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REVIEW

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Indicators for monitoring biological invasions at a national level

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Abstract

1. A major challenge for the management of biological invasions is to ensure that data and information from basic inventories and ecological research are used alongside data from the monitoring and evaluation of interventions to trigger and improve policy and management responses. To address this issue, South Africa has committed to report on the status of biological invasions and their management every 3 years.
2. We propose a framework of indicators for reporting on biological invasions at a country level; assess the feasibility of the indicators using South Africa as a case study; and outline steps needed for indicator development.
3. We argue that a national status report on biological invasions should explicitly consider indicators for pathways, species, and sites, and should report on interventions in terms of inputs, outputs, and outcomes.
4. We propose 20 indicators based on data currently available, as well as existing international policy initiatives. For each indicator, we have developed a factsheet that includes different hierarchical metrics (considering data availability) and provide suggestions on assigning confidence levels. We also combine these indicators into four high-level indicators to facilitate broader reporting and describe how forecasted indicators based on the concept of invasion debt could assist with scenario planning.
5. We found that many of the data required for these indicators are already available in South Africa, but they have been poorly collated to date. However, data for the indicators of most direct value to policy and planning—those dealing with the impact of biological invasions and the outcome of interventions—are scarce.
6. *Policy implications*. The framework of indicators developed here, for what we believe is the first ever national-level report on the status of biological invasions and their management, will facilitate the inclusion of biological invasions in environmental reporting at national and international levels. By identifying knowledge gaps, a status report will also focus efforts on determining the size of a country's invasion debt and what can be done to reduce it.

KEYWORDS
Aichi Target 9, biodiversity indicators framework, biological invasions, invasive alien species, monitoring and reporting, South Africa, status report

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1 | INTRODUCTION

The international community, through the Convention on Biological Diversity (CBD), has committed to monitoring the status of biodiversity and directing efforts to achieve targets aimed at minimising the negative impacts of global change (Tittensor et al., 2014). However, while there are indicators to assess the impact of some of the major drivers (e.g. climate change is measured by essential climate variables; habitat destruction by the rate of conversion of land), work on developing and applying a set of internationally agreed indicators to assess the status of biological invasions is still ongoing (Latombe et al., 2017; McGeoch, Chown, & Kalwij, 2006; McGeoch et al., 2010; Rabitsch et al., 2016). The indicators proposed so far (see Data S1) focus on available data that can be gathered by countries around the world. They provide a snapshot of a few selected aspects of the issue, but often focus on the resources available for control rather than the outcomes of the control (Early et al., 2016). Therefore, more work is needed to develop a conceptual framework underpinning the indicators (Rabitsch et al., 2016).

This paper: (a) develops a theoretical framework for reporting on biological invasions at a national level; (b) describes the application of the indicators to South Africa; and (c) outlines priorities for improving the indicators. Throughout the paper, the terminology used follows that of Richardson, Pyšek, and Carlton (2011), in alignment with the proposed Unified Framework for Biological Invasions (Blackburn et al., 2011).

2 | HOW SHOULD A NATIONAL STATUS REPORT BE STRUCTURED?

The phenomenon of biological invasions is caused by a combination of how taxa are moved around by humans (the introduction dynamics), the traits of individual taxa (which determines levels of invasiveness), and features of the environment (which define the susceptibility of the environment to particular alien species, that is, its invasibility). For example, the current distribution of invasive pines is a function of: (a) how pines have historically been moved to new regions and disseminated within these regions, for example, planted for forestry (Richardson, 1998); (b) which species have particular traits that predispose them to invade (Rejmánek & Richardson, 1996); (c) the fact that large parts of the world are susceptible to invasion by trees [e.g. treeless areas in New Zealand, South Africa, and South America (Rundel, Dickie, & Richardson, 2014)]; and (d) interactions between these factors (Procheş, Wilson, Richardson, & Rejmánek, 2012).

