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ORIGINAL PAPER

Using indicators to assess the status of biological invasions and their management on islands—the Prince Edward Islands, South Africa as an example

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Abstract Addressing the challenge biological invasions pose to island biodiversity is pivotal to achieving Target 6 of the Kunming–Montreal Global Biodiversity Framework. Using a suite of 24 indicators, we evaluated the current status of biological invasions and their management on the Prince Edward Islands, South Africa's sub-Antarctic territories, and provide recommendations for management. There are 45 established alien taxa on Marion Island, of which 25 are invasive, and nine invasive taxa on the less frequently visited Prince Edward Island. However, despite stringent biosecurity, new alien taxa continue to arrive, potentially through ten introduction pathways, but particularly as contaminants on goods and stowaways on transport vectors. Not all detected taxa have been systematically recorded or identified—identifying incursions to species level may help pinpoint gaps in biosecurity. Three invasive plant species have caused Major environmental impacts (as per the Environmental Impact Classification for Alien Taxa categories), and Massive impacts have been recorded for the house mouse. An ambitious plan to eradicate the house mouse is being developed. A further eight taxa are controlled and four monitored to determine whether they have been eradicated. We argue that systematically tracking and documenting biological invasions is vital to improve the appropriateness, adaptability, and responsiveness of management; and we recommend a dedicated, integrated reporting process involving all stakeholders. Such monitoring is particularly important for remote sites given competing demands to reduce the human footprint, manage biological invasions, and allow access. This article is part of the theme issue 'Managing biological invasions in protected areas: moving towards the new Global Biodiversity Framework targets'.

Résumé Adresser le défi des invasions biologiques sur les îles est essentiel pour atteindre la cible 6 du Cadre Mondial de la Biodiversité de Kunming-Montréal. En utilisant 24 indicateurs, nous avons évalué l'état des invasions biologiques et leur gestion sur les Îles du

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Prince Edward, territoires subantarctiques d'Afrique du Sud, et formulé des recommandations pour leur gestion. L'Île Marion abrite 45 taxons exotiques, dont 25 invasifs, tandis que l'Île du Prince Edward, moins fréquentée, en compte 9. Malgré des règles strictes de biosécurité, de nouveaux taxons exotiques sont continuellement détectés, arrivant par dix points d'entrée potentiels, en particulier via les marchandises et organismes transportés involontairement sur les vecteurs de transport. Tous les taxons détectés n'ont pas été systématiquement enregistrés ou identifiés–identifier les incursions au niveau de l'espèce pourrait aider à pointer des lacunes en biosécurité. Trois plantes invasives ont causé des dommages environnementaux Graves (d'après la Classification des Impacts Environnementaux, catégories des Taxons Exotiques), et des impacts Majeurs des souris grises ont été observés. Un plan ambitieux pour éradiquer ces dernières est en cours de développement. Huit taxons supplémentaires sont sous contrôle et quatre sous surveillance pour confirmer leur éradication. Nous avançons que le suivi systématique et la documentation des invasions biologiques sont vitaux pour améliorer la pertinence, l'adaptabilité et la responsivité de leur gestion; et nous recommandons le signalement dédié et intégré des processus impliquant les parties prenantes. Une telle surveillance est essentielle pour les sites éloignés, où il faut équilibrer réduction de l'empreinte humaine, gestion des invasions et autorisation d'accès.

Resumen Abordar el desafío que las invasiones biológicas representan para la biodiversidad insular es fundamental para lograr la Meta 6 del Marco Mundial para la Diversidad Biológica de Kunming-Montreal. Utilizando 24 indicadores, evaluamos el estado de las invasiones biológicas y su manejo en las Islas Prince Edward, territorios subantárticos de Sudáfrica, y proporcionamos recomendaciones para su manejo. En la Isla Marion hay 45 taxones exóticos establecidos, de los cuales 25 son invasores. En la Isla Prince Edward, menos visitada, hay nueve taxones exóticos. A pesar de estrictas medidas de bioseguridad, continúan llegando nuevos taxones, principalmente como contaminantes en mercancías y organismos transportados involuntariamente en vectores de transporte, a través de diez posibles vías de introducción. No todos los taxones detectados han sido registrados o identificados sistemáticamente—identificar incursiones a nivel de especie puede ayudar a señalar brechas en la bioseguridad. Tres especies de plantas invasoras han causado impactos ambientales Graves (según la Clasificación del Impacto Ambiental de Taxones Exóticos) y se han registrado impactos Muy graves para el ratón doméstico. Se está desarrollando un plan ambicioso para erradicar al ratón doméstico. Otros ocho taxones son controlados y cuatro monitoreados para confirmar su erradicación. El seguimiento y la documentación sistemáticos es vital para mejorar la idoneidad, adaptabilidad y capacidad de respuesta del manejo. Recomendamos un proceso de elaboración de informes integrado que involucre a todas las partes interesadas. Tal monitoreo es particularmente importante para sitios remotos, donde es necesario equilibrar la reducción de la huella humana, la gestión de invasiones y el acceso.

Keywords Alien species management · Global biodiversity framework · Indicators · Island conservation · Invasion ecology · Protected areas

Mots-clés **Gestion** des espèces exotiques · Cadre mondial pour la biodiversité · Indicateurs · Conservation des îles · Écologie des invasions · Aires protégées

Palabras clave Gestión de especies exóticas · Marco mundial de biodiversidad · Indicadores · Conservación de islas · Ecología de invasiones · Áreas protegidas

Introduction

Biological invasions represent a paramount threat to biodiversity on islands (Elton 1958; Clavero et al. 2009; Russell et al. 2017; Spatz et al. 2017). Invasive species are the primary driver behind population declines and species extinctions on island ecosystems globally (Reaser et al. 2007; Bellard et al. 2016; Doherty et al. 2016); and the overwhelming majority (90%) of known global extinctions predominantly attributed to invasive species have occurred on islands (IPBES 2023). Due to the vulnerability of these ecosystems, the Convention on Biological Diversity (CBD) has called repeatedly for islands to be prioritised for conservation (e.g., see https://www.cbd.int/island/islands.shtml).

The CBD adopted the Kunming–Montreal Global Biodiversity Framework in December 2022 (www.cbd.int/gbf; from here onwards GBF). The GBF consists of four global goals for 2050, and 23 targets for 2030. Target 6 focuses on biological invasions and aims to: '*Eliminate, minimize, reduce and or mitigate the impacts of invasive alien species on biodiversity and ecosystem services by identifying and managing pathways of the introduction of alien species, preventing the introduction and establishment of priority invasive alien species, reducing the rates of introduction and establishment of other known or potential invasive alien species by at least 50 per cent by 2030, and eradicating or controlling invasive alien species, especially in priority sites, such as islands*'. South Africa is a signatory and is, therefore, committed to develop strategies and take action to reach the GBF goals and targets. However, if countries are to report on progress towards Target 6, an improved understanding of the status quo and trends in biological invasions is required. This will require indicators specifically for biological invasions to track trends and assist with monitoring and reporting (e.g., Wilson et al. 2018; Vicente et al. 2022; McGeoch et al. 2023). Note, indicators are defined here as 'a set of measurements that give specific information about the state of something' (Zengeya and Wilson 2020).

The Prince Edward Islands (PEIs) are South African sub-Antarctic territories located ~2000 km South–East from Cape Town. They possess the highest level of protection under South African law and were declared a Special Nature Reserve in 1995 (meaning that they are dedicated to science and conservation, and tourism is not allowed) (DEA 2010), and declared a Marine Protected Area (MPA) in 2013 (Whitehead et al. 2019). Although relatively pristine, the islands (Marion and Prince Edward) are invaded by several invasive species (Chown and Froneman 2008; Greve et al. 2017, 2020). Despite their high level of protection and the strict biosecurity measures in place (DEA 2010), biological invasions remain an important issue for the conservation of the PEIs.

This study applies a set of 24 indicators to improve our understanding of the status and trends of biological invasions on the PEIs, with the broader aim of facilitating efforts to monitor and report on biological invasions on islands and remote sites more generally. The indicator framework used here was developed by Wilson et al. (2018) to report on invasions at the national level (Table 1). These indicators have been implemented for mainland South Africa in a series of national reports on the status of biological invasions and their management (van Wilgen and Wilson 2018; Zengeya and Wilson 2020, 2023). The latest report included a specific chapter on the PEIs, which formed the basis for this paper (Fernández Winzer et al. 2023). The 24 indicators cover four themes: pathways, species, sites, and interventions, with intervention indicators on inputs, outputs, and outcomes. There are 20 core indicators, with an additional four high-level indicators to summarise the information presented by the core indicators (Table 1). Because of the isolation of the PEIs, the relatively low level of human impact, and the long-term scientific research programmes that have been running on the islands for some decades (Chown and Froneman 2008), the PEIs provide an excellent study system for conducting a comprehensive case study using these indicators.

Although other indicator frameworks exist, we used that of Wilson et al. (2018) as it explicitly covers the various aspects of biological invasions (pathways, species, sites, and interventions) that need to be addressed to meet GBF Target 6 [details on other frameworks and how they compare to Wilson et al. (2018) are provided in the Supplementary materials; see also Vicente et al. (2022)].

The aims of this study were to: 1) summarise the status of biological invasions on the PEIs (and in doing so provide a baseline for future studies on the PEIs), 2) identify gaps and challenges to achieve GBF Target 6 on the PEIs, and 3) provide recommendations to achieve GBF Target 6 on the PEIs and other remote areas by 2030.

