Biodiversity and Conservation
https://doi.org/10.1007/s10531-020-02026-1

ORIGINAL PAPER

Check for updates

Biological invasions in World Heritage Sites: current status and a proposed monitoring and reporting framework

Ross T. Shackleton[1,2] · Bastian Bertzky[3] · Louisa E. Wood[4] · Nancy Bunbury[5,6] · Heinke Jäger[7] · Remco van Merm[8] · Christian Sevilla[9] · Kevin Smith[10] · John R. U. Wilson[1,11] · Arne B. R. Witt[12] · David M. Richardson[1]

Received: 24 July 2019 / Revised: 11 June 2020 / Accepted: 30 July 2020

Abstract

UNESCO World Heritage Sites (WHS) are areas of outstanding universal value and conservation importance. They are, however, threatened by a variety of global change drivers, including biological invasions. We assessed the current status of biological invasions and their management in 241 natural and mixed WHS globally by reviewing documents collated by UNESCO and IUCN. We found that reports on the status of biological invasions in WHS were often irregular or inconsistent. Therefore, while some reports were very informative, they were hard to compare because no systematic method of reporting was followed. Our review revealed that almost 300 different invasive alien species (IAS) were considered as a threat to just over half of all WHS. Information on IAS management undertaken in WHS was available for fewer than half of the sites that listed IAS as a threat. There is clearly a need for an improved monitoring and reporting system for biological invasions in WHS and likely the same for other protected areas globally. To address this issue, we developed a new framework to guide monitoring and reporting of IAS in protected areas building on globally accepted standards for IAS assessments, and tested it on seven WHS. The framework requires the collation of information and reporting on pathways, alien species presence, impacts, and management, the estimation of future threats and management needs, assessments of knowledge and gaps, and, using all of this information allows for an overall threat score to be assigned to the protected area. This new framework should help to improve monitoring of IAS in protected areas moving forward.

Keywords Biodiversity · Conservation · Global environmental change · Invasive alien species · IUCN · Management · Protected areas · UNESCO

Communicated by Dirk Sven Schmeller.

This article belongs to the Topical Collection: Invasive species.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10531-020-02026-1) contains supplementary material, which is available to authorized users.

✉ Ross T. Shackleton
rtshackleton@gmail.com

Extended author information available on the last page of the article

Introduction

Key drivers of global change are increasingly threatening the environment and areas with high natural and cultural value (Vitousek et al. 1997; Chape et al. 2005; Brook et al. 2008; Butchart et al. 2010; Watson et al. 2014), making the effective management of over 230,000 protected areas (PAs) globally a critical endeavour (UNEP-WCMC, IUCN and NGS 2019). These PAs safeguard important biodiversity and scenic landscapes and provide ecosystem services, which benefit human well-being and are essential for a sustainable world (Naughton-Treves et al. 2005; Egoh et al. 2007).

Responding to the need for conservation of natural and cultural heritage, the World Heritage Convention was established in the early 1970s by the United Nations Educational, Scientific and Cultural Organisation (UNESCO 1972). As of January 2020, the Convention recognised 1121 [869 cultural, 213 natural, and 39 mixed (cultural-natural)] areas of "Outstanding Universal Value" as World Heritage Sites (WHS). WHS are areas of "cultural and/or natural significance which are so exceptional as to transcend national boundaries and to be of common importance for present and future generations of all humanity" (UNESCO 2017). Natural and mixed WHS account for around 8% of terrestrial and 6% of marine protected surface area worldwide, thus contributing significantly to conservation globally (Strahm, 2008; Bertzky et al. 2014; Osipova et al. 2017). Similar to other PAs, WHS vary greatly in size (from < 20 ha to > 40 million ha; UNEP-WCMC and IUCN 2017); represent many different governance types (Dudley 2008); and differ in the threats they face and their capacities for protection, management and research (Osipova et al. 2017). New WHS are inscribed annually, but the WHS status can also be revoked for two reasons: the WHS has deteriorated to the extent that it has lost those characteristics which determined its inclusion in the World Heritage List; or there was a lack of corrective measures to protect the intrinsic qualities of a WHS from damage by human action (as outlined and within the time proposed by the State Party at the time of inscription). Biological invasions are a major threat to WHS (Osiprova et al. 2017), and can be one of many contributing factors which can lead to sites being put on a danger list (https://www.iucn.org/theme/world-heritage/natural-sites/danger-list). For example, the Galapagos Islands site was added to the danger list in 2007, due to the uncontrolled number of tourists in combination with impacts from biological invasions (https://www.iucn.org/content/galapagos-islands-added-world-heritage-danger-list).

Biological invasions are a key driver of change in the world's PAs, including WHS (Usher 1988; Foxcroft et al. 2013, 2017; Osipova et al. 2017; Padmanaba et al. 2017; Bomanowska et al. 2019; Shackleton et al. 2020). Biological invasions are the process whereby organisms are intentionally or accidentally moved by human activity from their native ranges into new areas, and where some of these 'alien species' establish and spread widely [meaning that they become invasive alien species, (IAS)], leading to negative impacts on native biodiversity, ecosystem services and/or human well-being (Richardson et al. 2000, 2011; IUCN 2000; Jeschke et al. 2014; see Box 1 in Supplementary file 1 for a glossary of terms). IAS impact the values and integrity of PAs by causing the decline and extinction of native species through a variety of mechanisms, such as predation, disease, competition and/or hybridisation (Clavero and García-Berthou 2005; Downey and Richardson 2016), and by altering ecological community structure and landscape/ecosystem function (Angassa 2005; Hejda et al. 2009; Pejchar and Mooney 2009; Vilà et al. 2010; Eldrige et al. 2011). They can also impact human wellbeing and how people experience these PAs (Shackleton et al. 2019). If not managed, the impacts due to existing

IAS are expected to increase over time. Moreover, the number of IAS globally are expected to increase both as more alien species become invasive in the future (e.g. by exiting a lag phase), and as more alien species are introduced (Essl 2011; Bellard et al. 2016; Johnson et al. 2017; Seebens et al. 2017). Thus, the impacts and threat posed by biological invasions continues to grow (Essl et al. 2011; Rouget et al. 2016).

According to the 2017 IUCN World Heritage Outlook assessment, biological invasions are considered the most significant current threat, and the third most significant future threat to WHS globally, particularly in North America and Oceania (Osipova et al. 2017). The overall threat of biological invasions to WHS is well known (Osipova et al. 2014, 2017; Veillon 2014), but detailed global reporting on IAS and their management in WHS is lacking, and only a small number of WHS have in-depth analyses and reports (e.g. Bradshaw et al. 2007; Van Damme and Banfield 2011; Hernandez-Enriquez et al. 2012). Improved knowledge about the presence and effects of IAS, and their current management, is crucial to facilitate decision-making at the site level, and to inform wider policy and management to maintain, or even improve, the outstanding values of WHS. The same can be said for other forms of PAs globally (Shackleton et al. 2020).

This paper provides a detailed assessment of the presence of IAS and their threat to the integrity of natural and mixed WHS, and to assess the implementation of IAS management efforts in WHS. To do this, we reviewed IUCN and UNESCO documents which we found to lack detail in monitoring and reporting. Therefore, we developed and tested a new framework to guide monitoring, assessment, and reporting of IAS in WHS and other protected areas. This proposed monitoring system could help track progress towards the Convention on Biological Diversity (CBD) targets and assist in developing new global standards and best practices for the monitoring and evaluation of biological invasions in all PAs.

Methods

A review of existing monitoring procedures

To ensure the effective conservation of WHS, various impacts and threats are monitored. However, while there are reports detailing the broad-scale impacts of biological invasions and other threats (e.g. Osipova et al. 2014, 2017), in-depth analyses for each of these threats are lacking. To provide more information on the topic, we conducted a detailed review of documents from past UNESCO and IUCN monitoring and reporting activities.

