Journal of Environmental Management 351 (2024) 119711

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Systematic conservation planning for Antarctic research stations

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ARTICLE INFO

Handling Editor: Jason Michael Evans

Keywords:
Footprint
Values
Pressures
Human impacts
Biodiversity
Management plan
Natural capital

ABSTRACT

The small ice-free areas of Antarctica are essential locations for both biodiversity and scientific research but are subject to considerable and expanding human impacts, resulting primarily from station-based research and support activities, and local tourism. Awareness by operators of the need to conserve natural values in and around station and visitor site footprints exists, but the cumulative nature of impacts often results in reactive rather than proactive management. With human activity spread across many isolated pockets of ice-free ground, the pathway to the greatest reduction of human impacts within this natural reserve is through better management of these areas, which are impacted the most. Using a case study of Australia's Casey Station, we found significant natural values persist within the immediate proximity (<10 m) of long-term station infrastructure, but encroachment by physical disturbance results in ongoing pressures. Active planning to better conserve such values would provide a direct opportunity to enhance protection of Antarctica's environment. Here we introduce an approach to systematic conservation planning, tailored to Antarctic research stations, to help managers improve the conservation of values surrounding their activity locations. Use of this approach provides a potential mechanism to balance the need for scientific access to the continent with international obligations to protect its environment. It may also facilitate the development of subordinate conservation tools, including management plans and natural capital accounting. By proactively minimising and containing their station footprints, national programs can also independently demonstrate their commitment to protecting Antarctica's environment.

1. Introduction

Antarctica is unique; as the world's most extreme and least modified continent (Brooks et al., 2019a), its environment, wildlife, wilderness, and role in climate regulation are considered more important than any use-value (McLean and Rock, 2016). Despite this, localised human impacts on the environment are substantial (Brooks et al., 2019a; Leihy et al., 2020; Tin et al., 2009) and expanding (Chown, 2018; Convey and Peck, 2019; Hughes et al., 2011). The source of these impacts is somewhat paradoxical: infrastructure to support the science (mainly research stations) and tourism activities that both seek Antarctica's unimpacted environment, and the logistical support needed to access it. Human activities have been accompanied by contamination and disturbance to wildlife, habitats and landscapes which have degraded many locations (Bargagli, 2005; Brooks et al., 2019a; Tin et al., 2009). Although *environmental management* (in an ISO 14001-sense) has been implemented by many Antarctic operators and has reduced harmful practices, this strategy does not necessarily curtail the spatial expansion of impacts. Indeed, documented conservation planning to limit impacts at research station sites, as would be standard practice in natural reserves

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https://doi.org/10.1016/j.jenvman.2023.119711
Received 5 July 2023; Received in revised form 21 November 2023; Accepted 22 November 2023
Available online 8 December 2023

elsewhere, is rarely evident. There has also been a general lack of coordination in regards to permitting new activities which cause known environmental impacts, such as the use of strategic environmental assessments (Roura and Hemmings, 2011). Increasing the coverage of Antarctic Specially Protected Areas (ASPAs) is an important instrument available to protect values, but strictly protecting such areas is not sufficient alone to ensure conservation of Antarctic biodiversity values (Margules and Pressey, 2000; Shaw et al., 2014) and is a somewhat narrow interpretation on the aims of the Protocol on Environmental Protection to the Antarctic Treaty (ATS, 2023) (hereafter the Madrid Protocol).

Ice-free areas in Antarctica are scattered around the continent characteristically as ‘island like’ pockets of land either close to the coast or as inland nunataks and mountain ranges. While research and tourism activities take place across much of the continent (Leihy et al., 2020), human presence and impacts are concentrated within these isolated ice-free pockets (Brooks et al., 2019a). This is because of their logistical convenience for access, the relative ease of station and facility construction, the requirement of many research disciplines for access to ice-free study material, and their concentrations of wildlife and other values that attract visitors (Tin et al., 2009). Therefore, the pathway to the greatest reduction of human impacts, particularly in ice-free areas, must be through better management of the areas which are impacted the most. In this study we provide a framework for developing conservation planning for the most heavily human impacted sites on the continent, particularly research stations, with the aim of assisting operators to continue their activities at the same time as enhancing the protection of Antarctica’s environment.

2. Stations and ice-free areas

The history of Antarctic research stations dates back to 1904, with the construction of the Scottish National Antarctic Expedition’s hut on Laurie Island, South Orkney Islands. Some of the early stations occupied sites with overlapping whaling and *heroic era* exploration histories (Headland, 2009). After World War II, the contemporary era of research-dedicated stations began, with continuous year-round operation on continental Antarctica beginning in 1954 (COMNAP, 2017). International research interest in Antarctica, including the construction of a continent-wide network of year-round stations, was catalysed, in particular, by the International Geophysical Year of 1957-58, which also led directly to the negotiation of the Antarctic Treaty, which was adopted in 1959 and came into force in 1961. Since their establishment, the key functions of stations have been to provide shelter, accommodation, communications, store supplies, house research infrastructure and to act as logistical hubs. They have, however, evolved (and typically expanded) to accommodate increasingly complex research equipment, technological advances, larger populations, safety requirements and comfort – particularly at year-round stations (Brooks et al., 2019a; Klein et al., 2008; Nielsen, 2013). Over three-quarters of the 76 currently active stations (plus further mothballed or abandoned ones) were established prior to 1998 (COMNAP, 2017), when the current framework for comprehensive environmental protection entered into force (the Madrid Protocol) (ATS, 2023). They have, thus, not been considered from a modern-day environmental impact assessment (EIA) approach, and many have significant ‘legacy’ impacts from long-discontinued practices (such as dumping waste). The largest source of new human impacts at stations is now through planned activities permitted through EIAs. Examples include establishing new stations, modernisation of ageing facilities (including the addition of renewable energy sources), building infrastructure to support new research activities, and expansion in the range of logistical capabilities, particularly to support aviation and deep field traverses (Australia, 2022; Brooks et al., 2018a; Chown, 2018; Convey et al., 2012; New Zealand, 2021; United States, 2019).

