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Abstract

Information on the number of alien species present in a country, their status (establishment, distribution, impacts), and how they entered and move around the country is crucial for effective management. Such information underpins regulations, the allocation of management resources, and evaluations of current and future threats. South African regulations first promulgated in 2014 mandated a triennial process of national reports on the status and management of biological invasions. This required a consolidated national list of alien species. This paper outlines the process followed to create this list, describes how the list evolved over time, and highlights lessons learnt, and challenges encountered. Over the production of three status reports, there have been major improvements in how data are presented, how changes are tracked, and the degree to which the information presented is consistent with international best practice. The development of documented and repeatable workflows has ensured that it is now clear why species are included on the list and facilitates reviews and updates. The focus for the next phase is to ensure that all historical data sources are incorporated into the list and to put systems in place to incorporate new information as it becomes available. We conclude with a reflection on what has worked over the last decade, and identify eight recommendations for those developing national lists of alien species: 1. structure data and make them available; 2. use data standards and metadata; 3. list the data sources used and the level of confidence in the data; 4. take a modular approach; 5. document workflows; 6. integrate with reporting requirements; 7. commit dedicated resources; and 8. learn by doing.

Introduction

Biological invasions are a major global threat to biodiversity and sustainable development, as highlighted by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services' (IPBES) Thematic Assessment Report on Invasive Alien Species and their Control (IPBES 2023). The IPBES assessment noted that invasive alien species cause severe impacts on various sectors of society across the globe but also noted that these impacts can be reduced through effective control measures (Roy et al. 2024). Moreover, biological invasions are the subject of one of the 23 targets of the Convention on Biological Diversity's 2030 Kunming-Montreal Global Biodiversity Framework (GBF). Target 6 asks member states to "Eliminate, minimize, reduce and or mitigate the impacts of invasive alien species on biodiversity and ecosystem services…" (CBD 2022). For these calls to action to be addressed, it is vital we know which invasive alien species are where.

Lists of invasive alien species, particularly from countries in the Global South, remain incomplete, potentially leading to an underestimation of biological invasions and their impacts (McGeoch et al. 2012). These lists provide information on how many alien species are present in a country, and in some cases their status (establishment, distribution, impacts), pathways of introduction and spread, and management. Such information is crucial to inform integrated governance (sensu Roy et al. 2024) and underpins regulations, the allocation of management resources, and evaluations of current and future threats. The importance of national lists of alien species is emphasised in the GBF, with Target 6 aimed at reducing the introduction of "known or potential" invasive species by 50% by 2030 and eradicating or controlling invasive alien species, especially in priority sites (CBD 2022). To this end, there has been several global initiatives to develop lists of alien species for various regions and countries (e.g., van Kleunen et al. 2019, Pagad et al. 2018, Roy et al. 2020, Leihy et al. 2023). Compiling national lists and keeping them accurate and relevant is, however, challenging (McGeoch et al. 2012). Lists are dynamic and need constant updating as new alien species are discovered, species die out or are eradicated, and as new information on distributions or impacts becomes available. As a result, national lists of alien species are never complete or perfect, but their value can be significantly improved by the adoption of a systematic, standard process of collating and updating them that is transparent and evidence-based (e.g., McGeoch et al. 2012, Latombe et al. 2017, Vanderhoeven et al. 2017, Pagad et al. 2022, Zengeya et al. 2025).

South African regulations on biological invasions, first promulgated in 2014, mandated the production of triennial national reports on the status and management of biological invasions

(Department of Environmental Affairs 2014). These reports (referred to hereafter as the 'status reports') required a consolidated national list of alien species (see Zengeya et al. 2025). This paper provides a brief narrative on the history of alien species lists in South Africa, outlines the process followed in the first three status reports (finalised in 2017, 2020, and 2023) to create the list, describes how the list evolved over time, highlights lessons learnt, and challenges encountered, and reflects on what advice we would give to those starting out with the development of a national list of alien species.

A brief narrative of South African alien species lists over time

South Africa has a long and varied history of biological invasions and a similarly long and varied history of developing alien species lists, checklists, inventories, databases, and atlases (Faulkner et al. 2015, van Wilgen et al. 2020). Lists of alien species have been developed for specific taxa [e.g., the Southern African Plant Invaders Atlas (Henderson, 1998)], sites [e.g., the first list of alien plants for Kruger Park was published in 1937, with periodic updates since (Foxcroft et al. 2003, 2023; van Wilgen et al. this issue)], and pathways [e.g., species in the pet trade (e.g., Nelufule et al. 2020)]. Lists were thus typically created to address particular needs. They were often produced once off and never updated and there were often one or few curators (Table S1).

In terms of regulatory lists (i.e., lists of alien species that as per South African law require management), various legislation date back well over a century, much of which was consolidated in the Weeds Act of 1937 (Act 42). Henderson and Anderson (1966) noted that "Lists… proclaimed for purposes of the application of the Act." included 37 taxa, a mix of alien and native plant species and families and they provided details (and line-drawn images) for a total of 207 weeds (including all those listed). As far as we are aware, the first legislation that promulgated an explicit list of alien species as part of the legislation itself was the revision of the Conservation of Agricultural Resources Act in 2001, which listed 198 alien plant taxa (and 43 native plant taxa as "declared indicators of bush encroachment"). The first comprehensive cross-taxon regulatory lists of alien taxa were published in 2014 as part of the Alien & Invasive Species Regulations under the National Environmental Management: Biodiversity Act (Act 10 of 2004) [NEM:BA A&IS Regulations and Lists; see Wilson and Kumschick 2024 for details of the process followed, Wilson (2025) for the lists themselves, and Lukey and Hall (2020) for a broader review of the history of regulation in South Africa].

Lists of alien species as part of South Africa's status report – evolution over time

In response to the requirements of the NEM:BA A&IS Regulations, three lists were developed for the first status report by simply combining the various lists that existed: 1) alien species reported as present in natural ecosystems in South Africa; 2) alien species that do not occur in South Africa, but that were listed in the regulations as either prohibited or invasive, or have been eradicated from South Africa; and 3) alien species that do not occur in South Africa, were not listed in the regulations, but for which a 'risk assessment' (as defined in the A&IS Regulations) had been completed. The lists from the first status report had several shortcomings—there were no metadata, there were several spelling errors, no standardised taxonomy, sources were not documented, and the lists were only available as tables in the printed report (so the lists were neither readily accessible nor interoperable) (van Wilgen and Wilson 2018). For the second status report, the process was more clearly laid out, so that changes could be tracked over time. Metadata were included, as were sources of information and data confidence levels (low, medium, high) following accepted best practice principles [see SANBI and CIB (2020) for details]. However, there was still no clear standardised taxonomy, and, while much of the detail of how the lists were constructed is available in the supplementary material, methodological information was not presented as a repeatable workflow. For the third status report, the metadata and structure were improved, making it possible to include ancillary enrichment data (though noting that much of the data is still being collated) [see SANBI and CIB (2023a)], there was an effort to standardise the nomenclature used against a few key sources (Faulkner, this issue), and workflows were presented that document the processes followed and decisions made [e.g., around taxonomy, nativity, occurrence status, degree of establishment, pathways, money spent, permits, and impacts; cf. SANBI and CIB (2023b)]. There is now a single list, are available in an Excel spreadsheet to provide easy access to the main end users. The vision is for the process to become fully transparent and semi-automated with clear workflows and processes to arrive at decisions where necessary. A synopsis of the lists over time is provided in Figure 1, with additional details in Supplementary Table 1 and a summary of the process followed to compile the lists provided below.

