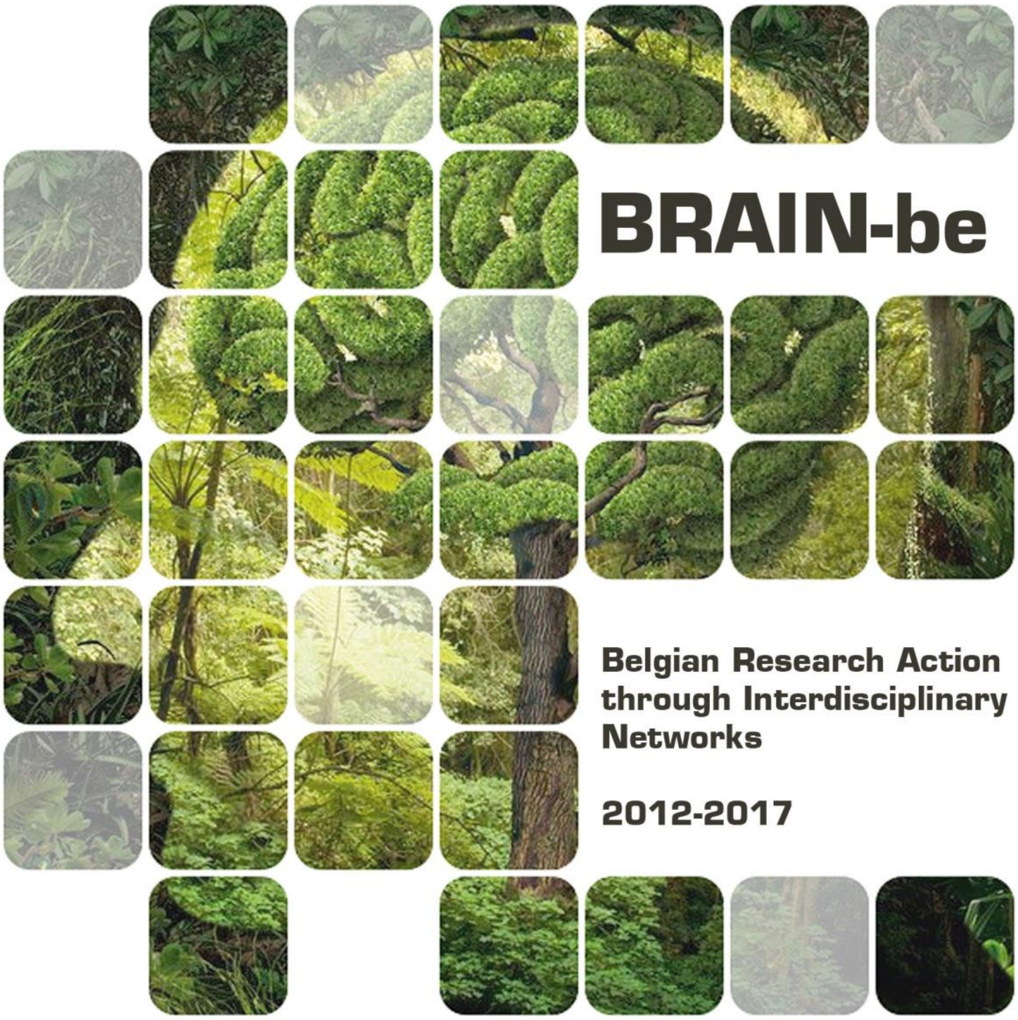

TrIAS

Tracking Invasive Alien Species: Building a data driven framework to inform policy

Quentin Groom, Sonia Vanderhoeven, Hilde Eggermont, Maxime Coupremanne, Tim Adriaens, Peter Desmet, Lien Reyserhove, Damiano Oldoni, Diederik Strubbe, Amy Davis, Luc Lens, Arnaud Monty, Grégory Mahy, Anne-Laure Jacquemart, Thomas Verleye, Gert Van Hoey, Ruben Van De Kerchove, Thierry Backeljau, Marc Dispas, Sciensano, Aline Vilain, Rozemien De Troch, Bert Van Schaeybroeck & Piet Termonia

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NETWORK PROJECT

TrIAS

Tracking Invasive Alien Species: Building a data driven framework to inform policy

Contract - BR/165/A1/TrIAS

FINAL REPORT

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1. INTRODUCTION

In our grant proposal we asked readers to "*Imagine a future where dynamically, from year to year, we can track the progression of alien species (AS), identify emerging problem species, assess their current and future risk and timely inform policy in a seamless data-driven workflow*". TrIAS has been about realising that vision. Creating open workflows that can be used to publish, analyse and evaluate data. However, it has also been a project about getting the right people in Belgium working together to create useful outcomes to address the pressing environmental issue of invasive alien species. Below we summarise the goals, methods, outputs and conclusions of TrIAS.

2. STATE OF THE ART AND OBJECTIVES

Invasive alien species are a defining feature of the Anthropocene (Tittensor et al. 2014; van Kleunen et al. 2015). The dispersal of invasive species by humans, either by accident or on purpose, is leading to the modification of some ecosystems and replacing others. This is leading to the loss of species, and negative impacts on agriculture, forestry and other benefits that humans derive from nature.

Wildlife managers, conservationists, policy makers and researchers have to make decisions on information that is rapidly out-of-date, because there are many species to monitor, new introductions arriving all the time and the area to cover is large. Access to recent, accurate and reliable distribution data are key to addressing the problems these invaders pose. However, even if data are collected they are not always shared in a way that makes them findable and usable by the people that need them. Reducing barriers to data sharing and reuse will improve our ability to react rapidly to new and changing biological invasions (Groom et al. 2015).

Furthermore, we not only need to manage current problems caused by invasive alien species, but also need to predict their impact in the future and design policies that are proactive, adaptable and proportionate. These policies need to take into account climate change and other anthropogenic environmental change likely to affect the distribution and impacts of invasive alien species. Nevertheless, ecological processes are hard to predict and policy needs a sound foundation in science, but also needs to be updated frequently as new data are collected and knowledge evolves (McGeoch et al. 2012; Roy et al. 2014).

In Europe, legislation, such as the EU Regulation 1143/2014 on IAS, has increased the need for Member States to collect, share and analyse data on IAS. However, this need has also highlighted the gaps in our knowledge and the range, quality and scope of information sources, supporting tools, data infrastructure and information systems. Furthermore, transparent use of available data in risk assessment and decision making is crucial to guarantee reliability, credibility and endorsement of the outcomes by stakeholders and the public (Hattingh 2011, McGeoch et al. 2012) and to ensure efficient allocation of available biodiversity conservation budget.

At the forefront of data sharing on biodiversity is Global Biodiversity Information Facility (GBIF), a global infrastructure providing data publishing services to data providers and equipping scientists with tools to examine these data. Alien species registries, exhaustive documented lists of species present in a territory, are important tools to address the selection of species for risk assessment and derived lists of IAS have formed the basis of many policy initiatives (Lodge et al. 2006, McGeoch et al. 2012, Roy et al. 2014, Latombe et al. 2016).

Nationally the Belgium Biodiversity Platform, a node of GBIF, has supported data publication and provided tools to allow policy decisions to be taken on invasive species. However, such systems only become optimal if they are supported with up-to-date and accurate data at appropriate spatial scales. Furthermore, Belgium has been a leader on the development of risk assessment protocols for invasive alien species (Vanderhoeven et al. 2015, D'hondt et al. 2015).

Yet, when TrIAS started workflows from biodiversity observations to science and policy were slow, not easily repeatable and their scope is often taxonomically, spatially and temporally limited. Lags are caused by the diversity of people and organisations involved and the closed, fragmented nature of the sources of these biodiversity data. Despite the obvious advantages of fast and open data availability for policy something needed to be done to meet the need for data and knowledge on invasive species.

TrIAS leveraged expertise and knowledge from nine former BELSPO projects and initiatives - Alien Alert, Invaxen, Diars, Inplanbel, Alien Impact, Ensis, CORDEX.be, Speedy and the Belgian Biodiversity Platform - TrIAS's goal was to mobilise data, and create workflows to make this sustainable; process data into indicators and models so that this could be repeated as new data arrives and use the information generated to assess the risk of alien species that appear to be emerging as invasive species.

3. METHODOLOGY

3.1 Data

We developed a semi-automated workflow for the publication of the **species checklists** (Reyserhove et al. 2020, Fig. 1). This workflow is open, reproducible and versioned and combines data standardisation to Darwin Core (DwC) with data publication on GBIF. It is a stepwise process and includes (i) source data management to produce 'tidy data', (ii) automated and reproducible data transformation to produce interoperable data, (iii) data documentation and (iv) data publication to produce FAIR and open data. Each of these components is under version control. The end product of this publication workflow is a dataset that is openly available and complies with the FAIR principles (Wilkinson et al. 2016). It is "Findable" by its globally unique and persistent Digital Object Identifier (DOI), described with rich metadata and registered in GBIF; "Accessible" by simply clicking on the download link provided in GBIF; "Interoperable" as it uses a broadly applicable biodiversity standard an vocabularies provided by TDWG and GBIF, and "Reusable" as it is associated with detailed provenance and released with a clear data usage licence.

The source data management and data transformation step resulted from a collaborative effort between the dataset author and the party responsible for the publication, i.e. INBO. However, in an ideal world, a species checklist or occurrence dataset is managed and published by the author of the dataset. To lower the barrier for data owners to publish their checklist using the reproducible workflow, we developed a "checklist recipe" (Reyserhove et al. 2018), which won the 2018 Ebbe Nielsen Challenge. The recipe is a template GitHub repository, specifically developed to assist data holders in standardising species checklists to DwC using R. The basic ingredients for this recipe are (i) a template spreadsheet with a list of predefined fields covering both taxonomic and distribution information, (ii) a template mapping script to transform the data to DwC and (iii) a wiki describing how to use these template documents. By providing the data providers with the necessary tools, tips and methods on how to maintain and publish their dataset, we empower them to publish their own dataset according to best practises.

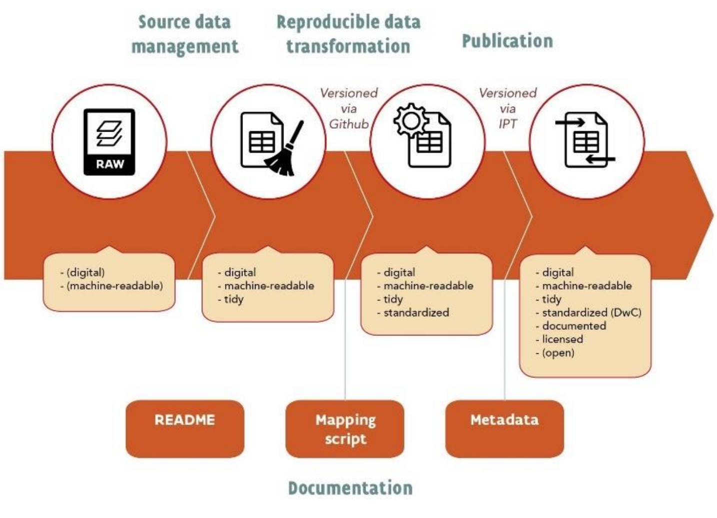


Figure 1: A diagrammatic representation of the TrIAS data publication process from Reyserhove et al. (2020). Raw data (left) are processed with scripts to make them 'Tidy' *sensu* Wickham (2014) and published to GBIF via the Integrated Publishing Toolkit (IPT). The results are Open Data that also comply with FAIR Data Principles (Wilkinson et al. 2016). When new versions of the raw data are generated it is a relatively simple process to repeat the work flow and create new updated versions of the data.