In total, less than 0.5% of Antarctica is ice-free, with estimates ranging from 21,000–54,000 km^2 (e.g. Burton-Johnson et al., 2016; Thomson and Cooper, 1993). In the last decade, these ice-free areas have been classified into 16 biologically-distinct Antarctic Conservation Biogeographic Regions (ACBRs) (Terauds et al., 2012; Terauds and Lee, 2016). The coastal margins of these ice-free areas (within 5 km of the coast), where the environmental envelope is most suitable for vegetation development and accessible for wildlife, are yet smaller, contributing just 0.06% of the continent’s landmass (Bergstrom et al., 2006; Brooks et al., 2019a). These scattered ‘islands in ice’ are vital for biodiversity values, providing key habitats for Antarctica’s terrestrial life (including terrestrial and limnetic microbes, algae, bryophytes and lichens, two native vascular plant species, invertebrates and most marine vertebrate breeding sites), as well as being the most accessible locations for studying Antarctica’s geological heritage (Bergstrom et al., 2006; Chown et al., 2015; Convey, 2017; Convey and Stevens, 2007; O’Neill, 2017; Pertierra and Hughes, 2019). As noted, human activity is disproportionately concentrated within these ice-free areas, containing 81% of all station infrastructure (by area), with 76% focused only within the coastal margin (Brooks et al., 2019a). Human impacts in ice-free areas are also spread out, with over half of all large coastal ice-free areas (>50 km^2) having ground disturbance visible from orbiting satellites (Brooks et al., 2019a). Many individual stations are also located within sites of exceptional values (pragmatically driven by the practical convenience of having stations and facilities constructed close to or on attractive research sites), including being situated within areas considered vital for Antarctic biodiversity (e.g. Robinson et al., 2018), warranting improved protection through formal conservation planning.

3. Impacts on values

Antarctic stations create focal points of human activities that are inevitably accompanied by impacts to the environment (Bargagli, 2008; Jabour, 2009; Tin et al., 2009). The extent and intensity of these impacts, however, are not universal and are varied and determined by a station’s size, layout, management, construction method, technology, intensity of use and, importantly, the sensitivity of the receiving environment (Brooks, 2014; Brooks et al., 2019a; O’Neill, 2017). Considered in the context of values protected by the Madrid Protocol (see Article 3: Environmental Principles https://www.ats.aq/e/protocol.html), common direct impacts to terrestrial ecosystems from established stations arise from multiple and often concurrent pressures including hydrocarbon, heavy metal, chemical, microbial and genetic contamination (Hwengwere et al., 2022; Kennicutt II et al., 2010; Klein et al., 2012; Stark et al., 2016; Tin et al., 2009), waste dispersal and pollution (Brooks et al., 2018b; Cincinelli et al., 2017; Fryirs et al., 2013; Reed et al., 2018), habitat damage/destruction (Micol and Jouventin, 2001; Wilson et al., 1990) and non-native species introductions (Bergstrom, 2021; Frenot et al., 2005; Houghton et al., 2014; Hughes et al., 2015). At coastal sites, contamination from sewage discharge and chemical run-off further extend impacts into the marine environment (e.g. Kennicutt II et al., 2010; Snape et al., 2001; Stark et al., 2016). Such pressures also implicitly impact scientific values by modifying natural baseline ecosystems (Bergstrom et al., 2006) and landscapes (e.g. the construction of a runway at Mario Zuchelli Station has destroyed a large portion of a long-term climate change soil monitoring site; Italy, 2016). Similarly, environmental modifications can result in irreversible losses in unique geomorphological and geological features of scientific value (Hughes et al., 2016; Klein et al., 2004; O’Neill, 2017). Although environmental and historic values in proximity to stations can gain enhanced conservation attention due to their accessibility, they conversely create recreational attractions resulting in ongoing visitation which can impact their archaeological significance and results in cumulative degradation (Bickersteth et al., 2008; Convey, 2020; O’Neill et al., 2013). The presence of stations, and the types of impacts described, can also degrade intrinsic values. Although these can be problematic to quantify, station infrastructure across Antarctica, known to impact wilderness and aesthetic values, has been estimated to have a visual footprint equivalent in size to the total ice-free area of the continent (Brooks et al., 2019a; Summerson and Bishop, 2012).

Understanding the impact that station footprints have on surrounding natural values is essential information for Antarctic environmental protection (Brooks et al., 2018a; Walton and Shears, 1994). The 'footprint' of a station can describe the area affected by a specific impact (e.g. hydrocarbon contamination of soil) (Brooks et al., 2018a), or capture areas impacted from multiple pressures more broadly through measures such as visibly disturbed ground or areas accessed (e.g. Brooks et al., 2019a; Pertierra et al., 2017). The use of disturbance footprint, a proxy representative of multiple impacts, is supported by numerous studies of the physical and biological pressures which result from disturbed substrate across Antarctica's ice-free regions (Brooks et al., 2019b). Typically, the intensity of a station's footprint matches a hub and spoke model, being most concentrated in areas of focussed activity (i.e. the centre of a station) (Hull and Bergstrom, 2006), then gradually decreasing outwards towards a baseline natural state (e.g. Corbett et al., 2015; Khan et al., 2019). The outer limits of the footprint often extend well beyond the immediate station area, through the establishment of remote infrastructure such as roads (Brooks et al., 2019a), walking tracks (Braun et al., 2012) and field sites (Bollard-Breen et al., 2014; Pertierra et al., 2013). How a station is planned also affects its footprint, with centralised infrastructure resulting in significantly smaller areas of disturbance (Brooks et al., 2019a). While the total footprint from all human activity (including tourism) at a continental scale is comparatively small, the inexorable spread of disturbance is diminishing the extent of remaining unimpacted areas (Brooks et al., 2019a; Hughes et al., 2011; Leihy et al., 2020), warranting improved conservation planning and management commensurate with the continent's designation as a natural reserve (ATS, 2023).

An opportunity to help balance the increasing human footprint associated with conducting and supporting national science programs in Antarctica against obligations to protect the environment, as agreed under the Madrid Protocol, can be provided through deliberate conservation planning of station sites. Recognition of the value of conservation planning being integral to station planning, constructions and operation spans the duration of the Antarctic Treaty (e.g. Carrick, 1960), with many specific recommendations for planning, zoning and monitoring being provided over time (e.g. Brooks, 2014; Kriwoken, 1991; Roura, 2004; Walton and Shears, 1994). Similarly, examples of valuable environmental research programs, monitoring and remediation methodologies have been developed (e.g. Klein et al., 2014; O'Neill et al., 2012; Tejedo et al., 2016). However, evidence that most Antarctic programs are conducting such work, as required by the Madrid Protocol, is generally not available (Hughes, 2010). There are very few published examples of consolidated, systematic or successful conservation planning approaches being employed to manage environmental protection for station sites.