[Insert Figure 1]

Scope and purpose

The mandate for SANBI to develop a national list as part of the status report emanated from the NEM:BA A&IS Regulations—the report was required to consider, "the status of listed

invasive species and other species that have been subjected to a risk assessment;". Given the Act and relevant regulations are administered by the national department responsible for the environment, it is unsurprising that the focus has been on environmental issues (note: over the past decade or so, the government department responsible for environmental affairs has gone through various name changes and has been configured with various other government departments). The first list focussed on "taxa [that] impact upon, or threaten, natural ecosystems" (van Wilgen and Wilson 2018), but the scope of species included on the lists has broadened over time, from all those regulated as 'invasive' (i.e., those on the regulatory lists) to include alien species regardless of where they are found, whether they have negative impacts, which taxonomic group they come from, and what stage of the introduction-naturalisation-invasion continuum introduced populations have reached (see Section S1.4 in van Wilgen and Wilson 2018). The lists have not to date included human diseases, nor has there been a concerted effort to include pests and weeds that affect agricultural crops (despite the threat these pose to sustainable development). However, there is no neat separation between transformed ecosystems (e.g., urban environments and agroecosystems) and "pristine" ecosystems (e.g., Potgieter et al. 2020), e.g., many protected areas are heavily influenced by human activities even in South Africa (e.g., van Wilgen et al. 2025); nor is there a clear separation between alien species that threaten the environment and those that threaten agricultural or socio-economic systems (e.g., Hulme 2020).

There have been challenges including particular taxonomic groups in the lists. Various efforts have been made to interpret frameworks in invasion biology for micro-organisms (e.g., for forest pathogens, see Paap et al. 2022), but the biogeography has often not been elucidated for species and biogeographic patterns may have eroded over time. The concept of a "species" can also be less directly relevant. Invasions happen at the level of individuals (more precisely holobionts) and populations rather than species (Colautti and MacIsaac 2004).

One decision made at the outset was that the definition of "invasive" should be based on biogeography and not impact, thus aligning with Darwin Core data standards (Groom et al. 2019). This was partly as measures of impact were subjective, but also as impact and degree of invasion need not be tightly correlated (Ricciardi and Cohen 2007). In the lists, information on the degree of establishment based on population processes (i.e., reproduction and spread from sites of introduction) is therefore clearly separated from information used to define the negative impacts (environmental and socio-economic) based on specific schemes (Blackburn et al. 2014,

Bacher et al. 2018). Information on positive impacts has not been routinely collated to date, but schemes are developing to address this (e.g., Vimercati et al. 2022).

We believe it is important to try to include all species introduced to South Africa (even including those in quarantine) on the basis that these species form an important component of the invasion debt (Rouget et al. 2016). There are, however, several species included that are known to not be present in the country. These include species that have been listed as prohibited under the NEM:BA A&IS Regulations (i.e., may not be introduced); species that were recorded as present but appear to no longer be present; and species that were recorded as present, but the records appear to be in error (see Matthys et al. this issue for a proposed approach to address these issues). It is important to retain such species on the lists for posterity so if someone searches for a particular species then it is clear why the species is included. For the same reason, although all names are checked against a standardised taxonomic backbone and the current accepted names used, names that were used for species in other sources are also included verbatim from the original source.

Species that are native to one part of South Africa and invasive in another part of the country (Nelufule et al. 2022, 2023a, b) are included. Notably such native-aliens are only included if they pass the biogeographic criterion for being established, as it would be unfeasible to include all cases that are in captivity and cultivation. The lists do not consider, however, native species that have undesirable impacts as a result of other aspects of global change (e.g., Nackley et al. 2017). For example, bush encroachment by native plants, the spread of native bird species into urban areas, and agricultural or ruderal weeds that are native. Such native species can present problems similar to alien species, but their management needs to be in the context of them as pests within their native ranges (van Wilgen and Wilson 2018).

Metadata & data structure

In the first status report, data were in several tables embedded in a PDF file, with metadata included in part as a preamble to the tables, but not in a systematic searchable form. In the most recent version of the list, the sources of the data that informed the recorded values are reported, with a dedicated source column for most of the variables. A full reference list is provided in a separate tab of the species list. This ensures transparency and allows those that compile and use the alien species list to go back and check the original values. This is a vast improvement on previous iterations, where a reference list was provided, but it was not clear which data came from which sources. The metadata try to adhere to the Darwin Core data standards (cf. Groom

et al. 2019) and species names are based on various taxonomic backbones, primarily the Global Biodiversity Information Facility (GBIF) for animals, and either the Botanical Database of Southern Africa (BODATSA) or Plants of the World Online (POWO) for plants (see Faulkner, this issue).

The latest list was also produced in line with recommendations to make the data tidy (Wickham 2014)—each row refers to a species and each column a particular variable with consistent units. The columns include information on species identity, taxonomic rank, status as an alien species, introduction dynamics, distribution, abundance, impact, legal status, information associated with regulatory status, and management. Detailed metadata are provided for all variables, with confidence and data sources for 23 of these (Zengeya et al. 2025). The metadata for the list are freely available on Zenodo (SANBI and CIB 2023a) in text-searchable format.

Sourcing data

Information incorporated into the lists was obtained from various sources including government reports, peer-reviewed papers, grey-literature, atlassing projects, and online databases (File S1). The information was obtained using three main strategies: 1) literature searches to identify relevant information and databases; 2) soliciting new syntheses, e.g., encouraging experts to contribute to a journal special issue (Wilson et al. 2017) and an encyclopaedic book on the status of biological invasions in South Africa (van Wilgen et al. 2020); and 3) direct requests to stakeholders for specific inputs. The number and type of sources used to inform the lists have increased dramatically over time (Figure 2). In the first status report, information was obtained from 42 sources comprised mainly of government/institutional reports, expert opinions, and peer-reviewed literature. The number of sources more than doubled in the second status report and increased to over 1000 sources in the third status report. The increase in data sources was mainly due to an increase in the use of peer-reviewed publications and online databases, and the deprecation of evidence based on expert opinion.

[Insert Figure 2]

Processing data and workflows

Information about the taxonomy, occurrence status, degree of establishment, and introduction status of species included in the list was obtained from various sources with different levels of confidence and completeness. In the first two status reports, the process of extracting and translating information from original data sources was not properly documented. This process

was improved in the third status report by creating a database of sources and intermediary files detailing what information was extracted from the original databases. The information from the various databases was then standardised based on schema outlined in the metadata (SANBI and CIB 2023a). Issues were flagged and noted in the intermediary files, such as unresolved terms, missing data, and any translated names and interpretations. The intermediary files were then manually merged by standardised names and unification of ancillary data. To mitigate individual subjectivity, all intermediary files were cross-checked against the metadata by at least one of the authors for consistency (TZ).