The explicit consideration of biological invasions in terms of pathways, species (or taxa), and sites is also crucial for management (McGeoch et al., 2016). Focussing management efforts on pathways is important to reduce rates of introduction and spread (Essl, Bacher, et al., 2015), but does not address current invasions. Focussing on species can be effective in reducing densities of a single species, but can simply clear the way for other species to invade (Zavaleta, Hobbs, & Mooney, 2001). And focussing on suites of co-occurring species at any given site is vital if impacts are to be managed (van Wilgen, Dyer, et al., 2011), but if pathways of introduction and spread are not also managed, management successes will be ephemeral.

Researchers and managers often separate work on biological invasions along taxonomic, disciplinary, or functional lines. For example, freshwater fish and riparian plants are viewed as separate problems, and particular management plans are developed for particular environments, for example, biomes or realms. There is not, however, a fundamental difference between invasions in aquatic and terrestrial environments nor between invasive fish, frogs, and ferns—the important questions are the same. For example: If propagule pressure can be reduced, will this reduce the likelihood of an invasion; What are the impacts?; Is a species definitely alien? Management can be much more effective if the focus is on entire systems, for example, by simultaneously managing freshwater fish invasions and riparian plant invasions (Impson, van Wilgen, & Weyl, 2013). Therefore, although reports on the state of biodiversity are often split along taxonomic or environmental lines, this is not ideal for a comprehensive report on biological invasions.

Invasions have long been considered as a series of stages. As a recent example, Wilson, Panetta, and Lindgren (2017) considered four main stages—pre-introduction, incursion, expansion, and dominance—that align with the four major management goals—prevention, eradication, containment, and impact reduction. When they overlaid the scheme of pathways, species, and sites with the different stages, there were 12 particular situations where interventions are required. However, while splitting into different invasion stages might be useful in various contexts, it greatly increases the level of complexity, and we found it was not an ideal basis for a report.

A report must also consider how effective interventions have been in reducing the magnitude of current problems. Assessments of the changing status of invasions are sometimes made purely in terms of inputs (e.g. how much money was spent on control efforts?) or outputs (e.g. how many animals were killed?). Input and output indicators tend to be easy to measure and are amenable to auditing, but the effectiveness of interventions must be assessed in terms of the outcomes (i.e. has there been an improvement in indicators that reflect the status of biological invasions, e.g. rates of introduction, densities, or impacts?) and broader consequences (i.e. has there been an improvement in biodiversity indicators not directly related to biological invasions?). The main problem is that the determination of outcomes requires a comparison with what would have happened if different, or no, control measures had been applied (McConnachie et al., 2016).

As such we decided to structure our report in terms of pathways, species, sites, and interventions (the latter separated in terms of inputs, outputs and outcomes).

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3 | PROPOSED INDICATORS

Indicators were developed for each of the components of the report as an integral part of the process of compiling the report itself (see Data S2). We proposed 20 indicators (Figure 1; see Data S3 for a more detailed discussion of the rationale for each indicator), and, as per the guidelines of the Biodiversity Indicators Partnership (2011), a factsheet for each indicator was developed, scrutinised, and updated (Data S4, see Appendix S1 for an example).

In terms of pathways, it is important to understand the potential routes into and within a country, as well as the degree to which each pathway is responsible for spreading organisms. On the basis of this, we proposed four indicators: (1) *introduction pathway prominence* (i.e. the sizes of the pathways to a country without taking into account how important each pathway is in terms of the introduction of organisms; Appendix S1); (2) *introduction rates* [essentially colonisation pressure as per Lockwood, Cassey, and Blackburn (2009) at a country level]; (3) *within-country pathway prominence*; and (4) *within-country dispersal rates*. A comparison of the potential routes and the degree to which they facilitate introductions provides an indication of the relative risk posed by pathways in different contexts. For instance, a country might have a large quantity of forestry imports, but few species are introduced through this pathway, either due to effective interventions or because the countries it imports from have a small pool of potential invaders (Bacon, Bacher, & Aebi, 2012; Liebhold, Brockerhoff, & Kimberley, 2017). A major problem in working on invasion pathways has been to determine consistent units of analysis. Therefore, if detailed route-specific data are not available, we propose using the hierarchical pathway classification scheme adopted by the CBD [see Data S5 for the scheme (Hulme et al., 2008; Scalera et al., 2016)].