Methods

Study system

The PEIs are located over 2000 km south-east of mainland South Africa in the Southern Ocean (Chown and Froneman 2008). There are two islands in the group: the larger Marion Island (270 km^2, 46° 54′S, 37° 45′E) and the smaller Prince Edward Island (45 km^2, 46° 38′S, 37° 57′E), 19 km apart from each other (Chown and Froneman 2008). Both are small islands that can be walked

Table 1 Four high-level summary indicators (1–4) and 20 core indicators (1.1–4.6) were used to assess the status of biological invasions on South Africa's sub-Antarctic Prince Edward Islands (PEIs)

Category	Indicator	Description
	1. Rate of unregulated introduction of new species	The number of new alien species introduced accidentally or intentionally but illegally over time
	1.1 Introduction pathway prominence	An evaluation of the opportunities provided by the pathways (as per the CBD introduction pathway categorisation) for the introduction of alien species to the PEIs from another region. The indicator considers the size or prominence of the introduction pathway based on socio-economic data (e.g., how many trips, volume of trade). It does not consider the propagule pressure along the pathway or how many introductions the pathway has facilitated
	1.2 Introduction rates	The number of new alien species introduced to the PEIs from another region broken down per pathway
	1.3 Within-country pathway prominence	The opportunities provided by pathways to facilitate the movement of alien species within and between the islands. The indicator considers the size or prominence of the pathway based on socio-economic data (e.g., how much equipment was moved around the islands). It does not consider how many alien species dispersed or were spread through the pathway
	1.4 Within-country dispersal rates	The number of alien species dispersed within and between the islands broken down per pathway
	2. Number of invasive species that have 'Major' impacts	The number of invasive species that are causing significant harmful impacts. This is defined as 'Major' or 'Massive' as per the IUCN's Environmental Impact Classification for Alien Taxa Scheme, EICAT (IUCN 2020b), or as per the Socio-Economic Impact Classification for Alien Taxa Scheme, SEICAT (Bacher et al. 2018). Note SEICAT was not scored here as the conservation status of the island means such impacts are inherently less important and less likely to occur
	2.1 Number and status of alien species	The number of alien species and, at a more advanced level of the indicator, their invasion status as per the framework of Blackburn et al. (2011) as interpreted by Groom et al. (2019) and adopted as a Darwin Core data standard (dwc: degreeOfEstablishment)
	2.2 Extent of alien species	How widespread alien species are (e.g., number of half minute grid-cells occupied)
	2.3 Abundance of alien species	An estimate of how common species are. Presented as a category, an estimate of numbers of individuals or similar appropriate unit (e.g., number of individuals per m^2). At a more advanced level, abundance can be broken down into life-stages or cohorts
	2.4 Impact of alien species	An estimate of the negative environmental and socio-economic impacts caused by the alien species. At a basic level, estimates are based on the IUCN's EICAT Scheme or the SEICAT Scheme
	3. Extent of area that suffers 'Major' impacts from invasions	The extent of invaded area that suffers impacts that are scored as 'Major' or 'Massive' in terms of delivering fewer or permanently lost ecosystem services, and/or supporting lower levels of biodiversity (the magnitudes are intended to align with the principles set out by the EICAT and SEICAT Schemes for the impacts of individual alien species)
	3.1 Alien species richness	The number of alien species at a particular site or grid-cell. At a more advanced level this can be broken down into the different introduction stages

Table 1 (continued)

Category	Indicator	Description
	3.2 Relative invasive abundance	The degree to which a site is invaded based on the combined abundance of all organisms from invasive populations relative to the abundance of all organisms
	3.3 Impact of invasions	The combined impact of invasions at a particular site on the delivery of selected ecosystem services or on biodiversity
	4. Level of success in managing invasions	An assessment of overall control effectiveness. It is calculated as the average percentage efficacy of pathway, species, and site interventions in the context of which interventions would be needed to effectively address biological invasions
	4.1 Quality of regulatory framework	An assessment of the degree to which authorities regulate biological invasions in a manner such that, if the measures were fully effective, impacts would be reduced to acceptable levels (an input indicator)
	4.2 Money spent	The monetary inputs into the management of biological invasions (an input indicator)
	4.3 Planning coverage	The degree to which required management interventions are covered by plans, and an evaluation of the quality of the plans themselves (an input indicator)
	4.4 Pathways treated	The degree to which pathways that need to be managed are being managed (an output indicator)
	4.5 Species treated	The degree to which alien species that need to be managed are being managed (an output indicator)
	4.6 Sites treated	The degree to which sites are being managed in terms of biological invasions (an output indicator)
	4.7 Effectiveness of pathway treatments	The degree to which pathway treatments are reducing the rate of introduction and within-country dispersal of alien species (an outcome indicator)
	4.8 Effectiveness of species treatments	The number of alien species that require management that are brought under different degrees of control (an outcome indicator)
	4.9 Effectiveness of site treatments	The number of sites for which the interventions to control biological invasions are effective, or, at a more complex level (as for 4.7–4.9) the return on investment of control operations taking non-target impacts into account (an outcome indicator)

The indicators were developed for reporting on biological invasions at a national level (Wilson et al. 2018) and have been applied in three national status reports for South Africa (van Wilgen and Wilson 2018; Zengeya and Wilson 2020, 2023) with the latest report including a chapter on the PEIs (Fernández Winzer et al. 2023). A detailed factsheet is available for each indicator with information on: the indicator's use and interpretation, potential for aggregation, possible reasons for upward or downward trends, implications for biodiversity management of a change in the indicator, units in which it is expressed, description of source data, calculation procedure, guide for applying confidence levels, most effective forms of presentation, limits to usefulness and accuracy, process for updating the indicator, and links to other indicators (Wilson et al. 2018). The indicators can be calculated at various levels (from basic to advanced), depending on the available data. These indicator factsheets are available at: https://tinyurl.com/5n6fbymh. Additional information is available in the metadata of the species list (see Appendix 2)

from one end to the other in a day. The PEIs are volcanic in origin, and, at between 200,000–450,000 years old, are relatively young islands (Rudolph et al. 2021). Their climate is cool, windy, and oceanic with little seasonal variation in temperature; though the climate has become considerably drier and warmer since climate records started in the 1960s (le Roux and McGeoch 2008; Nel et al. 2023). The soils of the PEIs are generally nutrient-poor, except at the coast and close to seabird nesting colonies, where marine mammals and seabirds deposit nutrients (Smith and Froneman 2008). The coastal areas thus also support the highest biomass of both native and invasive vegetation (Smith and Froneman 2008; Haussmann et al. 2013). Low elevations of the PEIs support tundra vegetation, while high elevations have been classified as polar deserts, and are mostly too harsh to support vascular plants, though they do support sparse bryophyte vegetation (Gremmen and Smith 2008).

For approximately 20 years in the early 1800s, the PEIs were visited by sealers (Cooper 2008; le Roux et al. 2013) but sealing ceased when seal populations were decimated. Subsequently, the islands were infrequently visited for, amongst other things, seal exploitation and scientific exploration (Cooper 2008). In 1947/48 the PEIs were annexed by the South African government, whereafter a permanent weather station was established, which is now a research station (Cooper 2008). The islands are managed by the South African Department of Forestry, Fisheries and Environment (DFFE), with much of the research, including much of the invasion science, funded by the South African National Research Foundation (NRF). The NRF issues grants to scientists, mostly based at South African universities, and the DFFE is responsible for biosecurity and the management of invasive species on the island.

Data collection and calculation of indicators

The indicators were populated using historical data up until 31 December 2023, obtained from the authority that manages the PEIs (DFFE), and information collected from the literature. To assess the trends for the core and high-level summary indicators, we compared data from the last decade with previous data available. To identify the literature containing data to calculate the indicators, the authors first identified relevant papers based on their extensive experience working on these islands, and then examined the studies cited within those papers. Finally, we conducted a systematic literature search using the Web of Science engine on 20 August 2024 to ensure comprehensive coverage. This search yielded 203 studies, including nine that had not been identified in the initial steps (and two that were previously identified but not cited). These additional sources were incorporated into the text (see Supplementary Material for search criteria and details, and Appendix 3 for the output of the Web of Science search, with notes on the decision process for identifying relevant papers).

The data obtained from the literature and other sources was used to populate the species list (Appendix 1). The species list includes, besides scientific names, data for all variables at species level required to populate the different indicators, and in each case, the confidence level and the source(s) of information for each entry. Darwin Core (DwC) terms were used where possible. The species list is accompanied by the metadata (see Appendix 2) that explains the question addressed by each variable (column), a description, possible values, and other relevant details. An updated species list was published on the Global Register of Introduced and Invasive Species (GRIIS; https://griis.org) (Fernandez Winzer et al. 2024), which includes a subset of the variables assessed in this study.

Once the species list was finalised, the indicators were calculated following detailed factsheets published by Wilson et al. (2018; https://tinyurl.com/5n6fbymh), which provide amongst other things, information and guidelines on use and interpretation of each indicator, description of source data, and calculation procedure. As per the factsheets, confidence in the indicator estimates were assessed.

Additional details on how data were collected for pathways, species, sites, and interventions indicators; and calculation of indicators are provided below.

Pathways

For all pathway indicators the introduction pathway classification framework of the Convention on Biological Diversity was used (CBD 2014), with adjustments proposed by Harrower et al. (2018). To estimate the opportunities available for introductions to the PEIs through the pathways (i.e., *introduction pathway prominence*; indicator 1.1) socio-economic data for the pathways were requested from the DFFE. Cargo lists for voyages of the SA Agulhas II, which is the scientific vessel undertaking annual expeditions to Marion Island, were obtained from the DFFE for 2014–2021. From the SA Agulhas II cargo lists, the weight of containers carrying goods to Marion Island were extracted by year, and were classified into: food, machinery, and ‘other goods’ (Fig. S1). Other vessels only rarely visited the island during this time period, e.g. in 2020 a yacht carrying no cargo but some scientists and a documentary crew travelled to Marion Island, while in 2016 food of unknown weight was delivered to Marion Island by another research vessel (Greve et al. 2017). Data for these rare visits by other vessels were not incorporated into estimates. For pathways for which data were not available (e.g., the number of visitors per year), information from the literature search was used for the assessment. The introduction opportunities provided by each of the pathways was classified into the five categories of *introduction pathway prominence* (i.e., not known, pathway not present, minor, moderate, and major). Introduction pathway prominence is an estimate of the size of the pathway to the region of interest rather than what has travelled along it (or what could in light of biosecurity interventions). Regulations governing the transport of organisms and goods were used to assess the current prominence of commodity pathways (deliberate introductions are now prohibited, meaning that these pathways no longer exist). Other pathways were scored using the above socioeconomic data. Because the scoring of this indicator is an expert opinion call and the indicator factsheets in Wilson et al. (2018) do not define what minor, moderate, and major mean (as they are context dependent), a set of criteria were defined to aid in the decisions and make the process more transparent and repeatable (see Supplementary material Table S3). Confidence was scored following Wilson et al. (2018).

To calculate *introduction rates*; indicator 1.2), the number of species introduced per pathway), the literature was consulted to ascertain the introduction pathway for each species, and, if these pathways were available, they were categorised according to the CBD pathway classification framework. The number of species that have been introduced per pathway was tallied. Species for which pathways are not known were excluded from this analysis. *Within-country pathway prominence*, or the opportunities for dispersal within and between the two islands per pathway; (indicator 1.3), was scored according to Wilson et al. (2018). Information from the literature search was used for these estimates. Information from the literature was also used to identify pathways that are likely facilitating the dispersal of alien species within and between the islands (i.e., *within-country dispersal rates*, indicator 1.4), but the number of species dispersing through each pathway could not be calculated as very little has been published on the within-island dispersal of alien species. Data collected from the literature on the year each species was first recorded on the islands were used to estimate the *rate of unregulated introduction of new species*; (indicator 1). To predict whether introduction rates are likely to change in the near future, changes in the recent (last 10 years) rate of unregulated introductions of new species, information on current management (DEA 2010), and details from DFFE regarding potential changes to practices were used.

Species and sites

To compile a list of taxa that have been introduced to the PEIs, a wide variety of published papers and books, grey literature (e.g., government reports), and expert opinion (from researchers and government staff) were consulted. This allowed an estimation of the *number and status of alien species* (indicator 2.1). The PEIs have a rich history of publications which provide lists and new records of invasive species (e.g. Bergstrom and Smith 1990; Hänel et al. 1998; Chown et al. 2002; Greve et al. 2017); many of these were published by a fairly small group of authors who have been, and still are, well-connected. All older literature on the PEIs is consolidated in the last published comprehensive bibliography of the islands (Hänel and Chown 1999), and more recent literature was extracted from search engines.