Next to the alien species checklists, several important sources of **alien species occurrence records** for Belgium were published as FAIR and open datasets to GBIF. For each source, we used a similar approach to mapping script to standardise the data to the DwC standard. The published occurrence data at least included the species name, date, location and source information for each record. Each dataset was documented with rich metadata and was published to GBIF. Some of the checklists and occurrence datasets are updated on a regular basis, but others can be updated as necessary. For those datasets, republication was done at least once in the course of the project.

3.1.1 Unified checklist of alien species in Belgium

Since the checklists published for the TrIAS project were of a specific taxonomic, geographic or thematic scope, they needed to be consolidated to effectively support research and policy. This is greatly facilitated by making checklists open and FAIR: scientific names from checklists published to GBIF are automatically matched to the GBIF Backbone Taxonomy (GBIF Secretariat, 2021) and are thus standardised by scientific names. By harvesting these interoperable checklist data using the GBIF Species Application Programming Interface (API), it is possible to create a unified checklist in an automated, transparent and repeatable way. The process of selecting, unifying and standardising the species checklists into a single unified checklist of alien species in Belgium is described Desmet et al. (2019). In short, a series of RMarkdown scripts were developed to choose the taxa, filter them on distribution, verify and match them with the GBIF backbone and unify them within and across checklists to produce a unique list of taxa. This unified checklist was accepted as the Belgian contribution to the Global Register of Introduced and Invasive Species (GRIIS) (Pagad et al. 2018).

3.1.2 Data Aggregation

Biodiversity occurrence data are collected at a wide range of scales, methods and resolutions, there are also some large differences in the survey effort between different habitats, areas and species. Before any indicators or models can be built with these data have to be harmonised to a common spatial and temporal resolution using a standard geographic grid system and period length. Early on in the project we examined downscaling techniques that are able to aggregate spatial data at different resolutions and predict occupancy at small resolutions (Groom et al. 2018). While downscaling was proven to be a useful tool, particularly for calculating area of occupancy at high resolutions, it does not support modelling of distributions at those resolutions. Therefore, we examine alternative methods for aggregating data. This led to the development of a novel method for aggregating data based upon a Monte Carlo approach (Oldoni et al. 2020a). This method was able to create data cubes with the dimensions of taxon, spatial grid cell and year. All the software to create these cubes is openly available on GitHub (https://github.com/trias-project/occurrence-cube-paper). These standardised datasets can be created on demand, but can also be deposited in a repository. We created them for Belgium and Italy and deposited them on Zenodo (https://doi.org/10.5281/zenodo.3637910). These data constructs conform to the concept of a Essential Biodiversity Variable for occurrence (Pereira et al. 2013). We built these cubes based upon the same grid system as environmental data so that they could be used as the source data for models and of indicators so that all downstream data products could be based upon the same source data and these provenance can be tracked right back to the source datasets and even individual observations.

The occurrence cubes developed for the TrIAS project are built on the Open Science principles and are intended to be completely reproducible (Oldoni et al. 2020a). To generate these occurrence cubes, raw occurrence data are harvested from GBIF in a reproducible way (Fig. 2). As all data published to GBIF are standardised to the Darwin Core format, they can easily be combined together. Some basic data quality assessment was performed to remove all invalid records: occurrences with invalid or suspicious coordinates or suspicious dates, occurrences related to fossil records or living specimens, or occurrences representing absences. For occurrences without spatial uncertainty, a default uncertainty of 1000m was chosen. After this data cleaning step, each occurrence was assigned to a 1×1 km [EEA reference grid]() cell and the occurrence cubes were generated by grouping species occurrence data by year, grid cell and taxon. For each grouping, the number of occurrences found in GBIF and the minimum coordinate uncertainty were calculated. The code to process the data to cubes is available on GitHub (https://github.com/trias-project/occ-cube-alien). The aggregated occurrence data at species level are available for non-native taxa in Belgium and Europe (Oldoni et al. 2020b) and for all taxa in Belgium and Italy (Oldoni et al. 2020c)

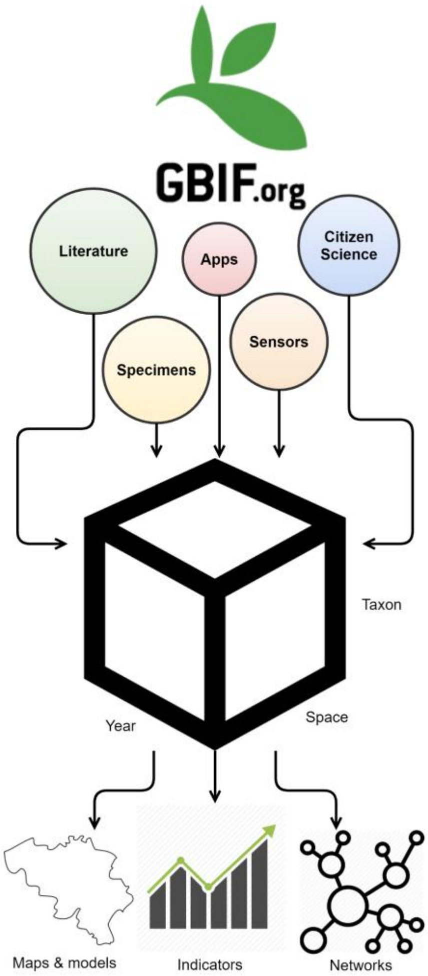


Figure 2: A diagrammatic representation of how diverse sources of biodiversity observations are aggregated into occurrence cubes of the dimensions taxon, time and space. Once aggregated to remove duplication, harmonise the resolution and simplify the data format the cubed data can be used to generate other products all of which are based on the same source data.

3.2 Trends and indicators

TrIAS implemented indicators for biological invasions in Belgium, based both on the checklist data and the occurrence data on GBIF. Much of this data was published by the TrIAS project, but a clear advantage of using GBIF as a central hub is that we automatically incorporate other datasets that have been published there, including data from citizen science platforms (e.g. iNaturalist and eBird) and from collections (e.g. museums and herbaria).

Indicators for checklist data are generated based on the unified checklist and the occurrence indicators are based on the occurrence cubes described above. Based on these data we can build indicators of (re)appearing and emerging species in Belgium. Emerging species were defined as species that show a marked increase in their number of observations or their occupancy in Belgium in recent years based on the available data. This procedure was implemented both with all Belgian data and a subset of grid squares in protected areas of the Natura2000 network in Belgium. These lists of emerging species were used to select species for risk assessment and also provide general trend information on alien species within and outside protected areas.

3.2.1 Checklist-based indicators

Checklists inform us of which taxa occur in Belgium. TrIAS checklists included data on the first recorded, most recent recorded date and the pathways of introduction. This has allowed us to generate three checklist based indicators:

- The number of introduced species present in Belgium as function of time shown as graphs
- The cumulative number of introduced species present in Belgium as function of time
- pathways of introduction shown as graphs and tables

3.2.2 The area of occupancy and number of observations

Although data aggregation reduces the duplication of data it cannot completely eliminate the differences in survey effort between different taxa and year. For example, birds are generally well surveyed, whereas bryophytes are not. Therefore, we needed a way to normalise data to make it comparable. We achieved this by normalising the data for each taxon to the number of records for the taxonomic rank of class for that taxon. So birds are normalised to all data for Aves, frogs are normalised to all records of Amphibia.

Based on the occurrence cube we build indicators of (re)appearing and emerging species in Belgium. New species are simply flagged by confronting newly published occurrences with the unified checklist. Emerging species are defined as species that show a significant increase in their number of observations or their occupancy in Belgium in recent years based on the available data.The emerging status is assessed by studying the sign of first and second derivatives of the applied Generalized Additive Model (GAM), which is an established methodology for time series analysis (e.g. Harrison et al. 2014). We defined the following categories of model (Fig. 3):

- Emerging (first derivative strictly positive, second derivative positive)
- Potentially emerging (first derivative positive, second derivative not zero)
- Unclear (first and second derivatives equal to zero)

- Not emerging (first derivative negative or first derivative zero and second derivative negative)

Where the model failed to converge due to a lack of data a decision tree was applied to provide an emerging status. The status is evaluated over the previous three years, but the current year is not used in the creation of the indicator because too much of the data can still be missing.

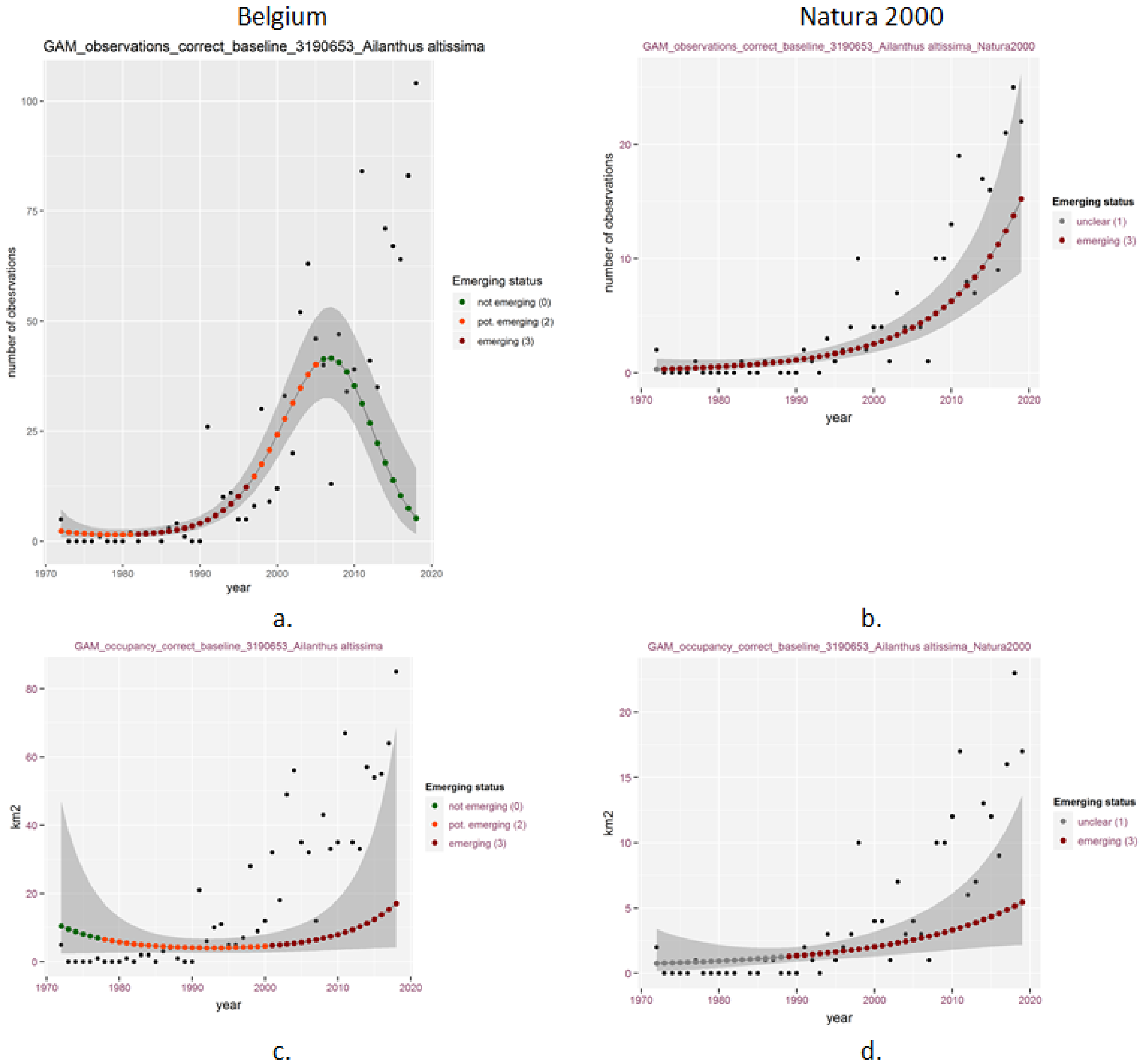


Figure 3: Modelled trend in the number of observations (a,b) and the occupancy (c,d) of *Ailanthus altissima* in Belgium (a,c) and within the NATURA2000 network (b,d), taking into account observer effort. Black dots represent the real number of observations/km^2 square, colours indicate emerging character of the species in any given year based on first and second derivatives of the applied Generalised Additive Model (GAM).