We gathered spatial data from the World Database on Protected Areas (UNEP-WCMC and IUCN 2017), and threat data from the IUCN World Heritage Outlook reports (Osipova et al. 2014, 2017) for all (241) natural and mixed WHS inscribed up to June 2018. UNESCO's World Heritage State of Conservation Information System (https://www.whc.unesco.org/en/soc), and the online portal of the IUCN World Heritage Outlook assessments (https://www.worldheritageoutlook.iucn.org/), store information on the state of WHS, and threats (including biological invasions) to their biodiversity and other values, and can help to track changes in the conditions of these sites through existing monitoring and reporting mechanisms. We reviewed the UNESCO and IUCN websites, and the documents available or cited on those websites, to extract data on the occurrence, impacts/threats and management of biological invasions for each WHS. The reviewed documentation (hereafter referred to as IUCN and UNESCO documents) included website summaries, periodic reports, State of Conservation reports, reactive monitoring mission reports, and World

Heritage Outlook assessments, as well as attached or cited scientific reports and publications. These documents are based on national monitoring mechanisms and processes, as well as internationally driven reporting to UNESCO and the IUCN. WHS are subject to international World Heritage monitoring and reporting processes which currently include: (1) UNESCO's periodic reporting to which States Parties (the countries that are parties to the Convention) contribute on a 6-year regional cycle; (2) reactive monitoring of the 'state of conservation', involving reports and missions, for sites with known issues, undertaken by UNESCO and its technical advisory bodies (IUCN for natural sites) in cooperation with States Parties; and (3) the independent and systematic IUCN World Heritage Outlook assessments for all sites, implemented by IUCN on a 3-year cycle (so far completed in 2014 and 2017; Osipova et al. 2014, 2017). The IUCN and UNESCO monitoring and reporting mechanisms have separate categories for "spreading species", including alien, invasive alien, translocated native, and 'hyper-abundant' native. The majority of the threat data clearly relates to alien (and more specifically invasive alien) species (sensu IUCN 2000; Richardson et al. 2011) and is the focus of this paper (see box 1 in Supplementry file 1). We removed "native invasive species/hyper-abundant native species" from the analysis and only focused on alien species.

These above-mentioned sources were reviewed for each of the 241 WHS, by reading through each dedicated website or document. For each WHS, we extracted data on the listing and reporting of alien species, threats and impacts of IAS, and information on the management of biological invasions. We compiled data on the number of alien species present at each site (either mentioned as a total number and/or each species listed as present in the WHS), noted IAS specifically named in the reports (lists of species), compiled information provided on threats (qualitative descriptions of impacts or citations of other work), and mention of IAS management for the WHS (yes, no or unknown). If management programmes were indicated, we collected further data on control approaches and methods used [preventative measures, eradication attempts, impact reduction or containment attempts, as well as the control techniques being used, including physical, biological, chemical, cultural, utilisation or integrated control (i.e. the use of multiple approaches) and evidence of a strategic plan (yes, no or unknown)].

Development of a monitoring and reporting framework.

The review of these IUCN and UNESCO documents yielded limited information on the presence, threat, and management of IAS within WHS, despite being a part of a comprehensive monitoring strategy. Reporting was irregular and/or incomparable. This is probably because of the lack of a detailed, comprehensive, and standardised monitoring and reporting framework, which is likely to be the case for all categories of PAs globally. We, therefore, developed a framework to improve monitoring and reporting and used seven case studies to test it. This framework combined the approaches of the IUCN World Heritage Outlook for assessing management and threats of IAS to the integrity of WHS (https://www.worldheritageoutlook.iucn.org/); CBD and IUCN for classifying introduction pathways (Hulme et al. (2008) as expanded and adapted by the IUCN (2017); the Environmental Impact Classification of Alien Taxa (EICAT) scheme set out in Blackburn et al. (2014) and Hawkins et al. (2015) (currently being updated by IUCN to be published as an official IUCN standard in 2020); and various other schemes that have developed indicators or guidelines for monitoring biological invasions (e.g. see McGeoch et al. 2010; Latombe et al. 2017; Wilson et al. 2018).

The framework we developed focuses on: monitoring and reporting of the current status of biological invasions in WHS; predicting threats and management needs; and assessing the overall threat level of the site (see Supplementary file 1 for details and instructions on how to apply the framework). The current status relates to evaluating pathways, compiling alien species lists, identifying and reporting key impacts caused by IAS, as well as reporting on the status of management. The section on predictions relates to identifying key threats and management needs that might arise in the future. The last section relates to identifying knowledge gaps and assigning a robust and evidence-based overall rating of the threat level posed by biological invasions to a specific site (for more details, see Supplementary file 1). Test examples using the new framework, and information on how these can be written-up, appear in Supplementary file 2. We suggest that monitoring and reporting should be done by local experts or managers (or regional or international experts knowledgeable about the local situation or area if local capacity is lacking). Future implementation of the monitoring and reporting framework should be driven by state authorities (as part of their reporting duties under the Convention for the sites on their territory) in partnership with local actors to ensure capacity building, learning, and ownership, and should incorporate published literature, grey literature, local research, and local knowledge. However, external processes and experts should help to facilitate this where needed.

The seven in-depth case studies to test the framework were applied to WHS in different social-ecological contexts, and with different reported threat levels from IAS (Fig. 1; Supplementary file 2). This includes sites on five continents, encompassing a range of social and ecological settings, as well as mainland and island WHS. Three sites had

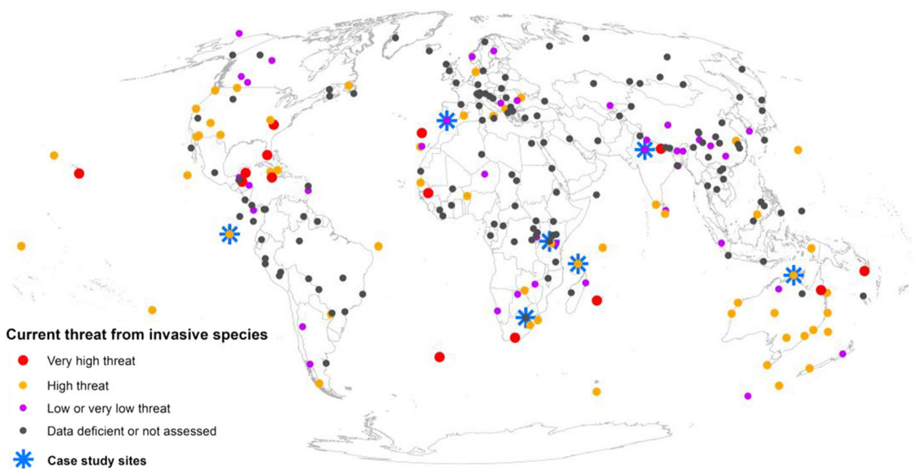

Fig. 1 Locations of the 241 natural and mixed World Heritage Sites (WHS inscribed as of early June 2018), and the seven case studies presented in this paper. The overall threat level from invasive alien species is based on data and categories used for the last IUCN World Heritage Outlook report (Osipova et al. 2017); see https://worldheritageoutlook.iucn.org/more/understanding-ratings for descriptions of WHS categories (NB: this is not based on our new framework). The case studies were Aldabra Atoll (Seychelles, tropical island with terrestrial and marine components), Doñana National Park (Spain, Mediterranean biome, wetlands and marine components), Galapagos Islands (Ecuador, over 100 arid to sub-tropical islands with terrestrial and marine components), Kakadu National Park (Australia, primarily savanna but including small patches of other biomes), Keoladeo National Park (India, broadleaf forests and wetlands), Serengeti National Park (Tanzania, savanna) and Vredefort Dome (South Africa, grasslands and savanna)

previously been identified as having high IAS threat levels, and four sites were previously listed as having no, low or medium threat levels. This gave us a broad range of contexts, to test the applicability of the framework. We collated information for our case studies from unpublished works and peer-reviewed and grey literature. In addition, many local researchers and managers working in, or knowledgeable on, specific WHS were consulted to obtain additional information or helped to write up the case studies.

Results

We present findings from the two components of this study: the review of past monitoring of the threat and management of IAS in WHS, and the introduction and application of the new monitoring and reporting framework.

A review of biological invasions and their management in World Heritage Sites globally

The overall presence of invasive alien species in World Heritage Sites

The data from the reviewed IUCN and UNESCO documents indicated that just over half (128; 53%) of all 241 WHS were explicitly or implicitly reported to be impacted by IAS (Fig. 1). This includes 119 WHS that are formally listed as being threatened by IAS in the IUCN World Heritage Outlook data, although many assessments make no further mention of any threatening species or their impacts (Fig. 2). For another nine WHS, IUCN and UNESCO documents mention the occurrence of known high impact IAS within their borders (e.g. *Dreissena polymorpha, Lantana camara*, *Opuntia* spp., *Prosopis juliflora*, and *Sus scrofa*), although IAS are not formally listed as a threat to these sites, suggesting inconsistency in reporting and threat categorisation.

