological threats over time, this product can provide insights into the dynamics of alien species impacts, helping assess whether current management practices are effective or need adjustment. The temporal analysis of impact enables targeted resource allocation, fostering proactive interventions to mitigate biodiversity loss and ecosystem degradation (McGeoch et al., 2010; Wilson et al., 2018).

Lastly, with the advanced deep learning technique for species distribution model (SDM) developed within the B3 project (Ryckewaert et al., 2025), our workflow can leverage the deep learning SDM to predict the impact of alien species across space and time. This will allow us to forecast the impact and stimulate appropriate policy and management responses.

4.1. Challenge and Limitation

The main limitation of this workflow is the current lack of EICAT impact assessment of most alien taxa, although there are ongoing efforts to assess many alien species within various projects, and many assessments are available in the scientific literature (e.g., Evans et al., 2016; Canavan et al., 2019; Volery et al., 2021; Jansen & Kumschick, 2022). However, these data are not yet open and completely adhere to FAIR Data Principles, and users have to feed in their own data manually for most taxa and regions. We assume that impact magnitude with a specific mechanism in a local region is often the same in other regions with the mechanism except for rare regions such as islands. Since most impact data assessed are not necessarily on the specific study area selected, the impact indicators presented here represent potential impacts, which can be different from the actual impact of alien species in the study area. If and when more impact data become available (i.e., more primary studies on impact are conducted), one can filter for only impacts relevant to or collected in the area of interest, but currently, data for most invaded sites is lacking.

Furthermore, since the impact score per species does not change over time, the spike in impact values between 2018 and 2021 (Fig. 3 & 5) is mainly due to spreading to new sites. However, the results found in this study regarding the rate of spread is not consistent with the study of Kotzé et al. (2023) which surveyed sites in South Africa for periods between 2007 - 2008 and 2016 - 2023 using observers in low-flying aircraft. They estimated only an increase of 10.6% between the two periods. The deviance of our results from Kotze et al. (2023) is most likely attributable to the difference in sampling effort of the data used for both analyses, and the data sources considered. Kotze et al's data is not included in our GBIF occurrences and the spike in occurrence from 2018 to 2020 is probably attributable to the addition of iNaturalist data to the GBIF database. Therefore, we highlight the caveat in interpreting our results because the occurrence data used is biased. Undoubtedly, there are trade-offs between FAIR data and sampling effort such as (i) delay in field data and publication on GBIF database (ii) non-open data and (iii) beginning of sharing of a large dataset (e.g., incorporation of iNaturalist data on GBIF). One way to address this issue is to allow the computation of indicators with local occurrences data with high sampling effort even if it is not on the GBIF database, and, more ideally, a better, faster and more complete incorporation of local datasets into GBIF.

4.2. Further development

The workflow and the package will be tested using other case studies over the next few months within the case studies selected in the B3 project. If needed, they can be adapted and improved to suit the specific needs of different stakeholders. Feedback will be collected via the issue tracker of the `impIndicator` GitHub repository (https://github.com/b-cubed-eu/impIndicator/issues).

The package will further be developed to integrate the bootstrapping technique embedded in the `dubicube` R package (Langeraert & Van Daele, 2025) to calculate the uncertainty related to the computed indicator. The `dubicube` resamples the individual observations (rows) of an original dataset (e.g., occurrence data merged with impact data) with replacement and then computes the indicator on the new data. Repeating the indicator computation on multiple, newly resampled data will allow users to derive confidence intervals for our data (https://github.com/b-cubed-eu/dubicube). In this way, we hope to account for uneven or unknown sampling effort, including delays between field observations and their subsequent publication on GBIF, as these issues can affect impact indicator results and trends.

5. Acknowledgements

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 thank, Maarten Trekels, Tsungai Zengeya, Dave Richardson, Tammy Robinson, Christiaan Gildenhuys, Lorenzo Ruaro for their contribution at the Mathematical Biosciences Hub, Stellenbosch University workshop titled "Quantifying potential impact of biological invasions using occurrence cubes and consensus-based impact categories" held on 21 October 2024. We appreciate the inputs made by Toon van Daele and Duccio Rocchini during their review of this report.