4. Current conservation planning

The responsibility for implementing environmental protection, and any supporting conservation planning for an Antarctic station, typically lies with the national Antarctic program (hereafter national program), that operates the facility concerned. This is based on obligations prescribed under the Madrid Protocol, which are enacted through domestic legislation for each Antarctic Treaty signatory Party (e.g. Australia, 2017). Environmental protection by national programs is supported by knowledge-sharing and international policy development through fora including the Committee for Environmental Protection (CEP) and the Council of Managers of National Antarctic Programs (COMNAP), feedback from station inspections undertaken under auspices of the Antarctic Treaty (Article VII), and from expert groups including the Scientific Committee on Antarctic Research (SCAR). In some cases, national programs are further supported by standardised environmental management systems such as ISO14001 (Sánchez and Njaastad, 2014). In regards to fuel handling, biosecurity and contemporary pollution management, national programs are generally improving, and recent measures put in place have aided the protection of the Antarctic environment (e.g. Bergstrom, 2021; Brooks et al., 2018b; Chown et al., 2017; Houghton et al., 2014; Hughes et al., 2009; Newman et al., 2018).

So why are existing environmental management systems insufficient for the task? As with elsewhere in the world, environmental management in Antarctica is primarily focused on controlling processes and frameworks that enable an operator to comply with regulations efficiently and minimise accidents and wastage. The best environmental management can still allow activities with substantial negative impacts and it is not a tool intended to conserve natural values (e.g. ISO14001-certified large-scale mining). Many Antarctic programs have implemented environmental management protocols (e.g. Brooks et al., 2018b), but evidence for their effectiveness in conserving the natural values intended to be protected by the Madrid Protocol is limited. There is also an 'implementation gap' (*sensu* Lacher, 2018) - while good policies and advice to address recognised environmental protection issues are generated by the CEP and SCAR, these do not automatically lead to substantive on-the-ground actions. Practical tools for enacting conservation, in addition to operating within an environmental management framework, are therefore required to achieve protection appropriate for Antarctica's outstanding natural values.

The effectiveness of the remaining suite of current environmental measures in containing the growth of station footprints across the continent, and their subsequent impacts on natural values, is also less evident (Chown et al., 2017). There are many possible reasons underlying this, including a general lack in coordination, strategic oversight or effectiveness of EIAs to reduce impacts (Gilbert, 2020; Hemmings and Kriwoken, 2010; Roura and Hemmings, 2011), inadequate resourcing to implement practical controls (Sánchez and Njaastad, 2014), as well as no or insufficient monitoring to detect cumulative impacts and change (Hughes, 2010; O'Neill, 2017). In addition to the impacts a 'creeping' footprint can have on natural values, a general lack of management boundaries to limit station expansions, both planned or incidental, is also in agreement with the criticism that Antarctica's environmental protection does not adequately meet the expectations of a 'natural reserve' (Coetzee et al., 2017).

5. Justification for further conservation planning

One of the most prominent challenges to Antarctica conforming with established definitions of a protected area (e.g. Coetzee et al., 2017) is the general absence of limits, or management, to prevent activities that cause potentially significant conservation impacts (Bastmeijer and van Hendel, 2009; Gilbert, 2020). A reaction, partly stimulated by this, has been a recent effort by the scientific community encouraging an increase of the coverage of ASPAs, particularly within the terrestrial environment (Australia, 2019; Chown et al., 2017; Coetzee et al., 2017; Shaw et al., 2014; Terauds and Lee, 2016). This focus has been based on recognition the current coverage of ASPAs across Antarctica is not representative or robust in many contexts (geographical, biodiversity, ecosystems or wilderness) and far from comprehensively protects ecosystems and biodiversity (Wauchope et al., 2019), biogeographical regions (Terauds and Lee, 2016) or landscapes (Hughes et al., 2016). Despite awareness of inadequate representation within the network, the total land area covered by ASPAs (as one metric) has not substantially increased for ~40 years (Chown et al., 2017). While efforts to expand the ASPA network to a representative system are entirely appropriate and are consistent with the Madrid Protocol (Annex V, Article 3.2), and global targets, the CEP has recognised that efforts to further develop the Antarctic protected area system should be considered in the context that the entire continent already receives environmental protection (Australia, 2019). Here, steps should be taken to strengthen the overall protection of Antarctica in parallel with efforts promoting further ASPA coverage (Bastmeijer and van Hendel, 2009). Furthermore, while new ASPA designations (and subsequent management plans) face the challenge of negotiating consensus approval among Antarctic Treaty Consultative Parties, conservation planning provides support for national programs to take individual action (acknowledging the exception of co-located facilities).

6. Methods

To support improvement in Antarctic environmental protection, we propose a systematic conservation planning approach, developed from consolidated international approaches (i.e. Pressey and Bottrill, 2009), for Antarctic stations. Systematic conservation planning is a process of deciding how to most efficiently allocate limited resources to conserve natural values within a framework that sets clear and explicit goals and considerations, prescribes how goals are addressed, acknowledges current achievement towards objectives, and provides a structure to maintain the effectiveness of conservation actions (Margules and Pressey, 2000). This approach complements broader-scale systematic conservation planning that has been developed for the Antarctic Peninsula region (SCAR and IAATO, 2023), its suggested use for expanding the Antarctic Specially Protected Area (ASPA) network (Coetzee et al., 2017), as well as meeting the aim of adapting international best practice conservation methods to the specific circumstances of Antarctic stations (*sensu* Hughes et al., 2018).

6.1. Developing a systematic conservation planning approach for stations

Our approach to systematic conservation planning is designed to produce a scalable tool, prescribing planning considerations for use by those involved in the management and operation of an Antarctic station. Its intention is to facilitate improved conservation of values within the constraint of not inhibiting the functional role a station provides. The guidance it provides may be tailored for planning any conservation goals or projects surrounding station sites, regardless of scale and complexity. Here we have used nine sequential stages of conservation planning (Table 1) primarily adopted from Pressey and Bottrill (2009) to meet the needs unique to station environments (i.e., self-sufficient logistical hubs).

Application of the stages in Table 1 was trialled in the vicinity of Australia's Casey Station (Fig. 1) and refined through consultation with 12 managers and personnel from the Australian national program (who were invited based on having directly relevant roles for station planning) through two workshop environments. Within the workshops, participants from science, policy, regulation and operational disciplines were presented with a synthesis of environmental monitoring data gathered on values and pressures within the station's area (Supplementary Information 1 and 2) and asked to assess how applicable the nine-stage-structure was for meeting their operational needs. Through these workshops no issues were identified with the draft stages developed by the project team, but participants' suggestions for improvements were provided which were incorporated within Table 1 and Supplementary Information 1. This consultation process revealed many interconnected issues when addressing conservation improvements but consistently corroborated the applicability of the stages in Table 1. To encourage station managers to implement systematic conservation planning, a detailed support tool providing steps and examples for each stage is provided (Supplementary Information 1).

Lessons learnt from the test application on Casey Station are provided here as an in-depth case study.

