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RESEARCH ARTICLE

Environmental management and stewardship practices in Antarctic science and tourism: do they align with environmental concerns?

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Abstract

In the Antarctic Peninsula, tourism and science operations are interconnected and overlap spatially and temporally, sharing practices aimed at reducing and mitigating the human footprint. Guided by the concepts of environmental management and environmental stewardship, we examined how these environmental practices address the various types of environmental impacts generated by these operations. For this, we categorized the environmental impacts identified in the literature and conducted an expert survey to assess which of these impact categories are the most concerning. Then, we consulted the Inspection Reports of the Antarctic Treaty Consultative Parties, tour operators' annual reports and documents from the International Association of Antarctica Tour Operators to capture environmental management and stewardship practices. Finally, we evaluated to what extent these practices address the categories of impacts. We identified 68 environmental practices for science and 63 for tourism operations. We classified them into nine categories, which range from mitigating soil and water contamination to limiting landscape modifications, minimizing impacts on flora, fauna and ecosystems and reducing greenhouse gas emissions. We identified a significant number of practices addressing local and specific impact categories. In contrast, a smaller number of practices were identified for the impacts that are most concerning in terms of their geographical scale, duration and severity, according to our experts' survey. We discuss that the number of practices does not reflect their effectiveness, and the positive influence of some practices in building formal management instruments. Greater collaboration among stakeholders will improve the protection of the Antarctic continent.

Keywords

Environmental protection; conservation; science operations; tourism; introduction of non-native species

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Abbreviations

ATCPs: Antarctic Treaty Consultative Parties
COMNAP: Council of Managers of National Antarctic Programs
IAATO: International Association of Antarctica Tour Operators
NAPs: National Antarctic Programs
NWO: Organisation for Scientific Research

To access the supplementary material, please visit the article landing page

Introduction

Over recent decades, human activities in Antarctica have increased significantly (McCarthy et al. 2022; Liggett et al. 2023). Science operations have expanded in terms of facilities and the number of researchers travelling south. In 1995, 17 nations operated 37 stations; currently, there are 76 facilities belonging to COMNAP members, and more are planned (COMNAP 2017). At the same time, tourism has increased tenfold in terms of visitor numbers, going from 12 000 in the 2000/01 season to ca. 122 000 in 2023/24 (IAATO 2024a). The variety of transport modes and activities has followed suit, with about 60 types of activities now being on offer ranging from wildlife watching and small boat cruising to snorkelling and ice climbing (Makanse 2024). Simultaneously, the academic community has been raising concerns about the environmental impacts and the management implications of human activities in Antarctica, especially science and tourism operations (Tin et al. 2009; Liggett et al. 2017; Hughes et al. 2019; Crossin et al. 2020; Cajiao et al. 2021; Hughes, Boyle et al. 2023).

Particularly on the Antarctic Peninsula, tourism and science (and their associated logistical operations) are two

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mobile and intertwined operations that overlap spatially and temporally, sometimes share use of some facilities and locations, are subject to similar regulations and practices and face similar operational challenges, for example, weather conditions and safety risks (Hughes & Convey 2010; Bender et al. 2016; Brooks, Jabour et al. 2019). Both operations exert overlapping pressures on Antarctic ecosystems while also implementing common practices to reduce or limit negative environmental impacts, such as biosecurity measures, wildlife approach protocols and recycling/reusing systems (Hodgson-Johnston et al. 2017; Crossin et al. 2020; Chignell et al. 2021; Tejedo et al. 2022; Hughes, Lowther et al. 2023; Liggett et al. 2023). While there are positive examples of international collaboration and practices among NAPs, researchers and tour operators (e.g., citizen science), the shared use of facilities for both tourism and science remains contentious. For instance, the dual use of infrastructure (e.g., air runways) has raised concerns about the potential legitimization and expansion of such facilities (Bastmeijer et al. 2008; Rogan-Finnemore et al. 2021).

Human activities in the Antarctic Treaty area are subject to the environmental regulations of the Antarctic Treaty System (Committee for Environmental Protection 2019), which regulates the international governance of Antarctica. The ensuing environmental management practices, including protected area management (Convey et al. 2012; Hughes 2013; Burrows et al. 2023), environmental impact assessments (Roura & Hemmings 2011; Hodgson-Johnston et al. 2017) and reporting requirements have been extensively studied. A common feature of these studies is that they focus on environmental practices that are part of conventional regulation while overlooking voluntary practices that go beyond written rules. The nature and prominence of these self-initiated environmental practices and their contribution to mitigating environmental impacts remain a blind spot. To date, no systematic assessment of self-initiated practices in science and tourism has been conducted.