6. References

Bacher, S., Galil, B., Nunez, M., Ansong, M., Cassey, P., Dehnen-Schmutz, K., Fayvush, G., Hiremath, A., Ikegami, M., Martinou, A., McDermott, S., Preda, C., Vila, M., Weyl, O. L. F., Fernandez, R., & Ryan-Colton, E. (2023). Chapter 4. Impacts of invasive alien species on nature, nature's contributions to people, and good quality of life. *IPBES Invasive Alien Species Assessment*, 1–222. https://doi.org/10.5281/zenodo.7430731

Blackburn, T. M., Essl, F., Evans, T., Hulme, P. E., Jeschke, J. M., Kühn, I., Kumschick, S., Marková, Z., Mrugała, A., Nentwig, W., Pergl, J., Pyšek, P., Rabitsch, W., Ricciardi, A., Richardson, D. M., Sendek, A., Vilà, M., Wilson, J. R. U., Winter, M., … Bacher, S. (2014). A Unified Classification of Alien Species Based on the Magnitude of their Environmental Impacts. *PLOS Biology*, *12*(5), e1001850. https://doi.org/10.1371/journal.pbio.1001850

Boyd, R. J., August, T. A., Cooke, R., Logie, M., Mancini, F., Powney, G. D., Roy, D. B., Turvey, K., & Isaac, N. J. B. (2023). An operational workflow for producing periodic estimates of species occupancy at national scales. *Biological Reviews*, *98*(5), 1492–1508. https://doi.org/10.1111/brv.12961

Boulesnane-Guengant, O., Rouget, M., Becker-Scarpitta, A., Botella, C., & Kumschick, S. (Submitted). Spatialising the ecological impacts of alien species into risk maps.

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*(S1), S245–S262. https://doi.org/10.1017/S095927090800035X

Butchart, S. H. M., Akçakaya, H. R., Chanson, J., Baillie, J. E. M., Collen, B., Quader, S., Turner, W. R., Amin, R., Stuart, S. N., & Hilton-Taylor, C. (2007). Improvements to the Red List Index. *PLOS ONE*, *2*(1), e140. https://doi.org/10.1371/journal.pone.0000140

Canavan, S., Kumschick, S., Le Roux, J. J., Richardson, D. M., & Wilson, J. R. U. (2019). Does origin determine environmental impacts? Not for bamboos. *PLANTS, PEOPLE, PLANET*, *1*(2), 119–128. https://doi.org/10.1002/ppp3.5

Carboneras, C., Genovesi, P., Vilà, M., Blackburn, T. M., Carrete, M., Clavero, M., D'hondt, B., Orueta, J. F., Gallardo, B., Geraldes, P., González-Moreno, P., Gregory, R. D., Nentwig, W., Paquet, J.-Y., Pyšek, P., Rabitsch, W., Ramírez, I., Scalera, R., Tella, J. L., … Wynde, R. (2018). A prioritised list of invasive alien species to assist the effective implementation of EU legislation. *Journal of Applied Ecology*, *55*(2), 539–547. https://doi.org/10.1111/1365-2664.12997

Cassini, M. H. (2023). A critical review of the precautionary approach of the IUCN impact classification for non-native taxa. *Conservation Biology*, *37*(2), e14037. https://doi.org/10.1111/cobi.14037

Delavaux, C. S., Crowther, T. W., Zohner, C. M., Robmann, N. M., Lauber, T., Van den Hoogen, J., Kuebbing, S., Liang, J., De-Miguel, S., & Nabuurs, G.-J. (2023). Native diversity buffers against severity of non-native tree invasions. *Nature*, *621*(7980), 773–781.

D'hondt, B., Vanderhoeven, S., Roelandt, S., Mayer, F., Versteirt, V., Adriaens, T., Ducheyne, E., San Martin, G., Grégoire, J.-C., Stiers, I., Quoilin, S., Cigar, J., Heughebaert, A., & Branquart, E. (2015). Harmonia+ and Pandora+: Risk screening tools for potentially invasive plants, animals and their pathogens. *Biological Invasions*, *17*(6), 1869–1883. https://doi.org/10.1007/s10530-015-0843-1

Dove, S. (2025). *b3gbi: General Biodiversity Indicators for Biodiversity Data Cubes* (Version 0.4.2) [R]. https://github.com/b-cubed-eu/b3gbi

Evans, T., Kumschick, S., & Blackburn, T. M. (2016). Application of the Environmental Impact Classification for Alien Taxa (EICAT) to a global assessment of alien bird impacts. *Diversity and Distributions*, *22*(9), 919–931. https://doi.org/10.1111/ddi.12464