For species, we also proposed four indicators: (5) *the number and status of alien species* [that requires an assessment both of whether a species is alien (Essl et al., 2018) and its status (e.g. Blackburn et al., 2011)]; (6) *the extent of alien species* (e.g. occupancy at a broad scale); (7) *the abundance of alien species* (e.g. the numbers of individuals for mobile taxa, and cover or biomass for sessile taxa); and (8) *the impact of alien species*. While metrics for indicators 5–7 are well developed, consistent metrics for the impacts of particular alien taxa have only recently been developed through the Environmental Impact Classification for Alien Taxa (EICAT) Scheme, and the Socio-Economic Impact Classification for Alien Taxa (SEICAT) Scheme (Bacher et al., 2018; Blackburn et al., 2014; Hawkins et al., 2015).

We proposed three indicators for sites. The first is (9) *alien species richness*, which gives an indication of the number of species that need to be considered. Second is (10) *relative invasive abundance* to indicate the presence of dominant alien species (Catford, Vesk, Richardson, & Pysek, 2012). For the third indicator, (11) *impact of invasions*, there is no accepted, unified system of classification. We propose to focus on provision of ecosystem services either using qualitative or quantitative estimates, with, if possible, a conversion into the monetary value of any reduction in services due to invasion. However, different countries and regions differ with regard to which ecosystem services they value most. For Europe, the proposed indicators were the incidence of livestock diseases and the impact of invasive alien species on the Red List Index (Rabitsch et al., 2016). For South Africa, a water scarce, mega-diverse country with many rural communities dependent on pastoralism, we chose to measure impact in terms of the reduction in water resources, biodiversity, and grazing capacity (van Wilgen, Reyers, Le Maitre, Richardson, & Schonegevel, 2008).

In terms of policy or management interventions, for inputs we proposed: (12) *the quality of the regulatory framework* [e.g. Roy et al. (2018)]; (13) *money spent* (i.e. expenditure rather than the financial costs of the impacts of invasions); and (14) *planning coverage* (i.e. the degree to which management plans are in place for the full suite of threats posed by biological invasions). For outputs we proposed: (15–17) *pathways*, *species*, and *sites treated*. These are defined as the