The modelling workflow described above produces 12 partial scores: four indicators applied to each of the last three years. To produce a final ranking of emerging species, we defined a ranking strategy based on the following priority rules, in order of importance:

1. The more recent, the higher the priority.
2. Emerging status in protected areas is more important than the status for Belgium.
3. Emerging status from occupancy indicators have priority above observation indicators.

4. The higher average minimal guaranteed growth (#obs/year), the higher priority the species is.

The last rule was introduced to resolve ties and for communication purposes as this value can describe the expansion we can expect for this taxon in Belgium in the near future.

By analysing data of the current year, we can also produce a list of appearing and reappearing species, where reappearing is defined as species occurring after a latency of three years. We choose this duration as species with less than 3 years latency can be analysed by the previous method.

While extracting data from the occurrence cube to prepare modelling, we can detect which taxa in the unified checklist are still without observations. During preprocessing we also filter out alien taxa whose year of introduction is before 1950, based on the information in the unified checklist.

Regarding checklist-based policy indicators developed in 2018 (see Annual Report 2018 - Task 3.2), we improved them. As promised, in 2019 we implemented these indicators with data from the unified checklist. We also solved a bug in splitting the pathways in pathway level 1 and level 2. Links to checklist-based indicators:

- Number of new introductions of alien species per year (graphs)
- Cumulative number of introduced species present in Belgium as function of time (graphs)
- Pathways associated with alien species introductions (graphs)

The indicators on the state of invasions were used in the WWF Living Planet Report. The information on pathways is currently used to prepare policies for preventative action plans on unintentional introductions of invasive alien species of Union Concern in Belgium.

3.3 Data-driven procedures for risk evaluation

Proper decisions for invasive alien species management depend on accurate spatial and temporal characterization of the evaluation of invasive species spread, impact and the consequences thereof (Venette 2010). As such, data-driven risk evaluation should provide timely insight about the potential range and impact of an alien species. In recent years, Belgium has drafted comprehensive risk assessments for a number of species (Vanderhoeven et al. 2015). However, these documents mostly represent single-expert assessments and for some aspects such as establishment potential, exposure or occurrence in natural areas, they are often based on expert knowledge rather than on empirical data. TriAS has built on the experience acquired through the use of the Belgian *Harmonia*+ protocol (D'Hondt et al. 2014, 2015) to develop a data-driven risk evaluation process founded on risk modelling, risk mapping and risk assessment, taking into account different future climatic scenarios. This process was applied to a set of emerging species identified from the trends and indicators.

3.3.1 Risk modelling and mapping

Spatially explicit predictions of where introduced species are likely to find suitable climates and habitats and become invasive can significantly strengthen existing invasive alien species risk and impact assessments (Srivastava et al. 2019). Knowledge of which areas that are most at risk of invasion can be used to identify species for preventive actions such as legal bans on trade, transport and possession, targeting early detection efforts both at entry points and in susceptible ecosystems, as well as risk management decisions to remove established populations or limit their further spread. However, the full uptake of these spatial modelling tools into invasive species decision-making workflows has been hindered by a number of methodological issues casting doubts on model outcomes including the accuracy and ease of interpretation of predicted invasive distributions.

Such issues include the impact on model predictions of, for example, modelling algorithm choice, the specific set of climate and habitat variables considered, the spatial grain used, as well as a number of more bespoke parameter settings – all of which have been shown to potentially result in variability in model forecasts. Methodological choices are unavoidable and can be accounted for, however, it is the common failure to record and share the methodological decisions made that forms the largest obstacle to fully realise the potential of invasion risk forecasts for informing invasive alien species risk assessment. Transparent and reproducible workflows for modelling invasion risk are thus urgently required.

Therefore, to support open, reproducible and transparent invasive alien species risk mapping , we developed an automatically reproducible workflow incorporating the state of the art species distribution modelling best practice (Fig. 4). To facilitate the production of risk maps using our 'wiSDM' workflow, we harmonised and openly published climate and land cover/land use data to a 1km^2 resolution with coverage for Europe. Our workflow integrates best practises in species distribution modelling including: correcting spatial sampling bias inherent to available species occurrence datasets, identification and removal of highly correlated climate and habitat predictor variables, using ensemble models integrating a range of modelling algorithms to predict risk, and assessment of the influence of spatial autocorrelation on model forecasts. In addition, we present a novel application for assessing transferability of the model by quantifying and visualising the confidence level of its predictions.

All modelling steps, parameter choices made, evaluation statistics used and other output are also automatically generated, and are saved in a R markdown notebook file. Our workflow requires minimal input from the user to generate reproducible maps at 1km^2 resolution for standard IPCC greenhouse gas emission representative concentration pathways (RCP) scenarios. The confidence associated with the predicted risk for each 1km^2 pixel is also mapped, enabling the intuitive visualisation and understanding of how the confidence of the model varies across space and RCP scenarios.

Our workflow can readily be applied by end users with a basic knowledge of R and does not require expertise in species distribution modelling but requires an understanding of the ecological theory underlying species distributions. For a detailed overview of the risk modelling framework used and for the R script visit https://github.com/trias-project/risk-modelling-and-mapping

The risk maps generated by our repeatable workflow provide an evidence-base in anticipation of the establishment of alien species under current and future climate change scenarios. They can be used to support risk assessments and guide surveillance efforts on alien species.

Figure 4: The workflow from occurrence data and environmental predictors to risk maps for invasive species.

3.3.2 Risk assessment

Risk assessment protocols are tools to condense species information into their perceived risks according to a common framework. The Belgian *Harmonia*+ risk assessment protocol (D'Hondt et al. 2014, 2015) is a first-line risk assessment scheme for potentially invasive organisms that may raise concerns for environmental, plant, animal and human health. *Pandora*+ is a complementary version of *Harmonia*+, suited for pathogenic and parasitic (micro)organisms, the results of which may feed into *Harmonia*+.
The TrIAS risk maps produced through risk modelling were used in *Harmonia*+ as supporting tools for experts to assess species establishment capacity, potential impact and the influence of climate change.
Primarily designed for freshwater and terrestrial species, *Harmonia*+ was adapted during TrIAS for marine species. It was optimised by updating the key guidance taking into account the specific marine terminology and habitats, questions were rephrased, relevant examples were added where necessary, and additional guidance was given to evaluate the establishment potential of marine species.
Twenty-two risk assessments were carried out for a range of identified emerging species, and other species for which there was a policy or conservation interest. Based on the availability of experts within and outside the consortium, the risk assessments were produced by a panel of experts independently in parallel or in co-construction by minimum two authors. A third party review process then follows.
The assessment of risks posed by alien species to human and animal health rely on a specific area of literature that is often underused in risk assessments. In an attempt to fill this gap, an extensive literature search was conducted for a range of bird species (*Psittacula krameri, Psittacula eupatria, Myiopsitta monachus, Acridotheres cristatellus)* subject to risk assessments. The resulting data source will contribute to post-TrIAS work to improve the consideration of diseases in risk assessment of animals.

3.4 Informing policy and society

A critical, yet often overlooked, area of risk analysis is the dissemination of information on the risks of alien species introductions through risk communication. Ensuring repeatability, reliability, and transparency in both the data mobilisation framework and the risk evaluation process effectively increases understanding of the risk encountered and therefore facilitates the decision-making (Venette, 2015). TrIAS has paid particular attention to two challenging issues: the use of open workflows and risk communication. TrIAS has brought these considerations to the forefront of a series of national and international events and initiatives, in the hope that they will be integrated into the various decision-making processes on invasive species and biodiversity conservation more widely. In the section below on Dissemination and Valorisation, some of the communication events we presented in TrIAS are listed.

4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

4.1 Data

In the data mobilisation framework, a total of 13 checklists and 20 occurrence datasets were published to GBIF (Table 1 & 3). INBO was responsible for the reproducible data transformation of the large majority of checklists, with the exception of the World Register of Introduced Marine Species (WRiMS) checklist which is managed and transformed to Darwin Core and published by VLIZ. All checklists include species names and taxonomic classification, described in the taxon core. When available, the following attributes are provided: vernacular names, establishment means, date of first and/or last observation, realm, species interactions, sources, native range, pathway of introduction and degree of establishment (Table 2). More than 31 thousand taxon records were published by TrIAS.

For the policy-relevant attributes - native range, pathway of introduction, degree of establishment and presence/absence - it is difficult to express information in Darwin Core. The current terms (dwc:establishmentMeans and dwc:occurrenceStatus) are not sufficient to capture the needed information. These changes were handled according to Section 3.3. of the TDWG Vocabulary Maintenance Specification (http://hdl.handle.net/1803/9512)(Baskauf et al. 2017a)

- https://github.com/tdwg/dwc/issues/237
- https://github.com/tdwg/dwc/issues/236
- https://github.com/tdwg/dwc/issues/235

4.1.1 Standards

It was recognised early on in the project that the standards available for the publication of invasive species data were lacking key terms and controlled vocabularies. The principle standard for publication of biodiversity observations is Darwin Core (Wieczorek et al. (2012). For what we wanted to achieve in TrIAS we wanted to be able to collate information on the native status of organisms, their pathways of introduction and their degree of establishment in the country. It was also clear that certain types of data were either not being published or were not being published in an open and interoperable format.

TrIAS partners and members of the Biodiversity Information Standards organisation (https://www.tdwg.org/) worked together to improve the Darwin Core standard for invasive species data. This resulted in the publication of a paper detailing these improvements (Groom et al. 2019). These changes were then ratified by the executive committee of Biodiversity Information Standards (http://rs.tdwg.org/decisions/decision-2020-10-13_25; http://rs.tdwg.org/decisions/decision-2020-10-13_23) and are now incorporated in the release for 2020-10-13 versions of Darwin Core and Audubon Core (https://github.com/tdwg/rs.tdwg.org/releases/tag/2020-10-13)

The three changes that have been made are as follows…

1. Add the term **pathway** to Darwin Core and recommend the use of the controlled vocabulary adopted by the Convention on Biological Diversity (Harrower et al. 2017).
2. Add the term **degreeOfEstablishment** to Darwin Core and recommend the use of a controlled vocabulary based upon Blackburn et al. (2011).

3. Redefine **dwc:dwc:establishmentMeans** and propose an adapted controlled vocabulary with terms related to the degree of establishment removed.

Now that these changes have been adopted in Darwin Core it is still necessary that they are adopted by the community. Therefore we have presented them at meetings of GEO BON, Biodiversity Information Standards, the International Conference on Ecological Informatics and COST Action meetings. These changes are currently being adopted by GBIF and are expected to be made available to users soon and there is an open issue under which GBIF are addressing this (https://github.com/gbif/ipt/issues/1532).