For those WHS that formally listed IAS as a threat (119 WHS), ~ 80% explicitly named at least one IAS (Fig. 2), while the rest made no mention of a single invasive

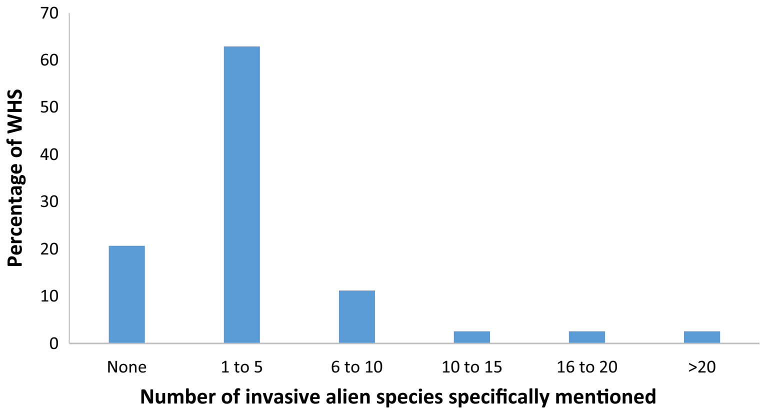

Fig. 2 Number of alien and/or invasive alien species specifically mentioned per natural and mixed World Heritage Site for those sites explicitly listed as being threatened by IAS (119 of 241) in the last World Heritage Outlook report (Osipova et al. 2017). This information was extracted from IUCN World Heritage Outlook data and the reviewed IUCN and UNESCO documents

species. Of those that mentioned IAS, just over a third listed only one species. Only 22 WHS specifically reported more than five alien or invasive species, of which only three sites named more than 20: Namib Sand Sea (Namibia) with 27, Gondwana Rainforests (Australia) and Socotra Archipelago (Yemen) with 24 each, athough the numbers for Socotra might be an overestiamte. Based on similar research from other PAs, if fewer than five species are reported to pose major threats it is likely due to under-reporting (Shackleton et al. 2020). Only seven WHS reported estimates of the total number of alien species occurring within their boundaries, which ranged from over 500 (Wet Tropics of Queensland in Australia), to 52 (Wadden Sea in Denmark, Germany and the Netherlands,—of which six are highly threatening).

Invasive alien species and their impacts mentioned in World Heritage Sites

In total, 290 different species/taxa were identified in the UNESCO and IUCN documents that were reviewed for all 241 WHS. These invasive taxa represented several different functional groups (Fig. 1 in Supplementary file 3). The most commonly reported functional group of IAS in WHS was land mammals, followed by trees, and then several other plant groups. Reporting on other taxonomic and functional groups in WHS was low, likely representing a common bias in research and monitoring in PAs (Shackleton et al. 2020), despite many of these "under-represented" functional groups having species with high impacts.

The three most commonly mentioned invasive alien taxa across all WHS were *Rattus* spp., *Felis catus* and *Capra hircus* (Table 1 in Supplementary file 3). They have been reported in many WHS globally, and cause severe problems for biodiversity, particularly on islands where they have driven extinctions of native species (e.g. Donlan et al. 2007; Duffy and Capece 2012; Dawson et al. 2014; Harper and Bunbury 2015). *Sus scrofa, Mus musculus*, and *Oryctolagus cuniculus* are other land mammals that are commonly reported as threats in WHS and have several major impacts on biodiversity and ecosystem function (e.g. Koichi et al. 2013; Saunders et al. 2013; Dawson et al. 2014).

The most commonly mentioned invasive alien plant was *Lantana camara* (Table 1 in Supplementry file 3), which negatively affects biodiversity and ecosystems in several WHS (e.g. Day et al. 2003; Aravind et al. 2010; Turner and Downey 2010; Shackleton et al. 2020). *Chromolaena odorata, Eichhornia crassipes, Mimosa pigra*, *Prosopis juliflora,* and *Psidium guajava*, which have similar impacts to *L. camara*, are also mentioned as present in many WHS (e.g. Cowie and Werner 1993; Foxcroft et al. 2013; Shackleton et al. 2020).

Other commonly listed IAS, from other taxonomic groups, with high impacts in WHS include: *Oncorhynchus mykiss*, *Phytophthora cinnamomi*, *Dreissena polymorpha* and *Linepithema humile* (e.g. Witt et al. 2004; Karssing et al. 2012; Rivers-Moore et al. 2013; Scarlett 2015) (Table 1 in Supplementary file 3). Mentions of other invasive taxa, such as birds, reptiles or amphibians, marine fish, and others were not common (Fig. 1 in Supplementary file 3).

Management of biological invasions in World Heritage Sites

Reporting on the management of biological invasions within WHS was often deficient in the UNESCO and IUCN documents that were reviewed. For 40% (48 of 119) of WHS with IAS formally listed as a threat, no information was available, or no mention was made of

Table 1 Evidence of attempted management and management plans for invasive alien species (IAS) in the 119 natural and mixed World Heritage Sites (WHS) reported as being threatened by IAS

	Yes		No		Ongoing/ mixed		Not reported	
	#	%	#	%	#	%	#	%
IAS management attempted in WHS (n = 119)	59	50	12	10	n/a	n/a	48	40
Management plan for IAS (n = 119)	44	37	14	12	n/a	n/a	61	51
Management success (*for those that have attempted management, n = 59)*	19	32	2	3	18	31	20	34

For management success, "Yes" indicates that the WHS has reported eradications and/or other successful control efforts

management, even though sites potentially have been conducting control activities (Table 1). Only 10% (12 of 119) of WHS with IAS present indicated no control interventions (Table 1), although this is likely to be higher, as many did not provide any information. Half of WHS with IAS listed as a threat (59 of 119 WHS) reported attempts to control IAS. Most of these are committed to long-term control, however, some sites mentioned opportunistic management based on funding availability.

In general, outcomes of IAS control were not elaborated on, with only 34% (20 of 59) of WHS providing any information on the success or failure of IAS management. However, some sites did highlight management successes (32%, or 19 of 59); and two sites mentioned that, despite management, the situation was getting worse (Table 1). Successes included containment and impact reduction of IAS (e.g. Pitons Managment Area and Kakadu), with some sites even achieving multiple eradications (e.g. Macquarie Island, Fraser Island and Galapagos Islands). It was difficult to assess management success or failure in some cases, as programmes were still underway (Table 1). Many WHS for which IAS are listed as a threat, and which are managing IAS, have broad-scale and/or species-specific IAS management plans (37%; 44 of 119), while some (12%) have informal approaches to management with no specific plan. Information on IAS management plans was lacking for half of the WHS with IAS (Table 1).

Only 10% of WHS (12 of 119), most of them islands, mention having biosecurity measures in place to prevent new introductions, but details are lacking for most of these. For control of IAS populations, physical interventions that involved cutting or digging out plants, and shooting or trapping animals, was by far the most common approach reported. Only nine WHS report the use of chemical control, always in combination with other approaches. Cultural control and control through utilisation are less traditional management techniques and are implemented in a few WHS (e.g. Keoladeo where authorities allow villages into the site to harvest *P. juliflora* as a control option and fishing of invasive *Pterois volitans* in the Belize Barrier Reef Reserve System). A few sites also mention the presence of biological control agents (e.g. Galapagos, Glacier International Peace Park, and Kakadu). The Pitons Management Area (Saint Lucia) is managing *Callisia fragrans* and *Tradescantia zebrina* using a volunteer programme which is showing signs of reducing spread. Some WHS have an integrated approach to management, using a combination of control techniques and approaches to maximise management effectiveness (e.g. Kakadu) (Paynter and Flanagan 2004).

A new framework for monitoring and reporting the presence, impacts and management of biological invasions in natural WHS and protected areas

Our review discussed above (e.g. Figure 2; Table 1) revealed obvious challenges to meaningful monitoring and reporting of biological invasions and their management within WHS, which is likely to also be a problem with other categories of PAs. Although substantial effort has been devoted to monitoring biological invasions and other threats in WHS (Osipova et al. 2017; IUCN 2018), essential data are often no reported in the IUCN and UNESCO databases, or it is inconsistent, or not detailed enough to be meaningful. As a result, there is a lack of usable information on which to base detailed and robust assessments of temporal changes to levels of threat or progress in the management of IAS in WHS. We therefore propose a framework (Fig. 3) to guide holistic and standardised monitoring and reporting of biological invasions. This will facilitate the provision of meaningful data, which would permit better spatial and temporal analysis and comparisons, aiding scientific understanding as well as policy and management development and implementation in PAs globally.

The newly proposed monitoring and reporting framework

The framework comprises three key components relating to: monitoring and reporting on the *current status* of biological invasions and their management; *predictions* regarding future threats and management needs; and an *assessment* which culminates in assigning an overall threat score for the site based on the availability and status of knowledge from the preceding components of the framework (Fig. 3).