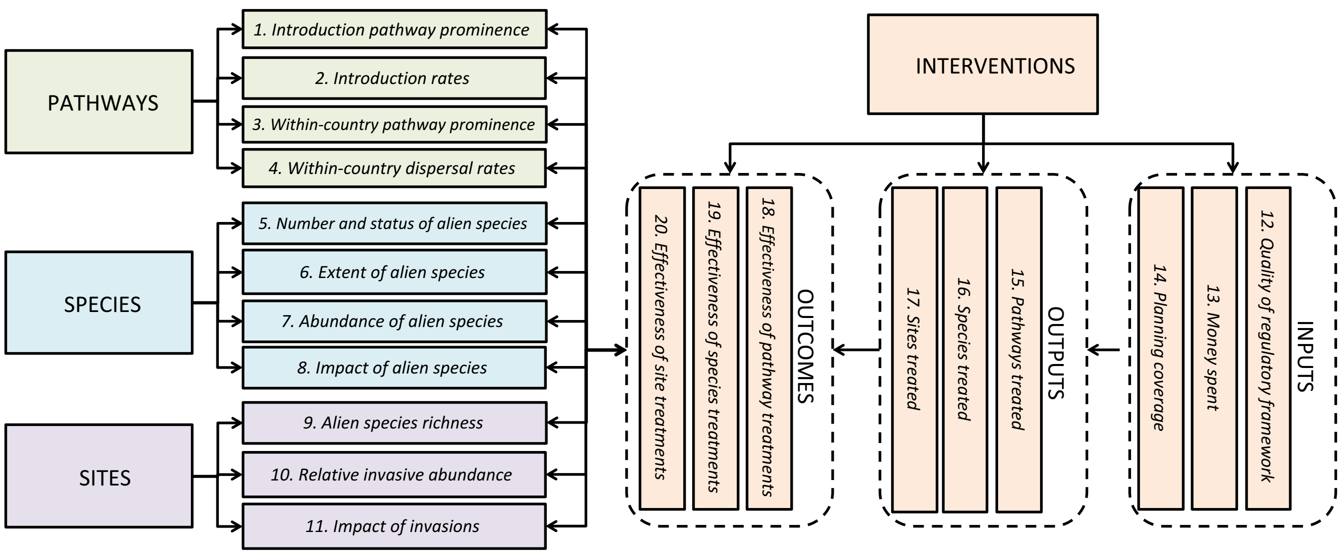

FIGURE 1 A proposed indicator framework for a national status report on biological invasions and their management. There are four main sections (in capital letters)—pathways, species, sites, and interventions—with proposed indicators in italics [Colour figure can be viewed at wileyonlinelibrary.com]

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degree to which the pathways, species, and sites that need to be managed are actually subjected to management interventions, ideally with some assessment of the quality of the interventions. For outcomes, the corresponding indicators are: (18–20) *effectiveness of treatments* for *pathways*, *species*, and *sites* (i.e. do policy and management interventions change the status of biological invasions?). For each intervention, there should also be a separate assessment of any negative impacts of control, for example, on non-target organisms or on ecosystem functioning (Zavaleta et al., 2001), as it is important to ultimately assess whether the management was justified.

While we consider the 20 proposed indicators to be necessary to assess biological invasions in their entirety, this is too many for the purposes of general national reports on the state of the environment. We therefore propose four high-level indicators (Table 1)—(A) *rate of introduction of new unregulated species*; (B) *number of invasive species that have major impacts*; (C) *extent of area that suffers major impacts from invasions*; and (D) *level of success in managing invasions*—that align with the pressure, state, response framework. The inclusion of a few high level, invasion-specific indicators in national reports on the state of the environment would raise the profile of biological invasions, improve the prospects for accessing funding for their management, and provide political focus to ensure that interventions are appropriately monitored, reported, and evaluated.

For each indicator, we tried to ensure that, in line with international proposals (Latombe et al., 2017), the status reported is modular, that is, if resources permit, more detailed data can be collected without compromising the ability to compare with situations where fewer data are available. For example, accurate distribution data might be available for birds, but not for microbes, and countries differ in the quality and quantity of biodiversity data collected (McGeoch et al., 2010). We also propose broad guidelines to assign a level of confidence (high, medium, or low) to the metrics, as is accepted practice in environmental assessments. If there is direct, recent evidence, then the confidence will be high, whereas if the evidence is ambiguous, not clearly documented, or based on assumptions, then the confidence will be low (see Data S6). The criteria for the different levels of confidence varies between indicators and is highlighted on the factsheets (e.g. see Appendix S1). Finally, we assessed the practicability of the framework based on our experience compiling the first national status report on biological invasions and their management for South Africa (van Wilgen & Wilson, 2018).

4 | ESTIMATING THE INDICATORS FOR SOUTH AFRICA

To estimate the indicators for South Africa, we used three main tactics to source information: (a) the status report team accessed and collated information themselves; (b) experts were invited to contribute a scientific paper to a journal special issue (Wilson, Gaertner, Richardson, & van Wilgen, 2017); and (c) through direct requests to experts and practitioners for specific inputs. Nonetheless most of our estimates were made with low confidence (Table 2).

While the low confidence suggests that indicators might be impractical, we believe there is substantial value in them. When discussing preliminary results with stakeholders, it was clear that many people felt that data were available (e.g. on management plans), but had not been accessed yet. If such data do exist, then the reporting process will serve an important function in providing a central place to curate and compare experiences. The indicators also provide an impetus to collect such data. The lack of data on the effectiveness of management interventions does not suggest that the indicators should be scrapped, but is rather an indictment of the current levels of project management. If we are to improve management, the efficacy of past interventions must be monitored. Finally, we felt it was important to create a framework that can deal with situations where reliable, relevant data are available, and where data are missing. In the next section, we discuss ways the framework can be improved for future reports.