Greve et al. (2017) was used as a baseline for the list of introduced taxa (see Appendix 1). This list was supplemented and corrected using information from the above-mentioned sources. Scientific names were checked against several taxonomic backbones and standardised: for plants, the scientific name follows the Botanical Database of Southern Africa (BODATSA, https://posa.sanbi.org/; accessed August 2022–May 2023), and if a name was not present in that database, Plants of the World Online (POWO, https://powo.science.kew.org/; accessed August 2022–May 2023). For all other taxa, the Global Biodiversity Information Facility backbone was used (https://www.gbif.org/dataset/d7dddbf4-2cf0-4f39-9b2a-bb099caae36c; accessed August 2022–May 2024). The resultant species list was checked against the 2020 GRIIS list for the PEIs (Pagad 2020), and the list from Leihy et al. (2023). There were some ambiguities and contradictions across the various lists [e.g. *Salvelinus fontinalis* (Mitchill 1814) was listed as introduced to Marion Island in a review of the freshwater fauna of the southern polar regions (Dartnall 2017), but not in the primary literature; Dartnall (2017) cited Cooper et al. (1992)]. In such cases, experts (e.g., John Cooper, Steven Chown) were consulted for clarification.

Extent of alien species (indicator 2.2) was obtained in half minute grid cells (hmgc; approximately 0.59 km^2 each), from le Roux et al. (2013), Mairal et al. (2022) and DEA (2010). Charles Hope, DFFE Assistant Director of Environmental Resource Management, provided up to date maps of extent of invasion in hectares for three plant species: *Agrostis gigantea* (black bent grass), *Luzula multiflora* (woodrush), and *Rumex acetosella* (sheep sorrel). The hectare values were then converted into hmgc for these species and added to the species list (See Appendix 1; column 'RangeHMGC' for values of extent per species; and Supplementary material to see the DFFE maps).

To estimate the *abundance of alien species* (indicator 2.3), occurrence and cover data were obtained for plants from Greve and le Roux (some unpublished data, also van der Merwe et al. 2023) and/or le Roux et al. (2013). Invertebrate abundance data were extracted from the literature that provided quantitative estimates of the abundance of species at multiple sites (with data presented at the species-level; e.g., Khoza et al. 2005; Hugo et al. 2006). Where abundance data were also presented for native species, the *relative invasive abundance* of invasive species was also calculated (indicator 3.2), the proportion of the total abundance or cover comprised by individuals from invasive species) was also calculated.

In order to estimate the *impact of alien species* (indicator 2.4), impact assessments conducted according to the EICAT (Environmental Impact Classification for Alien Taxa) procedure (IUCN 2020a, 2020b) and presented in Greve et al. (2017) were used, and updated if required (see Appendix 1; column 'impactEICAT-PrinceEdwardIslands' for impact assessment results per species, metadata in Appendix 2 for definition of EICAT categories, and Supplementary material for extended detail on the procedure followed for the impact assessments). Note that the assessments considered here are based solely on studies conducted on the PEIs, while standard EICAT assessments are typically based on global data. After assessing indicator 2.4, the higher-level indicator *number of invasive species that have 'Major' impacts*; indicator 2) can be calculated by adding together the number of species that received 'Major' or 'Massive' impact scores.

Alien species (richness indicator 3.1) was assessed for plants by comparing the richness between habitats on Marion Island and Prince Edward Island, and relating richness to elevation and proximity to the coast. The main source used to assess this indicator was le Roux et al. (2013) and Gremmen and Smith (2008) was also useful, while for invertebrates the only data found on richness were from for Chown et al. (2005). Given that we do not have data per sample for invertebrate richness, we can only give total alien richness (not local richness).

To estimate the *impact of invasions* (indicator 3.3) we searched for studies that reported data on the collective impacts of multiple species, rather than focusing on the impact of individual alien species, as specified by Wilson et al. (2018). Lastly, to calculate the *extent of area that suffers 'Major' impacts from invasions*; indicator 3), data was required on the distribution of all species with major impacts (Wilson et al. 2018).

Interventions

The latest management plan for the PEIs (DEA 2010), which sets out regulations for pathway treatments, was consulted. This was supplemented with information on interventions obtained from DFFE, with data on all nine indicators concerning interventions. This includes money spent on management of alien species on the PEIs (*money spent*, indicator 4.2), data on management and eradication plans *(planning coverage,* indicator 4.3), plus pathways, species, and sites treated and what is the effectiveness of these treatments (indicators 4.4–4.9).

To assess the *quality of regulatory framework* (indicator 4.1), we consulted the South African 'Alien and Invasive Species (A&IS) Regulations of the National Environmental Management: Biodiversity Act' (NEM:BA) of 2020 regarding alien species on the PEIs (Wilson & Kumschick 2024). This exercise aimed to identify which species present on the islands are regulated and in which category (eradication target, management target or not listed). Additionally, we examined species for which an eradication plan has been developed, considered their introduction status, and noted whether they are being monitored or treated. Relevant information on control measures implemented was also gathered.

For *planning coverage* (indicator 4.3) and *pathways treated* (indicator 4.4), the two management plans available (PEIMPWG 1996 and DEA 2010) were scrutinised. The DFFE provided yearly updates on eradication plans including which species are managed and how, as well as progress (*species treated,* indicator 4.5; and *effectiveness of species treatments,* indicator 4.8). As there was no standard for reporting this information (nor detailed standardised field protocols for surveying for species of interest), it was not possible to estimate trends across the study period. For details see Appendix 1: Species list, and Appendix 2 for corresponding metadata.

All written reports submitted by overwintering environmental control officers (ECOs) and independent consultants to DFFE that were made available to the authors were examined for information of which sites were treated and the effectiveness of those interventions (*sites treated,* indicator 4.6; and *effectiveness of site treatments,* indicator 4.9). Note that for the PEIs, the number of sites is two, namely Marion Island and Prince Edward Island.

Information on *money spent* (indicator 4.2) was obtained from a DFFE staff member (Debbie Muir) in relation to equipment to control invasive species, including personal protective equipment, and herbicides (two types); plus a report on a control exercise provided by a fieldwork manager at Stellenbosch University (Suzaan Kritzinger-Klopper) with costs of human resources and helicopter trips to remove plant material (more details on exact costs are in Supplementary S4.2, Fig. S9).

The *effectiveness of pathway treatments* (indicator 4.7) was evaluated by assessing which indicators previously present or active are no longer present. Additionally, information on alien species detected on the ship heading to the PEIs and on the island in recent years was included as a proxy for effectiveness. For instance, if new alien species were detected despite the management of pathways, then the score cannot be considered 'Effective'.

To assess the *level of success in managing invasions* (indicator 4), the proportion of pathways, species, and sites that require management and where a plan is in place was calculated. For pathways, species, and sites where treatments were applied, their effectiveness was evaluated as either: a) counter-productive, b) none/ineffective/not known, c) partial, or d) effective or permanent.

Results

Pathways

Introduction pathway prominence (indicator 1.1)

There are few pathways through which alien species can be introduced to the PEIs (Table 2). The SA Agulhas II, a ship owned by the South African government, usually travels to Marion Island from South Africa once a year during the relief voyage to bring people, food, and supplies to the island, and taking waste and people back to South Africa (Fig. S1). The SA Agulhas II is the only transport vessel that regularly visits the islands, with visits by other vessels occurring rarely. All travel to the PEIs, including by vessels other than the SA Agulhas II, must be approved by the DFFE. Helicopters transport people and supplies from the ship to the island. There are no permanent residents on the islands, and tourism is prohibited. People can overnight on Marion Island, with a limit of 80 people. Approximately 20–30 scientists and support staff inhabit Marion Island year-round, with these inhabitants changing yearly during the SA Agulhas II relief voyage (Greve et al. 2017). During the relief voyage, an additional set of people (~50–60) are brought to Marion Island to perform research or maintenance to the scientific station over approximately four weeks. On occasion some of the researchers visit research huts around Marion Island to perform field work, but as all accommodation and laboratories are at the research base, most activity occurs there. No-one lives on Prince Edward Island, and visits are strictly controlled, with a maximum of ten expeditioners permitted to visit for a period of eight days, at most once every four years (though during the most recent voyage in 2023, 13 people were permitted onto the Prince Edward Island as no expedition had taken place for more than a decade). No fresh produce may be brought to the islands. Fishing within 12 nautical miles of the islands is prohibited, but there are parts of the MPA around the islands where limited fishing is allowed (Whitehead et al. 2019). As of 2019, only two vessels had permits to fish in the area (Whitehead et al. 2019). Although no estimates of illegal fishing have been provided to the Conservation of Antarctic Marine Living Resources (CCAMLR) Secretariat since 2011, they suggest that undetected illegal fishing may still occur. Evidence includes the recovery of

Table 2 Pathways along which alien species have (or could be) introduced to the Prince Edward Islands (PEIs)

Mechanism of entry	Pathway category	Pathway subcategory	*Introduction pathway prominence*	Confidence of *introduction pathway prominence*	Number of taxa introduced *(introduction rates)*
Commodity	Release	Biological control	Pathway no longer present	High	4
		Fishery in the wild	Pathway no longer present	High	2
		Hunting	Pathway no longer present	High	2
		Landscape improvement	Pathway no longer present	High	3
	Escape	Pet	Pathway no longer present	High	8
		Farmed animals	Pathway no longer present	High	5
Transport vector	Contaminant	Food contaminant	Moderate	Medium	10
	Stowaway	Fishing equipment	Minor	Low	0
		Container and bulk cargo	Moderate	Medium	0
		Ship (excluding ballast water or hull fouling)	Minor	Medium	3
		Airplane (helicopter)	Minor	Low	0
		Machinery & equipment	Minor	Low	8
		People & luggage	Moderate	Medium	1
		Ballast water	Minor	Medium	0
		Hull fouling	Minor	Medium	0
Natural spread	Unaided	Natural dispersal	Minor	Low	1
Not known			NA		57

Some taxa are no longer present, including all those that were released or escaped. The introductions have been classified into corresponding pathways according to the framework proposed by the Convention on Biological Diversity (CBD 2014), with adjustments proposed by Harrower et al. (2018). Some species have more than one pathway, and some species were introduced more than once; hence, numbers across the pathways do not equate to the total number of species introduced to the PEIs. The table only represents dispersal events to the PEIs and does not represent dispersal events within and between the islands. *Introduction pathway prominence* Makes sense to have the links in the table legend so stand-alone, but rest of the text it is unnecessary. indicator 1.1) is a measure of the introduction opportunities provided by the pathways (not known, pathway not present, minor, moderate, major) and is estimated using socio-economic data. The extent to which these opportunities result in the introduction of alien taxa [*introduction rates* (Table 1; indicator 1.2)] depends on pathway management and biosecurity. See Fig. S1 for the data obtained from DFFE to estimate *Introduction pathway prominence*, and Table S3 for criteria to apply minor or moderate scores)

fishing gear from illegal fishing vessels in neighbouring areas and unconfirmed reports of illegal fishing activity (CCAMLR Secretariat 2023).