4.1.2 Availability of species interaction data

During the second half of TrIAS we started focusing on the risk assessment aspect of invasive species policy support. One of the key lessons we learnt was the importance of species interaction data to understanding the impacts of invasive species. This triggered work on species interaction by Quentin Groom on a TrIAS linked research trip funded by the Centre for Invasion Biology at Stellenbosch University in South Africa. Work on this won second prize of the GBIF Ebbe Nielsen Challenge with InteractIAS, A Jupyter notebook to support expert risk assessment on invasive species (https://github.com/AgentschapPlantentuinMeise/interactias). Furthermore, this work was further elaborated and contributed to a paper on how to encourage collection of species interaction data through citizen science and another paper on the importance of openly publishing data on domesticated, captive and cultivated organisms (Groom et al. 2021a, Groom et al. 2021b).

4.1.3 Climatic data and future scenarios

High resolution climatological data and models were required as input for species distribution modelling. A set of 13 climatological fields at a spatial resolution of 1 km^2 for Europe have been produced for present and future climate conditions (De Troch et al. 2020). The climatological data correspond to 35-year (1971-2005) and 30-year (2041-2070) mean values representing respectively the present and future climate conditions. To make these data most relevant to policy we used projections into the near-term future and three plausible emission scenarios as defined by the Intergovernmental Panel on Climate Change (RCP 2.6, RCP 4.5, and RCP 8.5). This is in line with the current minimum standards procedures used at European level to perform risk assessments for alien species.

The source data for the TrIAS climate layers were assembled from the EURO-CORDEX archive (Kotlarski et al. 2014). More specifically, we have used the regional climate model simulations for Europe at a spatial resolution of 12.5 km on which a three-step statistical downscaling approach has been applied (Fig. 5).

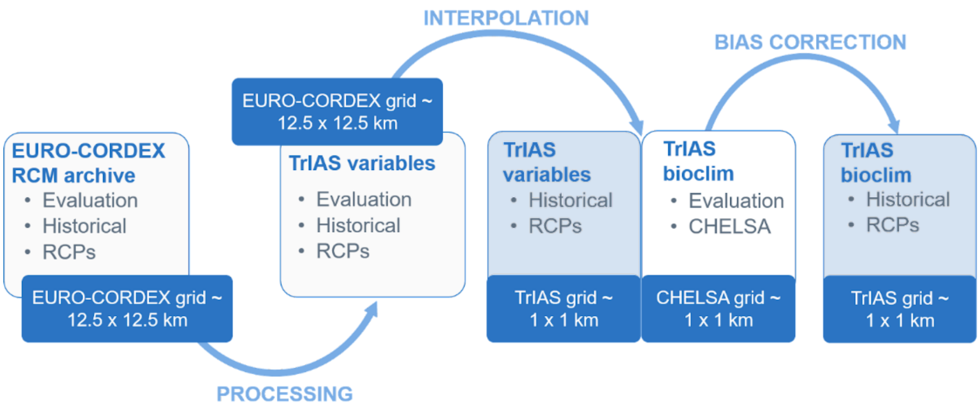


Figure 5: The workflow used to create 1 km^2 interpolated climate data under different RCP scenarios.

Firstly all time series of the model experiments (i.e. evaluation, historical, RCPs) for the required daily and monthly climatological parameters have been processed (averaging, totals, minimums etc) to obtain the climatic variables listed below.

1. Annual mean temperature
2. Annual amount of precipitation
3. Annual variation in precipitation (precipitation seasonality)
4. Annual variation in temperature (temperature seasonality)
5. Maximum temperature of the warmest month
6. Minimum temperature of the coldest month
7. Temperature annual range
8. Precipitation of the wettest month
9. Precipitation of the driest month
10. Growing degree days above 5°C
11. Annual mean potential evapotranspiration
12. Annual mean solar radiation
13. Annual variation in mean solar radiation

Next, each variable at the 12.5 EURO-CORDEX grid was re-gridded/interpolated to the 1-km CHELSA reference grid (Karger et al., 2017). The first ten of these variables are a subset of the so-called bioclimatic variables. These variables are often part of global gridded datasets that have been specifically developed for species distribution modelling and ecological applications. The derived bioclimatic variables are evaluated with the bioclimatic variables from the CHELSA bioclim dataset. This is done by calculating the differences or systematic biases between the resp. ERA-Interim driven variables (i.e. 'evaluation' experiment) and the corresponding CHELSA bioclimatic variables. Finally, a bias correction is applied where the biases from the previous step are subtracted from the 1-km-interpolated variables that follow the current and future climate conditions (so-called historical and RCP experiments), in order to account for the possible biases present in the climate models.

Table 1: Checklists of alien species published on GBIF by the TrIAS project. The datasets can be seen as a whole on GBIF here https://www.gbif.org/network/b153643d-735a-440f-a0e9-428b4f9d1cd2/dataset

Title	Publisher	GitHub repository	DOI	1st publication
Manual of the Alien Plants Belgium [2,606]	BGM	alien-plants-belgium	https://doi.org/10.15468/wtda1m	2017-09-13
Inventory of alien macroinvertebrates in Flanders, Belgium [73]	Ghent University	alien-macroinvertebrates	https://doi.org/10.15468/yxcq07	2018-01-31
Checklist of non-native freshwater fishes in Flanders, Belgium [25]	INBO	alien-fishes-checklist	https://doi.org/10.15468/xvuzfh	2018-02-05
Catalogue of the Rust Fungi of Belgium [755]	BGM	uredinales-belgium-checklist	https://doi.org/10.15468/2dboyn	2018-04-19
RINSE - Registry of non-native species in the Two Seas region countries (Great Britain, France, Belgium and the Netherlands) [6643]	INBO	rinse-registry-checklist	https://doi.org/10.15468/focajn	2018-06-15
RINSE - Pathways and vectors of biological invasions in Northwest Europe [359]	INBO	rinse-pathways-checklist	https://doi.org/10.15468/guejza	2018-06-29
Ad hoc checklist of alien species in Belgium [361]	INBO	ad-hoc-checklist	https://doi.org/10.15468/3pmlxs	2018-10-03
Registry of introduced terrestrial molluscs in Belgium [291]	INBO	alien-mollusca-checklist	https://doi.org/10.15468/t13kwo	2019-05-07

World Register of Introduced Marine Species (WRiMS) [7671]	VLIZ	wrims-checklist	https://doi.org/10.14284/347 and https://www.gbif.org/dataset/0a2eaf0c-5504-4f48-a47f-c94229029dc8	2019-05-10
Checklist of alien birds of Belgium [244]	INBO	alien-birds-checklist	https://doi.org/10.15468/wr3gis	2019-09-12
DAISIE - Inventory of alien invasive species in Europe [12,115]	INBO	daisie-checklist	https://doi.org/10.15468/ybwd3x	2019-09-20
Checklist of alien herpetofauna of Belgium [107]	INBO	alien-herpetofauna-belgium	https://doi.org/10.15468/pnxu4c	2021-03-22
Checklist of alien species in the Scheldt estuary in Flanders, Belgium [62]	INBO	alien-scheldt-checklist	https://doi.org/10.15468/8zq9s4	2021-05-10

Table 2: Details of the data fields published in the different checklist dataset published during TrIAS.

Title	**species profile [Darwin Core extension]**	**Native status [dwc:establishment Means]**	**date [dwc:eventdate]**	**vernacular names [dwc:vernacularName e]**	**native range [Species Distribution extension]**	**Pathway of introduction [dwc:pathway]**	**The degree ti which the taxon is established[dwc:degree of establishment]**	**resource relationship [darwin core extension]**
Manual of the Alien Plants Belgium	x	x	x		x	x	x	
Inventory of alien macroinvertebrates in Flanders, Belgium	x	x	x		x	x	x	
Checklist of non-native freshwater fishes in Flanders, Belgium	x	x	x	x	x	x	x	
Catalogue of the Rust Fungi of Belgium		x	x					x
RINSE - Registry of non-native species in the Two Seas region countries (Great Britain, France, Belgium and	x	x						

the Netherlands)								
Title	**species profile**	**establish mentMean s**	**eventDate**	**vernacular names**	**native range**	**pathway**	**degree of establish ment**	**resource relationsh ip**
RINSE - Pathways and vectors of biological invasions in Northwest Europe	x	x	x		x	x		
Ad hoc checklist of alien species in Belgium	x	x	x		x	x	x	
Registry of introduced terrestrial molluscs in Belgium	x	x	x	x	x	x	x	
World Register of Introduced Marine Species (WRiMS)								
Checklist of alien birds of Belgium	x	x	x		x	x	x	
DAISIE - Inventory of alien invasive species in Europe	x	x	x	x	x			
Checklist of alien herpetofauna of Belgium	x	x	x		x	x	x	
scheldt checklist	x	x	x		x	x	x	

Most species occurrence datasets were transformed and published by their respective hosting institutes such as INBO, SPW-DEMNA, ILVO, Natagora or Natuurpunt. The INBO provided assistance when needed.

Table 3: Species occurrence datasets published to GBIF as part of the TrIAS project.

Title	Publisher	GitHub repository	DOI	1st publication
Alien macro-invertebrates in Flanders, Belgium [2856]	Ghent University	alien-macroinvertebrates	https://doi.org/10.15468/xjtfoo	2016-01-06
Exotic plant occurrences in Wallonia [146,160]	SPW-DEMNA	inva-occurrences	https://doi.org/10.15468/cqfrx0	2018-06-04
Epibenthos and demersal fish monitoring at long-term monitoring stations in the Belgian part of the North Sea	ILVO		https://doi.org/10.14284/54	2019-02-08
Epibenthos and demersal fish monitoring in function of aggregate extraction in the Belgian part of the North Sea	ILVO		https://doi.org/10.14284/197	2019-02-08
Epibenthos and demersal fish monitoring in function of dredge disposal monitoring in the Belgian part of the North Sea	ILVO		https://doi.org/10.14284/198	2019-02-08
Epibenthos and demersal fish monitoring data in function of wind energy development in the Belgian part of the North Sea	ILVO		https://doi.org/10.14284/53	2019-02-08
Macrobenthos monitoring at long-term	ILVO		https://doi.org/10.14284/201	2019-02-08

monitoring stations in the Belgian part of the North Sea between 1979 and 1999				
Macrobenthos monitoring at long-term monitoring stations in the Belgian part of the North Sea from 2001 on	ILVO		https://doi.org/10.14284/202	2019-02-08
Macrobenthos monitoring in function of aggregate extraction activities in the Belgian part of the North Sea	ILVO		https://doi.org/10.14284/199	2019-02-08
Macrobenthos monitoring in function of dredge disposal monitoring in the Belgian part of the North Sea	ILVO		https://doi.org/10.14284/200	2019-02-08
Macrobenthos monitoring in function of the Water Framework Directive in the period 2007-2009	ILVO		https://doi.org/10.14284/52	2019-02-08
Zooplankton monitoring in the Belgian Part of the North Sea between 2009 and 2010	ILVO		https://doi.org/10.14284/55	2019-02-08
Subtidal epibenthos and demersal fish monitoring in function of a foreshore suppletion at the Belgian coast, period 2013-2016	ILVO		https://doi.org/10.14284/343	2019-02-22
Subtidal hyperbenthos monitoring in function of a foreshore suppletion at the Belgian coast, period 2013-2016	ILVO		https://doi.org/10.14284/344	2019-02-22