GBIF. (2025). *What is GBIF?* https://www.gbif.org/what-is-gbif

Grêt-Regamey, A., Sirén, E., Brunner, S. H., & Weibel, B. (2017). Review of decision support tools to operationalize the ecosystem services concept. *Ecosystem Services*, *26*, 306–315. https://doi.org/10.1016/j.ecoser.2016.10.012

Groom, Q. J., Adriaens, T., Desmet, P., Simpson, A., De, W. A., Bazos, I., De, J. C. A., Charles, L., Christopoulou, A., Gazda, A., Helmisaari, H., Hobern, D., Josefsson, M., Lucy, F. E., Marisavljevic, D., Oszako, T., Pergl, J., Petrovic-Obradovic, O., Prévot, C., … Vanderhoeven, S. (2017). *Seven recommendation to make your alien species data more useful*. JRC Publications Repository. https://doi.org/10.3389/fams.2017.00013

Groom, Q., Strubbe, D., Adriaens, T., Davis, A. J., Desmet, P., Oldoni, D., Reyserhove, L., Roy, H. E., & 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). https://nora.nerc.ac.uk/id/eprint/526284/

Harrison, J. A., Allan, D. G., Underhill, L. G., Brown, C. J., Herremans, M., Parker, V., & Tree, A. J. (1997). *The atlas of southern African birds* (Vol. 1). BirdLife South Africa Johannesburg. https://www.researchgate.net/profile/Leslie-Underhill/publication/310607366_References/links/58336a5008ae138f1c0aa27e/References.pdf

Henriksen, M. V., Arlé, E., Pili, A., Clarke, D. A., García-Berthou, E., Groom, Q., Lenzner, B., Meyer, C., Seebens, H., Tingley, R., Winter, M., & McGeoch, M. A. (2024). Global indicators of the environmental impacts of invasive alien species and their information adequacy. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *379*(1902), 20230323. https://doi.org/10.1098/rstb.2023.0323

Huybrechts, P., Trekels, M., Abraham, L., & Desmet, P. (2024). *B-Cubed software development guide*. B-Cubed Documentation. https://docs.b-cubed.eu/guides/software-development/

IPBES. (2023). Summary for Policymakers of the Thematic Assessment Report on Invasive Alien Species and their Control of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Roy, H. E., Pauchard, A., Stoett, P., Renard Truong, T., Bacher, S., Galil, B. S., Hulme, P. E., Ikeda, T., Sankaran, K. V., McGeoch, M. A., Meyerson, L. A., Nuñez, M. A., Ordonez, A., Rahlao, S. J., Schwindt, E., Seebens, H., Sheppard, A. W., and Vandvik, V. (eds.). *IPBES Secretariat, Bonn, Germany*, 1–56. https://doi.org/10.5281/zenodo.7430692

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

IUCN. (2020a). *IUCN EICAT Categories and Criteria: The Environmental Impact Classification for Alien Taxa*. IUCN Gland, Switzerland.

Jansen, C., & Kumschick, S. (2022). A global impact assessment of Acacia species introduced to South Africa. *Biological Invasions*, *24*(1), 175–187. https://doi.org/10.1007/s10530-021-02642-0

Kumschick, S., Bertolino, S., Blackburn, T. M., Brundu, G., Costello, K. E., de Groot, M., Evans, T., Gallardo, B., Genovesi, P., Govender, T., Jeschke, J. M., Lapin, K., Measey, J., Novoa, A., Nunes, A. L., Probert, A. F., Pyšek, P., Preda, C., Rabitsch, W., … Bacher, S. (2024). Using the IUCN Environmental Impact Classification for Alien Taxa to inform decision-making. *Conservation Biology*, *38*(2), e14214. https://doi.org/10.1111/cobi.14214

Kumschick, S., Journiac, L., Boulesnane-Genguant, O., Botella, C., Pouteau, R., & Rouget, M. (2025). Mapping potential environmental impacts of alien species in the face of climate change. *Biological Invasions*, *27*(1), 43. https://doi.org/10.1007/s10530-024-03490-4

Langeraert, W., & Van Daele, T. (2025). *dubicube: Calculation and Interpretation of Data Cube Indicator Uncertainty* (Version 0.5.0) [Computer software]. https://b-cubed-eu.github.io/dubicube/

Latombe, G., Pyšek, P., Jeschke, J. M., Blackburn, T. M., Bacher, S., Capinha, C., Costello, M. J., Fernández, M., Gregory, R. D., Hobern, D., Hui, C., Jetz, W., Kumschick, S., McGrannachan, C., Pergl, J., Roy, H. E., Scalera, R., Squires, Z. E., Wilson, J. R. U., … McGeoch, M. A. (2017). A vision for global monitoring of biological invasions. *Biological Conservation*, *213*, 295–308. https://doi.org/10.1016/j.biocon.2016.06.013