Introduction rates (indicator 1.2)

Strict biosecurity measures are in place to prevent accidental terrestrial and marine introductions (see below), but such actions are not perfect (Table 2, Fig. 1). Although the exact introduction pathway for most alien species is not known (57 out of 96) (Greve et al. 2017), most recent introductions have been accidental as stowaways in containers and bulk cargo, and with people and their luggage (Table 2). For example, alien plant seeds and live insects have been found in, or on, shipping containers and the expeditioner's belongings (Lee and Chown 2009a).

In addition, although no alien marine organisms have been recorded and action is taken to prevent hull-fouling, organisms, some invasive elsewhere, were recorded on the hull of the SA Agulhas, the ship used to visit the islands up until 2012 (Lee and Chown 2007, 2009b). Introduction pathways to the PEIs have changed considerably over time (Table S4). In the past, several alien species were intentionally introduced to the PEIs; these included animals for food from the early 1800s until the 1960s (Cooper 2008); trees in the 1950s and 1960s (La Grange 1954); and some pets (Watkins and Cooper 1986). One of the most consequential deliberate introductions was that of the cat *Felis catus* to Marion Island in 1949. Cats were introduced to the meteorological base to provide companionship and to control mouse populations within the base (Bloomer and Bester 1992; Bester et al. 2000; Cooper 2008). The cats reproduced and escaped from the base, feeding extensively on native birds while having seemingly limited impacts on mouse populations (van Aarde 1980). A biological control agent, the feline panleucopaenia virus, was released in 1977 to control cat populations (Bester et al. 2002). There have been no intentional introductions to the islands since 1964, when *Salmo trutta* (brown trout) was released (Cooper et al. 1992), and notably none of the species that were intentionally introduced are still present. Intentional introductions, i.e. the release and escape pathways, are prohibited (DEA 2010) and have been since the 1980s when an informal code of conduct was implemented (Cooper and Condy 1988). The introduction of alien organisms as stowaways on transport vectors has occurred since humans started visiting the PEIs in the early 1800s (Cooper 2008), and these probably remain the most prominent pathways in terms of their potential to introduce new species. In all, six pathways that were present in the past are no longer active due to biosecurity regulations (Table 2).

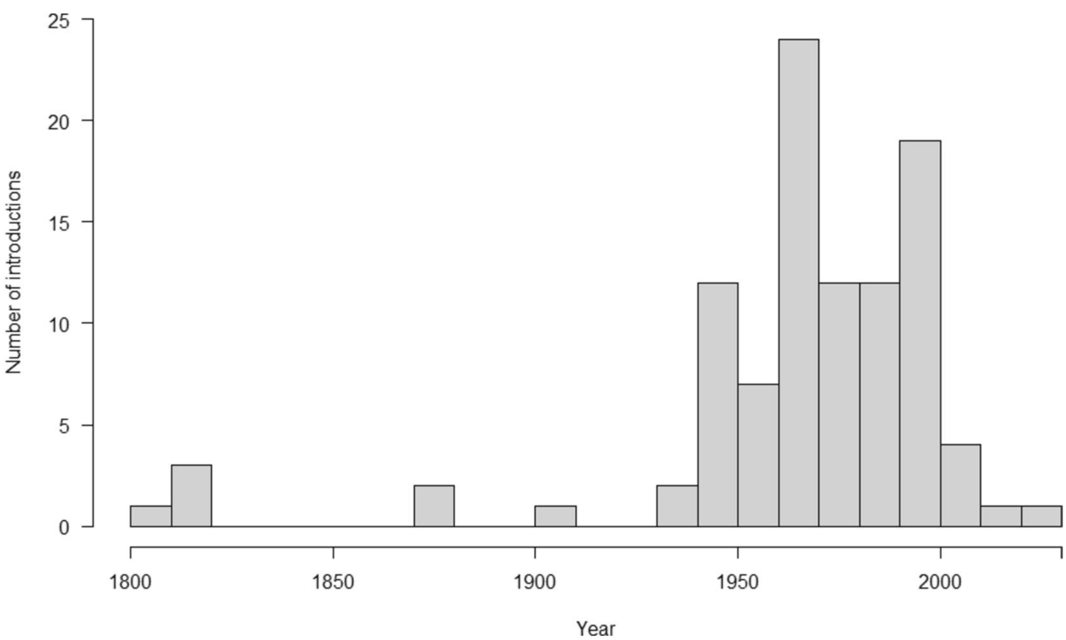

Fig. 1 Number of new alien taxa recorded on the Prince Edward Islands (PEIs). The data are grouped here by decade as sometimes the date of first record is uncertain. Detections from the most recent two decades are thought to be an underestimate compared to the preceding two to three decades due to the loss of taxonomic expertise from the research programmes active on the PEIs. The pattern seen here is thus likely to be only a partial reflection of introduction rates (McGeoch et al. 2023). Search effort has likely varied markedly over time (depending on the presence of scientists and specifically field scientists trained to identify particular taxa), though it will be difficult to estimate this systematically, meaning adjustments for search effort to determine actual introduction rates will likely be unreliable (Buba et al. 2024)

Rate of introduction of new, unregulated taxa (indicator 1)

The rate at which new species have been detected has changed over time, with two peaks, first in the late 1940s after the PEIs were annexed by South Africa, and second when the research base on Marion Island was constructed (Fig. 1). Since the early 2000s the number of new alien taxa recorded on the islands has been relatively low and stable (an average of < 1 per year). This decline coincides with the implementation of strict biosecurity regulations (see below). Recently reported alien species include house and fruit flies, crickets, and various plant propagules and, most recently (2022), a cockroach, that is yet to be identified to species level (Greve pers. obs.). As most introductions occur at the research base on Marion Island, where biologists are stationed, there is likely to be a short delay between an introduction to Marion Island and its detection. Nonetheless, the rate of unregulated introduction (illegal, intentional; and accidental introductions) is not known, as some detected individuals are destroyed before they can be identified, and those that are identified are often not identified to the species level. However, it is very unlikely that there is a large difference between our estimates and the true introduction rate (since, e.g., tens to hundreds of unaccounted for alien species are not being introduced to the islands). Little is known about the historical and current introduction of micro-organisms.

Within-country pathway prominence (indicator 1.3)

Once transported to the islands, the pathways through which alien species can spread within or between the islands are limited (Table S5). Human-assisted dispersal is likely to be one of the most common pathways on Marion Island. Expeditioners traverse the island on foot as part of their work and, once a year, supplies are transported in shipping containers by a helicopter to the research base and huts. It is possible that alien species are accidentally transported during these activities. The extent to which people move around the island has not been quantified, and thus neither has the potential for expeditioners to spread alien species. However, supplies are infrequently transported around Marion Island, there are currently relatively strict biosecurity measures in place, and a steel helicopter pad has been constructed at the research base to reduce the transport of propagules from the base to field huts (DEA 2010). Therefore, the opportunities for spread provided by re-stocking activities are currently relatively low. In contrast, the frequent strong winds and many seabirds likely provide opportunities for the natural dispersal of invasive plants (Ryan et al. 2003; see also Mazibuko et al. 2024).

Within-country pathway dispersal rates (indicator 1.4)

The extent to which these opportunities result in the spread of alien species is unclear. Seeds from alien plant species have been found on the clothes of expeditioners returning from the islands (Lee and Chown 2011); and the spread of *Sagina procumbens* (birdeye pearlwort) from the research base to elsewhere on Marion Island was likely facilitated by re-stocking activities (Gremmen and Smith 1999). Alien taxa on Marion Island have naturally dispersed to Prince Edward Island (Ryan et al. 2003); and on Prince Edward Island, where humans are absent for years at a time, the spread of alien plant species has been rapid (le Roux et al. 2013), with the dispersal of invasive plants [e.g., *S. procumbens* and *Poa annua* (annual meadow grass)] attributed to passive dispersal by wind and by seabirds (Ryan et al. 2003). This suggests that natural dispersal is important for alien plants on the islands, and is likely a common pathway of dispersal.

Species

Number and status of alien species (indicator 2.1)

There are 45 alien species currently present on the PEIs. Of these, 25 are invasive (56%), 15 are naturalised (but not invasive, 33%), and five cannot be categorised as their introduction status is unclear (11%) (see Appendix 1 for a complete list of species; Fig. 2). 92 alien taxa have been recorded as present at some point on the islands, but 42 (46%) are now absent, either because they did not survive (e.g., trout), or they were eradicated (e.g., cats). Five species are recorded as doubtful as they are being monitored to confirm eradication [one invertebrate: *Porcellio scaber* (woodlouse); and three plant species: *Alopecurus geniculatus* (marsh foxtail), *Holcus* *lanatus* (common velvet grass), and *Stellaria media* (common chickweed)].

Two spider species of the *Myro* genus that were recorded as alien (Watkins and Cooper 1986) have been recategorised as native (Chown and Froneman 2008). Similarly, *Ochetophila trinervis* was thought to be alien, but more recent research has shown that seeds of the plant were likely brought by vagrant birds travelling from South America (the plant's native range), and as this is a natural dispersal event, the plant is classified as native (Kalwij et al. 2019). Finally, two taxa are cryptogenic (Cillibidae and *Dendrolaelaps* spp.), given that specialists cannot determine if they were introduced or were already present on the islands when the first humans arrived (Marshall et al. 1999; Hugo et al. 2006; Chown and Froneman 2008).

No species are currently in captivity or under cultivation, but in the past animals were kept as a food source [chickens, sheep, domestic pigs and goats; (Watkins and Cooper 1986)]. Of the 25 invasive taxa, the majority are invertebrates (17 taxa), followed by plants (six taxa), mammals (one taxon) and fungi (one taxon) (see Supplementary Material Fig. S2). No alien birds, reptiles or amphibians have been recorded to date. All alien species are either terrestrial or freshwater; no marine alien taxa have been recorded to date despite sampling efforts (Greve et al. 2020).

Extent of alien species (indicator 2.2)

Some alien species are widely distributed across both islands, with *S. procumbens* being the most widespread (Fig. 3a), recorded in 166 half-minute grid cells, followed by *P. annua* (204 hmgcs) and *Cerastium fontanum* (mouse-ear chickweed; found in 162 hmgcs) (DEA 2010; le Roux et al. 2013; Mairal et al. 2022). Additionally, the invasive springtail *Pogonognathellus flavescens* has expanded its distribution to higher elevations, possibly due to climate change related increases in temperature (Kgopong 2019). Further details can be found in Appendix 1.