Several workflows have been developed over time to outline the process used to compile the lists. There were no workflows developed for the first status report, but the process is captured as methodological notes (van Wilgen and Wilson 2018). The second status report includes details of how the list was compiled in the supplementary material (Zengeya and Wilson 2020b). The third status report specifically presents discrete workflows for various aspects used to compile the report (SANBI and CIB 2023b). These include a protocol of how to add alien species and enrichment data to the species list and an automated process to check taxonomic information (see Faulkner, this issue). These workflows are intended to be step-by-step guides as to where to source data and how such data should be collated, processed, and analysed. The intention is that the process to compile the list is transparent, can be readily repeated, and that future analyses can be automated as much as possible. Some of these workflows required specific protocols with the intention that they be applied for purposes other than the status report. For example, protocols have been developed to classify native-alien populations (Nelufule et al. 2022), to estimate the monetary cost of biological invasions (McCulloch-Jones et al. 2024), and to incorporate findings from molecular analyses (Fernández Winzer et al. 2025). For future status reports, the vision is to develop and curate workflows for various processes that are required to compile the reports and to automate these workflows to appropriate levels. These include workflows for: protocol for new introductions; processing occurrence records to give species richness and abundance estimates for different spatial units; impacts on key ecosystem services; regulatory processes (beyond just the permit database); and evaluating species-specific control plans and their implementation.

Tracking change

A typology of change was developed during the production of the second status report and is used to track why values change between iterations of the list (Figure 3). Based on the typology, there are five reasons why values change (data are no longer relevant; data need to be

reinterpreted; new data were collected; confidence levels need to change; or there was a 'true' change). A 'true' change (type 4 in Figure 3) is when there is an actual change in biological invasions, such as when the introduction status of a species changes from 'naturalised' to 'invasive' as it begins to spread (see Figure S1). When a change is made, the type of change is documented in a change tracker, and the number of changes and reasons why are presented in the supplementary materials of the status report. Thus, it is explicit where and why changes were made. Estimates of trends in biological invasions require true change (type 4 in Figure 3) to be calculated from a revised baseline that accounts for all other types of changes (types 1, 2, and 5 in Figure 3; note that for type 3 there is no change in actual values although the confidence in an estimate might increase as new information becomes available). The typology of change, therefore, assists with documenting and interpreting change, and the calculation of trends. It also informs proposed actions in response to changes. For example, in cases where errors were corrected, the existence of these errors should be communicated to those that compiled the source of the original data; or in the case of true change, management may need to be adjusted (e.g., a change in how a species is regulated may be required if it is under complete biological control).

[Insert Figure 3]

Data mobilisation and reporting

The list is freely available on Zenodo (SANBI and CIB 2023c) as an Excel file, which makes it findable, accessible, and easy to use for end users. The data on the list are used to calculate the indicators that form the backbone of the status report (Wilson et al. 2018), with visualisations and summary statistics presented in the report. The status report itself is published as a static document every three years, but the medium-term vision is for the data, visualisations of the data, and summary statistics to be provided to the end user through an online dashboard which will be updated as new information becomes available. Annual summaries can then be generated with detailed published assessments of broad issues every decade or so as needs arise. The list is currently not harmonised with other external datasets (e.g., South Africa's GRIIS list, Robinson et al. 2020), but the intention is that this list will form the basis of future GRIIS lists and the lists will be aligned with other lists as far as possible. This will reduce confusion on the difference between the various lists, and which list should be used for which purpose.

The list, once corrected for changes that are not true changes, is intended be used to inform the management and regulation of alien species in South Africa. For example, if a species' invasion status changes from 'presentAsAlienNotNaturalised' to 'NaturalisedNotInvasive' as it has escaped from captivity then, depending on the risks posed, an incursion response may be considered. Similarly, a species' whose invasion status changes from 'NaturalisedNotInvasive' to 'Invasive' as it spreads might need to be reassessed in terms of how it is regulated and how much of a priority it is for management.

The list was specifically developed to report on status and trends of biological invasions at a national level. The intention is also that the list will be used to monitor and report on progress towards Target 6 of the GBF, which requires signatories, including South Africa, to reduce the introduction rates of invasive species by 50% and minimise their impacts (CBD 2022). The indicators used for the status report (e.g., rate of introduction of unregulated species) are not identical to those proposed under the GBF (e.g., rate of invasive alien species establishment), but the list does include the types of information required to calculate the CBD indicators given sufficient capacity.

Stakeholder engagement

Stakeholders [including researchers and academics, managers of biological invasions, the public, and various government entities (e.g., SANParks) and departments (Department of Forestry, Fisheries and the Environment; Department of Agriculture; Department of Transport)] play various roles in the process – they provide data and written inputs, serve on the status report's research and advisory committee (RAC), review and comment on drafts of the status report, and use the data and information it provides. Engagement with these stakeholders, therefore, occurs in various ways. At the beginning of the status report production process, formal requests for data are sent to some data providers; individuals are requested to write specific sections (e.g., boxes that focus on specific case studies); and the RAC is appointed. Feedback to data providers is provided during the production of the status report (e.g., on errors). Several meetings with the RAC are held throughout the production of the status report, and they review and comment on all drafts. Several drafts of the status report as well as the list, and all other supplementary materials are sent out for review by stakeholders, comments that are received are recorded in a database, with each comment responded to and changes made to the report as required. The database of comments is not publicly available but is available upon request. For the second and third status reports, a round of expert review was

also conducted on an advanced draft of the status report. The chair of the RAC checks the database of comments before the status report is finalised to ensure all comments have been addressed appropriately. Following the production of the status report, the team engages with the key receivers of the status report – the Department of Forestry, Fisheries and the Environment; and various materials are prepared for the status report's release (e.g., press releases, videos). On the day the status report is released to the public, the report, the list and all other supporting documents are made live on Zenodo, and an event is held, with various members of the media in attendance.

Discussion

South Africa's national alien species list

The initial list consolidated existing readily accessible data and aimed to comply with regulatory requirements (van Wilgen and Wilson 2018). Over time, there have been major improvements in how data are presented, how changes are tracked, and the degree to which the information presented is consistent with international best-practice (Zengeya and Wilson 2020a, 2023a). The development of documented and repeatable workflows has ensured that it is now clear why species are included on the list and facilitates reviews and updates. The focus for future updates is to ensure all historical data sources are incorporated into the list, to formalise processes [e.g., declaring a species alien and present (Matthys et al. this issue)], and to put systems in place to incorporate new information as it becomes available [e.g., Faulkner (this issue), Fernández Winzer et al. 2025].