Subtidal macrobenthos monitoring in function of a foreshore suppletion at the Belgian coast, period 2013-2016	ILVO		https://doi.org/10.14284/342	2019-02-22
Invasive species - Rudy duck (Oxyura jamaicensis) in Flanders, Belgium	INBO	data-publication	https://doi.org/10.15468/ufhbyv	2019-03-11
Invasive species - Chinese muntjac (Muntiacus reevesi) in Flanders, Belgium	INBO	data-publication	https://doi.org/10.15468/sr8bn2	2019-03-14
Invasive species - New Zealand pigmyweed (Crassula helmsii) occurrences in Flanders, Belgium	INBO	data-publication	https://doi.org/10.15468/ckq9l7	2019-05-08
Observations.be - Non-native species occurrences in Wallonia, Belgium	Natagora	natagora-alien-occurrences	https://doi.org/10.15468/p58ip1	2019-06-26
Waarnemingen.be - Non-native plant occurrences in Flanders and the Brussels Capital Region, Belgium	Natuurpunt		https://doi.org/10.15468/smdvdo	2017-06-27
Waarnemingen.be - Non-native animal occurrences in Flanders and the Brussels Capital Region, Belgium	Natuurpunt		https://doi.org/10.15468/k2aiak	2017-06-27
DEMNA-DNE : Exotic animal occurrences in Wallonia, Belgium	SPW-DEMNA	inva-occurrences	https://doi.org/10.15468/bcuhep	2019-07-04

4.2 Data-driven procedures for risk evaluation

4.2.1 Risk modelling and mapping

Risk maps have been produced for 35 species identified as actual and potential invasive species in Belgium, and can be consulted at https://trias-project.github.io/risk-maps/ (Fig. 6). A manuscript presenting the wiSDM workflow is currently under preparation as a 3000-word 'Application' note to the journal 'Methods in Ecology and Evolution'. (Amy J.S. Davis, Tim Adriaens, Quentin Groom, Sonia Vanderhoeven, Damiano Oldoni, Peter Desmet, Lien Reyserhove and Diederik Strubbe. Reproducible wiSDM: a workflow for reproducible invasive alien species risk maps under climate change scenarios using standardised open data).

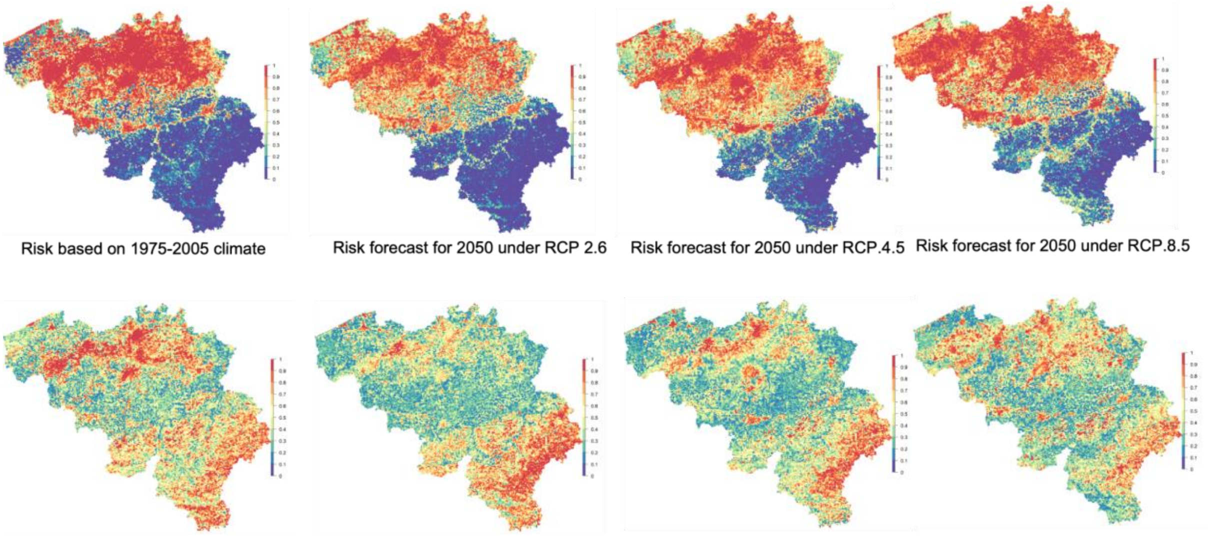


Figure 6: Example of risk maps produced for Belgium - *Cyperus eragrostis* (top) and associated confidence risk maps (bottom). These upper maps show modelled current suitability of the environmental conditions for this species and under three RCP scenarios in 2050. The lower maps indicate the confidence of the models in their output.

A dedicated online tool was set up to support the risk assessment experts in assessing the establishment capacity of alien species under current and climate change scenarios (Fig. 7).

Figure 7: A screen capture of the TrIAS risk maps tool (https://trias-project.github.io/risk-maps/). The tool presents distribution data for all alien species in Belgium, but some identified as targets for risk assessment have been modelled with the wiSDM workflow and show the modelling results for current climate and for three different RCP scenarios in 2050.

4.2.2 Risk assessments

Twenty-two risk assessments were carried out for a range of identified emerging species, and other species for which there was a policy or conservation interest. The species concerned are presented in table 4. Although the drafts are finalised for all species, the review process is still ongoing. The drafts can be consulted on the TrIAS project website: https://trias-project.be/).

Table 4: The list of risk assessed species under TrIAS. These species were identified by the indicators as emerging invasive species within Belgium for which risk assessments were urgently needed.

	Marine species
Crepidula fornicata (common slipper shell)	*Hemigraspus takanoi* (brush-clawed shore crab)
Ensis leei (Atlantic jackknife clam)	*Mnemiopsis leidyi* (warty comb jelly)
	Bird species
Aix galericulata (mandarin duck)	*Aix sponsa* (wood duck)
Anas sibilatrix (Chiloé wigeon)	*Acridothes cristatellus* (crested myna)
Psittacula krameri (rose-ringed parakeet)	*Myopsitta monachus* (monk parakeet)

Syrmaticus revesii (Reeves's pheasant)

Plant species

Symphiotrichum lanceolatum (lance-leaved aster)

Symphiotrichum novae-anglae (Michaelmas daisy)

Symphiotrichum novi-belgii (New York aster)

Rosa multiflora (multiflora rose)

Rosa glauca (red-leaved rose)

Impatiens capensis (orange jewelweed)

Impatiens balfourii (Kashmir balsam)

Rubus spectabilis (salmonberry)

Rubus lacinatus (cutleaf evergreen blackberry)

Vaccinium corymbosum (northern highbush blueberry)

Campylopus introflexus (heath star moss)

4.3 Informing policy and society

4.3.1 Promotion of open workflows

Using open repeatable informatics workflows are a cross cutting issue in TrIAS from the publication of checklists and observations, the creation of data cubes, the calculation of indicators and the modelling of current and future species distributions. We have promoted a cyclic view of biodiversity data workflows (Fig. 8). Informatics workflows both use data from a wide range of stakeholders, but these stakeholders should also benefit from these workflows as otherwise they have no motivation to contribute to them. We published a “perspective” making this point in the journal “Citizen Science: Theory and Practice” (Groom et al. 2019). This paper makes five recommendations of great relevance to conservation, wildlife and invasive species policy in Belgium and globally.

1. Use open by default for data, software, and communication. Without an open approach to sharing data none of the other recommendations are possible. This is fundamental to providing all the services to citizens, scientists, and decision-makers.
2. Support data infrastructure for biodiversity. Providing a financial and legal framework under which open informatics infrastructure can operate underpins national and international biodiversity data science.
3. Strengthen communication. The aims of biodiversity scientists, conservationists, and policy-makers need to be communicated clearly and regularly. Scientists should also seek innovative visualisations to attract citizen interest. Communication should also be ongoing and in both directions supporting a collaborative approach. For example, communication should be based on good case studies of citizen science.

4. Improve mutual understanding. Seek to increase the mutual understanding of the motivations of all players. This allows for the deeper engagement of the different parties, democratisation of science, and increased ownership of the results.
5. Support citizen science globally. All countries should support citizen science, because biodiversity loss is a global issue and this is a cost-effective proven solution to gathering data.

Figure 8: An illustration of the cyclic workflow of data from policymakers, researchers, conservationists and citizen scientists who both create data, fund data creation and use the results of the workflows. From Groom et al. (2019).

We were also invited to contribute to the sTwist project (https://www.idiv.de/en/stwist.html) funded by the German Centre for Integrative Biodiversity Research (iDiv). This project was also towards developing theory and workflows for tracking alien and invasive species. A paper has already been published from this project about standardised workflows for integrating data and another has been submitted on the subject of indicators of species invasions (Seebens et al. 2020). We have also contributed to a summary publication of the frameworks used in invasion biology, which is part of the ongoing evolution of the discipline (Wilson et al. 2020).

4.3.2 Risk communication

Adapting general principles of risk communication to the invasive species

Risk communication is traditionally presented as one of the three traditional components of risk analysis along with risk analysis and risk management. It is the interactive process of information and opinions exchange among individuals, groups and institutions regarding a proven or potential risk (Robinson et al. 2017, Lundgren & McMakin 2018). While much work has been done on risk communication for environmental, safety and health risks, little effort has been made to apply these principles to communication on invasive species to our knowledge. TrIAS addressed these aspects to hamper constraints to effective risk communication on invasive species, in particular the consideration of the differences between 'Care communication', 'Crisis communication' and 'Consensus communication' (Fig. 9). This work is currently the subject of a manuscript in preparation.

Figure 9: IAS communication and risk communication : the consideration of care, consensus and crisis communication.

Considering uncertainty in alien species citizen science

Citizen science has become a pillar of research on alien species and an important element in their monitoring in Belgium and beyond. It is therefore important in communicating the risk associated with alien species to recognise and properly apprehend the uncertainty associated with citizen science data.

In the framework of the COST Action *Alien-CSI* project CA17122 (Increasing understanding of alien species through citizen science), TrIAS contributed to an international workshop, the objective of which was to review the different sources of uncertainty and to develop guidance on how to best deal with them and properly address accuracy and uncertainty when communicating. An article currently under revision is based upon results from the workshop: Probert et al. *Identifying, reducing, and communicating uncertainty in citizen science: a focus on alien species.*

5. CASE STUDY : ALIEN SPECIES IN THE MARINE WATERS

5.1 Introduction (current situation)

In 2020, 79 alien species with established populations were identified in the Belgian part of the North Sea and adjacent estuaries (Verleye et al. 2020 - *VLIZ Alien Species Consortium*). The arthropods (Arthropoda) represent 39% of these. This diverse group includes crabs, copepods, barnacles and small shrimp-like crustaceans. Algae and weeds (15%) and molluscs (Mollusca) (10%) follow at a considerable distance. An overview of those species and their characteristics (date of introduction, place of origin, introduction pathways, environmental requirements, impact, species morphology, etc.) is since 2021 online accessible via www.vliz.be/niet-inheemse-soorten.

Five species appear to have been present on Belgian territory since the 19th century. The number of new introductions has been increasing steadily throughout the 20th century (until the 1990s) with five or fewer new species per decade. In the year 1990, 33 alien species were known in the study area. However, the 1990s saw a sudden increase in the number of introductions with 23 new species in just ten years. Despite the fact that the number of new species introduced since 2000 seems to be declining steadily, it is still well above the level of before the 1990s (Fig. 10).