Abundance of alien species (indicator 2.3)

Unsurprisingly, the two alien plants with the largest extent on the islands are also the most abundant: *S. procumbens* (mean cover = 0.90%), and *P. annua* (0.39%), followed by *Agrostis stolonifera* (creeping bent grass; 0.10%), *C. fontanum* (0.07%), and *Poa pratensis* (Kentucky bluegrass; 0.04%).

The abundance of invasive (and cryptogenic) invertebrates exhibits significant variation across habitat types and, on Marion Island, with elevation (Fig. S8). Specifically, invasive springtails are most abundant in mires characterized by *Sanionia uncinata*, with densities reaching over 40,000 individuals/m^2, while alien and cryptogenic mites prefer salt-spray vegetation dominated by the native *Cotula plumosa*, where densities of > 2500 individuals/m^2 have been recorded (Fig. S8). On Prince Edward Island, *C. plumosa*-dominated salt-spray vegetation harboured the highest concentration of alien and cryptogenic mites (~ 15,000 individuals/m^2), whereas invasive springtails were found on slopes covered by the native *Blechnum penna-marina* fern, reaching a density of 234 individuals/m^2.

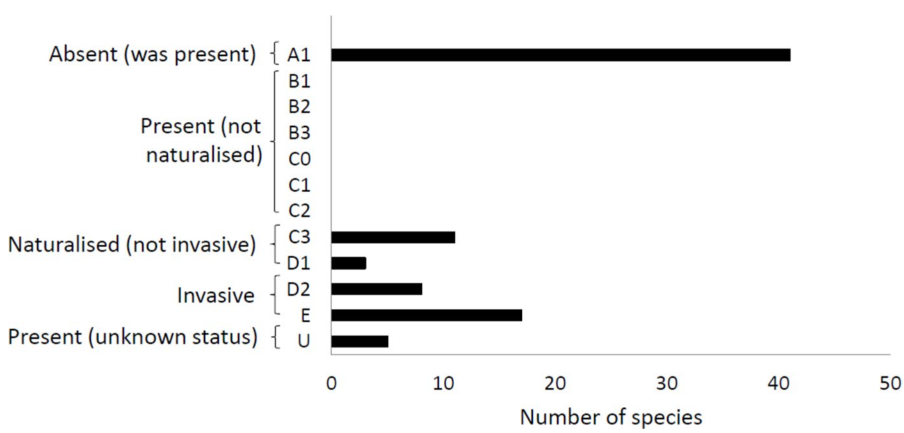

Fig. 2 The number and status of alien taxa introduced to the Prince Edward Islands as per the Unified Framework for Biological Invasions (Blackburn et al. 2011). Taxa that were present in the past but are currently absent (A1) are included. See Supplementary Material Fig. S2 for a break-down into functional groups

The densest known mouse population on Marion Island are ~230 mice/ha, which was measured in lowland mires between 2008 and 2011, culminating in a total estimated population size of 1.76 million mice at lowland elevations (below 300 m a.s.l.) (McClelland et al. 2018; Fig. 3b). The annual peak density of mice experienced a 430% increase over the thirty-year period from 1979–1980 to 2008–2011 (McClelland et al. 2018).

Impact of alien species (indicator 2.4)

The impacts of specific invasive taxa have been documented in limited instances on Marion Island. For example, studies have quantified the effects of the now-eradicated *F. catus* (Van Rensburg and Bester 1988; Hunter 1990; Cerfonteyn and Ryan 2016; Connan et al. 2022), as well as *Mus musculus* (house mouse) (Crafford 1990; Jones et al. 2019), the grass *A. stolonifera* (Gremmen 1997; Gremmen et al. 1998), and the parasitic wasp *Aphidius matricariae* (Lee and Chown 2016). Environmental impacts have been estimated following the guidance of the EICAT scheme for 20 of the taxa currently present on the PEIs (Table 3). However, these EICAT assessments have not been formally reviewed and, therefore, the confidence in them (as specified in the indicator factsheets) is medium.

The house mouse stands out for its significant impacts, categorised as 'Massive'—defined as causing at least local extinction of species and irreversible changes in community composition; even if the alien species is removed, the system does not recover its original state. Present exclusively on Marion Island, this species has caused havoc at both ecosystem and species levels. Its detrimental effects extend to the island's sole shorebird (Huyser et al. 2000), as well as various seabird species (Jones and Ryan 2010; Dilley et al. 2017; Jones et al. 2019), native vegetation (Phiri et al. 2009), and invertebrate populations (McClelland et al. 2018). Notably, the house mouse has adversely affected the survival and reproduction of plant species such as *Azorella selago* and *Uncinia compacta* (Phiri et al. 2009; Chown and Smith 1993), while also impacting invertebrate abundance, biomass, and body size (Crafford and Scholtz 1987; Chown and Smith 1993; Treasure and Chown 2014; McClelland et al. 2018), and the survival of albatross chicks (Jones and Ryan 2010; Dilley et al. 2017). There is also indirect evidence of mice potentially being a disease vector. The deaths of hundreds of fur seals in 2007 on Marion Island, might have been caused by novel bacteria (*Streptococcus* and *Helicobacter* species) the mice on

Fig. 3 Examples of invasive taxa on Prince Edward Island (PEI: **a**, **d**) and Marion Island (MI: **b**, **c**). **a** *Sagina procumbens* (birdeye pearlwort) in light green invading a habitat that was previously dominated by *Azorella selago*. **b** *Mus musculus* (house mouse) damaging the native cushion *A. selago*. **c** *Deroceras panormitanum* (European slug); and **d** *Isotomurus maculatus*, an invertebrate already present on MI, recorded for the first time on PEI in November 2023. Photographs: **a**, **d** Charlene Janion-Scheepers; **b**, **c** Elsa van Ginkel

the island carry, which are known to cause zoonotic diseases (de Bruyn et al. 2008; Candice 2011). Furthermore, mouse burrowing behaviour alters sediment movement rates (Eriksson and Eldridge 2014) and likely influences nutrient cycling (Crafford 1990; Smith and Steenkamp 1990). Recent evidence indicates a shift in mouse behaviour, with instances of predation on seabird chicks and even attacks on adult seabirds have been recorded, including the killing of adult albatrosses (Jones et al. 2019; Connan et al. 2023). The escalating impact of mice on seabirds underscores the urgency of eradication efforts.

Additionally, three invasive plant species have caused 'Major' impacts—defined as changes in community composition that are reversible upon removal of the alien—on native vegetation and soil fauna communities (Gremmen 1997; Gremmen et al. 1998). Information on the impacts of alien terrestrial invertebrates remains minimal; out of 28 species, impact data are available for only six species (see Appendix 1 and Supplementary material S3 for details). Finally, the fungal ascomycete *Botrytis cinerea* may potentially affect the distribution and abundance of the native Kerguelen cabbage (*Pringlea antiscorbutica*) (Kloppers and Smith 1998), which is also affected by the invasive diamond-back moth *Plutella xylostella* (de Villiers and Cooper 2008).

Number of invasive species that have 'major' impacts (indicator 2)

Four species on the PEIs were found to have 'Major' or 'Massive' impacts. Three plant species were identified as having 'Major' impacts, namely *Agrostis stolonifera*, *Festuca rubra* and *Sagina procumbens*. *Agrostis stolonifera* was found to cause impacts on other vegetation as well as on soil invertebrates (see Gremmen et al. 1998). Chown and Froneman (2008) stated that *F. rubra* can form dense stands that smother the native vegetation. Finally, *S. procumbens* has altered ecosystem function on MI and is expected to have a similar effect on the neighbouring Prince Edward Island (Ryan et al. 2003). The house mouse is the species that has 'Massive' impacts, and details can be found in the previous section (indicator 2.4).

Sites

Alien species richness (indicator 3.1)

The richness of alien plant species on Marion Island is highest in areas with human activity and disturbances (both contemporary or historic), including the research station and field huts (particularly in the northern and eastern coastal areas; le Roux et al. 2013). The highest alien plant species richness was at the research station, with eight species recorded within the corresponding half-minute grid cell (hmgc). The alien vascular plant species richness is lower at higher elevation on Marion Island (although alien plants have been moving upslope since the 1960s; Chown et al. 2013). The richness of alien plant species is lower on Prince Edward Island, with at most three alien plant species recorded per hmgc, and higher richness at the coast and along the escarpment on the north-west of the island (le Roux et al. 2013).

While the richness of alien plant species is relatively low on the PEIs, alien plants do have a broad distribution with alien plant species occurring in 53% of Prince Edward Island's hmgcs and slightly fewer

Table 3 The number of alien taxa currently present on the Prince Edward Islands (PEIs) with different levels of recorded environmental impact. Taxa were assigned to various categories of impact based only on studies from the PEIs (Greve et al. 2017). Note that *Stellaria media* was included, even though its presence is currently doubtful. For the full details of which taxon scored which impact see Appendix 1

Taxon	Magnitude of environmental impact					
	Data deficient	Minimal	Minor	Moderate	Major	Massive
Mammals	0	0	0	0	0	1
Microbial species	0	0	0	1	0	0
Terrestrial and freshwater plants	4	4	2	3	3	0
Terrestrial invertebrates	22	0	5	1	0	0

(42%) of Marion Island's hmgcs (likely due to a much larger proportion of Marion Island comprising of high elevation polar desert, which lacks native or alien vascular plant cover). Nonetheless, across both islands the cover of alien plants is low (<5% of the PEIs; Gremmen and Smith 2008). Indeed, recent surveys of 501 quadrats of 3×3 m on Marion Island (largely excluding polar desert habitats) suggest alien plant cover was typically only high in coastal quadrats, and less than 4% of quadrats had alien plant cover exceeding 20% (Greve unpublished data). Given that these plots cover only a small percentage of the island, confidence in this estimate is low. There is spatial variation in relative invasive abundance across Marion Island. Coastal habitats are generally more invaded than inland habitats.

The richness of alien invertebrates was found to positively covariate with the richness of native invertebrates on Marion Island (Chown et al. 2005).

Relative invasive abundance (indicator 3.2)

Native plants are more abundant than alien plants, with native plants on average having 54.6% coverage, while bare ground and rock cover accounts for 42.8%, and alien plants just 2.6%, based on plot data from across Marion Island (Greve and le Roux, unpublished data).

The relative abundance of alien invertebrates (i.e. their abundance relative to native species of the same taxon) differed strongly between habitats, with adequate data for springtails and mites across the PEIs, and other taxa less extensively surveyed (Fig. 4). The relative abundance of alien springtails was low on Prince Edward Island (0–2%) but considerably higher on Marion Island (mean = 28%, range = 0–90%), with the highest relative abundance in bryophyte- and fern-dominated habitats and at lower elevations (Treasure et al. 2019; Chown et al. 2022). Alien mite species showed similar patterns with lower relative abundance on Prince Edward Island (mean = 8%, range = 0–26%; Hugo et al. 2006) than on Marion Island (mean = 14%, range = 3–38%; Barendse et al. 2002). The relative abundance of these alien mite species varied considerably between habitats, but not in a predictable manner (e.g., relative abundance was low in the *Crassula moschata*-dominated saltspray vegetation on Marion Island, but high in this same habitat on Prince Edward Island). Taxonomic uncertainty, specifically about the status of a mite species from the Cillibidae family, does add substantial doubt to these numbers as the Cillibid species may comprise >95% of individuals in some samples from Marion Island.