The first step of the process is to identify the *current status* of biological invasions and their management (see Supplementary file 1 for more details and instructions for applying the framework). This step focuses particularly on: (1) assessing pathways of introduction using the CBD framework; (2) reporting the total number of alien species present (broken down, if possible, into total numbers for different taxa and separating out those that are

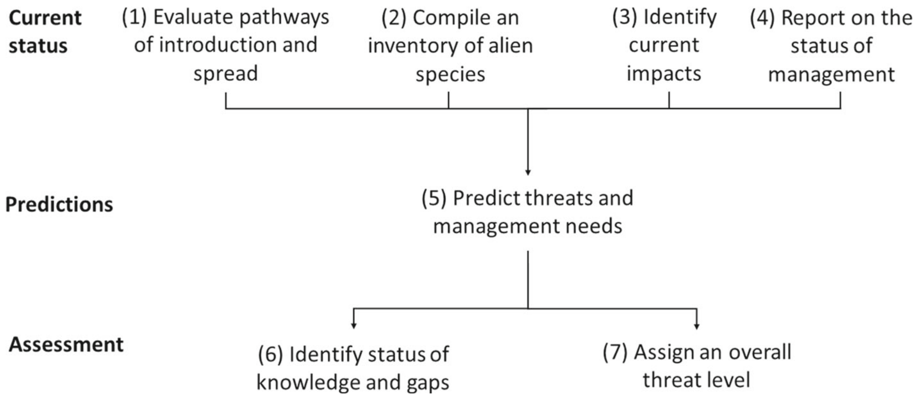

Fig. 3 A proposed framework for monitoring and reporting on biological invasions and their management in natural and mixed World Heritage Sites globally. The result of the process (i.e. stage 7) is that each site is given an overall threat level ("very high", "high", "moderate", "low", or "data deficient"). Instructions on how to implement the framework are given in Supplementary file 1, and case study examples of its application are in Supplementary file 2

alien vs invasive), with this information potentially based on various sources of ex situ or in situ information; (3) listing harmful IAS and highlighting their impacts [using either local evidence, global evidence or EICAT scores (IUCN, in press)]; and (4) an assessment of management interventions for the site (cf. Van Wilgen and Wilson 2018). For component (4), reporting should state whether any IAS management is in place at the site. If yes, each approach should be commented on, including: prevention initiatives, incursion response activities, attempts at eradication or containment, and asset protection measures. This will include a discussion of the various control techniques used (e.g. biological, manual, chemical control, etc.), as well as the effectiveness of the techniques and the degree to which approaches have achieved the stated management goals. Any barriers to management should also be identified here, and, if possible, details of budgets for control should also be provided. For management, the collected evidence from the previous components should be evaluated, and an overall management status should be assigned to the site: highly effective, effective, some concern, serious concern, or data deficient (Table 2).

Following the first step of the framework, which assesses *current status* (components 1–4), the next component (5) relates to *predictions* and assesses future threats posed by biological invasions and likely future management needs. This includes identifying and listing alien species that are likely to be introduced in the future or that are present and likely to increases in abundance and extent; highlighting potential future impacts; and identifying and listing future management needs. This can draw on various data and approaches, including suitability models and expert opinion. Components 1–5 should also include expert assessments of trends over time for each of these factors (i.e. for component 3: the assessor should indicate whether they believe that the overall impacts of IAS in the site are: increasing, decreasing, stable, or unknown over time).

The final part of the framework relates to *assessment.* The first part, component (6), deliberates on the status of knowledge and assesses the level of confidence in the information provided in components 1–5 ranking them as either high, moderate, low or data deficient. The second part, component (7), draws on all the proceeding information to assign an overall threat level (very high threat, high threat, moderate threat, low threat

Table 2 Categorisation of the effectiveness of management, linked to those alredy used by the IUNC (IUCN 2018)

Category	Category description
Highly effective	Successful management is reducing the overall threat and impact of biological invasions and ensures the values and integrity of the site in the long term. There is a guarantee of adequate and sustained funding for management and management implementation
Effective	Management has reduced the threat and impacts of most IAS but more effort is needed to ensure the values and integrity of the site, in the long term. Funding for management in the long run is almost certain and adequate
Some concern	Management is taking place but is not effectively reducing the threat and impact of IAS—this could affect the values and integrity of the site in the long term—adaptive management could potentially improve the situation. There is funding but it might not be adequate or sustained in the long run
Serious concern	No management interventions in place, or management interventions are not reducing the threat and impact (spread) of IAS and the values and integrity of the site are in jeopardy in the future. There is no funding for management
Data deficient	No information available

Table 3 Categorisation of overall threat levels posed by biological invasions to World Heritage Sites as per the proposed monitoring and reporting framework (Fig. 3)

Very high threat	Invasive alien species have or are likely to induce irreversible changes to community structure and ecosystem services with no likelihood of them returning to their original state resulting in irreversible damage to the values and integrity of the site even with effective management
High threat	Can cause changes to community composition, substantially alter the supply of ecosystem services and thus poses a substantial threat to the values and integrity of the site but can be avoided or reversed with highly effective management
Moderate threat	May cause minor changes in community composition and reduce the supply of some ecosystem services resulting in small-scale (localised) impacts but not fundamentally alter them. These impacts are reversible through management, or impacts will not raise substantially without management and therefore do not post significant threats to the values and integrity of the site
Low threat	May alter individual species fitness but has limited effects on ecosystem services. The threats posed to the values and integrity of the site are limited. Management could remove these species altogether or absence of management would not raise the threat posed
Data deficient	Not enough information available

or data deficient) for the site (Table 3). More in-depth details and guidelines on how to apply the framework appear in the supplementary material (Supplementary file1).

Application of the newly proposed framework at seven World Heritage Sites

Using the seven case studies with highly different social–ecological settings, we highlight the value of the new framework to allow for improved reporting of PAs. Detailed write-ups for each WHS after applying the framework (Fig. 3) are provided in the Supplementary file 2.

Applying the framework has yielded more information than past monitoring initiatives. For example, the IAS threat level indicated in the 2017 IUCN World Heritage Outlook for the Serengeti, Keoladeo, Doñana, and the Vredefort Dome sites was "data deficient" or "low threat" or "not listed", whereas all of these WHS are now categorised as facing moderate to high threats from biological invasions based on our assessment informed by the framework (Table 4: Supplementary file 2).

Serious threats as a result of IAS were reported for some sites in the IUCN and UNESCO documents based on previous monitoring, but detailed and accurate information was missing, for example in the case of the Galapagos Islands (Table 4). The additional data provided for the Galapagos Islands sheds light on the threats and management of IAS at the site and suggests a very high threat instead of a high threat as indicated in the 2017 IUCN World Heritage Outlook (Table 4). Interestingly, the application of the in-depth framework has also highlighted some successes, where through effective management (eradications), the overall number of IAS has decreased on Aldabra.

Application of the framework more than doubled the number of IAS reported for all sites except for Aldabra, which has had an overall decrease in IAS through effective eradication campaigns (Table 4). Our review also highlighted that several globally important IAS are present in many of the case study WHS but have not yet been reported in UNESCO and IUCN databases and documents. These include species such as *Carpobrotus edulis* and *Opuntia ficus-indica* in Doñana National Park; *Arundo donax, Eucalyptus* spp.

Table 4 In-depth case studies of invasive alien species (IAS) and their management in seven World Heritage Sites based on the reporting framework proposed in this paper (see Fig. 3; and Supplementary files 1 and 2 for full details)

Site name (country)	# of IAS listed based on assessments using the new framework (# of IAS previously listed)	List of IAS in each site with the highest threat based on new framework	Management success based on this study	Overall threat level based on in-depth assessments made in this study (threat levels according to the 2017 World Heritage Outlook)
Aldabra Atoll (Seychelles)	5 (7)	*Rattus rattus; Felis catus Casuarina equisetifolia; Icerya seychellarum; Stachytarpheta jamaicensis*	Effective	High threat (High threat)
Doñana National Park (Spain)	75 (5)	*Azolla filiculoides; Eucalyptus camaldulensis; Carpobrotus edulis; Cyprinus carpio; Eriocheir sinensis; Linepithema humile; Micropterus salmoides; Procambarus clarkii*	Some concern	High threat (Low threat)
Galapagos Islands (Ecuador)	60 (12)	*Cedrela odorata; Felis catus; Rattus norvegicus, Rattus rattus; Philornis downsi; Polistes versicolor; Psidium guajava; Solenopsis geminata; Rubus niveus; Wasmannia auropunctata*	Some concern	Very high threat (High threat)
Kakadu National Park (Australia)	60 (19)	*Andropogon gayanus; Salvinia molesta*; *Mimosa pigra; Hymenachne amplexicaulis*; *Pennisetum polystachion; Themeda quadrivalvis; Jatropha gossypiifolia*	Some concern	High threat (High threat)
Keoladeo National Park (India)	14 (5)	*Bos taurus; Clarisa gariepinus; Eichhornia crassipes; Lantana camara; Parapoynx diminutalis; Paspalum distichum; Prosopis juliflora*	Serious concern	High threat (Low threat)
Serengeti National Park (Tanzania)	23 (4)	*Opuntia stricta; Lantana camara; Parthenium hysterophorus; Pistia stratiotes; Opuntia monacantha: Chromolaena odorata*	Serious concern	High threat (data deficient)
Vredefort Dome (South Africa)	44 (0)	*Arundo donax; Cestrum laevigatum; Cyprinus carpio; Eichhornia crassipes; Eucalyptus* spp.; *Gleditsia triacanthos; Micropterus salmoides; Myriophyllum aquaticum; Opuntia* spp.; *Tamarix ramosissima*	Effective	Moderate threat (threat level not listed)

and *Eichhornia crassipes* in Vredefort Dome; and *Lantana camara* and *Parthenium hysterophorus* in Serengeti National Park. All of these taxa are amongst the 49 worst IAS in PAs globally according to Foxcroft et al. (2017) and are threatening IAS in other WHS (Supplementary file 2, 3). After applying the framework, further insights into management successes and challenges were uncovered, which could be beneficial for guiding future control. However, many sites still face challenges, which are important to acknowledge to guide future policy and control (Table 4; Supplementary file 2).