Lusizi, Z., Motsi, H., Nyambo, P., & Elephant, D. E. (2024). Black (*Acacia mearnsii*) and silver wattle (*Acacia dealbata*) invasive tree species impact on soil physicochemical properties in South Africa: A systematic literature review. *Heliyon*, *10*(2), e24102. https://doi.org/10.1016/j.heliyon.2024.e24102

McGeoch, M. A., Butchart, S. H. M., Spear, D., Marais, E., Kleynhans, E. J., Symes, A., Chanson, J., & Hoffmann, M. (2010). Global indicators of biological invasion: Species numbers, biodiversity impact and policy responses. *Diversity and Distributions*, *16*(1), 95–108. https://doi.org/10.1111/j.1472-4642.2009.00633.x

McGeoch, M. A., Genovesi, P., Bellingham, P. J., Costello, M. J., McGrannachan, C., & Sheppard, A. (2016). Prioritizing species, pathways, and sites to achieve conservation targets for biological invasion. *Biological Invasions*, *18*(2), 299–314. https://doi.org/10.1007/s10530-015-1013-1

Nentwig, W., Kühnel, E., & Bacher, S. (2010). A Generic Impact-Scoring System Applied to Alien Mammals in Europe. *Conservation Biology*, *24*(1), 302–311. https://doi.org/10.1111/j.1523-1739.2009.01289.x

Oldoni, D., Groom, Q., Adriaens, T., Davis, A. J. S., Reyserhove, L., Strubbe, D., Vanderhoeven, S., & Desmet, P. (2020). *Occurrence cubes: A new paradigm for aggregating species occurrence data* (p. 2020.03.23.983601). bioRxiv. https://doi.org/10.1101/2020.03.23.983601

Potgieter, L. J., Aronson, M. F. J., Brandt, A. J., Cook, C. N., Gaertner, M., Mandrak, N. E., Richardson, D. M., Shrestha, N., & Cadotte, M. W. (2022). Prioritization and thresholds for managing biological invasions in urban ecosystems. *Urban Ecosystems*, *25*(1), 253–271. https://doi.org/10.1007/s11252-021-01144-0

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. https://doi.org/10.1016/j.jnc.2015.12.001

Richardson, D. M., Roux, J. J. L., & Marchante, E. (Eds.). (2023). *Wattles: Australian Acacia Species Around the World*. CABI. https://doi.org/10.1079/9781800622197.0000

Roy, H. E., Pauchard, A., Stoett, P., Renard Truong, T., Bacher, S., Galil, B. S., Hulme, P., Ikeda, T., Sankaran, K. V., & McGeoch, M. (2023). *Summary for policymakers of the thematic assessment report on invasive alien species and their control of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. IPBES. https://researcharchive.lincoln.ac.nz/entities/publication/cf8c4863-c5e1-4bd5-9239-f3f500c07842

Ryckewaert, M., Marcos, D., & Joly, A. (2025). *Report on deep learning development. B3 project delivarable D4.2*.

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

UNEP. (2022). *Decision adopted by the Conference of the Parties to the Convention on Biological Diversity*. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf

Vicente, J. R., Vaz, A. S., Roige, M., Winter, M., Lenzner, B., Clarke, D. A., & McGeoch, M. A. (2022). Existing indicators do not adequately monitor progress toward meeting invasive alien species targets. *Conservation Letters*, *15*(5), e12918. https://doi.org/10.1111/conl.12918

Volery, L., Jatavallabhula, D., Scillitani, L., Bertolino, S., & 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), 1003–1016. https://doi.org/10.1111/gcb.15467

Wilson, J. R. U., Faulkner, K. T., Rahlao, S. J., Richardson, D. M., Zengeya, T. A., & Van Wilgen, B. W. (2018). Indicators for monitoring biological invasions at a national level. *Journal of Applied Ecology*, *55*(6), 2612–2620. https://doi.org/10.1111/1365-2664.13251

Yahaya, M. M., Kumschick, S., MacFadyen, S., Landi, P., & Hui, C. (2025). *impIndicator: Impact Indicators of Alien Taxa* (Version 0.2.0) [Computer software]. https://github.com/b-cubed-eu/impIndicator