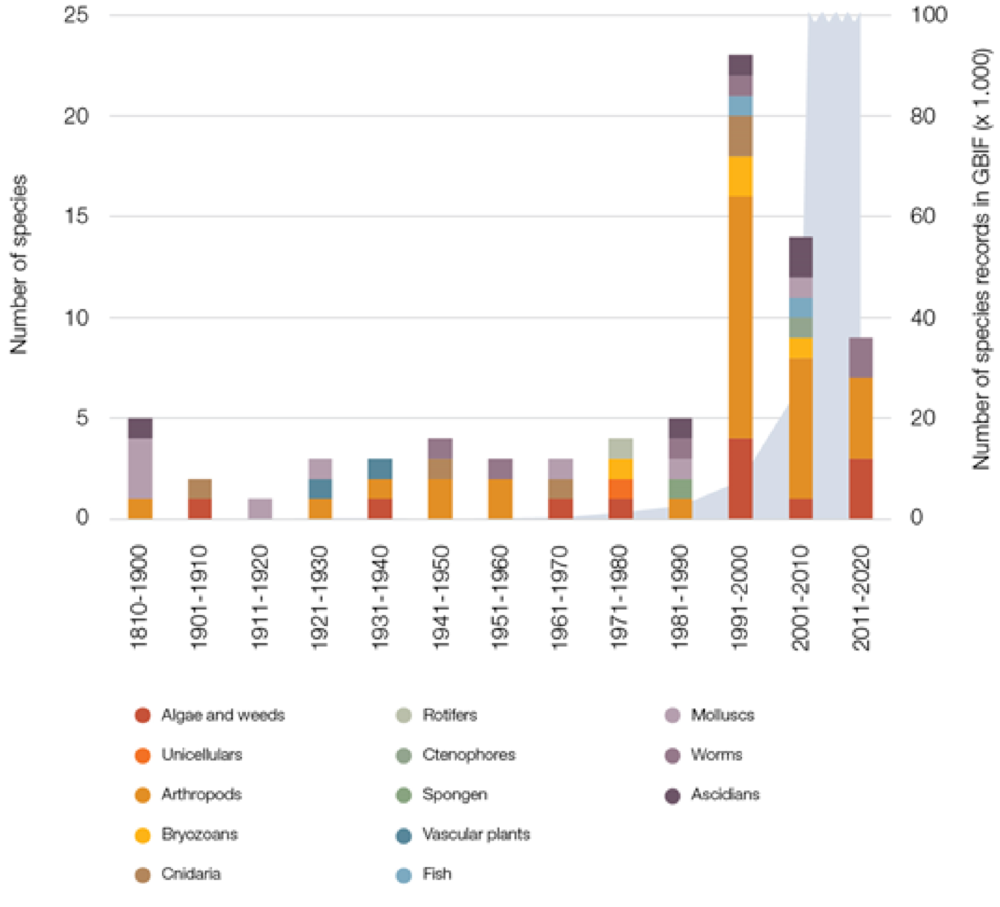


Figure 10: The number of new alien species in the study area per decade, categorised by species groups. The grey area diagram shows the number of species records in GBIF for the 'Animalia' kingdom in the Belgian part of the North Sea and adjacent estuaries, and is an indicator of the intensity of biological sampling (Source: Verleye et al. 2020).

Worldwide, international shipping plays a major role in the unintentional spread of marine organisms outside their area of origin, next to aquaculture/live import. The fact that the Flemish seaports are located along one of the busiest maritime shipping routes therefore increases the risk of new introductions. The strong increase in the number of alien species in the Belgian part of the North Sea probably relates to the increase of 'intercontinental' shipping towards the main Belgian seaports since 1990 (see also Verleye et al. 2020). Maritime transport between the port of Antwerp and Asia (in volume) increased sevenfold in the last three decades and goods transport with America and Africa doubled (**Merckx 2020, personal communication**). In line with this trend, 60% of the introduced species in Belgian marine/brackish waters originate from the NW Atlantic and N Pacific region, of which 7 out of 10 were introduced after 1990 (Fig. 11). Now, the International Convention for the Control and Management of Ship's Ballast Water and Sediment (BWMC) aims to significantly reduce or prevent the spread via ballast water within the framework of international maritime transport in the future. For an extensive overview of the international and national regulatory and policy instruments aimed at limiting the harmful impact of the (un)intentional introduction of alien species by preventing new introductions as much as possible, controlling and eradicating species where possible and providing a management framework for widespread exotic species, see Verleye et al. (2020).

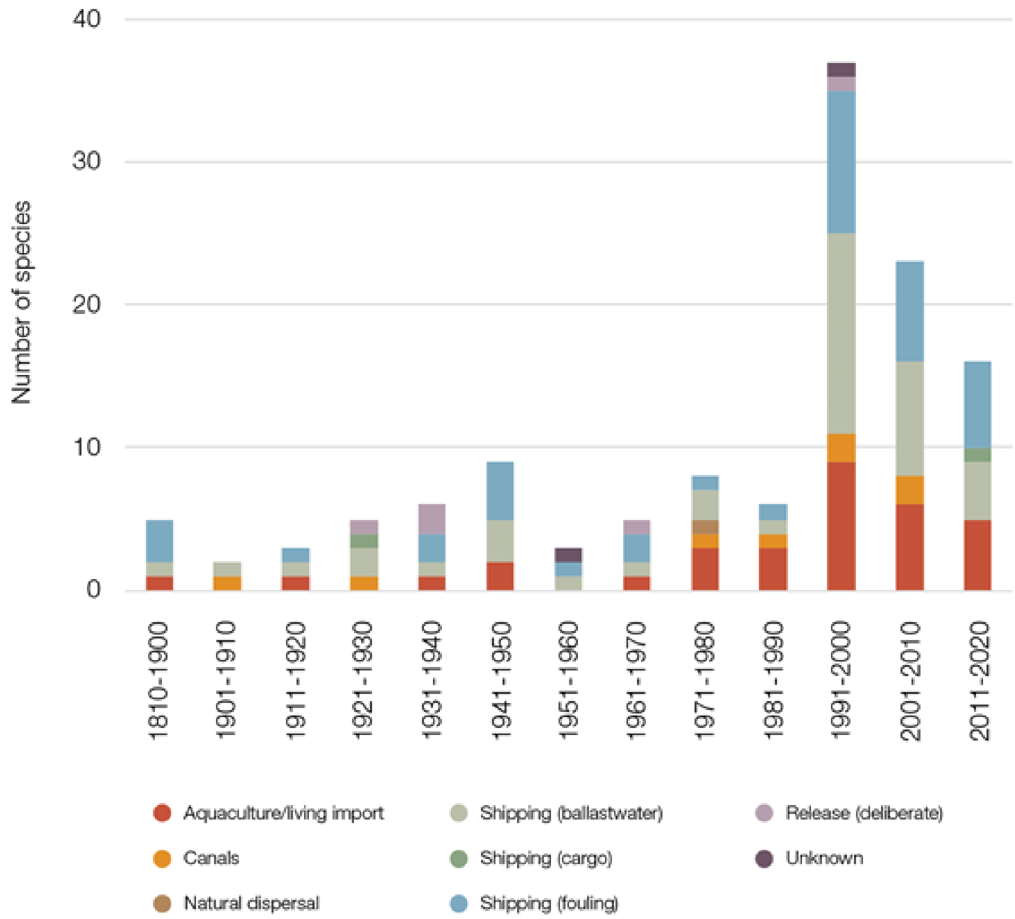


Figure 11: Overview of modes of introduction as a function of time. The sum over the different decades is higher than the actual number of species because there is often uncertainty about the mode of primary introduction (several possibilities) or because some species were introduced several times separately from each other from the area of origin (Source: Verleye et al. 2020).

In addition to shipping and aquaculture, introductions in Belgian marine and brackish waters took place through the construction of canals between regions that were initially separated by physical barriers, which encourages the further spread of species beyond their area of origin (e.g. connection with Pontokaspian region). Alien species can also be deliberately introduced through the stocking or planting of exotics.

Another possible explanation for the sudden increase in the number of non-indigenous species after 1990 - which occurs mainly in arthropods, algae and seaweed - is the increase in biological sampling effort and the development of monitoring campaigns at sea. For example, the number of species records in GBIF (Global Biodiversity Information Facility - www.gbif.org/tools/observation-trends) for the Belgian part of the North Sea and adjacent estuaries show an increase since the 1970s and a sharp acceleration since 1990 (Fig. 11). These data indicate a more intensive biological sampling, which also increases the chances of discovering new alien species. As a result, for some species the first observation may be later than the actual year of introduction.

5.2 Checklist of introduced marine species

In order to create a unified Belgian checklist of alien species (*Global Register of Introduced and Invasive Species – Belgium*) that can be harvested by GBIF, data publication and data processing pipelines were developed for the TrIAS project, benefiting from various taxonomic and project-based checklists. For marine species, a data processing pipeline was implemented between the World Register of Introduced Marine Species (WRIMS; **Flanders Marine Institute 2019**) and the GRIIS-Belgium. This allows the extraction of all Belgian non-native marine taxa from WRIMS. To this end, (1) the custom WRIMS Darwin Core exports from Aphia were automated, (2) two fields were added ('description' for impact, pathway and vector information, and 'countryCode') and (3) a DOI was requested. A taxonomic standardisation was done using the GBIF Backbone Taxonomy. In total, eleven sources were used for the unified checklist of which only one can be considered as fully marine. Two other checklists contain a few marine or brackish species, those are (1) the Inventory of alien macroinvertebrates in Flanders, Belgium (**Boets et al. 2018**) and (2) the Checklist of alien species in the Scheldt estuary in Flanders, Belgium (**Soors et al. 2021**).

At the time of writing, the source data from WRIMS, which feeds into GRIIS-Belgium, contains 103 different taxa. This number significantly differs from the number of species identified by the VLIZ Alien Species Consortium (VLIZ ASC, i.e. 79 species anno 2020 - see **Verleye et al. 2020**). The main reason for this is the fact that the consortium focuses on alien species with an scientifically proven established population in the Belgian part of the North Sea or adjacent estuaries. WRIMS, on the contrary, als includes species that have only been observed once. During TrIAS, species records in WRIMS and VLIZ ASC were compared, so that all established marine species are available in WRIMS. Within the framework of the VLIZ ASC, species that are only sporadically observed (of which the establishment has not yet been scientifically proven) or that have not yet been found in Belgium, but have been found in the nearby waters of our neighbouring countries, are kept up to date by the VLIZ in a so-called 'Watchlist'. This list mainly includes molluscs (*Cardita calyculata, Mulinia lateralis, Ocinebrellus inornata, Potamocorbula amurensis, Simnia patula, Urosalpinx cinerea, Yoldia limatula*) and arthropods (*Anilocra frontalis, Asthenognathus atlanticus, Ceratothoa steindachneri, Goneplax rhomboides, Grandidierella japonica, Ianiropsis serricaudis, Nerocila* *bivittata, Penaeus aztecus, Septosaccus cuenoti*). In addition, Bryozoa (*Bugula neritina*), a fish (*Gobiosoma bosc*) and a worm (tube worm *Bispira polyomma*) are also on the list. The evolution of these species is monitored together with the VLIZ ASC.