Discussion

Natural and mixed WHS and other PAs face major and growing threats from biological invasions (Usher 1988; Foxcroft et al. 2013, 2017; Osipova et al. 2017; Witt et al. 2017; Liu et al. 2020; Shackleton et al. 2020) (Fig. 1; Table 4). IAS threaten the outstanding values of PAs and WHS by impacting on biodiversity and the delivery of ecosystem services (e.g. García Murillo et al. 2007; Jäger et al. 2009; Dawson et al. 2014; Mukherjee et al. 2017). IAS are also a financial burden, as costs for IAS management can be extremely high (van Wilgen et al. 2016; Shackleton et al. 2020). It is, therefore, crucial to monitor and understand the status of biological invasions and their management in PAs.

Our research shows that although IAS are recognised as a major risk to WHS globally, detailed knowledge and reporting on their threats and management is highly variable, and are scarce for many sites, despite the long-term monitoring via IUCN and UNESCO mechanisms (Fig. 2; Table 1). For example, for most WHS where IAS are listed as a threat, little is known about which species are present, what impacts they are having, or what interventions are being applied (Fig. 2; Table 1). This might be due to a lack of knowledge and capacity, inconsistent reporting, and/or the lack of a standardized procedure for reporting. To address the issues relating monitoring and reporting, we proposed a new framework (Fig. 3; Supplementary file 1) and tested this using seven diverse case studies (Table 4; Supplementary file 2). Recent publications highlight the importance of well-designed monitoring and reporting procedures for IAS that facilitate comparisons over space and time (e.g. Latombe et al. 2017; Wilson et al. 2018; Pergl et al. 2020). Standardised long-term monitoring of IAS and their management in WHS and other PAs would help to realise the vision of robust monitoring of biological invasions globally (Latombe et al. 2017) to guide adaptive management, aid with policy development, and improve the understanding of invasion dynamics.

A standardised monitoring and reporting mechanism for biological invasions in World Heritage Sites

The new seven component reporting and monitoring framework (Fig. 3) should complement the existing monitoring processes. It could also serve as a guide for future assessments and reporting of IAS in all PAs globally as it draws on other widely applied schemes such as the CBD pathway framework and the EICAT assessment framework (e.g. see Blackburn et al. 2014; CBD 2014; Hawkins et al. 2015; Harrower et al. 2017; Osipova et al. 2017; Wilson et al. 2018). Use of this framework would improve the consistency, comparability and overall value of future reporting on IAS threats and management. Over time and with further testing, the IUCN and UNESCO could adapt the framework to develop a finer set of indicators and revise it accordingly (see Wilson et al. 2018).

We suggest that all PAs should report on pathways of introduction to guide pre-emptive management (Hulme 2009; Saul et al. 2007; Foxcroft et al. 2019). Pathway assessments are lacking for most PAs but form the basis for effective biosecurity interventions and surveillance (Colunga-Garcia et al. 2013; Toral-Granda et al. 2017) and can be very useful to guide management and understand future impacts (Foxcroft et al. 2019). Such information will help managers to monitor relevant areas, saving time and money. It could also help to prevent new introductions and to monitor problematic species, which could be quickly eradicated before they establish (Meyerson and Reaser 2002; Keller et al. 2007; Wilson et al. 2013). For example, Hemp (2008) reports that the increased level of hiking in the Kilimanjaro National Park has increased the introduction and spread of numerous invasive plants. Introduction of ornamental plants in lodges and staff villages has led to biological invasions in many PAs (Foxcroft et al. 2008). In Keoladeo, the purposeful introduction of *P. juliflora* to provide provisioning services to local communities has become a major issue (Mukherjee et al. 2017), and the same mistake was repeated more recently by introducing *Clarias gariepinus* to promote aquaculture (Supplementary file 2). The Kakadu site is threatened by natural dispersal of *Rhinella marina* from other areas (Kearney et al. 2008) and Galapagos faces major challenges from stowaways and transport contaminants (Toral-Granda et al. 2017) to a greater extent than other island protected areas like Aldabra (Supplementary file 2). Understanding these pathways can lead to the implementation of improved control methods, such as disinfecting hikers' equipment and prohibiting the planting of non-native species at lodges, disinfecting transported goods. Similarly, anticipatory monitoring could be implemented to prevent future introductions and spread.

Producing lists of all alien and invasive alien species present is important for management and a key target for monitoring (McGeoch et al. 2012). Such lists are baseline indicators that track changes in threat or the implementation of effective management over time (Fig. 3; Table 4). For example, Aldabra Atoll shows a decrease in the number of IAS listed due to effective eradications, showing great management success. Since current UNESCO and IUCN reporting mechanisms do not stipulate the provision of full species lists, listing of alien species varies considerably between WHS, and many sites may still lack the necessary data and research to generate accurate lists. A large proportion (21%) of WHS that specifically highlighted IAS as a threat did not indicate the number of IAS present, and many of these did not name a single IAS (Fig. 2). Lists can be derived using in situ or ex situ information and combining several different approaches, such as literature searches, GIS-based techniques, and ground-based surveys. Lists of IAS need to be carefully reviewed by experts and should be standardised as much as possible (McGeoch et al. 2012; Latombe et al. 2019; Groom et al. 2019). Funding should be made available to conduct surveys at all under-resourced WHS to inform the reactive "state of conservation" assessments undertaken by UNESCO and IUCN. Other options could also be the use of monitoring based on citizen science (Devictor et al. 2010; Mannino and Balistreri, 2018). Several WHS already have projects on iNaturalist, such as, the Everglades National Park in the USA (https://www.inaturalist.org/places/everglades-national-park-world-heritage-site) and iSimangaliso Wetland Park in South Africa (https://www.inaturalist.org/places/isimangaliso-wetland-park-world-heritage-site). Initiating such projects for all WHS would be an important first step towards providing up-to-date and freely accessible lists that apply standardised taxonomy, and would provide the means for flagging new incursions to allow for rapid response.

High priority IAS (top 10 or more) and their impacts should be specifically mentioned in the text or highlighted in some way. Scientific names, rather than common names, should be used. This was not common practice in previous reporting in IUCN and UNESCO documents, where many IAS were reported using only common names which leads to confusion in some cases. Although there is growing evidence that many IAS have major impacts in PAs (Foxcroft et al. 2013, 2017), including WHS (e.g. see citations in Sect. 3.1.2, and in the detailed case studies in Supplementary file 2), there is a need for more detailed information on how biodiversity and ecosystems are affected. Very few WHS documents provided evidence or mentioned actual impacts. Research to document and provide objective quantification of negative impacts of invasions could be used to help secure funding for management and therfore greatly needed. Assessments of impact can be done by local researchers in PAs or through approaches such as impact scoring (e.g. EICAT or SEICAT) based on global literature (Blackburn et al. 2014; Hawkins et al. 2015; Bacher et al. 2018).

It is also important to review and provide information on past and current management practices to assess successes and failures to inform future management planning (Shackleton et al. 2020). Documents for a large proportion of WHS that specifically list IAS as a threat make no mention of management (Table 1) Knowledge and reporting on management history is crucial for understanding changes in threat levels over time and for assessing capacity and success rates in responding to threats (Shackleton et al. 2020). Major successes and failures should be highlighted (Fig. 3; Supplementary files 1, 2). Reporting should note whether management plans are in place, and the key goals of plans should be stated. Summaries should discuss different approaches for preventive biosecurity measures, management goals such as eradication and impact reduction, and control methods used such as biological, mechanical, chemical control and utilisation (it must be noted that promoting utilisation can have limited effect on invasions and can be controversial in PAs). Information on control plans and techniques was lacking in previous reporting (Table 1) but useful information was collected through the new reporting framework (see Supplementary file 2).