Spiders and isopods have been much less extensively sampled on Prince Edward Island. The absence of native isopods means that the alien *P. scaber* (if still present) comprise all isopods. Data from the eastern sector of Marion Island shows alien spiders comprise c. 37% of all spiders, but relative invasive abundance varies considerably (range = 0–98%; Khoza et al. 2005), and is higher at lower elevations.

Impact of invasions (indicator 3.3)

Studies documenting the impacts of invasive species on biodiversity on the PEIs have found varying results. The grass *A. stolonifera* has a negative impact on native plant richness and biomass, but a positive impact on the richness of macroinvertebrates and mites (Gremmen 1997; Gremmen et al. 1998). Within Marion Island, Gabriel et al. (2001) found native springtail richness and abundance unaffected by alien springtails. However, when comparing the PEIs with the uninvaded Heard Island, data suggested that these invasive springtails can strongly negatively impact the abundance of native springtail species (Chown et al. 2022). This last finding is mirrored by studies comparing Marion Island and Prince Edward Island, with the mouse-free (and overall less alien species-rich) Prince Edward Island having significantly higher native invertebrate biomass (Crafford and Scholtz 1987). To date, no studies have looked at the impacts of invasions on ecosystem services or monetary impacts on the PEIs.

Extent of area that suffers 'Major' impacts from invasions (indicator 3)

Due to the severity of impacts not being known for the majority of species and the distributions not being accurately documented for most alien taxa, this indicator could not be calculated.

Interventions

There are nine indicators for interventions, that we present next in a concise manner due to the extensive nature of the data. More detailed information

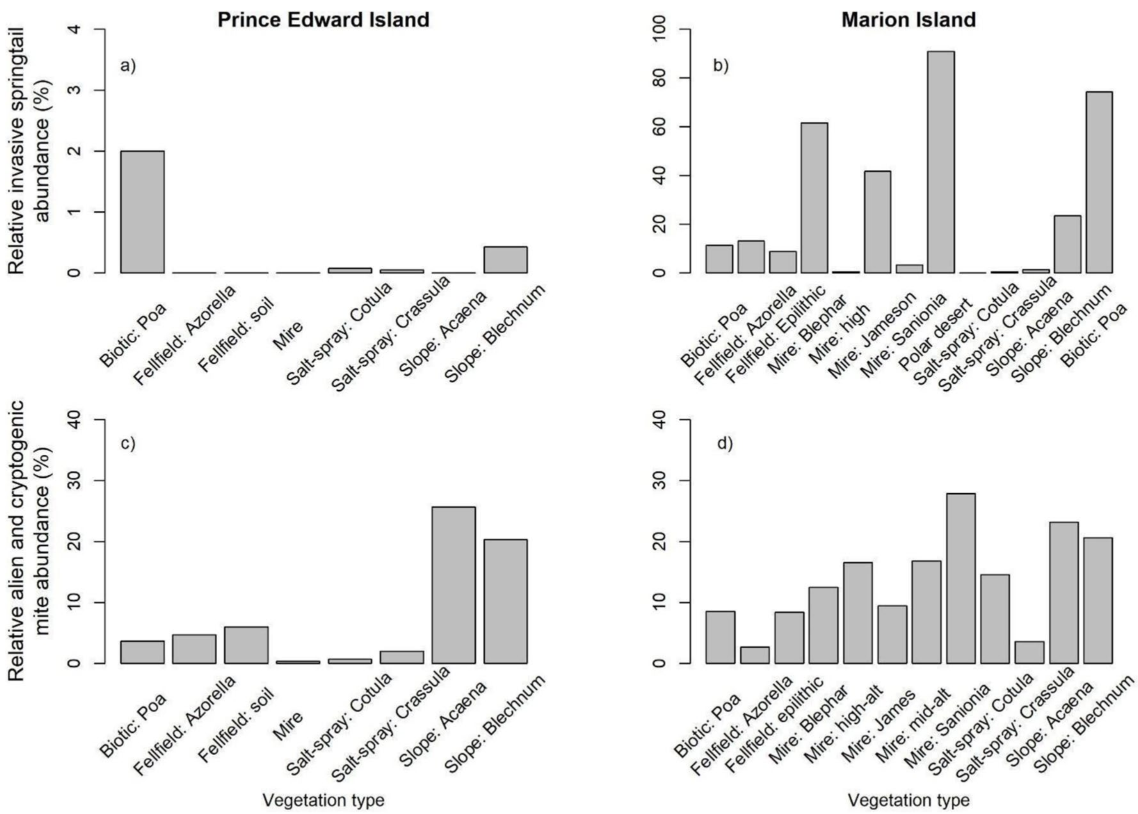

Fig. 4 Relative abundance of: **a** invasive springtails on Prince Edward Island; **b** invasive springtails on Marion Island; **c** alien and cryptogenic (i.e., uncertain origin) mites on Prince Edward Island; **d** alien and cryptogenic mites on Marion Island. Labels on the x-axis indicate vegetation type and, where appropriate, the plant species or the elevation sampled within the vegetation type—Biotic: Poa = Biotic grassland and herb field (*Poa cookii*); Azorella = *Azorella selago*; Salt-spray = Coastal salt-spray; Cotula = *Cotula plumosa*; Crassula = *Crassula moschata*; Acaena = *Acaena magellanica*; Blechnum = *Blechnum penna-marina*; Blephar = *Blepharidophyllum densifolium*; high-alt = high-elevation; James = *Jamesoniella colorata*; mid-alt = mid-elevation; Sanionia = *Sanionia uncinata*. Note that the y-axis limits differ between panels

on status and trends can be found in Table 4 and a comprehensive overview in Supplementary material (S4.1–S4.7).

The *quality of regulatory framework* (indicator 4.1) is considered partial, as not all invasive species are regulated, and not all regulated species are being controlled.

The *money spent* (indicator 4.2) on controlling invasions by the DFFE is known in some detail. This information forms part of the reported costs of management (see Supplementary material S4.2 and Fig. S9), noting that the current amount spent on management is an underestimate as a full value was not provided.

Sites have the largest *planning coverage* (100%; indicator 4.3), as both Marion Island and Prince Edward Island are included in the latest, now outdated, management plan (scheduled for revision every four years; DEA 2010). Nine out of ten active pathways have a management plan in place (90%), as 'fishing equipment' is not considered in DEA (2010). Lastly, 12 out of 45 alien species are included in the DFFE eradication plan (26%), which is updated annually.

Regarding *pathways treated* (indicator 4.4), biosecurity measures manage most pathways for accidental introduction of alien species, except for fishing equipment (from commercial fisheries) and natural dispersal (i.e. 'unaided' pathway) (DEA 2010). Of the 13 listed alien taxa (12 plant species and one mammal), eight plant species are treated *species treated,* (indicator 4.5), either through direct control or via monitoring to confirm eradication in all the areas where they are present, while mice are only controlled at the base and huts (see Table 4 and S7). Given that no control occurs on Prince Edward Island, *treated* (indicator 4.6) was scored as 50%.

In relation to the *effectiveness of pathway treatments* (indicator 4.7), there have been no recorded marine introductions to date, which may be attributed in part to the effective management of ballast water and hull fouling, as well as notable differences between the marine environment (e.g., seawater temperatures) and the conditions off the coast of mainland South Africa. Nevertheless, a small number of terrestrial species have been accidentally introduced to the island in the last decade (see Supplementary material S3 for more details and Table 4). As a result, the status is considered partially effective.

The *effectiveness of species* and *site treatments* (indicators 4.8 and 4.9 respectively) on Marion Island is assessed annually by the environmental control officers (ECOs). For invasive plants, the percentage of individual plants (or plant cover) killed per area treated varies between species, with values between 30 and 100% (DEA and DST-NRF CIB 2021). Additionally, DFFE:EP (Environmental Programmes) conduct independent assessments every three years to correlate the effectiveness of control measures with the established plan. While much of the implementation of management plans seems adequate, there is a noticeable absence of updated plans, and progress reports often lack sufficient detail. Consequently, the level of effectiveness in implementing these management plans is uncertain.

Level of success in managing invasions (indicator 4)

One out of ten pathways have a plan in place and are being quite successfully managed, given the low introduction rates. Twelve out of 45 alien species are being managed, this is not the whole extent of the invasive species, and although some of the treated species are now being monitored to confirm eradication, others continue to spread, therefore the level of success is partial.

Discussion

Biological invasions have for many years been the major driver of biodiversity decline on the PEIs. Substantial periods of activity have led to the introduction of more than 90 taxa, of which more than 40 are currently still present, with impacts ranging from Massive. By using a set of known indicators, this study summarises the information available on the status and management of alien taxa on the PEIs to date. Here we discuss key issues for the PEIs, present recommendations for management, and draw insights for the management of biological invasions in similarly remote sites.

The PEIs are remote, strictly protected islands, with little human activity (i.e., there is relatively little land and sea use change, exploitation of species or pollution). The key threats are biological invasions, climate change, and the Patagonian toothfish (*Dissostichus eleginoides*) fishery (Whitehead et al. 2019). Managing biological invasions is, therefore, critical to achieving several of the global biodiversity framework targets for the PEIs, e.g., Target 1 requires all areas to be managed to reduce biodiversity loss; Target 3 aims to conserve land, water, and seas; and Target 4 aims to halt species extinction and protect genetic diversity. Monitoring progress towards Target 6 (that refers to biological invasions) on the PEIs is therefore an essential part of monitoring biodiversity on the PEIs.