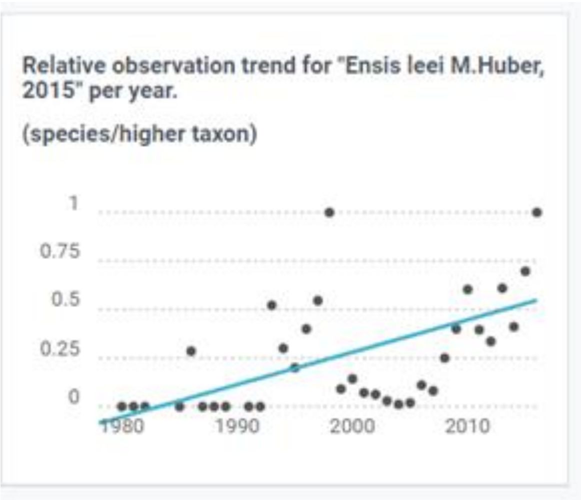
5.3 IAS indicators

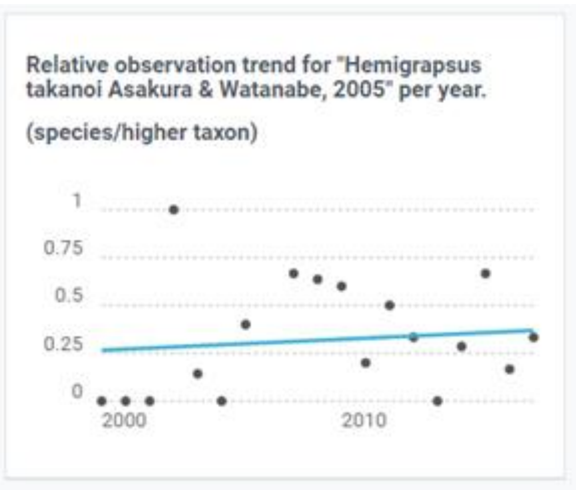
Within TrIAS, some existing IAS indicators were reviewed. For the marine species, two checklist-based indicators were used, as reported in Verleye et al. (2020) and outlined in 1.1: (1) Number of new introductions of alien species per year (Fig. 10) and (2) Pathways associated with alien species introductions (Fig. 11). Some other indicator tools are available to evaluate the occurrence and the status of the alien species itself, as (1) relative observation trends (GBIF tool); (2) an emerging status assessment (e.g. GAM analyses on observations). Also, a map with the occurrence records, through GBIF, gives information on the geographical spread of those species.

One of goals within TrIAS was to ensure that the regular monitoring data of ILVO on soft-sediment habitats in the Belgian Part of the North Sea is publicly available in GBIF, to allow analyses on their occurrence in space and time. For four selected marine species (*Ensis leei, Hemigrapsus takanoi, Mnemeopsis leydi* and *Crepidula fornnicata)*, for which enough data were available and which are characterised by different living environments, analyses on their occurrence in space and time was made.

5.3.1 Relative observation trends

The relative observation trends are determined for Belgian marine waters and show whether the number of annual observations for the species is increasing or declining as a proportion of the overall observations of the selected higher taxon. By normalising against a higher taxon group, the analysis attempts to compensate for biases in the observation effort.





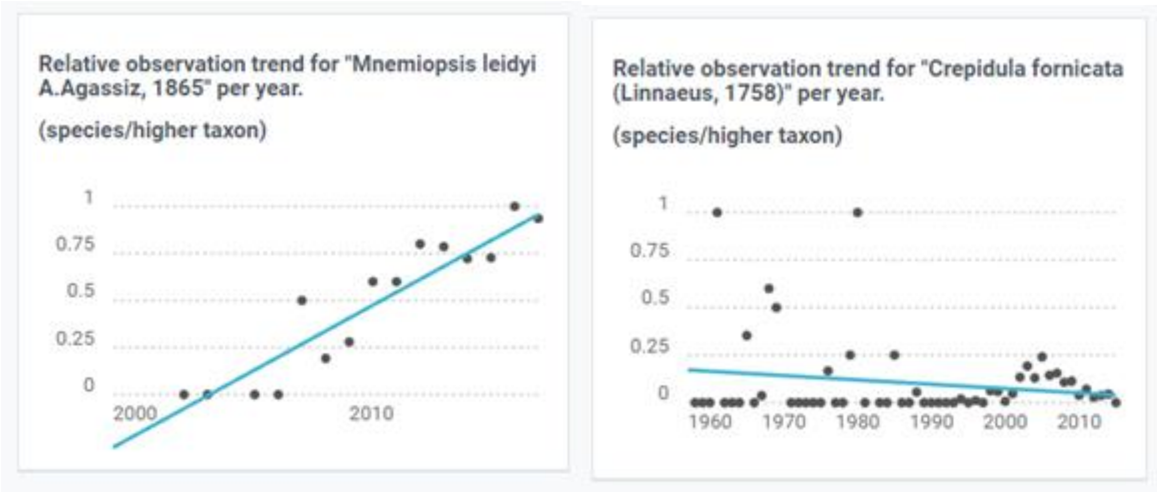


Figure 12: Relative observation trends for four marine species (Ensis leei, Hemigrapsus takanoi, Mnemeopsis leydi and Crepidula fornnicata) (source: GBIF).

For *Ensis leei* (Belgian coastal waters), we observe a strong increasing trend in comparison to the overall observations within the family Pharidae (Fig. 12). Also an increase in occurrence of *Ensis leei* is observed in comparison to Bivalve observations (not visualised). The occurrence of *Hemigrapsus takanoi* in Belgian harbours is very slightly increasing in comparison to the overall Decapoda observations in harbours. The observations of *Mnemiopsis leidyi* in Belgian coastal waters and Westerscheldt estuary is strongly increased compared to the overall Ctenophora observations. For *Crepidula fornicata* observations, a slight downward trend is observed compared to the overall Gastropoda observations. A long time trend is available for *Crepidula*, but before 2000 the number of observations was very low to make conclusions on the population. Whereas from 2000 onwards, we observe an increase in observations, which decreased again around 2007-2008 onwards.

5.3.2 Emerging status

For two marine species with enough data (*Ensis leei* and *Hemigrapsus takanoi)*, the emerging status was determined based on the GAM approach (Fig. 13). For *Ensis leei* the status was emerging in the beginning of the 2000's and shifted to potential emerging in the period 2008-2013. In the current period, the situation is rather unclear. In the example of *Hemigrapsus takanoi*, the emerging status is potential from 2003 to 2011, whereas the status is evaluated as not emerging anymore.

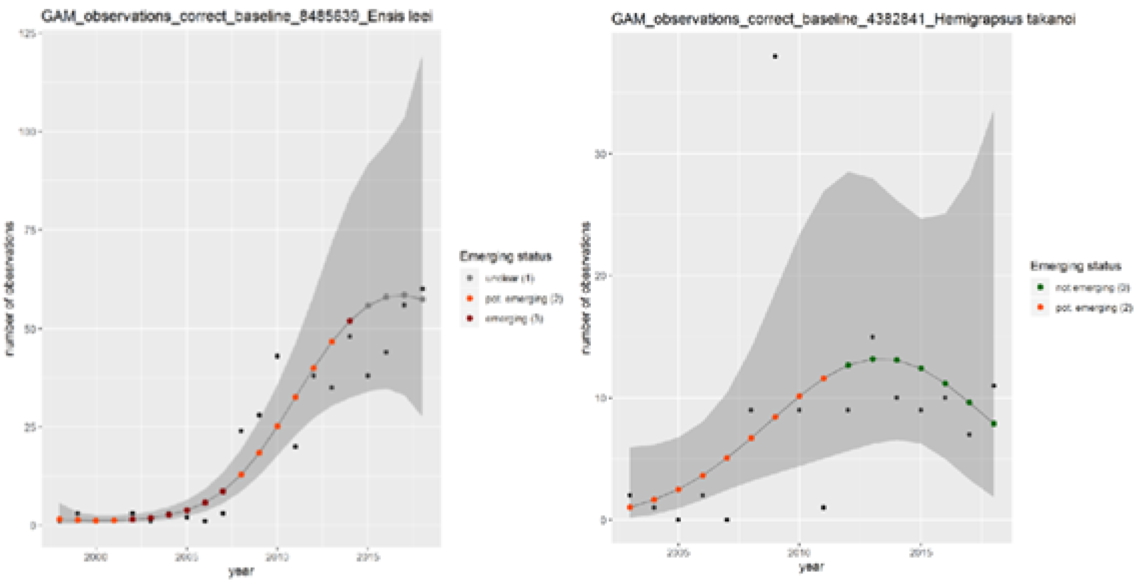


Figure 13: GAM model on the observations of *Ensis leei* and *Hemigrapsus takanoi* to determine their emerging status over the study period.

5.4 Harmonia+

5.4.1 Adaptations Harmonia+

Harmonia+ is a recently developed scheme for the first-line risk assessment of potentially invasive alien species (D'hondt et al. 2015; more information on https://ias.biodiversity.be/harmoniaplus). Until now, the protocol was focussing on terrestrial and aquatic organisms. Consequently, difficulties were encountered when applying the protocol to marine species (Vansteenbrugge, 2015). It was therefore desirable to adapt the protocol to make it applicable for marine alien species. The full *Harmonia+* protocol provides general guidance on how to answer questions. They are set to minimise ambiguity with regard to the questions and their potential answers, every single question is furthermore provided with ample guidance, including definitions, conceptual underpinnings, cut-off values and specific examples. Therefore the Harmonia+ protocol was optimised by updating the key guidance taking into account the specific marine terminology and habitats, questions were rephrased and relevant examples were added where necessary (Task 4.3 Risk Assessment Protocol Development).

5.4.2 Risk assessment test for Marine species

5.4.2.1 Methodology

Four marine species were selected for risk assessment (PRA) based on the new Harmonia+ protocol: *Crepidula fornicata, Ensis leei, Hemigrapsus takanoi* and *Mnemiopsis leidyi*. In order to determine the potential risk of the respective species, we asked several experts to contribute to the assessment to strive for three assessments per species. Different experts had one to a maximum of three species to assess. Only for *Ensis leei*, we received only two assessments, whereas for the other species three assessments were performed. The risk assessment was conducted independently and the results outlined as received. No consensus building process was started so far to get an approved risk assessment among the experts.

The most important aspect of this exercise was to get a view on the applicability of *Harmonia+* on marine species. Nevertheless, the risk assessment gives some insights on the potential risk.

5.4.2.2 Results risk assessments

In general, all four species show a relatively high invasion score (> 0.5) and a lower impact score (<0.4), leading to a low risk (Table 5). These results are used to test the applicability of the *Harmonia+* protocol for the risk assessment of marine species and are not final agreed scores. Lessons learnt from this process can be taken forward to perform a complete risk assessment, including a consensus building process, on the marine introduced species list in the future.

Table 5: Risk assessment outcomes of *Harmonia+* for four marine species.

		invasion	impact	risk			invasion	impact	risk
C. fornicata	1	0.794	0.417	0.331	M. leydi	1	0.55	0.333	0.183
	2	0.874	0.6	0.524		2	0.63	0.25	0.158
	3	0.63	0.167	0.105		3	0.572	0.25	0.143
		0.766	0.395	0.320			0.584	0.278	0.161
H. takanoi	1	0.679	0.25	0.17	E. leei	1	0.693	0.083	0.058
	2	0.437	0.458	0.2		2	0.63	0.375	0.236
	3	0.663	0.417	0.276			0.662	0.229	0.147
		0.593	0.375	0.215					

A short evaluation of the outcomes of those species is described in the section below:

Crepidula fornicata risk is determined as 0.320 (on average, based on three assessments), with differences between the three assessments. This is related to the fact that in one assessment the impact is estimated higher, because the invasion score is rather similar. This species has clearly the highest invasion score of the assessed species and is related to its high natural and human way of being introduced, combined with a high score for spread and establishment potential. Also the impact score is the highest among the assessed species, but is maybe an overestimation, as this species has caused dramatic changes in certain other regions (e.g. coast of Normandy-Brittany), but this is not the case in our waters. Evaluation of the ‘potential’ impact of the species can therefore be biassed among experts, despite the fact that the evaluation is for the area under study.