7. Results

7.1. Casey Station case study

7.1.1. Stage 1: scope and process planning

Australia's Casey Station is located within the Windmill Islands along

Table 1
The stages of Systematic Conservation Planning.

Stage	Context (Tasks and Notes)
1. Scope and Process Planning	Determine the geographic boundaries of the planning area, and techniques to be used to inform the process. Develop the framework and resources (capacity) needed to implement each stage.
2. Identify and involve stakeholders	Identify the stakeholders who operate or use Antarctic research stations. Include determining the extent to which stakeholders will influence, be affected by, or have responsibility for implementing, the planning process. Although stations are generally national government facilities, many are operated by several different national agencies, with differing needs and goals. Many are also operated by, or in concert with, research organisations, foundations, universities, contractors and military logistical support. A small number of stations are operated by, or include facilities operated by, more than one nation. Engagement with the primary operators of a station is key to successful implementation and should take place early within the process. Involvement with remaining stakeholders should be proportional to the extent they are affected by the planning.
3. Describe research station context and background	Detail the purpose of the station and how its presence impacts the environment. Antarctic research stations are inherently varied in history, function, activities, location and management, providing support for a range of research disciplines. Documenting context and background requires consideration of the social, economic, and political setting for conservation planning. Define pressures and threats to natural values that could be mitigated by spatial planning as well as the broad constraints on, and opportunities for, conservation actions. These may be priority-listed by completing an 'environmental risk assessment'.
4. Identify conservation goals	Identification of conservation goals for a station will be determined by its context (Step 3), compliance with the Environmental Principles (Article 3 of the Madrid Protocol) and the legal requirements and cultural expectations of its operating nation. These should be broad statements which are progressively refined into qualitative goals about the preservation of values. These goals will also inform data requirements (Step 5).
5. Quantify values, pressures and threats (data collection and creation)	Quantitatively document biological, physical, scientific, historic, aesthetic and wilderness values present within the planning area, as well as pressures and threats, with a focus on collecting spatially and temporally explicit data. Data are collated to map constraints and opportunities for conservation actions. This step will also involve anticipation and prediction of any expansion of threatening processes. This process should identify gaps in information where further assessment, or the precautionary principle, should be applied.
6. Review current achievement of objectives	All research station operators will have existing laws, approaches and management in place to meet their environmental protection obligations under the Antarctic

(*continued on next page*)

Table 1 (*continued*)

Stage	Context (Tasks and Notes)
	Treaty System. The effectiveness of these, along with any additional domestic measures, should be assessed against field data for their adequacy to achieve desired conservation objectives. This assessment will inform their contribution to, or potential integration within, conservation planning, as well as identify what objectives have already been achieved.
7. Set conservation objectives	Assess conservation goals against values and pressures data to set clear quantitative objectives. This will include spatially-explicit targets for the conservation of values, ongoing human pressures (e.g. current and future footprint projections) and qualitative objectives related to management strategies for degraded areas, station configurations and other criteria.
8. Apply conservation actions to stations	Application of conservation actions to a station will require action along a variety of administrative, legal, operational, scientific and technical pathways. Many components of these actions will already be in place (e.g., environmental impact assessment), but may be more effective if brought together under systematic conservation planning. As the capacity to implement these actions will be finite, priority listing should be provided; based on an assessment of values, risk of further impact, feasibility and appropriateness.
9. Maintenance and monitoring of achievement against objectives	Initiate management strategies to ensure conservation actions are demonstrably effective, sustainable in the long-term, and contribute towards promoting the persistence of values around station activities and meeting objectives. Develop a plan for periodic monitoring of values and pressures against baselines or targets to inform planning efficacy. Review periods should also be set to assess progress towards achieving conservation goals.

Fig. 1. Casey Station's location on the coast of East Antarctica.

the Budd Coast in East Antarctica (66°16′57″S, 110°31′36″E). For this case study, the geographic boundary was restricted to the area shown on Fig. 2.

Australian Antarctic Data Centre (AADC) records, scientific literature, and the SCAR Biodiversity Database were reviewed for any applicable data on values present within the immediate vicinity of Casey Station (see Supplementary Information 2).

Aerial imagery, satellite imagery and a GIS methodology (Brooks et al., 2019a) were used to map medium- (similar to spoil) and heavy-intensity (similar to roads) disturbance footprint from imagery obtained in 2002, 2008, 2015, and 2018 (see Supplementary Information 2).

The resources needed to implement each stage would be dependent on Stage 4.

7.1.2. *Stage 2: identify and involve stakeholders*

Casey Station is operated by the Australian Antarctic Division (AAD) on behalf of the Australian Government. The AAD owns and manages most assets, provides logistics and resupplies the station, and employs most personnel. Major external stakeholders include the Australian Bureau of Meteorology, the Australian Defence Force, Geosciences Australia, the Commonwealth Scientific and Industrial Research Organisation, Serco, Skytraders, and numerous Australian universities including the Universities of Tasmania, Wollongong, Queensland, Adelaide and Monash.

7.1.3. *Stage 3: describe research station context and background*

Casey Station is operated year-round and acts as an important logistical hub for Australian inter- and intracontinental flights and shipping. Its original construction began in the 1960s to serve as a replacement for the now abandoned Wilkes Station (located ~2.5 km north on the opposite side of Newcomb Bay). It has continued to evolve and expand southwards (with peak expansion during the 1980s), to accommodate new buildings and infrastructure. Due to its size and activity, Casey Station has a substantial building and disturbance footprint on the local environment. Local sediments, including within the marine environment, also have elevated concentrations of hydrocarbon and heavy metal contamination due to historic practices including *in-situ* waste disposal (Snape et al., 2001).

The surrounding Windmill Islands region consists of a series of ice-free islands and peninsulas which are recognised as one of the most important areas in continental Antarctica for biodiversity, especially for its luxuriant moss beds and extensive lichen cover (Melick et al., 1994; Robinson et al., 2018; Smith, 1988). These values are particularly prominent within the Bailey and Clark Peninsulas where Casey and the abandoned Wilkes Stations, respectively, are located (Melick et al., 1994). The region, and especially its islands, is also known for their Important Bird Areas (Harris et al., 2015).

As a result of this context, Casey Station's buildings and areas of human activity are closely surrounded by a mix of rich biological values (see Fig. 2). This is particularly pronounced due to the station site overlapping with the most important micro-climate envelope for vegetation development in this region: moist, nutrient-rich, northerly aspects, protected from high-salinity maritime winds (Melick et al., 1994). Consequently, human activity, disturbance and legacy impacts from 60 years of occupation are embedded in and surrounded by an area with exceptional natural values.