As part of reporting and monitoring, future issues need to be identified. This can help to guide strategic planning of management interventions. Tools that can be used include horizon scanning or modelling approaches, pathway analysis or simple tools to create watch lists (Gasso et al. 2012; Faulkner et al. 2014; Roy et al. 2014; Toral-Granda et al. 2017; Witt et al. 2017). Future needs for management should also be highlighted to aid with planning and prioritisation and helping to ensure successful control programes (Downey 2010; van Wilgen et al. 2011; Shackleton et al. 2017; te Beest et al. 2017). When reporting on invasions and their management, it is important that information on the status of knowledge and uncertainty is provided to help guide future comparative analyses and research (Wilson et al. 2018; Latombe et al. 2019). Based on a good overview of threats, management and knowledge levels, an overall threat score can be assigned based on clearly defined criteria (Table 3; Supplementary files 1, 2).

The seven case studies conducted using the new framework (Table 4; Supplementary file 2) show that this proposed framework and approach is useful in guiding and standardising data collection. Application of the framework resulted in many case study WHS changing from being listed as “data deficient or low threat” to being listed as having “moderate to high threat” levels (Table 4). Better collation of data also allows successes in managing invasions that were not highlighted before to be uncovered, as in the case of the Aldabra Atoll (Table 4). Like other success cases of management in PAs (te Beest et al. 2017; Shackleton et al. 2020), much can be learned from these cases to guide management elsewhere.

Application of this framework in WHS and other PAs would help facilitate comparisons and the sharing of best practices between sites and help to guide the allocation and prioritisation of funding to manage IAS. Furthermore, application of the framework could provide the basis for a freely available global information system with an inventory of IAS threats to WHS and other PAs. This information could be included on the existing UNESCO and IUCN websites, in the online portal for the IUCN World Heritage Outlook assessments, or on platforms such as the Global Invasive Species Database (GISD; https://www.iucngisd.org/gisd/) and CABI's Invasive Species Compendium (https://www.cabi.org/isc/). We suggest that reports could be provided every three years and the framework could be modified as more knowledge is gained and following further testing of its application in practice in different contexts. This would be a major step towards the vision of robust monitoring of biological invasions globally (Latombe et al. 2017) and is greatly needed to guide future research, policies and management pertaining to biological invasions.

Acknowledgements We acknowledge funding from the DSI-NRF Centre of Excellence for Invasion Biology, the office of the Vice Rector: Research, Innovation and Post-Graduate Studies at Stellenbosch University (a "Consolidoc" Grant to RTS), the National Research Foundation, South Africa (Grant 85417 to DMR), the Oppenheimer Memorial Trust (Grant OMT 18576/03 to DMR). JRUW thanks the South African Department of Forestry, Fisheries, and the Environment (DFFtE) for funding, noting that this publication does not necessarily represent the views of DFFtE or its employees. This publication is contribution number 2194 of the Charles Darwin Foundation for the Galapagos Islands. We thank Elena Osipova and Yichuan Shi at IUCN for sharing the threats data from the 2014 and 2017 IUCN World Heritage Outlook assessments and for their advice. Many people kindly provided information for the case studies for which we are most grateful, including Charlotte Causton, Marilyn Cruz, Viviana Duque, Lesley Henderson, Guyonne Janss, Rocio Fernandez-Zamuido, Mavis Moyo, Calvin Murakami, Malvika Onial, Kuppusamy Sivakumar, Darragh Woodford and John Richard Mbwambo. Piero Genovesi and Mizuki Murai commented on early versions of the manuscript and provided valuable suggestions. Finally, we thank the reviewers whose detailed comments helped to shape and improve this manuscript considerably. The opinions expressed in this article do not necessarily reflect the views or policies of IUCN or other contributory organisations.

Author contributions Data are available in the supplementary material and on IUCN and UNESCO websites. BB, DMR and RTS conceived the study. BB provided data and did the mapping. LEW and RTS conducted the review. JRUW and RTS developed the monitoring framework, with contributions from all other authors. RTS, LEW, NB, HJ, CS, and ABRW conducted the case study data collection and write up with further comments from all other authors. RTS wrote the first draft of the manuscript with input from all other authors.

Funding Open access funding provided by University of Lausanne.

Compliance with ethical standards

Conflict of interest There are no conflicts of interest.

References

Angassa A (2005) The ecological impact of bush encroachment on the yield of grasses in Borana rangeland ecosystem. Afr J Ecol 43:14–20

Aravind NA, Rao D, Ganeshaiah KN, Shaanker RU, Poulsen JG (2010) Impact of the invasive plant, *Lantana camara*, on bird assemblages at Male Mahadeshwara Reserve Forest, South India. Tropical Ecol 51:325–338

Bacher S et al (2018) Socio-economic impact classification of alien taxa (SEICAT). Meth Ecol Evol 9:159–168

Bellard C, Cassey P, Blackburn TM (2016) Alien species as a driver of recent extinctions. Biol Lett 12:20150623

Bertzky B, Engels B, Howard P, Nozawa C, Obura D, Seely M, Strahm W, Thorsell J (2014) World heritage and species: safe havens for wildlife? World Heritage 73:28–37

Blackburn TM, Essl F, Evans T, Hulme PE, Jeschke JM, Kühn I, Kumschick S, Marková Z, Pergl J, Pyšek P, Rabitsch W, Ricciardi A, Richardson DM, Vilà M, Wilson JRU, Winter M, Genovesi P, Bacher S (2014) A unified classification of alien species based on the magnitude of their environmental impacts. PLoS Biol 12:e1001850

Bomanowska A, Adamowski W, Kirpluk I, Rewicz OA (2019) Invasive alien plants in Polish national parks: threats to species diversity. PeerJ 7:e8034

Bradshaw CJA, Field IC, Bowman DMJS, Haynes C, Brook BW (2007) Current and future threats from non-indigenous animal species in northern Australia: a spotlight on World Heritage Area Kakadu National Park. Wildl Res 34:419–436

Brook BW, Sodhi NS, Bradshaw CJ (2008) Synergies among extinction drivers under global change. Trends Ecol Evol 23:453–460

Butchart SH et al (2010) Global biodiversity: indicators of recent declines. Science 328:1164–1168

[CBD] Convention on Biological Diversity (2014) Pathways of introduction of invasive species, their prioritization, and management. UNEP/CBD/SBSTTA/18/1

Chape S, Harrison J, Spalding M, Lysenko I (2005) Measuring the extent and effectiveness of protected areas as an indicator for meeting global biodiversity targets. Philos Trans R Soc B 360:443–455

Clavero M, García-Berthou E (2005) Invasive species are a leading cause of animal extinctions. Trends Ecol Evol 20:110

Colunga-Garcia M, Haack RA, Magarey RD, Borchert DM (2013) Understanding trade pathways to target biosecurity surveillance. NeoBiota 18:103–118

Cowie ID, Werner PA (1993) Alien plant species invasive in Kakadu National Park, tropical northern Australia. Biol Conserv 63:127–135

Dawson J, Oppel S, Cuthbert RJ, Holmes N, Brid JP, Butchart SHM, Spatz DR, Tershy B (2014) Prioritizing islands for the eradication of invasive vertebrates in the United Kingdom overseas territories. Conserv Biol 29:143–153

Day M, Wiley CJ, Playford J, Zalucki MP (2003) Lantana: current management status and future prospects. ACIAR, Canberra, ACT

Devictor V, Whittaker RJ, Beltrame C (2010) Beyond scarcity: citizen science programmes as useful tools for conservation biogeography. Divers Distrib 16:354–362

Donlan CJ, Campbell K, Cabrera W, Lavoie C, Carrion V, Cruz F (2007) Recovery of the Galápagos Rail (*Laterallus spilonotus*) following the removal of invasive mammals. Biol Conserv 138:520–524

Downey PO (2010) Managing widespread, alien plant species to ensure biodiversity conservation: a case study using an 11-step planning process. Invasive Plant Sci Manage 3:451–461

Downey PO, Richardson DM (2016) Alien plant invasions and native plant extinctions: a six-threshold framework. AoB PLANTS 8:plw047

Dudley N (2008) Guidelines for applying protected area management categories. IUCN, Gland

Duffy DC, Capece P (2012) Biology and impacts of Pacific Island invasive species. 7. The domestic cat (*Felis catus*). Pac Sci 66:173–213

Egoh B, Rouget M, Reyers B, Knight AT, Cowling RM, van Jaarsveld AS, Welz A (2007) Integrating ecosystem services into conservation assessments: a review. Ecol Econ 63:714–721