Hemigrapsus takanoi is a crab species, which is frequently encountered in our harbours. The invasion risk is assessed as high, but impact scores are lower, leading to a low risk score. In the marine waters, it is only occurring in the harbours, which are ecologically poor ecosystems, which reduce the risk it has. This can be different for the estuarine systems wherein this species is more widespread.

The risk scores for ***Mnemeopisis leydi*** are in good agreement between the three assessments performed. The invasion is scored high in the three assessments, but impact is rather low. In our waters this species has currently not led to a high impact on our ecosystem, in contrast to observations in other regions (e.g. Black Sea).

Ensis leei has only two assessments and there is some discrepancy, whereof one clearly evaluates the risk to be higher. Nevertheless, the risk scores are low (impact scores are low). *Ensis leei* is a well-established species in our marine waters, which seems to have some small effect on our ecosystem, but does not threaten it (Houziaux et al., 2012).

Table 6: Overview of the discrepancies, expressed as the amount of different answers compared to the amount of answers (e.g. 1/6) for the questions in each module. For certain modules, also a lot of questions are not answered (because they are irrelevant or having no knowledge), as outlined in the lowest half of the table.

	Modules of Harmonia+ protocol									
	Introduction	Establishment	Spread	Environ-mental impact	Plant impact	animal impact	human impact	other impact	services	climate
Differences in questions per module:										
Crepidula fornicata	1/9	0/6	2/6	6/17	0/3	1/7	0/4	0/3	2/9	2/23
Ensis leei	1/6	0/4	0/4	2/8	0/2	0/5	0/4	0/2	2/6	0/13
Hemigrapsus takanoi	4/9	0/4	4/6	6/18	0/7	4/9	0/4	1/3	2/9	7/22
Mnemiopsis leydi	4/9	0/4	1/6	1/18	1/3	0/4	1/4	0/3	2/9	6/24
Unanswered questions:										
Crepidula fornicata				1	12	5				1
Ensis leei				2	6	2				3
Hemigrapsus takanoi					8	5				2
Mnemiopsis leydi					12	5				

Lessons learnt from the *Harmonia*+ evaluation, based on the discrepancies in answers in certain modules (Table 6):

- Disagreements in answers exist on the introduction level, as mainly observed for *H. takanoi* and *M. leydi*. This can be related to the fact that it is difficult to define what the level of natural and human way of introduction is, as it is mostly both ways or human way in another area and then spread by natural means in the study area. In the current evaluation, it seems not clear on how to judge on this. On top, there is in most cases a lack of knowledge to define this.

- The same difficulty can exist to evaluate the module spread, as shown in the discrepancies of the answers for *H. takanoi*.

- The way to evaluate the environmental impact is not straightforward for all analysts, as mainly observed for *C. fornicata* and *H. takanoi*. This can be related to the fact that those questions focus on their effect on species of nature conservation concern. This aspect is less clear for marine waters, where no list of species of conservation concern exists and it is rather the effect on the entire ecosystem that is looked at. And then it is difficult to standardise what is reversible or irreversible. Probably more guidance on those aspects is needed for the Harmonia+ risk assessments on marine introduced species.

- The fact that the risk evaluation of impact (environmental, plan, animal, human, other) should be evaluated in relation to the study area and not be based on wider areas (where they cause problems or not) may result in different approaches among experts. Of course, it is not because there is currently no problem in our study area that future problems (as in other regions) can be excluded. It seems to be difficult to have a balanced view on it among experts.

- Plant impact module is less relevant for our marine waters, as we have no seagrass in our area. The only question that was scored by experts was: "*The Organism has a (...) effect on plant targets, by affecting the cultivation system's integrity.*" In the marine world, the focus should here be on algae and phytoplankton, which should be thought about for future evaluations.

- The discrepancies in the services module evaluation is not related to a certain question, but is one scoring level difference for a certain question. This is natural in the expert evaluation process. Therefore, there seems to be no unclarity in the evaluation of the questions for this module.

- In the climate module, there seems no unclarity on the questions, but it is sometimes difficult to estimate the score for certain species (e.g. *H. takanoi* and *M. leydi*) on certain questions, as "*ESTABLISHMENT - Due to climate change, the likelihood for The Organism to overcome survival & reproduction barriers will (…).*" and "*SPREAD - Due to climate change, the risk of The Organism to overcome dispersal barriers & (new) environmental barriers within The Area will (…)*." On those questions, there was most discrepancy among the experts, which can be related to a lack of knowledge (e.g. lack of climate predictions for introduced marine species).

5.4.3 Risk mapping of marine species

VLIZ and ILVO were not directly involved in the technical developments related to tasks 4.1 and 4.2 (i.e. Risk Model Development and Risk Mapping Development), which must improve the assessment of establishment capacity within the Harmonia+ protocol by generating species specific maps including different climate change scenarios rather than rough global climatic similarity. Due to the complexity related to marine species (lower resolution in occurrence data, non-homogenous spread in spatial observation data (see also **Saelens & Verleye 2015**), what are the environmental predictor variables and how do they interact, etc.), no risk mapping results are available for marine species yet.

5.5 Marine Aliens species assessment

Through TrIAS, we optimised our communication in informing and reporting on new marine alien species among the monitoring institutes (ILVO, KBIN, VLIZ) and the policy (FOD Environment). This is necessary to allow early detections and adequate reporting. This is an obligation under the Marine Strategy Framework Directive (MSFD), which has a descriptor tackling the evaluation of non-indigenous species (descriptor 2). In the last evaluation (Belgische staat, 2018), the conclusion was: "*The number of non-indigenous species (= introduced species) introduced by human activities continues to increase, thereby failing to achieve good environmental status under the MSFD. During the assessment period from 2011 to 2016, eight new introduced species were identified (Table 7), three of which may cause significant ('non-negligible') ecosystem changes as a result of their permanent introduction*." Those species were not yet recorded in the regular ILVO monitoring, and those records were based on ad-hoc monitoring of RBINS (by Francis Kerkhof) along the beach and on artificial hard structures.

Table 7: Overview of the newly introduced species, as reported under the MSFD (taken from https://odnature.naturalsciences.be/msfd/nl/assessments/2018/page-d2).

Soort	Eerste identificatie	Plaats	Taxonomische groep	Ecosysteem-veranderend effect
Boccardia proboscidea	2011	Koksijde	borstelworm	
Boccardiella hamata	2011	Zeebrugge	borstelworm	
Caulacanthus ustulatus	2011	Heist	roodwier	
Gracilaria vermiculophylla	2011	Heist	roodwier	Ja
Ammothea hilgendorfi	2013	Westhinderbank-gebied (offshore)	zeespin	
Ruditapes philippinarum	2014	Zeebrugge	tweekleppig weekdier	Ja
Dasysiphonia japonica	2015	Zeebrugge	roodwier	
Balanus glandula	2015	Zeebrugge	zeepok	Ja

Only two new alien species were observed in the regular ILVO monitoring over the period 2017-2020 (i.e. after MSFD reporting):

- *Mulinia lateralis*: First record in September 2019. Currently, this species is recorded in 15 beam trawl samples and 15 Van Veen samples over the period September 2019-March 2021. Mainly observed at the east coast, but also already recorded at the west coast. Full description of this species is given in Creaymeersh et al. (2019) and conclude: "*In view of its ecology and distributional range in the native area M. lateralis has the potential to become an invasive species. Its ability to quickly colonise defaunated areas, its high fecundity and short generation time, its tolerance for anoxia and temperature extremes and its efficient exploitation of the high concentrations of phytoplankton and natural seston at the sediment-water interface may bring it into competition with native species for food and space*."

- *Yoldia cf. limatula*: First and only one record in March 2021 at station ft7103 (51,434 – 3.126). Previously, already recorded in beach strandings (autumn 2020). This species was catched in a beam trawl sample. First record in the Netherlands was in samples of 2019. The extent to which this exotic species is invasive is unknown.

6. GENERAL CONCLUSION

An important goal of TrIAS was to change the way that biodiversity monitoring is done. Yet changing ingrained habits and established procedures in the decision-making processes is a long-term challenge that is not yet finished. Fortunately, the involvement of the Belgian Biodiversity Platform in the project ensures mid- and long-term continuity so that these changes are implemented in practice in Belgian processes. The same applies to risk communication and more broadly to communication on invasive alien species. Nevertheless, a major evolution is that the TrIAS partners have committed to following and implementing the following Open Science principles. These apply to invasion biology, but can also be understood more broadly in terms of decision-making on biodiversity in general. These principles include…

- Making data Open first, aggregate and using it later
- Building upon, and contribute to, Open Source and Open Data infrastructures
- Using repeatable data-driven workflows to support policy
- Ensuring the transparency and traceability of information that support policy decisions
- Developing sound and reciprocal dialogue with stakeholders, including all those generating and using data
- Engaging society in decision-making processes

Over the 54 months the TrIAS project ran it has generated a large number of publications, presentations and datasets. We have worked with many people and organisations, both in Belgium and abroad and we hope the legacy of TrIAS will continue and we believe we have done enough to ensure this. Below are some of the outputs of TrIAS.

Recommendations for improving the use and quality of alien species information for decision processes in Belgium

- Further mobilise checklist data on (alien) species checklists to feed the TrIAS dataflows to the unified checklist of alien species in Belgium (e.g. on invertebrates and other taxa)
- Implement a governance structure for performing regular (e.g. yearly) updates and quality control of the unified checklist by liaising with the Belgian expert community
- Develop tools to empower checklist owners and data holders to maintain checklist data at the source in appropriate formats and to seamlessly and regularly publish data on gbif using the TrIAS checklist recipe
- Further improve the automated publication procedures for the unified checklist based on the latest adaptations implemented in the Darwin Core data standard for alien species (see 4.1)
- Ensure repeated publishing of occurrence data to sustainably feed the indicator pipelines and decision support tools (e.g. risk mapping) developed by TrIAS
- Further develop new and existing information and decision support tools using the TrIAS products to tailor the needs of the user community at the science-policy interface

6.1 Funding proposals stemming from TrIAS

The TrIAS project led to several funding proposals.

1. The TrIAS Aware project was funded by Belspo and was used to create dissemination materials on invasive species to raise awareness and encourage data collection by the general public.
2. The Living Belgium proposal was to build on the data publishing aspects of TrIAS. Despite receiving 95 out of a maximum possible score of 102 and a recommendation of highly recommended for funding this project was not funded.
3. The SIN City proposal was to extend the work TrIAS had done on data publication and species interactions. It received a score of 88 out of a maximum possible score of 102 and was ranked as ‘good’. It was not selected for funding.
4. The LIFE RIPARIAS project started in January 2021. In this project, a work package is dedicated to the establishment of a system that interrogates the various sources of invasive alien species occurrence data and centralises these data to optimise early warning and rapid response for invasive alien species. This work is based on the workflow set up in TrIAS for occurrence data through GBIF.
5. The B^3 proposal has been submitted to the Horizon Europe program of the European Commission in October 2021 and we are awaiting the result in April 2022. This proposal builds on the TrIAS work on biodiversity data cubes, workflows, indicators and modelling. The proposal has a value of 4.8 million euros and thirteen partners and will bring 1.8 million of funding to Belgium if funded.

6.2 Dissemination and Valorisation actions of TrIAS

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