Several challenges remain. These include significant gaps in our knowledge of the presence and distribution of taxa not currently covered by specific atlassing projects. The numbers of alien terrestrial plant species and vertebrate species are well documented as a result of several atlassing projects such as the Southern Africa Bird Atlas Project 2 (SABAP2) (http://sabap2.birdmap.africa/), the Botanical Database of Southern Africa (BODATSA) (http://posa.sanbi.org/), and the Southern African Plant Invaders Atlas (SAPIA). However, less is known for other taxa such as invertebrates, soil organisms, and microbes (Janion-Scheepers et al. 2016, 2020; Wood 2017; Paap et al. 2018). Similarly, there are reliable data on the extent of plants and birds, but not for other taxa. The integration of GBIF with citizen science platforms such as iNaturalist and the digitisation of historical records in museums and herbaria has increased knowledge of the distribution of some alien species (Zengeya and Wilson 2023a). However, there has also been a decline in active surveillance for plants, specifically a hiatus in

SAPIA, which has reduced the ability to track plant invasions across South Africa. In addition, there continue to be very few reliable data sources on the relative abundance (cover, biomass or population size) of alien species at specific sites. Remote sensing is still a promising approach to improve distribution data but has not yet delivered tangible results that can be used to compile the list (but see Cardoso et al. 2025, Kotze et al. 2025). Only a few species have been assessed formally for impacts, much more information needs to be evaluated and systematically incorporated (Zengeya et al. 2020, van Wilgen et al. 2022). Key historical data sources that still need to be included in the list were identified in the third status report (SANBI and CIB 2023b). Until these lists are incorporated, however, we do not have a baseline of the number and status of alien species in South Africa (or rather the baseline will need to be continually and significantly revised as old data are incorporated). A baseline would allow us to track trends in the number and status of alien species in the country and to assess the effectiveness on interventions put in place to address issues around biological invasions. Nonetheless the process for compiling the list is now well established.

Lessons learned

Reflecting back on the decade or so since we started developing a consolidated list of alien species for South Africa, we identified several key lessons. We realise these issues will be viewed as elementary to biodiversity data scientists (e.g., the need for data to be FAIR and tidy), but as 'naïve' invasion biologists tasked with developing a list of alien species, we believe we would have appreciated these insights when starting the process.

1. Structure data and make them available—so data are '*Findable*', '*Accessible*', '*Reusable*', and *tidy* (see Wickham 2014, Wilkinson et al. 2016). For example, the list of alien species in South Africa is *Findable* on Zenodo, an online repository (http://dx.doi.org/10.5281/zenodo.14937470). Each published iteration of the list was assigned a version number and a Digital Object Identifier (DOI) to ensure that the list can be appropriately cited and located, and that information can be updated and changes tracked. The list is currently made available as a static database in Excel, a common format that is *Accessible* for most users. Other database formats are not easily accessible as they either require specialised software or expertise, and some databases are provided in formats that are not easy to transcribe especially for large datasets (e.g., datasets embedded in Word or PDF documents). On the downside, .xlsx is a proprietary format that can have issues with interoperability. The information contained in the list is *Reusable* by making sure it is easy to determine who generated the original data and obtaining permission for others to use the data. The list was

also produced in line with recommendations to make the data tidy which makes it easier to manipulate — each row refers to a species and each column a particular variable with consistent units.

2. *Use data standards and metadata*—so terms are used consistently, i.e., '*Interoperable*'. Interoperability allows for datasets and metadata to be merged easily, across different applications, without repetitive manual tasks. Biodiversity monitoring requires access to rapid, reliable, and repeatable monitoring data that can be used to inform policy, decision-making, and interventions (Groom et al. in prep). Providing such information – from local to global levels and within timescales relevant to policy – calls for improved integration of data on biodiversity from different sources such as citizen scientists, museums, herbaria, and researchers. We aspire to having a list for South Africa that adheres to international best practices for biodiversity data such as the Darwin Core data standards (Groom et al. 2019). This enables the list to be *Interoperable* with local initiatives from researchers in academia and natural science facilities (museums and herbaria) and global initiatives, such as GBIF, that use standardised data formats and protocols (see also 6. *Integrate with reporting requirements*).

3. *List the data sources used and the level of confidence* —to facilitate checks, updates and mitigate uncertainty. A list of data sources helps improve the saliency of the list as it allows for checks to verify that key data sources have been consulted. It also helps track changes to the list as new information is added and old information is either deprecated or updated. From our experience, adding information that is not clearly sourced makes it very difficult to resolve errors and it is likely that discussions on such issues are repeated over and over again.

The level of uncertainty also varies among data sources, and this is due to various factors such as different methods used to collect the data, different levels of completeness, and relevance of data sources (e.g. outdated vs. current information). It is therefore prudent to have a process to mitigate the different levels of uncertainty among data sources. For the list of alien species in South Africa, we have put in place a process to assign confidence levels (low, medium, high) for data to account for uncertainty following accepted best practice principles.

4. *Take a modular approach*—so it is easy to add detailed information on some species while retaining very coarse information on other species for which little is known. The process to compile a national list of alien species should ideally be modular (e.g., McGeoch and Squires 2015, Latombe et al. 2017). A modular approach facilitates the collection of baseline data in situations where there is limited data and resources, while also allowing for comparisons with

situations that have high-level data and more resources. Countries differ widely in the level of existing information on alien species, and in the resources and capacity available to generate new data and to collate existing data. However, all countries can provide some information on the status of biological invasions. Over time, this information can be built upon systematically as new information or resources become available to improve the completeness of alien species lists. For example, in South Africa we began developing a national list of alien species by cataloguing data on invasive alien species, because their occurrence in the country was well documented. This list has been further developed by adding more alien species as they are discovered and adding in new information as it becomes available on less conspicuous alien species that are not yet invasive. The list should be updated regularly to add or remove species because of new introductions and/or effective eradications.

5. *Document workflows*—so the process can be understood, errors are found and corrected, and the process can be replicated [and ultimately (semi-)automated]. The development of documented and repeatable workflows ensures it is clear why species (and associated information) are included in the list and facilitates reviews and updates. Workflows ensure that the processes used to create the list are documented and can easily be repeated. They also assist with the automation and standardisation of the process, which reduces the burden of regular monitoring and reporting by decreasing the time between information being collected and when it is incorporated into the list (cf. Fernández Winzer et al. 2025).

6. *Integrate with reporting requirements*—so the lists are directly used. One of the main motivations for creating national lists of alien species is to facilitate reporting against national and international conventions. Integrating with existing processes and reporting requirements also helps to incentivise stakeholder participation (e.g., Díaz-Reviriego et al. 2019, Krug et al. 2020). Increased stakeholder participation promotes inclusivity, enhances knowledge, increases relevancy, and improves effectiveness of interventions (Nuñez et al. 2024). Regular monitoring of biological invasions facilitates South Africa`s reporting to several international conventions that it is signatory to, including Target 6 under the GBF. A process has also been initiated to integrate South Africa’s list with the global initiatives to create national lists such as the Global Register of Introduced and Invasives Species (GRISS) (Pagad et al. 2022) and the broader GBIF platform (https://www.gbif.org/). The current list (Zengeya et al. 2025) will be used to inform future revisions to the GRIIS list for mainland South Africa [this has already been done for the lists for the Prince Edward Islands, sub-Antarctic territories of South Africa (Fernández Winzer et al. 2024)].