7.1.4. *Stage 4: identify conservation goals*

The publicly available environmental policy of the AAD (Australia, Australian Government, 2018) states it "will demonstrate leadership in environmental protection across all its activities in Antarctica", including complying with Australian Antarctic legislation and the principles of the Madrid Protocol. Based on this, we anticipate conservation goals for Casey Station including action on existing and predicted future pressures (*sensu* Bergstrom et al., 2021) which are likely to

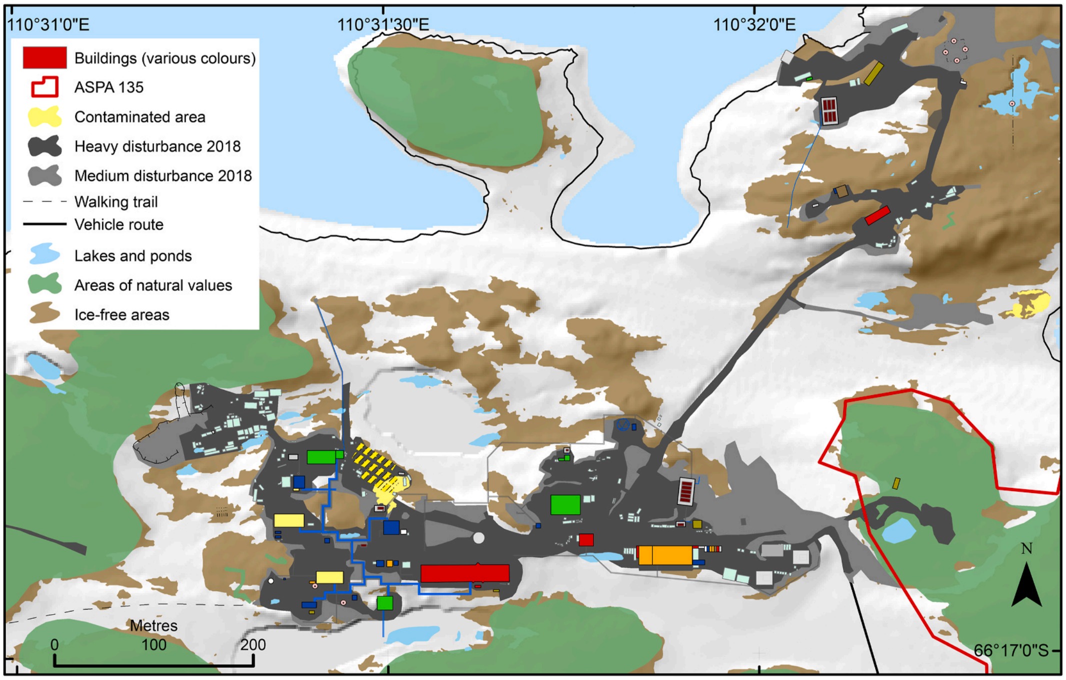

Fig. 2. Map of Casey Station local area with recorded areas of natural values and disturbance footprint illustrated. More values (e.g., moss turves and invertebrate communities) are present in this area but were not mapped due to insufficient spatial data being available. Further areas of disturbance may be present but were obstructed by snow cover during aikssessment. Horizontal Datum: WGS84. Projection: UTM Zone 49S. Disturbance footprint layers are original. Infrastructure, digital elevation model, routes, ASPA, and ice-free area data: Australian Antarctic Division. Remaining values and pressures layers produced from data sources listed in Supplementary Information 2. Produced by S.T. Brooks.

include prevention of non-native species establishment, fuel spills, waste release, remediation of existing sediment contamination, maintaining native biodiversity and for any change in footprint to be in a manner that minimises new impacts. Furthermore the AAD's policies 'to ensure environmental decision-making is transparent and responsive to emerging issues and challenges' and to 'monitor and report environmental performance against objectives and targets' are relevant here. We also expect the AAD would be cognizant that a number of other countries have adopted a goal to reduce footprint in their station redevelopment plans through more efficient layouts (e.g. New Zealand, 2021; United States, 2019).

7.1.5. *Stage 5: quantify values, pressures and threats*

In total, reports of five bryophyte and 24 lichen species occur with high frequency and density close to infrastructure (Fig. 2, Supplementary Information 2). Substantial algal, fungal and other microbial diversity has also been identified in both terrestrial and limnetic environments (Verleyen et al., 2010; Zhang et al., 2020). Three flying bird species are recorded, with snow petrel nesting sites surrounding station infrastructure. Adélie penguins are frequent visitors to the station area with the nearest rookery located ~750 m to the west on Shirley Island. There are no important seal sites within the station area (i.e., breeding or moulting), but haul-outs on nearby sea ice are common. Monitoring data for invertebrates within the station area were limited; however, high densities of rotifers, tardigrades, nematodes and mites have been recorded. The invertebrates also demonstrated significant heterogeneity in their habitat requirements. The area has several geomorphological features of interest, including raised beach sequences, abandoned penguin colonies, and 42 lakes and ponds interspersed within the immediate station area. These geomorphological features, along with the general climate of the region, are contributing factors for the regionally good development of vegetation (Melick et al., 1994). Although quantifying scientific values is difficult, Casey's importance is evident from its generation of the most scientific papers and biological records amongst Australia's continental stations. While there are no designated historic sites within the station area, memorial crosses are located on nearby Reeves Hill, as well as there being some historic value in remnant buildings from the 1960s. Aesthetic values are present at Casey Station with its mix of glacial and ice-free landscapes, vegetation and fauna, resulting in a 'favourite place' ranking by AAD and associated staff (tourism visitation is very rare) compared to the other two continental stations (Summerson, 2013). Wilderness values, however, are substantially affected in this region due to the visibility of extensive outlying infrastructure and antennae (Summerson, 2013).

Although the Windmill Islands have a mild climate for continental Antarctica, current modelling, even under the Intergovernmental Panel on Climate Change's RCP8.5 climate scenario, suggests a low risk of non-native species establishment and ice-melt into the future (Duffy and Lee, 2019; Lee et al., 2017). The non-native species modelling by Duffy and Lee (2019), however, was limited to 24 species, and continuing incursion risks from human activities (Brooks et al., 2018b; Houghton et al., 2014) may provide enough propagule pressure for a climatically tolerant species to become established. Indeed, a *Lycoriella* sp. fly is already established synanthropically within the warmed conditions of station buildings (Hughes et al., 2005), and a further 12 fungal taxa have been found restricted to soil surrounding station buildings, suggesting human introduction (Azmi and Seppelt, 1998). Despite a small projected increase in ice-free land within the region by 2100 (Lee et al., 2017), this change may actually be detrimental to vegetation, with observations of a current drying trend already impacting moss health and distribution in the area (Bergstrom et al., 2021; Robinson et al., 2018). This may be further exacerbated by extreme events, such as the heatwave that occurred in 2020 (Robinson et al., 2020). Similarly, a low but plausible risk exists for non-native marine incursions (Holland et al., 2021).