5 | FUTURE DIRECTIONS

The next steps, as recommended by the Biodiversity Indicators Partnership (2011), will be to communicate and interpret the indicators as part of the final report itself; develop monitoring and reporting systems in an attempt to fill the data gaps; test and refine

TABLE 1 The four proposed high-level indicators for reporting on the status of biological invasions at a national level. See Figure 1 for the 20 proposed indicators that are used to calculate these indicators, and Data S4 for all the indicator factsheets

Indicator name	Section	Units	Indicators used in calculations
A. *Rate of introduction of new unregulated species*	Pathways	Number of species per unit time (e.g. per year)	2, 5, 12, 14, 15, 18
B. *Number of invasive species that have major impacts*	Species	Number of species	5–8, 11
C. *Extent of area that suffers major impacts from invasions*	Sites	Area or % of national sub-divisions	6–11
D. *Level of success in managing invasions*	Interventions	% of pathways, species, and sites that require management and that are managed effectively	1–20

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the indicators with stakeholders; and, as recommended by Hill et al. (2016), build simulation models to assess the inter-relationship and value of indicators. More broadly, however, for the indicators to be effective they need to: (a) be amenable to extrapolation; (b) be linked to targets; (c) be able to deal with different contexts; and (d) explicitly consider enabling conditions.

TABLE 2 The level of confidence in our knowledge of the status of biological invasions in South Africa as per the proposed indicator framework (van Wilgen & Wilson, 2018). NA = not assessed. See Data S4 for the indicator factsheets. See Data S6 for a detailed explanation of the confidence levels, but in broad terms, the confidence is high if there is direct, recent evidence, and low if the evidence is ambiguous, not clearly documented, or based on assumptions. A range in confidence values is possible as there might be more reliable evidence for some pathways, taxa, or sites than others

Indicator	Confidence	Notes and recommendations
1. Introduction pathway prominence	Medium	Data were available for introduction pathway prominence and historical data on introduction rates, but the pathway of introduction for most alien species is unknown (Faulkner, Spear, Robertson, Rouget, & Wilson, 2015). Almost no data were available for within-country dispersal.
2. Introduction rates	Low	
3. Within-country pathway prominence	NA	
4. Within-country dispersal rates	NA	
5. Number and status of alien species	Low	Known for a variety of groups such as vertebrates (Picker & Griffiths, 2017) and marine organisms (Robinson et al., 2016), but these assessments often did not include taxa in cultivation and the coding for invasion status was inconsistent. For over 40% of known alien species, it was not possible to indicate whether the species was introduced, naturalised or invasive. Status as per the Unified Framework is known only for a few groups (Jacobs, Richardson, Lepschi, & Wilson, 2017; Robinson et al., 2016). A census of all alien species is needed.
6. Extent of alien species	Low—Medium	Data from atlassing projects for birds, frogs, plants, and spiders allowed the estimation of the distribution of some taxa. There are some data on abundance of alien plants, but these are crude and 20 years out of date.
7. Abundance of alien species	NA	
8. Impact of alien species	NA	There was a remarkable dearth of studies that document the impacts of alien species, despite this having been recognised as a major gap for many years (Richardson & van Wilgen, 2004). Few studies have scored impact according to the Environmental Impact Classification of Alien Taxa Scheme, with data mostly limited to expert opinion (Measey et al., 2017; Zengeya et al., 2017).
9. Alien species richness	Low—Medium	Atlas data at a national scale were available for terrestrial plants and most vertebrates, but abundance data and data on relative invasive abundance were only available for a limited number of sites (e.g. some protected areas).
10. Relative invasive abundance	NA	
11. Impact of invasions	Low	Estimates are entirely based on three studies (de Lange & van Wilgen, 2010; Le Maitre, Forsyth, Dzikiti, & Gush, 2016; van Wilgen et al., 2008).
12. Quality of regulatory framework	Medium	Assessment was done by a semi-independent team of invasion scientists but the team did not include anyone from the legal profession.
13. Money spent	Low	Based solely on funds provided by the Department of Environmental Affairs (and so is an underestimate), data from other governmental and private initiatives need to be collated.
14. Planning coverage	Low—High	Some pathway management plans are in place, species and site plans are well documented where available, but a better system of collation is needed.
15. Pathways treated	Low	Not consistent, agricultural commodities are inspected and legislation relating to the discharge of ballast water has been drafted but not finalised.
16. Species treated	Low	Control operations are often poorly documented, and so the level of treatment is uncertain.
17. Sites treated	Low	Based on a few case studies and extrapolations, management data are of poor quality or not consistently recorded.
18. Effectiveness of pathway treatments	Low	Of the pathways classified as having effective management it is not clear if the intervention was successful or that the pathway declined due to changing socio-economic conditions.
19. Effectiveness of species treatments	Low	Changes in the distribution of invasive species over time recorded in atlas projects have allowed for estimates of the effectiveness of species treatments (e.g. Henderson & Wilson, 2017). Returns on investment from the implementation of control measures have only been adequately assessed for some biological control of invasive alien plants (de Lange & van Wilgen, 2010).