Under Target 6, signatories to the GBF are required to identify and manage introduction pathways to prevent the introduction of priority invasive species, and reduce the rates of introduction of other known or potential invasive species by at least 50% by 2030 (CBD 2022). Historically (before the 1980s), introductions to the PEIs occurred through many introduction pathways, but due to strict regulation only few pathways remain through which alien species can be introduced. These pathways are known and are relatively well understood (Greve et al. 2020). Notably, however, fine-scale data for some pathways (e.g., on the number of people visiting the PEIs; and number of people traversing Marion Island) is either not collected or was not made available to us. As such, even for remote, small, and tightly controlled islands, such as the PEIs, fine-scale pathway data is lacking (IPBES 2023). Rigorous biosecurity measures are implemented addressing all identified pathways

Table 4 A summary of the status, trend and findings related to core and high-level indicators on the Prince Edward Islands (PEIs). If the indicator has been assessed, the status is either a value or a table or figure if more than one value is obtained when the indicator is calculated. The status and trends have been assessed considering changes in the last decade (2012–2022), drawing from chapter 5 of the report '*The status of biological invasions and their management in South Africa in 2022*' (Zengeya and Wilson 2023) and updated where relevant

Category	Indicator	Status	trend and (confidence)	Notes and outlook
	1. Rate of unregulated introduction of new species	see Fig. 1	→ (medium)	The rate of introduction does not appear to have changed in the last ten years. No future change is envisaged. Traffic and pathways to the islands are not expected to change because the same protocol is strictly followed every year and it is unlikely to change in the near future. Recent improvements (e.g., no Velcro) and continuing work on biosecurity would be needed if the goal of zero introductions is to be achieved. However, if the 'Mouse Free Marion' eradication plan goes ahead, more introductions could be expected as eradication efforts will bring more people onto the island and result in more traffic across the island. Faster spread of invasive species might be expected as those involved in the eradication will be operating from areas other than the base
	1.1 Introduction pathway prominence	see Table 2	→ (high)	No changes in practices and regulations. No future change is envisaged. Traffic and pathways to the islands are not expected to change because the same protocol is strictly followed every year and is unlikely to change in the near future
	1.2 Introduction rates	see Table 2	→ (medium)	All intentional introductions were historical. Escape and release pathways have not been present since the 1980s. Pathway of introduction remains unknown for most alien taxa, but accidental introductions such as stowaways or food contaminants have been the most common recent pathways. Strict biosecurity measures are implemented. No major change is envisaged due to strict control of pathways. However, work to develop and release of biological control agents could occur in future if approved by the PEIs Advisory Committee. Biosecurity efforts (e.g., no Velcro) might result in lower numbers of introductions, but this decline will be hard to detect given already low levels
	1.3 Within-country pathway prominence	see Table S5	→ (low)	The number of people walking around the islands has changed little and there is no known change in the spatial coverage of research actions on the island. No change expected. Highly regulated environment; practices on islands hardly change from year to year. If the 'Mouse Free Marion' Project goes ahead, the trend could increase due to more movement of goods using air support around the island
	1.4 Within-country dispersal rates	*Not assessed*		Three pathways are suspected to be the cause of alien species spread [natural dispersal (wind and seabirds), people and their luggage/equipment (fieldworkers) and hitchhikers in or on airplane (helicopter)], but the exact number of species using each pathway is unknown. No change envisaged, except if the 'Mouse Free Marion' project goes ahead in the future, since biosecurity measures will have to be reinforced to avoid alien species spread during deployment of poison around Marion Island

Table 4 (continued)

Category	Indicator	Status	trend and (confidence)	Notes and outlook
	2. Number of invasive species that have 'Major' impacts	4 species see Table 3	→ (medium)	Three plant species currently have 'Major' impacts (cause changes in community composition, which are reversible if the alien species is removed). No new invasive species have been introduced to the islands recently, although existing invaders are spreading, and their impacts might have increased. One species, the house mouse, has 'Massive' impacts. Expectation is that current range restricted taxa will be managed to avoid spread, and so any changes to this will be due to existing widespread invaders increasing in terms of the impacts they cause
	2.1 Number and status of alien species	25 invasive, 15 naturalised (Appendix 1 and Figs. 2 and S2)	→ (medium)	No known introductions or successful eradications. Eradication attempts for four taxa are underway. Four taxa for which presence is doubtful could be confirmed as eradicated in the upcoming years if they have been undetected for more than ten years. This will reduce the number of alien species present on the PEIs, although new introductions could increase the number
	2.2 Extent of alien species	see Appendix 1 (column 'Range-HMGC')	↗ (medium)	It is probably that many alien species have not reached equilibrium with the environment across the PEIs and are still spreading. Five of the six widespread alien plants have increased their distribution considerably since the 1960s (le Roux et al. 2013). Localised alien plant species have shown more mixed patterns. Extent might increase because some species are not being treated (as eradication deemed unfeasible), and climate change is expected to benefit some taxa [some invasive plants, springtails (Janion et al. 2010), and mice (McClelland et al. 2018)]. The range of some taxa might decline if control is effective (to the point of eradication in some instances)
	2.3 Abundance of alien species	See Appendix 1 (column 'organismQuantityExact') and Fig. S8	↗ (low)	Abundance of alien plants, invertebrates, and mice has been assessed. Abundance on both islands depends strongly on habitat type and varies with elevation on Marion Island. There are no data on trends in abundance, except for mice that have increased in abundance (McClelland et al. 2018). Because most alien species are not being controlled, abundance is expected to increase
	2.4 Impact of alien species	See Table 3	↗ (low)	Twenty alien species have been assessed for impacts. One has a 'Massive' impact (house mouse) and three plants have 'Major' impacts. The fungus has 'Moderate' impact, and most invertebrates are 'Data Deficient'. The house mouse is causing the greatest impacts, it has reduced the density of invertebrates (McClelland et al. 2018) and impacts seabirds, as well as native vegetation. Few data have been collected for other taxa. Impacts are expected to increase as species spread across the islands, increasing island-wide impacts; but also expected to increase as climate amelioration may make the environment more favourable for generalist invaders

Table 4 (continued)

Category	Indicator	Status	trend and (confidence)	Notes and outlook
	3. Extent of area that suffers 'Major' impacts from invasions	*Not assessed*		Several alien species have not reached equilibrium with the environment across the PEIs and are still spreading. Some of these have 'Major' impacts (e.g., *Sagina procumbens*). This indicator is expected to increase as species spread across larger extents of the island, increasing island-wide impacts; but also expected to increase as climate amelioration may make the environment more favourable for generalist invaders
	3.1 Alien species richness	0–8 alien vascular plant species per half minute grid-cell	↗ (medium)	No known introductions or successful eradications. Eradication attempts are underway. As species distributions reach equilibrium with the environment, increases in the local scale richness of alien species is expected as a consequence of range in-filling and the broadening of distributions across the islands (see e.g., Chown et al. 2013)
	3.2 Relative invasive abundance	See Fig. 4	↗ (low)	Mean plant cover on Marion Island (MI) 2.6%; no plant data for this indicator on PEI. Invertebrates' relative invasive abundance varies between 0–2% for PEI springtails to 28% on MI; for mites between 8% at PEI and 14% at MI; however, the uncertainty of nativity status for Cillibidae makes this estimate very low confidence. Spiders have been studied only on MI (37% mean relative abundance) and there are no data for insects due to a lack of complete surveys. Several alien species have likely not reached equilibrium with the environment, and therefore may still increase in abundance at sites that have more recently been colonised, and also as climate amelioration may make the environment more favourable for generalist invaders
	3.3 Impact of invasions	Not known	↗ (low)	Due to potential increases in the distribution and relative abundance of many alien species, the number of impacted sites and the impact of invasions at the site-level is likely to increase. Impacts on biodiversity are varied, and no assessment of impacts on ecosystem services or on monetary terms have been done on the PEIs to date
	4. Level of success in managing invasions	Partial	→ (high)	The proportion of pathways that require management and where a plan is in place equals 90%, the same proportion but for species is 26% and 100% for sites. Some management actions have been successful, and species are being monitored to confirm eradication. The distribution of some other taxa has remained stable (in some cases, due to taxa being controlled). However, a few taxa have increased in extent. So overall there is no change, and the level of success is partial. If successful, the 'Mouse-free Marion' Project would be a significant achievement, and although less pressing, other eradications would lead to an improvement in this indicator
	INPUT 4.1 Quality of regulatory framework	Partial	↗ (high)	The PEIs are governed by South African law, and South Africa's 'Alien and Invasive Species (A&IS) Regulations of the National Environmental Management: Biodiversity Act' (NEM:BA). There is a mismatch between species regulated that should be managed and those that are being managed (See Supplementary Material S4.1, Table S6). An assessment of management strategies within the framework of the PEIs Management Plan and decoupled from national-level regulations and processes would likely provide sufficient information to guide interventions

Table 4 (continued)

Category	Indicator	Status	trend and (confidence)	Notes and outlook
	INPUT 4.2 Money spent	See Fig. S9	↗ (medium)	Detailed expenditure records were not available (for more details see Supplementary Material S4.2). Given the discrete nature of the PEIs and the limited personnel involved, it should be feasible to accurately estimate the expenditures incurred in controlling invasions
	INPUT 4.3 Planning coverage	100% of sites 90% of pathways and 26% of species	↗ (high)	The current management plan delineates the quarantine and biosecurity protocols to be implemented across introduction pathways and offers recommendations for invasive species management. Encompassing both islands, the PEIs Management Plan ensures that all sites are equipped with a tailored management strategy (100% plan coverage for sites). However, the current management plan does not cover the fishing equipment pathway, therefore the plan coverage for pathways is 90% (nine pathways with coverage out of ten active). An eradication strategy was developed for Marion Island, targeting six priority invasive plant species and one invertebrate. Twelve out of 45 alien species have a management plan in place (26% plan coverage for alien species). The eradication of *Mus musculus* (house mouse) entails a distinct project ('Mouse-Free Marion'; https://mousefreemarion.org). It is a partnership between the DFFE and BirdLife South Africa
	OUTPUT 4.4 Pathways treated	Substantial	→ (high)	The current biosecurity measures are stipulated in the management plan from 2010, but different measures were introduced over time. In the 1980s, the introduction of alien taxa was prohibited by an informal code of conduct (Cooper and Condy 1988). In 1992 a formal Code of conduct was established, and in 1995/96 the first management plan was published. Fresh produce, for example, was banned in 1996 (Hughes et al. 2011). Expeditioners must inspect and clean their belongings (e.g., clothes, equipment) before traveling to the PEIs. A 'minimum Velcro policy' is in place to reduce the entrapment of propagules. On MI, the spread of plant seeds is minimised by using walkways around the base and transporting containers from the helicopter deck to huts, avoiding vegetated areas. Stricter measures for PEI ensure that only new equipment and clothes are used, and expeditioners are dropped at PEI first to prevent transfer from MI. To avoid contaminant introduction via food, fresh produce is banned, and all other foods must be irradiated, frozen, or sterilised. Marine introductions are controlled by prohibiting ballast water release within 200 nautical miles of the islands and following biofouling prevention guidelines (DEA 2010). Fishing is strictly limited to a few licenced vessels (Whitehead et al. 2019). As the PEIs lie within the area managed by the Commission on the CCAMLR, licenced fishing vessels also need to adhere to the conservation measures (Whitehead et al. 2019). Illegal fishing vessels, which might fish in the Marine Protected Area, are unlikely to adhere to any of these requirements (Whitehead et al. 2019)

Table 4 (continued)