Eldridge DJ, Bowker MA, Maestre FT, Roger E, Whitford RJF (2011) Impacts of shrub encroachment on ecosystem structure and functioning: towards a global synthesis. Ecol Lett 14:709–722

Essl F, Dullinger S, Rabitsch W, Hulme PE, Hülber K, Jarošík V, Kleinbauer I, Krausmann F, Kühn I, Nentwig W, Vilà M (2011) Socioeconomic legacy yields an invasion debt. Proc Natl Acad Sci USA 108:203–207

Faulkner KT, Robertson MP, Roget M, Wilson JRU (2014) A simple, rapid methodology for developing invasive species watch lists. Biol Conserv 179:25–32

Foxcroft LC, Richardson DM, Wilson JRU (2008) Ornamental plants as invasive aliens: problems and solutions in Kruger National Park, South Africa. Environ Manage 41:32–51

Foxcroft LC, Pyšek P, Richardson DM, Genovesi P (2013) Plant invasions in protected areas: patterns, problems and challenges. Invading nature series Volume 7. Springer, Berlin

Foxcroft LC, Pyšek P, Richardson DM, Genovesi P, MacFadyen S (2017) Plant invasions in protected areas: progress and priorities. Biol Invasions 19:1353–1378

Foxcroft LC, Spear D, van Wilgen NJ, McGeoch MA (2019) Assessing the association between pathways of alien plant invaders and their impacts in protected areas. NeoBiota 43:1–25

García Murillo P, Fernández Zamudio MDR, Cirujano Bracamonte S, Sousa Martín A, Espinar JM (2007) The invasion of Doñana National Park (SW Spain) by the mosquito fern (Azolla filiculoides Lam). Limnetica 26:43–250

Gassó N, Thuiller W, Pino J, Vilà M (2012) Potential distribution range of invasive plant species in Spain. NeoBiota 12:25–40

Groom Q, Desmet P, Reyserhove L, Adriaens T, Oldoni D, Vanderhoeven S, Baskauf SJ, Chapman A, McGeoch M, Walls R, Wieczorek J, Wilson JRU, Zermoglio PFF, Simpson A (2019) Improving Darwin Core for research and management of alien species. Biodivers Inf Sci Stand 3:e38084

Harper GA, Bunbury N (2015) Invasive rats on tropical islands: their population biology and impacts on native species. Glob Ecol Conserv 3:607–627

Harrower CA, Scalera R, Pagad S, Schönrogge K Roy HE (2017) Guidance for interpretation of CBD categories on introduction pathways. Technical note prepared by IUCN for the European Commission.

Hawkins CL, Bacher S, Essl F, Hulme PE, Jeschke JM, Kühn I, Kumschick S, Nentwig W, Pergl J, Pyšek P, Rabitsch W, Richardson DM, Vila M, Wilson JRU, Genovesi P, Blackburn T (2015) Framework and guidelines for implementing the proposed IUCN Environmental Impact Classification for Alien Taxa (EICAT). Divers Distrib 21:1360–1363

Hejda M, Pyšek P, Jarošík V (2009) Impact of invasive plants on the species richness, diversity and composition of invaded communities. J Ecol 97:393–403

Hemp A (2008) Introduced plants on Kilimanjaro: tourism and its impact. Plant Ecol 197:17–29

Hernandez-Enriquez O, Alvarez R, Morelli F, Bastida F, Menendez CD (2012) Low-impact chemical weed control techniques in UNESCO World Heritage Sites of Cuba. Commun Agric Appl Biol Sci 77:387–393

Hulme PE (2009) Trade, transport and trouble: managing invasive species pathways in an era of globalisation. J Appl Ecol 46:10–18

Hulme PE, Bacher S, Kenis M, Klotz S, Kuhn I, Minchin D, Nentwig W, Olenin S, Panov V, Pergl J, Pyšek P, Roques A, Sol D, Vila SW (2008) Grasping at the routes of biological invasions: a framework for integrating pathways into policy. J Appl Ecol 45:403–414

IUCN (2000) Guidelines for the Prevention of Biodiversity Loss Caused by Alien Invasive Species. Approved by the 51st Meeting of the IUCN Council, Gland Switzerland

IUCN (2017) Guidance for interpretation of CBD categories on introduction pathways. Technical note prepared by IUCN for the European Commission

IUCN (2018) World Heritage Outlook: Understanding ratings [On-line], January 2018. IUCN, Gland, Switzerland and Cambridge, UK. https://www.worldheritageoutlook.iucn.org/

IUCN (in press) IUCN EICAT categories and criteria. The environmental impact classification for alien taxa, 1st edn. IUCN, Gland

Jäger H, Kowarik I, Tye A (2009) Destruction without extinction: long-term impacts of an invasive tree species on Galápagos highland vegetation. J Ecol 97:1252–1263

Jeschke JM et al (2014) Defining the impact of non-native species. Conserv Biol 28:1188–1194

Johnson CN, Balmford A, Brook BW, Buettel JC, Galetti M, Guangchun L, Wilmshurst JM (2017) Biodiversity losses and conservation responses in the Anthropocene. Science 356:270–275

Karssing RJ, Rivers-Moore NA, Slater K (2012) Influence of waterfalls on patterns of association between trout and Natal cascade frog *Hadromophryne natalensis* tadpoles in two headwater streams in the Ukhahlamba Drakensberg Park World Heritage Site, South Africa. Afr J Aquat Sci 37:107–112

Kearney M, Phillips BL, Tracy CR, Christian KA, Betts G, Porter WP (2008) Modelling species distributions without using species distributions: the cane toad in Australia under current and future climates. Ecography 31:423–434

Keller RP, Lodge DM, Finnoff DC (2007) Risk assessment for invasive species produces net bioeconomic benefits. Proc Natl Acad Sci USA 104:203–207

Koichi K, Cottrell A, Sangha KK, Gordon IJ (2013) What determines the acceptability of wildlife control methods? A case of feral pig management in the Wet Tropics World Heritage Area, Australia. Hum Dimens Wildl 18:97–108

Latombe G et al (2017) A vision for global monitoring of biological invasions. Biol Conserv 213:295–308

Latombe G, Canavan S, Hirsch H, Hui C, Kumschick S, Nsikani MM, Potgieter LJ, Saul WC, Turner SC, Wilson JRU, Richardson YFA (2019) A four-component classification of uncertainties in biological invasions: implications for management. Ecosphere 10:e02669

Liu X, Blackburn TM, Song T, Wang X, Huang C, Li Y (2020) Animal invaders threatern protected areas worldwide. Nat Comm 11:2892

Mannino AM, Balistreri P (2018) Citizen science: a successful tool for monitoring invasive alien species (IAS) in Marine Protected Areas. The case study of the Egadi Islands MPA (Tyrrhenian Sea, Italy). Biodiversity 19:42–48

McGeoch MA, Butchart SH, Spear D, Marais E, Kleynhans E, Symes A, Chanson J, Hoffmann M (2010) Global indicators of biological invasion: species, numbers, biodiversity impact and policy responses. Divers Distrib 16:95–108

McGeoch MA, Spear D, Kleynhans EJ, Marais E (2012) Uncertainty in invasive alien species listing. Ecol Appl 22:959–971

Meyerson LA, Reaser JK (2002) Biosecurity: moving toward a comprehensive approach: a comprehensive approach to biosecurity is necessary to minimize the risk of harm caused by non-native organisms to agriculture, the economy, the environment, and human health. Bioscience 52:593–600

Mukherjee A, Velankar AD, Kumara HN (2017) Invasive *Prosopis juliflora* replacing the native floral community over three decades: a case study of a World Heritage Site, Keoladeo National Park, India. Biodivers Conserv 26:2839–2856

Nauhton-Treves L, Holland MB, Brandon K (2005) The role of protected areas in conservation biodiversity and sustaining local livelihoods. Annu Rev Environ Resour 30:219–252

Osipova E, Shi Y, Kormos C, Shadie P, Zwahlen C, Badman T (2014) IUCN World Heritage Outlook 2014: a conservation assessment of all natural World Heritage sites. IUCN, Gland

Osipova E, Shadie P, Zwahlen C, Osti M, Shi Y, Kormos C, Bertzky B, Murai M, van Merm R, Badman T (2017) IUCN World Heritage Outlook 2: a conservation assessment of all natural World Heritage sites. IUCN, Gland

Padmanaba M, Tomlinson KW, Corlett HAC (2017) Alien plant invasions of protected areas in Java, Indonesia. Sci Rep 7:1–11

Paynter Q, Flanagan GJ (2004) Integrating herbicide and mechanical control treatments with fire and biological control to manage an invasive wetland shrub, *Mimosa pigra*. J Appl Ecol 41:615–629