(Continues)

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TABLE 2 (Continued)

Indicator	Confidence	Notes and recommendations
20. Effectiveness of site treatments	Low	A small (but growing) number of case studies have sought to assess management effectiveness at the scale of individual protected areas, catchments, or farms (e.g. McConnachie, Cowling, van Wilgen, & McConnachie, 2012; van Wilgen, Fill, Govender, & Foxcroft, 2017). These have demonstrated effective (Te Beest et al., 2017), somewhat effective (Fill, Forsyth, Kritzinger-Klopper, Le Maitre, & van Wilgen, 2017), and ineffective (Kraaij, Baard, Rikhotso, Cole, & van Wilgen, 2017) management interventions.
A. Rate of introduction of new unregulated species	Low	The lack of data on the 20 core indicators meant the confidence in the high-level indicators was inevitably low. Formal impact assessments need to be conducted to allow for a reliable baseline estimate of the *number of invasive species that have major impacts*. The *level of success in managing invasions* could be estimated based on available data from legislated requirements, management plans, and the evaluation of management. We suspect that, relatively small changes to management practices and the monitoring of management could result in substantial improvements in this indicator.
B. Number of invasive species that have major impacts	NA	
C. Extent of area that suffers major impacts from invasions	Low	
D. Level of success in managing invasions	Low	

On the basis of the concept of invasion debt (Rouget et al., 2016), we suggest an additional four indicators that could be used to assist with forecasting—*introduction debt*, *establishment debt*, *spread debt*, and *impact debt*. Over time, a country's invasion debt can result in new introductions, new invasions, more area invaded, and greater impacts. The challenge will be to develop models and techniques that can help improve decision-making and allow for adaptive management at a variety of scales (Figure 2). In particular, although South Africa has started efforts at proactive management (Wilson, Ivey, Manyama, & Nänni, 2013), it is difficult to demonstrate the economic value of avoiding the predicted negative impacts of invasions that do not occur (Leung et al., 2002). We have started to estimate some aspects of invasion debt for South Africa (Faulkner, Robertson, Rouget, & Wilson, 2016; Rouget et al., 2016), but much more work is needed.Figure A1 (Indicator 1.3)—The number of ocean going vessels arriving at South African ports over time. Data from the National Ports Authority of South Africa

While the indicators on their own have value, for them to have impact on management they must also be linked to targets. For example, under the IUCN's Honolulu Challenge on invasive alien species (https://www.iucn.org/theme/species/our-work/invasive-species/honolulu-challenge-invasive-alien-species), the New Zealand Government has committed to eradicate all pests from all island nature reserves by 2025, and to develop a method for eradicating