7. *Commit dedicated resources*—so lists can be curated, updated, and there is a clear line of communication for data providers and users. From our experience, it takes a lot of data, time, effort, and expertise to compile and curate a national list. It is therefore prudent to plan for sufficient resources and capacity to ensure that the process is sustainable. Financial resources are required to attract and retain skilled personnel to oversee and develop processes. Lists are also inherently complex and require expertise on different aspects of biological invasions such as data management, taxonomy, pathways, different taxa, and management. Therefore, several people may be involved in the process. It is thus important to have a project plan with clear roles and responsibilities. In South Africa, the compilation of the list is coordinated through a national hub/institution (SANBI) by a small core team that draws on inputs from a managed network of stakeholders from an active community of practice in biological invasions (Byrne et al. 2020). Coordination through a national hub reduces duplication of effort, and stakeholder consultations promote buy-in and saliency of the list. We have been fortunate in receiving sustained government funding (albeit with some uncertainty at times), however, to date we have not had anyone specifically dedicated as the custodian of the list. This is partly as we have been developing the lists and their structure as the status report developed. But it is clear we must have a dedicated person to work on the list going forward. Many people are needed to spot errors and provide updates but as few as possible should be responsible for making the actual changes.

8. *Learn by doing*—during the initial phase of developing a national list, it is better to work with the resources available (leaving room for setbacks and mistakes) and document processes in place so people can provide feedback and corrections. We accidentally embraced the concept of adaptive learning (i.e., learning by doing and developing systems over time). This was partly because when compiling the first status report, there were no comparable processes elsewhere to draw on and we had to adapt to new approaches and data standards as they become available. For example, the Darwin Core standard for some biological invasions terms were substantially revised between the completion of the first and second status report (Groom et al. 2019). The process of devising the metadata was done in parallel with data entry and this proved challenging. However, the back and forth based on issues encountered was necessary to improve both the metadata and how information was collated. It is envisaged that development of the metadata has largely matured, and future updates will be done without disrupting other processes. But it was an important process to go through.

We have also learned and improved our processes by adopting practices from other initiatives on compiling lists such as the Tracking Invasive Alien Species (TrIAS) project (Vanderhoeven et al. 2017, https://osf.io/7dpgr/wiki/home/) and the Biodiversity Building Blocks for Policy (B-Cubed) project (Groom et al. in prep, https://b-cubed.eu/). The overarching objective of the B-Cubed project is to develop pipelines to improve the integration of biodiversity data into data cubes that are then used as the basis for models and indicators to monitor biodiversity status and change. The data cubes, models, and indicators developed under the B-Cubed project will feed into the process of revising the list of alien species in South Africa by providing information that will help address three of the six identified key gaps in previous status reports (alignment of indicators, mobilisation of spatial data, mobilisation of impact data); and assist the automation and standardisation of the process and how the status reports are communicated (e.g., including workflows and dashboards).

Conclusion

The process of compiling a national list of alien species is a daunting task that requires dedicated resources, expertise, and commitment. National lists of alien species are never complete or perfect. Lists are dynamic and need constant updating as new alien species are discovered, populations die out or are extirpated, and as new information becomes available. Therefore, lists should not be viewed as an end *per se* but as a pragmatic process that captures the current state of knowledge that can be improved on as better technology, expertise, and information become available. We argue it is essential that the lists are compiled and updated using systematic and standardised processes that are transparent, and evidence based. This facilitate checks, updates, and allows for a process to be put in place to mitigate uncertainty around sources of information. The eight recommendations highlighted here are undoubtedly selective and biased. We hope we will learn more as the list develops and would appreciate insights from elsewhere on other issues faced and tips as to how to address them.

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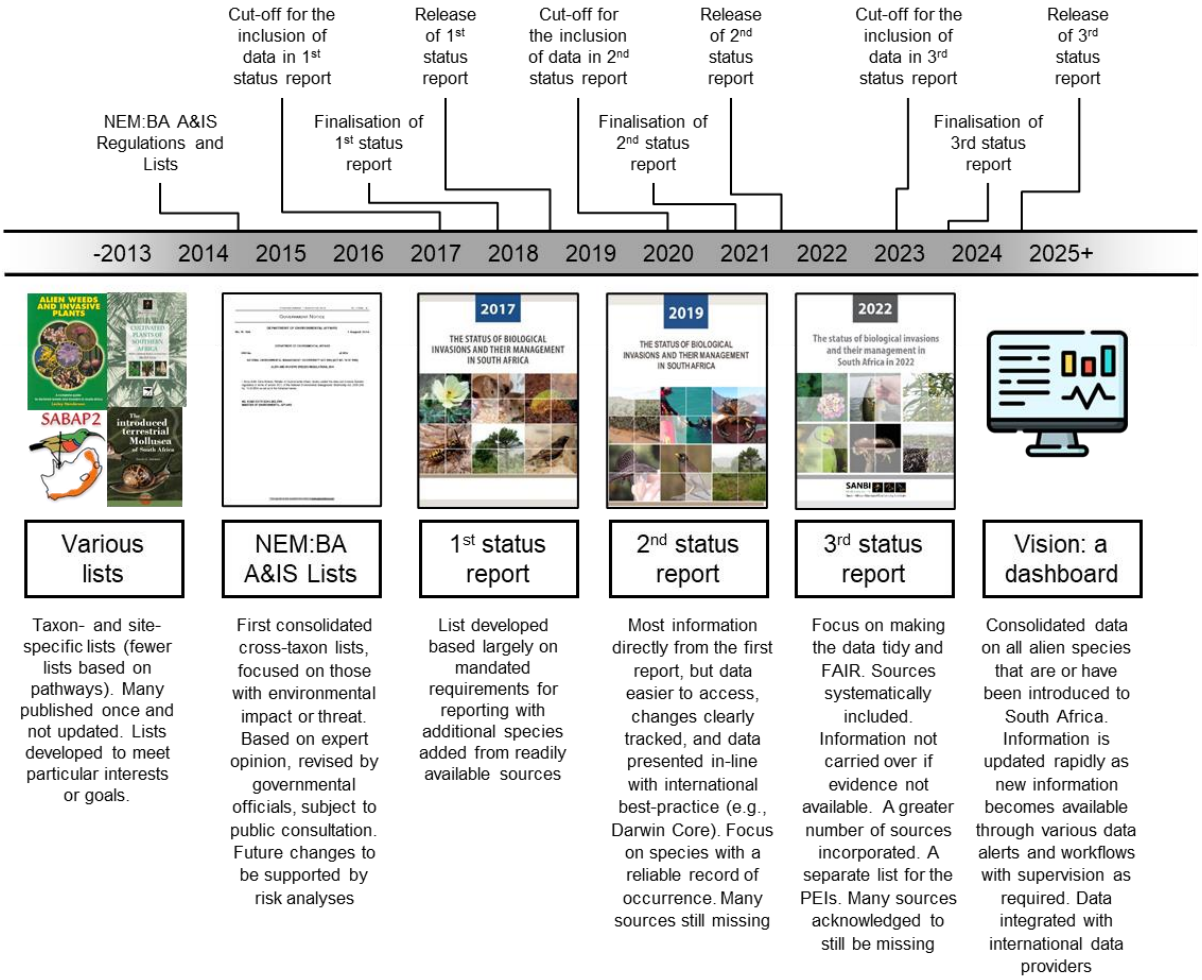


772
773 Figure 1: How lists of alien species in South Africa have developed over time. For further
774 details see Supplementary Material S1. PEIs: Prince Edward Islands.
775