The median station population over winter is 19 staff, increasing to around 80 during summer (increasing slightly in the past decade). The station uses ~750,000 L (l) of diesel fuel per year across all infrastructure (generators, incinerators and vehicles), with the amount used per year increasing by 32% over the period reviewed (January 2009 to December 2015). Four major fuel spills totalling >14,000 l of diesel occurred at Casey between 1999 and 2018 (e.g. Brooks et al., 2018b; McWatters et al., 2016). Data available for the biological oxygen demand and suspended solids in sewage discharged into the marine environment from 2009 to 2018 show these were typical for wastewater with secondary treatment only (BOD median 26.25 mg/l, SS 26.5 mg/l).

The footprint of Casey Station is significant, both as it is the current eighth largest station by built area on the continent and 15th for disturbance (Brooks et al., 2019a), and because it is situated directly within an area of high vegetation values. In January 2018, its heavy disturbance footprint area was 72,002 m^2, an increase of 18% over the preceding 16 years. The medium-intensity disturbance footprint, extending beyond the heavily impacted areas, was 32,021 m^2, an increase of 42% since 2002. Between 2008 and 2018, there was an increase in the building footprint of 1670 m^2 (27%) while, over the same period, 325 m^2 (5%) of buildings were removed (with the area reused, not rehabilitated). These figures demonstrate that the station's footprint has been increasing, and it will potentially further expand to support new traverse capabilities, logistical support and maintenance in the near future (Australia, 2022).

7.1.6. Stage 6: review current achievement of objectives

Casey Station has been the site of ongoing contamination remediation research (e.g. McWatters et al., 2016), which has helped inform clean-up across Antarctica (e.g. ATS, 2019). The station also has a commendable history of responding to environmental incidents (e.g. Brooks et al., 2018b). Any environmental impacts from sewage discharge may also improve with a recently replaced wastewater treatment plant.

Although some of the extensive moss beds and lichen-dominated communities are protected within nearby ASPA 135, these values are present throughout the station area and have experienced damage from human activities. In the summer of 2013, for example, road sediment was accidently dumped on moss beds behind a building as a result of snow clearing, as well as broken glass on the vegetation (Bergstrom, pers. obs.). There is no 'buffer' zone to protect the vegetation within the ASPA from adjacent human activity (Kriwoken, 1991), with a vehicle route traversing parallel to the protected area's boundary, and accidental incursions have occurred (Brooks et al., 2018b). Station activities in the past have also impacted vegetation health remotely, such as wind-borne deposition of chemical-containing dust (Adamson et al., 1994). As a consequence, conservation of vegetation values is warranted both within and beyond the ASPA. Furthermore, despite the region around Casey having some of the best records of biodiversity available in Antarctica (Terauds et al., 2012), data points are still sporadic, collection is largely opportunistic and monitoring has been predominately focussed within remaining intact natural areas. As a result, the usefulness of existing data for detecting impacts from the station are limited, highlighting the invaluable information a comprehensive monitoring grid, similar to that used at McMurdo Station (Klein et al., 2014), would contribute towards management and planning.

The growth in the footprint during the observation period reflects an increase in infrastructure, particularly to meet increased accommodation requirements following the establishment of an intercontinental air link and improvements in accommodation quality that now form part of operator requirements for their personnel. However, it also results from many small, incremental and possibly unplanned, expansions into previously intact locations. Most examples where this was observed were infilling between previously forked infrastructure, or incremental outward 'creep'. The causation here was primarily expanding storage (e.g., more aviation fuel drums) or extending vehicle access routes (e.g., adding loops to terminuses). Although 'infilling' of areas within a station is a demonstrated approach to meet an expanding need for space while minimising footprint (Brooks et al., 2019a), most instances observed here appear to have been opportunistic rather than coordinated (e.g., none were part of a plan large enough to trigger a publicly-accessible EIA). Therefore, it is impossible for this study to determine to what extent conservation of values was considered in planning these expansions. A dilemma also arises about whether natural values that have become established within 'disturbed' station environs need to be conserved (e.g., sheltered moist areas under elevated pipework at Casey have allowed dense areas of moss to establish).

7.1.7. Stage 7: set conservation objectives

To manage the need for continued use and to support expanding logistical and science capability demands on Casey Station, we expect that the planning guidance provided through using systematic conservation planning would help station managers define objectives that meet their operational requirements as well as improve the conservation of values present within the immediate station area. Controls on the incremental growth of the station's footprint would be beneficial, with clearly defined boundaries for vehicles, machinery, and storage to prevent the inadvertent creep of disturbance. Minimising the area of footprint to that which is necessary may also help protect biological values in the face of climate change; reducing pressure from human activities could maximise their resilience to environmental changes, as well as providing more intact ground for potential range shifts into the future. Similarly, many problematic non-native plants are ruderal species, so minimisation of new disturbed ground around the station area may additionally help restrict or contain future establishment events.

7.1.8. Stage 8: apply conservation actions to stations

Station planning should incorporate existing footprint and natural value data (e.g., Fig. 2) to strategically site new buildings and storage which efficiently meet operational requirements with negligible increases in new disturbance. For example, the site of the removed 1960s-era buildings at Casey, closer to the coast, has negligible biological values detected, has already been disturbed, and therefore may be better utilised for further station development to avoid damage to significant vegetation elsewhere. Conversely, concentrated natural values were detected on the western, southern and eastern boundaries of the main station area (Fig. 2), suggesting a possible need to limit any future expansion in these directions.

Boundaries that protect values or contain footprint should also be set. These may be either physical or administrative, depending on the circumstances, and should assist station managers and on-the-ground operators in their duties by preventing unintended deviation from already disturbed areas (such as during snow cover).

7.1.9. Stage 9: maintenance and monitoring of achievement against objectives

Because this case study at Casey Station is largely retrospective and does not relate to an existing plan, some elements of the stages (6–9) presented here cannot contain the specific detail which a national operator would have access to. Instead, it is inferred by the proposed actions to be taken where possible, rather than informed by 'real' data on the progress of the conservation objectives. Notwithstanding this, Stage 9 at Casey would include regular spatially-explicit mapping of footprint, undisturbed areas of vegetation and other biota, supplemented with quality-scoring, to monitor the effectiveness of conservation actions and track long-term progress towards goals and objectives (Stages 4 and 7). Similarly, there would need to be ongoing surveys of those features that are better counted (such as nesting snow petrels), and these would need to capture a range of expert-defined and meaningful values and pressures that would be indicative of environmental performance.