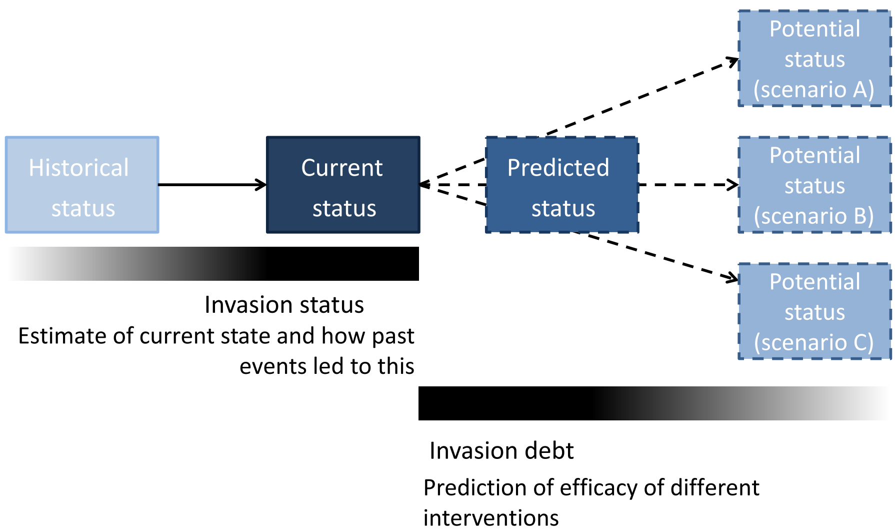

FIGURE 2 A national report on the status of biological invasions, by definition, should focus on what the current state is, but this is often largely a function of historical events and processes. Given that the report will form the baseline for predictions of how problems will evolve under different scenarios, that is, invasion debt, indicators need to be responsive to changes (Essl, Dullinger, et al., 2015). We propose that forecasted indicators [*introduction debt*; *establishment debt*; *spread debt*; and *impact debt* (Rouget et al., 2016)] can form the currency by which to assess management options [Colour figure can be viewed at wileyonlinelibrary.com]

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one of the key target pests from mainland New Zealand. These are clearly very specific context-dependent targets that require specific indicators to track progress, but at a broad scale such interventions would be captured in the indicator framework developed here.

Indicators also need to be flexible enough to deal with different contexts. A major motivation for the South African Government's invasive plant control programmes is to provide employment opportunities (van Wilgen, Khan, & Marais, 2011), and therefore the number of jobs created is a core indicator. Similarly, successful interventions require institutional capacity, research, data and information management, and public awareness and engagement (Wilson, Panetta, et al., 2017). For example, for management to maintain sustained political support, decision-making needs to actively involve society (Crowley, Hinchliffe, & McDonald, 2017). Ensuring that such enabling factors are reflected in the indicators is an important area for future work. Ultimately, however, the effectiveness of interventions must still be monitored in terms of the impact on the invasions themselves. The challenge of jointly meeting the social goal of poverty alleviation through job creation, and the biodiversity goal of reducing invasions has not yet been met in South Africa (van Wilgen & Wannenburgh, 2016).

6 | CONCLUSIONS

We believe the framework proposed here is a useful starting point for national-scale reports on biological invasions and their management. Over time the proposed indicators will likely need to be adjusted, but they should capture trends and enable assessments of the efficacy of different interventions. Countries around the world are increasingly focussing on proactive interventions. We feel that such initiatives can be better supported and scrutinised by linking the indicators proposed to the concept of invasion debt (Rouget et al., 2016). We suspect, however, that strengthening the links between research, planning, implementation, monitoring, and reporting will remain the major challenge facing invasion science (Esler, Pozesky, Sharma, & McGeoch, 2010). We hope the indicator framework developed here will help this process.

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AUTHORS' CONTRIBUTIONS

J.R.U.W. conceived the idea and developed the framework in collaboration with D.M.R. and B.W.v.W. S.J.R., T.A.Z., and K.T.F. helped refine the framework. All authors helped develop the factsheets. J.R.U.W. led the writing, and all authors contributed critically to the drafts and gave final approval for publication.

DATA ACCESSIBILITY

Data have not been archived because this article does not contain data.

The National Status Report will be available through the South African National Biodiversity Institute (https://www.sanbi.org/resources/).

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