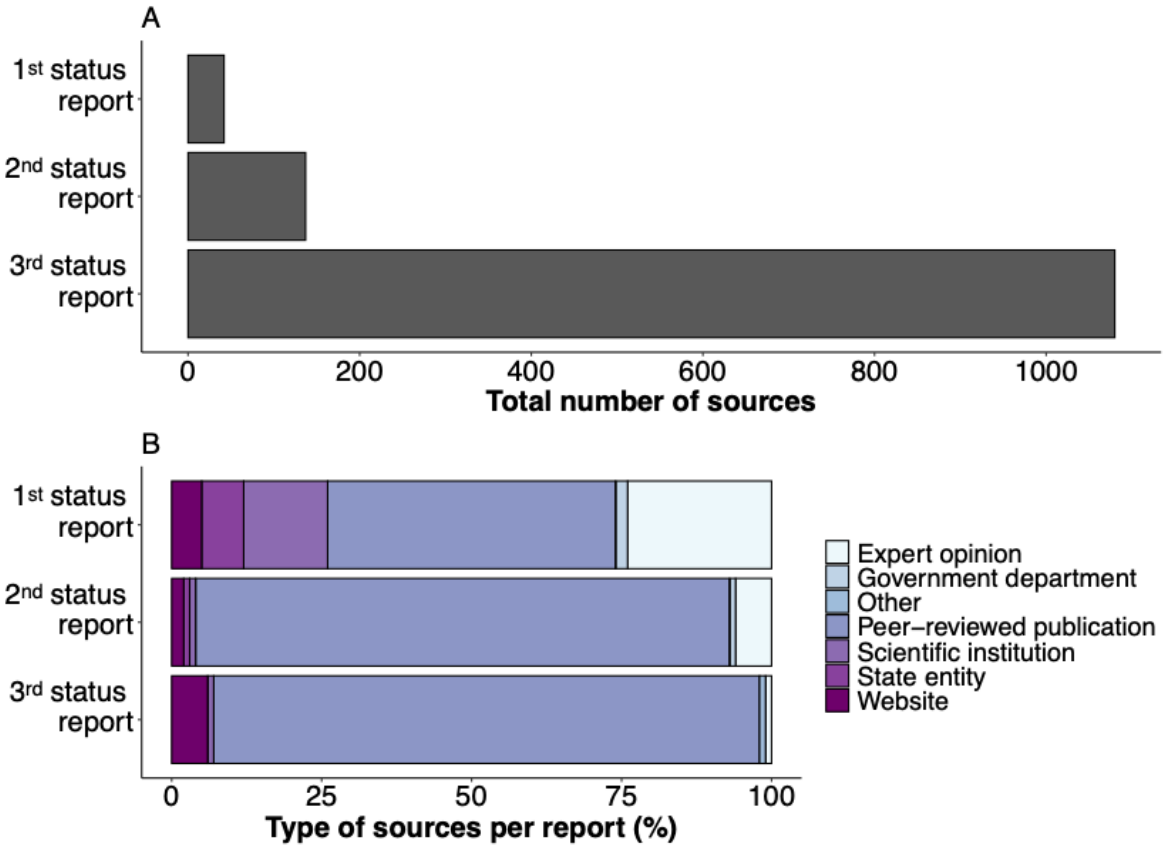
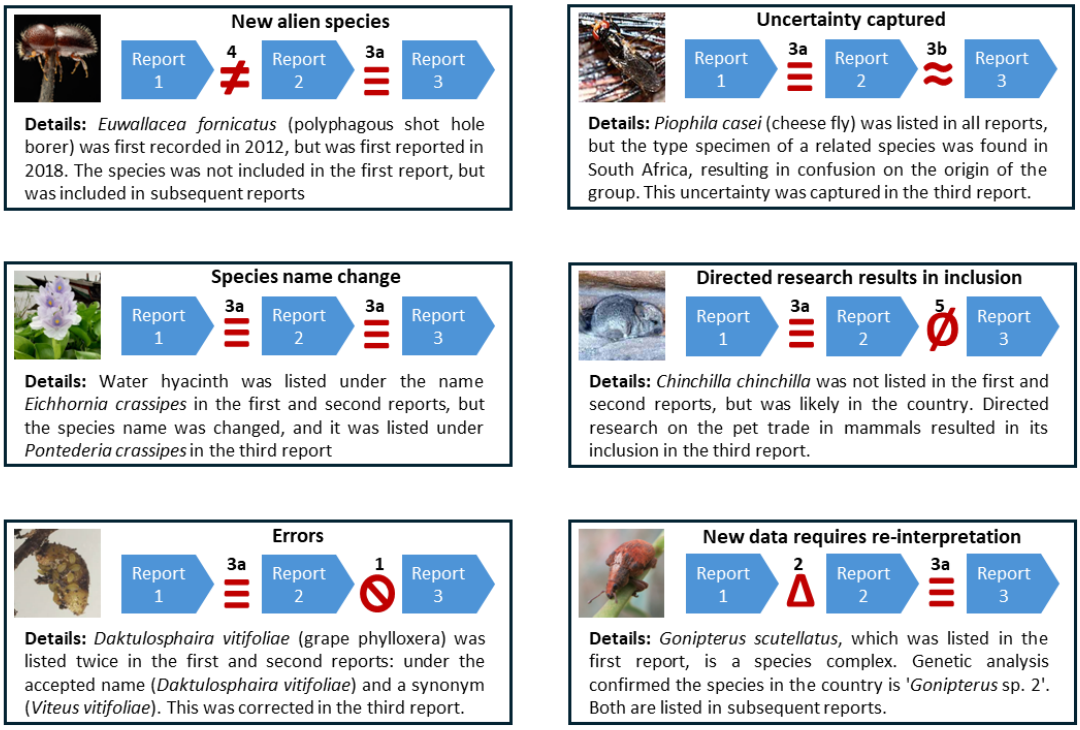


Figure 2: The (A) number and (B) type of sources used to populate the lists of alien species compiled as part of South Africa's national reports on the status and management of biological invasions. For a database of sources, see File S1.



Types of changes	Description	Reasons
1 Report t ⊘ Report t+1	Data collected for a previous report but are no longer relevant	• Change in indicators • Errors
2 Report t Δ Report t+1	Data were collected for a previous report, but need to be reinterpreted	• Change in indicators • A change in the data (e.g., a species has split into two taxonomic units, or new regulations are developed)
3a Report t ≡ Report t+1	Data were collected for a previous report, and there is no change in the values	• No new data were found • New data support the previous data • New data results in changes, but not to values (e.g. there is a change to the species name)
3b Report t ≈ Report t+1	Data were collected for a previous report and while the value has not changed, the confidence changed	• The confidence has changed (new data either support the previous data or cast doubt on the value) • More rigorous application of indicator values
4 Report t ≠ Report t+1	Data collected indicates the value has changed since a previous report	• Data collected since publication of previous report • Data were collected before publication of previous report, but not included in previous report
5 Report t Ø Report t+1	Data collected where no data were available for previous reports	• Data were not available previously, and were collected since publication of previous report • Data were collected before publication of previous report, but not included in previous report • The specific indicator is new

Figure 3: Details on the types of changes made to the alien species list across status reports; and examples from the national reports on the status and management of biological invasions in South Africa. For a schematic, showing an example of changes due to new data (type 4), see Figure S1. This typology assists with documenting, interpreting and tracking changes. Photos: Garyn Townsend (*Euwallacea fornicatus*), Andrew Meeds (*Piophila casei*), Symoum Syfullah Priyo (*Eichhornia crassipes*), Jaime E. Jimenez (*Chinchilla chinchilla*), Czif~commonswiki (*Daktulosphaira vitifoliae*), Rosa Knoppersen (*Gonipterus* sp. 2).