8. Discussion

8.1. Applying systematic conservation planning to stations

8.1.1. Operations

Through the process of developing this systematic conservation planning approach, many conservation issues, potential areas for improvements, and possibilities for decision-support to aid the practical operation of a station were identified. Cumulative impacts from human activity, particularly from vehicles and machinery, were one of the most significant sources of ongoing pressures around a station environment. In station environs where this pressure does not occur (e.g., rarely accessed areas behind buildings, under elevated cable trays), some biological values have remained or re-established post-construction (although lichen-dominated areas have been observed to remain unchanged decades after damage). Learning from this observation, simple measures identified through systematic conservation planning open up opportunities to increase conservation of values while having a negligible impact on day-to-day operations. These measures could include designation of non-infrastructure use-areas such as container and material storage locations, parking, walking routes and snow/spoil dumping areas, as well as tools to support defining those areas. These may include short- and long-term barriers for vehicles (e.g., bollards, large rocks, ropes lines, geofencing on telemetry-enabled plant) to prevent unintended incursions onto values (e.g., Fig. 3) and defined paths for pedestrian movement, such as elevated walkways to pass over areas of values if necessary (e.g., Fig. 4). The information gained from systematic conservation planning may also assist in making choices in regard to broader station management, including instances where opportunities to conserve values provide enough additional weight to overcome economic inhibitions such as ‘sunk costs’ (unrecoverable expenses) for modernisation of existing infrastructure. This is particularly applicable to ‘renovate-versus-rebuild’ decisions (e.g., Scott Base redevelopment; New Zealand, 2021). Similarly, by identifying a national program’s conservation goals through the systematic conservation planning process, some objectives may directly benefit from technological solutions (e.g., an objective of reducing pressure on the marine environment could be addressed by advanced sewage treatment).

8.1.2. Monitoring and repair

As a general hypothesis, any remnant natural values in a station area would likely be at their least in the centre of activity and increase with distance outwards towards a baseline state. Indeed, the environment within the immediate vicinity of some stations (e.g. McMurdo Station; Klein et al., 2014) should now be considered entirely a ‘brownfield’ site, where conservation work would not represent a good investment (*sensu* Raymond and Snape, 2017), but this is far from universal or accepted (Convey, 2020). Many stations, especially smaller ones, still have rich values present within core areas (e.g. nesting birds at Dumont d’Urville, bryophyte vegetation at Casey, and vascular plants at Arctowski; Kozeretska et al., 2010; Melick et al., 1994; Micol and Jouventin, 2001). To maintain such values, as well as those on a station’s periphery, monitoring is required to identify and determine their extent, whether current conservation strategies (either active or passive) are effective, or to support decision making to take further planned actions to protect them. Although the Madrid Protocol requires station activities to ‘be planned and conducted on the basis of (sufficient) information - about their possible impacts’ (Article 3.2.c), there is either limited evidence that targeted or effective monitoring (beyond some vertebrate species) to meet this obligation across Antarctica is occurring (Hemmings and Kriwoken, 2010; Hughes, 2010; Wall et al., 2011), or the data are not being publicly released. Furthermore, awareness of a station’s footprint can be used to similar effect (Walton and Shears, 1994) but, again, there are few examples of national programs meaningfully capturing this information (Brooks et al., 2018a).

From the consultation process carried out during the development of this trial systematic conservation planning approach, the most prominent feedback from station managers was their desire to have access to information on the weighting of values for conservation within the station environment to support decision making, especially in regard to balancing the compromise between environmental protection and developing station capabilities. Although the Madrid Protocol (and its Annexes), and the scientific literature, provide limited assistance for weighting of, for example, environmental, scientific, historic or intrinsic values (also see Supplementary Information 1), rigorous detection and monitoring would be an essential first step to support such a process. The weighting of values may be assisted through sophisticated modelling processes (SCAR and IAATO, 2023); however, the complexity of conducting these may inhibit many national programs from adopting them unless a continent-wide dataset is provided. Station managers also

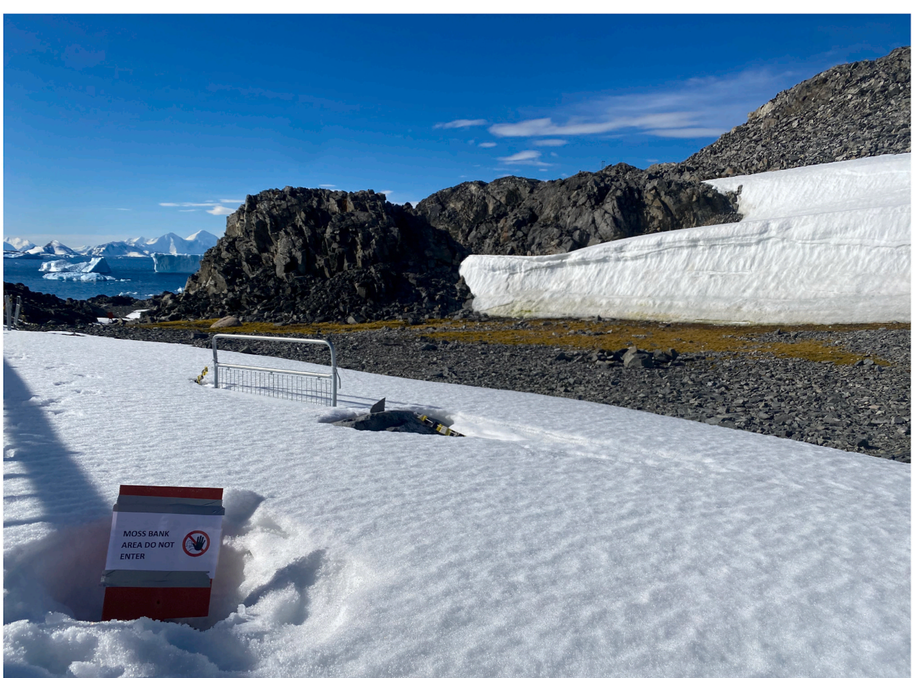

Fig. 3. Temporary measures including signs, flags, movable barriers and warning tape used to prevent person and vehicle access onto moss beds during earlier periods of snow cover at Rothera Station. Photo credit: Juan Guerrero.