Pejchar L, Mooney HA (2009) Invasive species, ecosystem services and human well-being. Trends Ecol Evol 24:497–504

Pergl J, Pyšek P, Essl F, Jeschke JM, Courchamp F, Geist J, Hejda M, Kowarik I, Mill A, Musseau C, Pipek P (2020) Need for routine tracking of biological invasions. Conserv Biol. https://doi.org/10.1111/cobi.13445

Richardson DM, Pyšek P, Rejmánek M, Barbour MG, Panetta FD, West CJ (2000) Naturalization and invasion of alien plants: concepts and definitions. Divers Distrib 6:93–107

Richardson DM, Pyšek P, Carlton JT (2011) A compendium of essential concepts and terminology in invasion ecology. In: Richardson DM (ed) Fifty years of invasion ecology. The legacy of Charles Elton. Wiley-Blackwell, Oxford, pp 409–420

Rivers-Moore NA, Fowles B, Karssing RJ (2013) Impacts of trout on aquatic macroinvertebrates in three Drakensberg rivers in KwaZulu-Natal, South Africa. Afr J Aquat Sci 38:93–99

Rouget M, Robertson MP, Wilson JR, Hui C, Essl F, Renteria JL, Richardson DM (2016) Invasion debt–Quantifying future biological invasions. Divers Distrib 22:445–456

Roy HE et al (2014) Horizon scanning for invasive alien species with the potential to threaten biodiversity in Great Britain. Glob Change Biol 20:3859–3871

Saul WC, Roy HE, Booy O, Carnevali L, Chen HJ, Genovesi P, Harrower CA, Hulme PE, Pagad S, Jeschke PJ (2017) Assessing patterns in introduction pathways of alien species by linking major invasion data bases. J Appl Ecol 54:657–669

Saunders KM, Harrison JJ, Hodgson DA, de Jong R, Mauchle F, McMinn A (2013) Ecosystem impacts of feral rabbits on World Heritage sub-Antarctic Macquarie Island: a palaeoecological perspective. Anthropocene 3:1–8

Scarlett K, Daniel R, Shuttleworth LA, Roy B, Bishop TF, Guest DI (2015) Phytophthora in the Gondwana rainforests of Australia world heritage area. Australas Plant Pathol 44:335–348

Seebens H et al (2017) No saturation in the accumulation of alien species worldwide. Nature Comm 8:1–9

Shackleton RT, Le Maitre DC, van Wilgen BW, Richardson DM (2017) Towards a national strategy to optimise the management of a widespread invasive tree (*Prosopis* species; mesquite) in South Africa. Ecosyst Serv 27:242–252

Shackleton RT, Shackleton CM, Kull CA (2019) The role of invasive alien species in shaping local livelihoods and human well-being: a review. J Environ Manage 229:145–157

Shackleton RT, Foxcroft LC, Wood LE, Pyšek P, Richardson DM (1980s) Assessing biological invasions in protected areas: revisiting targeted nature reserves 30 years after the 1980s SCOPE programme. Biol Conserv 243:108424

Strahm W (2008) World Heritage and the IUCN Red List. World Heritage 49:18–29

te Beest M, Howison O, Howison R, Dew LA, Mgobozi Poswa M, Dumalisile L, Van Rensburg SJ, Terblanche C (2017) Successful control of the invasive shrub *Chromolaena odorata* in Hluhluwe-iMfolozi. In: Cromsigt JPG, Archibald S, Owen-Smith N (eds) Savanna ecology and management. Conserving Africa's mega-diversity in the Hluhluwe-iMfolozi Park. Cambridge University Press, Cambridge, pp 336–357

Toral-Granda MV, Causton CE, Jäger H, Trueman M, Izurieta JC, Araujo E, Cruz M, Zander KK, Izurieta A, Garnett ST (2017) Alien species pathways to the Galapagos Islands, Ecuador. PLoS ONE 12:e0184379. https://doi.org/10.1371/journal.pone.0184379

Turner PJ, Downey PO (2010) Ensuring invasive alien plant management delivers biodiversity conservation: insights from an Assessment of *Lantana camara* in Australia. Plant Prot Q 25:102

UNEP-WCMC, IUCN, NGS (2019) Protected planet live report 2019. UNEP-WCMC, IUCN and NGS, Washington

UNESCO (1972) Convention Concerning the Protection of the World Cultural and Natural Heritage. UNESCO, Paris

UNESCO (2017) Operational Guidelines for the implementation of the World Heritage Convention. UNESCO, Paris

Usher MB (1988) Biological invasion of nature reserves: a search for generalisations. Biol Conserv 44:119–135

Van Damme K, Banfield L (2011) Past and present human impacts on the biodiversity of Socotra island (Yemen): implications for future conservation. Zool Middle East 54:31–88

Van Wilgen BW, Wilson JR (eds) (2018) The status of biological invasions and their management in South Africa in 2017. South African National Biodiversity Institute, Kirstenbosch and DST-NRF Centre of Excellence for Invasion Biology, Stellenbosch

van Wilgen BW, Dyer C, Hoffmann JH, Ivey P, Le Maitre DC, Moore JL, Richardson DM, Rouget M, Wannenburgh A, Wilson JRU (2011) National-scale strategic approaches for managing introduced plants: insights from Australian acacias in South Africa. Divers Distrib 17:1060–1075

van Wilgen BW, Fill JM, Baard J, Cheney C, Forsyth AT, Kraaij T (2016) Historical costs and projected future scenarios for the management of invasive alien plants in protected areas in the Cape Floristic Region. Biol Conserv 200:168–177

Veillon R (2014) State of conservation of world heritage properties: a statistical analysis: 1979–2013. UNESCO World Heritage Centre, France

Vilà M, Basnou C, Pyšek P, Josefsson M, Genovesi P, Gollasch S, Nentwig W, Olenin S, Roques A, Roy D, Hulme PE (2010) How well do we understand the impacts of alien species on ecosystem services? A pan-European, cross-taxa assessment. Front Ecol Environ 8:135–144

Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997) Human domination of the earth's ecosystems. Science 1997:494–499

Watson JEM, Dudley N, Segan DB, Hockings M (2014) The performance and potential of protected areas. Nature 515:67–73

Wilson JRU, Ivey P, Manyama P, Nanni I (2013) A new national unit for invasive species detection, assessment and eradication planning. S Afr J Sci. https://doi.org/10.1590/sajs.2013/20120111

Wilson JRU, Faulkner KT, Rahlao SJ, Richardson DM, Zengeya TA, van Wilgen BW (2018) Indicators for monitoring biological invasions at a national level. J Appl Ecol 55:2612–2620

Witt ABR, Geertsema H, Giliomee JH (2004) The impact of an invasive ant, *Linepithema humile* (Mayr) (Hymenoptera: Formicidae), on the dispersal of the elaiosome-bearing seeds of six plant species. Afr Entomol 12:223–230

Witt ABR, Kiambi S, Beale T, van Wilgen BW (2017) A preliminary assessment of the extent and potential impacts of alien plant invasions in the Serengeti-Mara ecosystem, East Africa. Koedoe 59:1–16

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Affiliations

Ross T. Shackleton[1,2] · Bastian Bertzky[3] · Louisa E. Wood[4] · Nancy Bunbury[5,6] · Heinke Jäger[7] · Remco van Merm[8] · Christian Sevilla[9] · Kevin Smith[10] · John R. U. Wilson[1,11] · Arne B. R. Witt[12] · David M. Richardson[1]

✉ Ross T. Shackleton
rtshackleton@gmail.com

1 Centre for Invasion Biology, Department of Botany and Zoology, Stellenbosch University, Stellenbosch, South Africa

2 Institute of Geography and Sustainability, University of Lausanne, Lausanne 1015, Switzerland

3 European Commission, Joint Research Centre (JRC), Via Enrico Fermi 2749, 21027 Ispra, VA, Italy

4 Centre for Environment Fisheries and Aquaculture Science, Barrack Road, Weymouth DT4 8UB, UK

5 Seychelles Islands Foundation, La Ciotat Building, Mont Fleuri, PO Box 853, Victoria, Seychelles

6 Centre for Ecology and Conservation, University of Exeter, Cornwall Campus, Penryn TR10 9FE, UK

7 Charles Darwin Research Station, Charles Darwin Foundation, Santa Cruz, Galapagos, Ecuador

8 International Union for Conservation of Nature (IUCN), Gland, Switzerland

9 Galapagos National Park Directorate, Galapagos, Ecuador

10 International Union for Conservation of Nature (IUCN), Pembroke Street, Cambridge CB2 3QZ, UK

11 South African National Biodiversity Institute, Kirstenbosch Reseach Centre, Cape Town, South Africa

12 Centre for Agriculture and Biosciences International (CABI), Nairobi, Kenya