Supplementary Material

Figure S1: How the introduction status of a species might change through time (specifically between status reports).

Table S1: A summary of the various lists of alien species in South Africa over time with details of what information they contain, how they were constructed, and by whom.

File S1 (note: included as a separate file): Full list of data sources used (Name, Description, Scope, and When incorporated)

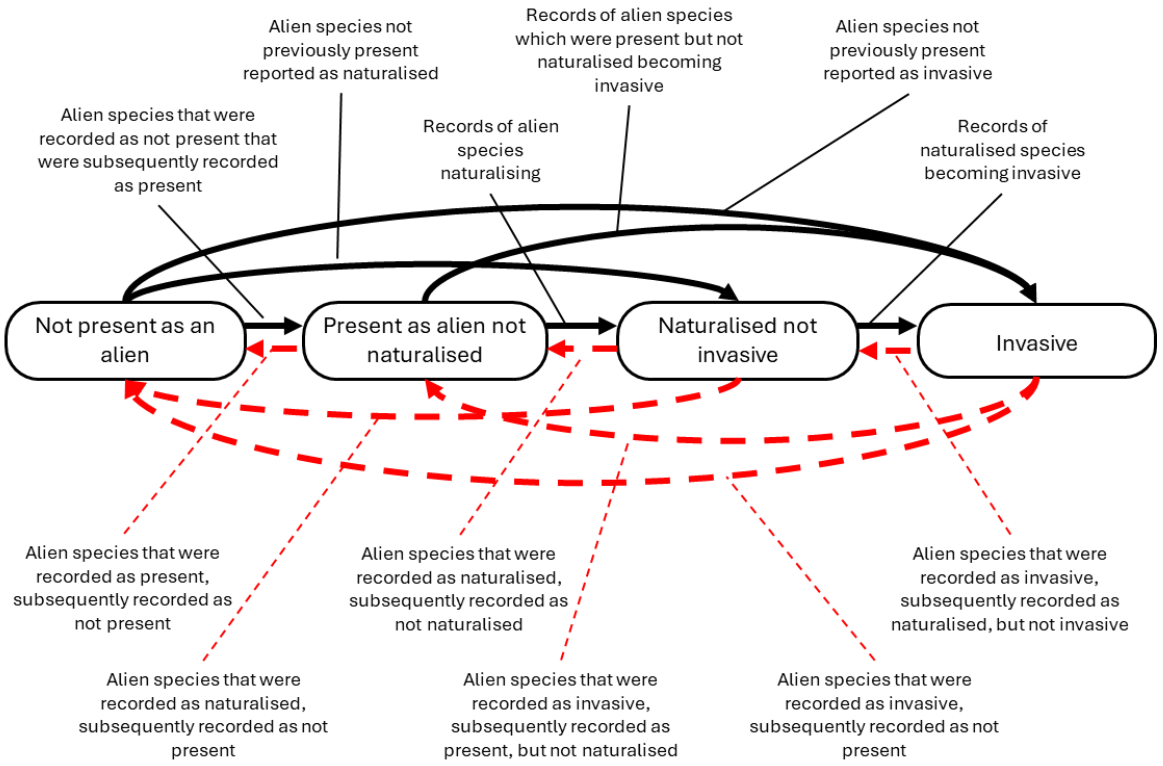


Figure S1: How the introduction status of a species might change through time. The diagram is shown here for ease of interpretation, but the information can be presented in the form of a matrix to ensure it is machine-readable and more easily analysed. Importantly, the risk that a species poses can be more about how quickly it moves through these stages rather than which stage it is at (Brock & Daehler, 2020).

Table S1: A summary of the various lists of alien species in South Africa over time with details of what information they contain, how they were constructed, and by whom. Note the following is not an exhaustive list. For example, a Global Register of Introduction and Invasive Species (GRIIS) list for South Africa was produced in 2020 (Robinson et al. 2020), though the intention is for a subset of the list developed for the status report to replace the GRIIS list. References to relevant sections of pages of the various status reports are indicated.

	<2014	**2014 NEM:BA A&IS Lists**	**First status report (2018)**	**Second status report (2020)**	**Third status report (2023)**	**Vision**
Synopsis	Taxon- and site-specific lists (fewer lists based on pathways). Many published once and not updated. Lists developed to meet particular interests or goals	First consolidated cross-taxon lists, focussed on those with environmental impact or threat. Based on expert opinion, revised by governmental officials, subject to public consultation	List developed based largely on mandated requirements for reporting on species listed under the 2014 NEM:BA A&IS Regulations, with additional species added from readily available sources	Much of the information inherited directly from the first status report. Significant development on the data architecture intended to make data easier to access (digitised), to be clear how changes are tracked, and to ensure information is presented in a manner consistent with international best-practice (e.g., Darwin Core). Focus on only species with a reliable record of occurrence. Many sources acknowledged to still be missing	Greater focus on making the data tidy and FAIR, including through systematic inclusion of the evidence (i.e., sources) underpinning the information. Information was not carried over from previous lists if the evidence was not available. A greater number of sources were incorporated. A separate list was produced for the Prince Edward Islands (South Africa's sub-Antarctic territories). Many sources acknowledged to still be missing	Consolidated data on all alien species that are or have been introduced to South Africa. Information is updated rapidly as new information becomes available through various data alerts and workflows that can be supervised as required. Data integrated with international data providers

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	<2014	2014 NEM:BA A&IS Lists	First status report (2018)	Second status report (2020)	Third status report (2023)	Vision
Structure	Often published as a table in a book or publication, though in some cases as stand-alone databases	22 lists split into various taxonomic and functional categories and whether species were considered present or absent from the country	3 lists published as tables in the status report: present in natural ecosystems; regulated (including prohibited) but not known to occur in South Africa; not regulated, do not occur in South Africa but a 'risk assessment' was conducted	A single flat database with 66 columns	A single flat database with 79 columns	Data available on-line that can be downloaded in various formats and can be accessed directly via an application programming interface
Number of species	Massive variation. Possibly the largest list is that of 9000 cultivated plants though that includes native and alien species (Glen, 2002)	1118 [559 (in country) and 559 (prohibited not in the country)]	2655 [2033 (list 1), 570 (list 2), 52 (list 3)]	2743 [1888 present, 596 absent, 258 not applicable, 1 not evaluated]	6197 [3802 present, 739 absent, 1639 doubtful, 17 not evaluated]	Comprehensive
Sources	Various, and list-specific	Expert consultations, expert workshops, and public consultations	42 sources listed including a mix of personal communications and references with citations broken down into broad groupings (taxonomic, functional, or regulatory) (First status report, Table 4.1 p48+)	137 sources listed in the species list and supplementary material (Second status report Table S3.6)	1080 references included in the species list and supplementary material (Third status report Tables S2.1 and S4.7)	Updated database of sources