Fig. 4. An elevated walkway around an Adélie penguin colony between infrastructure on the coast and the main station area at Dumont d'Urville Station, facilitating access while limiting disturbance. Photo credit: Alex Piekutowski.

suggested that readily accessible value and pressure data for station areas were highly desirable, but current access was prevented by factors including varied expertise in GIS-use between personnel, no single compilation of data layers, and general difficulty in finding information. Here, the majority of data found for the test application (Supplementary Information 2) were either already in GIS format, or easily translated into such, and could be compiled and made readily accessible across a national program through the creation of a user-friendly web-based mapping portal. Such a development may also help identify which monitoring data are most useful for station management and conservation, subsequently informing more targeted data collection into the future.

8.1.3. Administration

Systematic conservation planning offers a strategic approach to develop, implement, and manage any conservation objectives developed for a station. Documentation of how each stage of systematic conservation planning is addressed would be essential to assist in guiding conservation actions. For a station-wide values-conservation plan, such documentation would form the basis of a management plan – a commonly-used tool for managing complex protected areas with competing demands. From the review conducted here, no publicly-accessible conservation-oriented management plans were found for any Antarctic stations, despite suggestions to use them predating the 1991 Madrid Protocol (i.e. Kriwoken, 1991). Building and engineering 'master plans' are used, but environmental planning arguably should not be reduced to a later consideration within a natural reserve. Similarly, fuel spill, non-native species and legacy waste clean-up manuals have been developed or are in the process (ATS, 2019; CEP, 2019; COMNAP, 2008), yet no guiding documentation exists to assist station managers to prescribe decisions, limits, or boundaries to the impacts of a station. Consequently, conservation management for stations typically occurs on a reactive basis, with no guiding documentation available, requiring assessments of activities that will have environmental impacts to be made dependant on the knowledge and decisions of individual staff.

A station management plan, created through systematic conservation planning, can provide a guiding document to assist day-to-day decision making by national programs. These would be developed from expert- and values-based data, to provide long-term station planning, prescribe areas for protection or potential use, and define limits and boundaries to development. Similarly, guidance provided by management plans may deliver long-term strategies that reduce the risk of numerous Preliminary Assessments, and even Initial Environmental Evaluations (the two lower-level EIAs under the Madrid Protocol), cumulatively resulting in more than minor or transitory impacts. In this way, the consistent direction provided by a station management plan may fulfil the niche of a localised strategic environmental assessment (*sensu* Roura and Hemmings, 2011). In locations where multiple stations are present (specific key examples being on King George Island in the South Shetland Islands, and in the Larsemann Hills), joint conservation management plans would help coordinate efforts, especially in association with the creation of Antarctic Specially Managed Areas (*sensu* Convey, 2020). Although management plans are traditionally statutory documents prescribed by domestic law, this should not be necessary for stations and, rather, provide an opportunity to organise conservation management and decision making.

Finally, validating the effectiveness of conservation planning could also be assisted by utilising natural capital accounting – the recording and tracking of the condition and extent of a range of natural assets and land-use over time as a set of 'accounts' (Mace, 2019). This would involve framing quantitative monitoring data for individual natural values, using either total number (e.g., snow petrel nests) or spatial area (e.g., areal extent of vegetation) along with a corresponding quality rating, for a defined area affected by the station's operations, within a set of natural capital accounts. Likewise, the extent of a station's disturbance footprint, and other forms of land-use, could be tracked in an account alongside the natural values. These accounts would enable net changes to be easily detected over time as well as facilitate national programs setting tangible commitments (e.g., no net loss of biodiversity) and tracking progress on interim conservation goals. It would also be an efficient tool for streamlining the presentation of monitoring data into a scorecard for providing information to decision-makers, governments, and the public, such as in 'state of the environment' reporting.

9. Conclusions

The footprint of research stations in Antarctica, especially on ice-free areas, is growing. Construction of new stations, expanding infrastructure, and replacement of dated buildings contribute to this growth, with only a few examples of redundant stations being removed, and the environment rehabilitated, to offset their impacts. It is imperative that this mounting pressure is met with careful consideration of the opportunities arising from a better understanding of the existing footprint of stations, including the potential for their reconfiguration or even relocation, to optimise their use while improving protection of natural values. Simultaneously, climate change in the Antarctic is happening at varying rates across the continent, and its impacts are already being observed. Here, reducing the pressure human activities have on vulnerable biological values may enhance their resilience to changing climate. To facilitate this, national operators could set voluntary limits or boundaries around their stations to limit the increase in cumulative impact with time, thereby preventing expansion of footprint that may displace natural values. Planning to conserve extant values within a station's vicinity must be deliberate. Systematic conservation planning provides an efficient framework to develop strategies to deliver this. The cost of implementing conservation planning, including the monitoring required to support it, would be low compared to the operational expense of running an Antarctic station, yet would provide multifaceted benefits for operators as well as streamline compliance with obligations under the Madrid Protocol. Ultimately, the use of systematic conservation planning to develop effective conservation management plans, with the capacity and commitment by national operators to apply them, would deliver the best results for protecting the environment and the most benefits for the operators.

Key recommendations for station operators

1. Acknowledge the need for more strategic consideration of values conservation around stations (either for new sites or existing stations).
2. Monitor and map values.
3. Use included planning tool (Supplementary Information 1) to develop station conservation plan, including consideration of potential future needs.
4. Develop guidelines for station management to prioritise values (e.g., scientific/logistical versus natural values).
5. Map 'soft' limits/boundaries for station infrastructure, to provide accessible guidance on constraints for engineers, architects, planners and operators.
6. If relevant, use natural capital accounting.

CRediT authorship contribution statement

Shaun Brooks: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Validation, Writing – original draft, Writing – review & editing. **Julia Jabour:** Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **Kevin A. Hughes:** Conceptualization, Funding acquisition, Resources, Writing – review & editing. **Fraser Morgan:** Conceptualization, Funding acquisition, Writing – review & editing. **Peter Convey:** Conceptualization, Funding acquisition, Writing – review & editing. **Elias T. Polymeropoulos:** Writing – review & editing. **Dana M. Bergstrom:** Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

S.T.B. was supported by an Australian Government Research Training Program Scholarship. This work was funded and supported by the Australian Antarctic Division, Australian Antarctic Science project 4565. P.C. and K.A.H. are supported by NERC core funding to the BAS 'Biodiversity, Evolution and Adaptation' Team and Environment Office, respectively. F.J.M is supported by Te Pūnaha Matatini, a New Zealand Centre of Research Excellence. This article contributes to the 'Integrated Science to Inform Antarctic and Southern Ocean Conservation' (Ant-ICON) research programme of the Scientific Committee on Antarctic Research (SCAR). We thank Anthony O'Grady, Ewan McIvor, Tessa Bird, James Fleming and Andy Sharman for their comments on an earlier version of this manuscript, and the 12 AAD staff that participated in the stakeholder workshops supporting this project.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jenvman.2023.119711.

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