Category	Indicator	Status	trend and (confidence)	Notes and outlook
	OUTPUT 4.5 Species treated & OUTPUT 4.6 Sites treated	69% of alien regulated species treated on MI, none on PEI50% of sites treated See Table S6	→ (high)	Nine out of 13 regulated alien species present on MI are managed—at least five plant species are deemed too widespread, and 15 species are not invasive (see Table S6 and Appendix 1). No management occurs on PEI. On MI, active management efforts are focused on eight vascular plant species, one invertebrate species (*Porcellio scaber*, woodlouse, not regulated), and *M. musculus*. Treatment protocols are implemented for all these species, except the house mouse, across all known occurrence sites (Neethling 2019; DEA and DST-NRF CIB 2021). These sites are predominantly situated on the eastern side of MI, with the majority located within a kilometre of the research base. *Mus musculus* control measures extend to the research base and all field huts, covering only a fraction of the species' range on the island. It is emphasised that the objective of these efforts is not eradication, but to control the species near human infrastructure
	OUTCOME 4.7 Effectiveness of pathway treatments	Partially effective	↗ (low)	Historically there have been introductions through six pathways, which are now effectively managed, and through which introductions can no longer occur (Table 2). The effectiveness of pathway interventions is not monitored or estimated, but as several alien taxa have been detected recently on the ship and at the research base, it appears that these interventions are only partially effective
	OUTCOME 4.8 Effectiveness of species treatments & OUTCOME 4.9 Effectiveness of site treatments	Partial (MI) NA (PEI)	↗ (high)	Four species are believed to have been eradicated through effective chemical and mechanical interventions: three plant species, *Alopecurus geniculatus* (marsh foxtail), *Holcus lanatus* (common velvet grass), and *Stellaria media* (common chickweed); and the invertebrate *P. scaber*. Conflicting assessments regarding the effectiveness of control measures have emerged for certain species. For example, while herbicide treatments for *Agrostis gigantea* reportedly resulted in the eradication of 90–100% of plants according to DEA and DST-NRF CIB (2021), Neethling (2019) indicates that although the species was eliminated at three sites, new populations were discovered near each location. There appears to be a deficiency in precise site-level monitoring (Neethling 2019). In response to this concern, the DFFE is implementing monitoring maps with site-level density data (see Supplementary material; Debbie Muir, pers. comm., 2023)

DFFE the South African National Department of Forestry, Fisheries and the Environment, *MI* Marion Island, *PEI* Prince Edward Island

[1]→no change; ↗ an increase; ↘ a decrease

except for those considered ‘unaided’ and those associated with fishing equipment. While most pathways are accounted for in the management plan, ensuring their effective management remains crucial. Moreover, attention must be given to the ‘fishing equipment’ pathway not currently addressed in the plan.

To demonstrate a reduction in the rate of introduction of at least 50% by 2030, it is imperative to accurately assess the current rate of introductions. This necessitates proper identification and reporting of incursions detected on the SA Agulhas II or on the islands. Although the number of new alien taxa recorded per year is relatively low, the true rate of introduction is currently still unknown. This is because most detections are not identified to species level, and as current estimates of the rate of introduction are based on raw introduction records that do not consider survey effort or ease of detection (McGeoch et al. 2023). While the PEIs boast strict biosecurity measures and a detailed management plan, ensuring their correct implementation is paramount for success. It would probably be impossible to prevent all introductions, and as the rate of introduction is already very low, it would be difficult to reduce it further. This suggests that while the GBF Target 6 provides a good basis for stimulating action; achieving a specific target of a 50% reduction in introductions to the PEIs will either not be possible or not be demonstrable. Nonetheless, we recommend that efforts to document the situation are improved and that routine regular monitoring of biosecurity is conducted and recorded (e.g., Lee and Chown 2009a,b).

Even though the biosecurity measures outlined by the PEIs’ management plan are comprehensive and detailed, the implementation could be enforced and improved. Identifying incursions and closer co-operation between management and research could strengthen the protection and conservation of the islands. There are examples of what we see as the main challenges when assessing indicators: data accessibility and communication between researchers and managers. For example, even though data are collected on costs and number of people travelling to the islands per year, such data are not routinely collated in a way that they can be easily reported upon. Better communication between researchers and managers (e.g., on the outcomes of effectiveness of control measures for certain species) and the development of workflows and data pipelines would allow reporting to become routine and facilitate management to become more adaptive.

Systematic monitoring of treated species is crucial to evaluate effectiveness and track progress towards eradication or control. Continuing herbicide treatments for invasive plants that are not yet widespread, along with appropriate follow-up, is vital to maintaining adaptive management and achieving eradication. Moreover, assessing and measuring the impacts of invasive invertebrates is imperative for prioritising interventions concerning these taxa. Monitoring efforts for *P. scaber*, the only invertebrate targeted on Marion Island, have shown promising results, with eradication potentially confirmed by 2024 after 12 years of no sightings.

To the best of our knowledge, there has been no specific exercise to identify priority species whose introduction should be prevented or emergency responses to target key potential future invaders, a critical gap in proactive management. It could be argued that such an exercise is not required in cases, such as the PEIs, where intentional introductions are prohibited, and pathway-based management approaches, rather than species-based approaches, are in place to prevent harmful introductions in general (Hulme 2006). However, such an exercise would be useful if actions are taken further than simply identifying harmful species that are likely to be introduced. For example, emergency response plans could be developed, and pre-approval of herbicides could be obtained.

The threat posed by biological invasions to the PEIs, and the management challenge they pose is set to increase with climate change (Greve et al. 2020). Climate change is likely to cause changes to introduction pathways, facilitating more introductions through some pathways, and reducing the number of introductions through others. The climate of the PEIs is warming and becoming drier (le Roux and McGeoch 2008), making the islands more suitable for the establishment of many alien species (Duffy et al. 2017). Thus, in the future, new introductions are more likely to establish; alien species that are present but not invasive, could become invasive; and those that are invasive could become more abundant and widespread (Frenot et al. 2005; Greve et al. 2020). There is already some evidence for these changes—on Marion Island, an advanced breeding season, driven by precipitation changes, has led to an increase in the density of the house mouse (McClelland et al. 2018); and several alien plants have extended their ranges, with recent increases in the rate of spread being attributed, at least partly, to changing climate (le Roux et al. 2013). These shifting threats have not, as yet, been considered in management planning.

Finally, while it is important to ensure there is integrated governance (IPBES 2023); we argue that attempts to integrate the management of biological invasions on the PEIs with strategies (e.g., South Africa's draft National Invasive Species Strategy and Action Plan) and regulations (e.g., the NEM:BA A&IS Regulations; Wilson and Kumschick 2024) designed for the mainland are inappropriate. We recommend that discrete PEIs management strategies are developed and regularly reviewed, with simplified regulations such that all alien taxa are deemed undesirable and must be controlled if possible.

Indicators

Out of the 24 indicators assessed in this study, 21 were successfully calculated, while one remained unknown (*impact of invasions*, indicator 3.3) and two could not be assessed due to a lack of available data (*within-country dispersal rates*, indicator 1.4 and *Extent of area that suffers 'Major' impacts from invasions*, indicator 3). However, here we do not discuss the performance of the indicators per se, as this analysis is still pending, including a sensitivity analysis. This will be a crucial next step for the research, both in terms of refining and further developing the indicators of Wilson et al. (2018), and improving how South Africa reports on the status and management of biological invasions more broadly.

Implications for other remote sites

In conducting the exercise for the PEIs we realised that the challenges for monitoring and how biological invasions can best be managed are likely qualitatively different on such remote locations than in highly populated regions. In particular, the need for systematic reporting on biological invasions is, we believe, particularly important. Some island, deep water, and high mountain sites (Voight et al. 2012; Lamsal et al. 2018), are visited infrequently and such trips need to be planned well in advance. There are often substantial limitations on how much equipment or supplies can be taken. This means that the control of biological invasions needs to be proactive and preventative rather than solely adaptive. Adaptation is limited to the time-scales at which the site is visited (e.g., it is not possible to go out and buy more herbicide or a particular type of trap, in the case of Marion Island improving the control method would have to wait until the following year)'s relief voyage.

Consistent data collection over time allows researchers to track the spread and impact of invasive species, identify trends, and assess the effectiveness of management strategies. In addition, systematic and open reporting fosters collaboration and information sharing among scientists, conservationists, and policymakers at local, national, and international levels. Invasive species do not recognise political boundaries (e.g., between sub-Antarctic archipelagos), making coordinated efforts crucial for effective management. Shared databases and standardised reporting protocols enable cross-border cooperation and help ensure that efforts to combat invasions are based on the best available science (e.g., Bester et al. 2002; Cooper et al. 2011).

Even in the 12 months between the National Status Report on Biological Invasions in South Africa (Zengeya and Wilson 2023) and this study, several changes have occurred. The accepted names of two species have been updated, a new species (*Isotomurs maculatus*) was detected on Prince Edward Island, and a species monitored for eradication (*Juncus* cf *effusus*) was rediscovered. These developments highlight the need for regular updates.

The use of biological control is currently prohibited in terms of the PEIs management plan because it involves deliberately introducing an alien species (the control agent). However, due to logistical difficulties of physical and chemical control and the need to reduce the negative impacts of control (e.g., trampling and the potential spread of propagules by management staff); biological control has been proposed as an opportunity for permanently improving the status of invasions on the islands (Canavan and Paterson 2023). Biological control is likely to be particularly suitable on the PEIs as there are few native species and so few concerns about the host specificity of agents and, if released, agents will not be able to disperse from the PEIs to other sites; (Canavan and Paterson 2023). Similar considerations could be made with other emerging technologies (e.g., gene drive, Teem et al. 2020), and these strategies could also be effective for other remote areas that are not frequently visited. If used judiciously both biological control and gene drive could offer opportunities for control where no control would otherwise be possible (IPBES 2023). However, given the sensitivity of the PEIs' ecosystem, such technologies would have to be approached with caution.

In general, in remote sites, a trade-off must be made between allowing invasive species to reproduce and spread and attempting control that might result in undesired non-target impacts. It is also essential to balance the desire for better information, effective management of biological invasions, and opportunities to derive benefits (e.g., through tourism), with the likely resulting increased human footprint and risk of new invasions. In the near future, we anticipate the potential for increased visitation to the PEIs as the South African government is under pressure to turn the PEIs into profitable territory (e.g., tourism, and mining and gas exploration; see Lombard et al. 2008). BirdLife South Africa organised bird watching cruises to create awareness and raise funds for the Mouse Free Marion eradication project in 2022 and 2025 (see Supplementary Material S5 for more details). These cruises do not allow visits to the islands (ships remain in the waters around Marion Island), but demonstrate the considerable appetite for tourism opportunities in the region. This, we believe, appropriately illustrates the tension between an increased human footprint (albeit a small increase in visitation rates by those interested in biodiversity in a setting where risks could be managed and monitored) and the need to derive greater and broader benefits from the island (e.g., commercial benefits). Such activities clearly need to be carefully considered, perhaps with a precautionary approach requiring evidence of low risk before they are considered. Whatever the decision, a monitoring framework explicitly required to report on biological invasions, as demonstrated in this paper, will be vital to ensure baseline information is available to monitor the consequences of such initiatives.

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Data availability All data supporting the findings of this study are available within the paper and its Supplementary Information. Species list is provided in Appendix 1 and respective metadata in Appendix 2. Additional data are provided in Supplementary.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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