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	<2014	2014 NEM:BA A&IS Lists	First status report (2018)	Second status report (2020)	Third status report (2023)	Vision
Formatting of data	Various Data presented in very different ways according to relevant conventions	In several tables in a pdf (see Wilson 2025 for a retrofitted interoperable and accessible version)	Embedded in three separate pdf tables (First status report 1: p309; 2: p380; 3, p394)	Separate Excel file with all data in one spreadsheet with a separate tab for metadata. Each row represents a species and each column a discrete variable (i.e., tidy), though some cells are empty	Separate Excel file with all data in one spreadsheet with a separate tab for references. Tidy (with no empty cells). Aligns with Darwin Core where possible. The decision to keep it in a proprietary format was on the basis of ease of usage for end users and to avoid losing formatting (italics specifically)	As required by the user, i.e., both machine readable and in formats appropriate for analyses and presentations
Taxonomic backbone	Rarely explicitly specified	Not specified. No single explicit backbone but checked at some point by experts, synonyms variously included (see Wilson 2025 for a version retrofitted to a taxonomic backbone)	Not specified, though species authorities are included for all species	Not specified, species authorities are not included for all species	For each species, the source and the date when the source was consulted is specified. Various sources were used, primarily GBIF for non-plant taxa, and for plants the 'Plants of Southern Africa' database or the 'Plants of the World Online'. See Faulkner this issue for details of the standardisation of this process	Full and direct integration with relevant international and national data-sources

	<2014	2014 NEM:BA A&IS Lists	First status report (2018)	Second status report (2020)	Third status report (2023)	Vision
Process for compilation	Various, not always clearly documented, though often the work of one specific curator in consultation with experts	Draft lists were published for public comment in 2007, 2009, 2013, and 2014; with various inputs by expert working groups on specific taxa. The lists were revised in 2016 and 2020 with additional draft lists sent for public comment in 2015 and 2018. See Wilson & Kumschick (2024) for full details	The lists were developed based on the information that was specified as required under the NEM:BA A&IS Regulations, with a few additional sources. Three main strategies were used to obtain information: personal knowledge of authors and literature searches; by encouraging experts to contribute to a journal special issue (Wilson et al. 2017); and identifying and engaging specialist contributors. There were two rounds of public review (First status report p8–11, van Wilgen & Wilson 2018)	Five main sources were used: 1) data from the first report; 2) published literature; 3) an open-access book on biological invasions in South Africa produced in line with the status report (van Wilgen et al. 2020); 4) South Africa's National Biodiversity Assessment (SANBI 2019); and 5) unpublished information provided by stakeholders. There were two rounds of public review and one round of expert review (Second status report p4, Zengeya & Wilson 2020a)	A set workflow was used to incorporate information sources with intermediate data files stored (SANBI & CIB 2023b), noting there had to be a citable source for any information. As such data were not simply carried over from the previous status reports. There were two rounds of public review and one round of expert review (Third status report p6–8, Zengeya and Wilson 2023a)	Set workflows in place to ensure regular transparent updates. System in place to allow manual review of changes and quality checks
Resources / human capacity	Usually a single person developing and curating information either as part of their mandate or from personal interest	A collaborative effort that drew directly on the expertise of many taxonomists and specialists in South Africa. Led by government officials	No single person dedicated to the job. Taxonomic experts consulted as required to resolve issues	No single person dedicated to the job. Taxonomic experts consulted as required to resolve issues	No single person dedicated to the job. Taxonomic experts consulted as required to resolve issues	Biodiversity data manager with connections to relevant experts for verification. Expert panel established to decide on particular issues (e.g., nativity)

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	<2014	2014 NEM:BA A&IS Lists	First status report (2018)	Second status report (2020)	Third status report (2023)	Vision
Ownership / mandate	Various, and not always clear if the information is in the public domain	South African Department of Forestry, Fisheries and the Environment; based on NEM:BA 2004. Licence not specified, but in the public domain	South African National Biodiversity Institute with mandate from the NEM:BA A&IS Regulations of 2014. Licence text equivalent to CC BY-NC	South African National Biodiversity Institute with mandate from the NEM:BA A&IS Regulations of 2016. Licence text equivalent to CC BY-NC	South African National Biodiversity Institute with mandate from the NEM:BA A&IS Regulations of 2020. Licensed under CC BY-NC 4.0	Mandate to consider all species (beyond those affecting biodiversity). Information be free to use (even for commercial purposes), either CC BY or CC0
Metadata	Different terminologies used, but details of ancillary data not always clearly outlined	Explanation of regulatory categories, but otherwise no metadata	Included in text (First status report p305–308) and in table legends	Combined with species list in an Excel file	Separate Word document with bookmarks so easily searchable, standardised formatting for each variable	
Error checking and version control	In general one curator, changes not always documented. Often once-off publications	The process of error checking is unclear. The rationale for changes to the listings is not publicly documented (as of the 2020 lists)	No version control as first version	Change tracker (Zengeya & Wilson 2020b)	Change tracker (Zengeya & Wilson 2023b)	Periodic manual checks of data
Ancillary data	Various and list-specific. Often distribution data included	Regulatory category & any prohibitions or exemptions. Nothing on introduction status or degree of establishment	Regulatory grouping | common name | legal status | introduction status | distribution | impact status | risk assessment | permits granted/refused	31 variables, though not specifically structured and some of the variables were simply to link to other data sources	38 variables covering: species identity | taxonomic rank | status as an alien species | introduction dynamics | distribution | abundance | impact | legal status | information associated with regulatory status | management	Species-level information necessary to populate all indicators used in reporting on biological invasions at a national and international level, and that is useful to end-users of the data

	<2014	2014 NEM:BA A&IS Lists	First status report (2018)	Second status report (2020)	Third status report (2023)	Vision
Uncertainty	Often includes information as to whether a presence was disputed or not, but usually as notes rather than a specific standardised coding	Not specified	Not specified. Had estimated completeness and accuracy for large sections of the lists (e.g., mammals) rather than the entry for a specific species	Source and/or confidence [high, medium, or low (if appropriate)] for most variables (but not scientficName)	Source and/or confidence [high, medium, or low (if appropriate)] available for 23 variables (including scientificName)	Sources regularly checked and information updated. Uncertainty specified with a link to proposed actions for each level and indication whether the uncertainty is aleatoric or epistemic
FAIR	Sometimes not Findable nor Accessible. Rarely clear if Reusable. Generally not Interoperable	Findable and Reusable not Accessible or Interoperable	Findable and Reusable not Accessible or Interoperable	Mostly FAIR	FAIR	FAIR
Reference	See Supplementary File 1	Department of Environmental Affairs (2014), see Table S1 in Wilson & Kumschick (2024) for details of other regulatory lists	van Wilgen & Wilson (2018)	Zengeya & Wilson (2020a, b)	Zengeya & Wilson (2023a, b) and Fernández Winzer et al. (2025) for the Prince Edward Islands.	Digital Object Identifiers (DOIs) issued for particular data extractions (cf. the protocol used by GBIF), with a single DOI used to access the latest version

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