In this paper, we draw a distinction between environmental management practices and environmental stewardship practices, based on the degree of institutionalization. By "environmental management" practices we mean those practices that are part of, or follow, established regulatory or management mechanisms and frameworks. By "environmental stewardship" practices, we mean self-initiated practices that go beyond any written or conventional mechanism.

In the Antarctic context, environmental management refers to all the regulations and policy instruments established and adopted to protect the Antarctic, together with other specific instruments and practices designed with the same aim. This includes the Protocol on Environmental Protection to the Antarctic Treaty—known as the Environmental Protocol—and all measures (legally binding), decisions and resolutions (not legally binding) adopted by the ATCPs, that is, the Treaty Parties with voting rights (Cajiao et al. 2021). For tourism operations, environmental management practices also include general codes of conduct, visitor site guidelines, guidelines for wildlife watching, biosecurity and operational procedures and a Field Operations Manual compiled and encouraged by IAATO (2024b). Although IAATO codes and protocols operate within a framework of self-regulation, we classify them as environmental management practices because of their established character and critical role in shaping tourism operations. For example, current codes of conduct and site guidelines that were initiated as environmental stewardship practices addressing "common sense" areas of concern transitioned into policy instruments adopted by the ATCPs and currently promoted by IAATO (Haase et al. 2009; Lamers et al. 2012).

Stewardship is generally understood as "caring for what we value" (Mathevet et al. 2018: 363). Environmental stewardship, more specifically, has been defined by Bennett et al. (2017: 559) as "the actions taken by individuals, groups, or networks of actors, with various motivations and levels of capacity, to protect, care for, or responsibly use the environment in pursuit of environmental and/or social outcomes in diverse socio-ecological contexts." In the Antarctic context, environmental stewardship, and the related concept of custodianship, have surfaced as part of self-regulation encouraged by IAATO (n.d.), the environmentally responsible operations of national science programmes (National Science Foundation n.d.) and the governance of gateway cities (Leane et al. 2021). In the context of this analysis, we define environmental stewardship as a range of practices aimed at the protection of, care for or responsible operation in the Antarctic environment in different spatial and institutional contexts, which go beyond formal or adopted management practices (e.g., policy and regulatory instruments).

In this study, we analyse environmental management and environmental stewardship practices in Antarctica around three key questions: (1) what environmental practices occur in science and tourism operations?; (2) what are the most pressing environmental impacts produced by tourism and science operations? and (3) do environmental practices address the most pressing environmental impacts of these operations? First, we present the methodology applied for this study, consisting of a literature review, document appraisals and expert assessments. After presenting and discussing the results, we conclude the paper by reflecting on the extent to which current environmental practices contribute to reducing or mitigating environmental impacts produced by science and tourism operations in Antarctica.

Material and methods

We developed this analysis in a process that mirrored our three guiding questions: (1) consultation of ATCPs Inspection Reports, tour operators' annual reports and IAATO documents to identify environmental management and environmental stewardship practices; (2) identification and expert assessment of the main categories of environmental impacts and (3) association of environmental impact categories with environmental management and environmental stewardship practices concerning science and tourism operations.

Identifying environmental management and environmental stewardship practices

For science operations, we extracted information about environmental practices from Inspection Reports. These reports result from inspections of research stations by teams of ATCP representatives in the context of implementing the Environmental Protocol. They provide recommendations to improve the environmental management of science and associated logistical operations, while also acknowledging the environmental stewardship practices implemented in the field that could be replicated in other stations. The reports thereby offer an independent view of how management and stewardship take shape at research stations and in the operations of various ATCPs. Inspection Reports describe the physical features of the station, its scientific activities, environmental management, logistics and infrastructures, emergency and medical response capabilities, safety, training and emergency procedures, as well as policies regarding tourism visits. A single Inspection Report may cover multiple stations. A total of 17 Inspection Reports for the period 2010–2023 were available, corresponding to 47 stations and five facilities (e.g., refuges, laboratories).

For tourism, no independent source of information comparable to Inspection Reports was available. Instead, we obtained information about environmental practices from publicly available written sources, including the annual reports and websites of five tour operators, which contained information on the operational aspects of Antarctic trips. We also analysed the guidelines promoted by IAATO for the development of tourism activities (IAATO n.d.). The raw lists of practices for science and tourism were checked for duplicates and similar entries and then organized into categories (Tables 1, 2). They were organised in a way so as to align as much as possible with the

Table 1 Categories of environmental management and environmental stewardship practices and representative examples.

Categories	Representative examples
Environmental stewardship	
Minimizing impacts on flora, fauna and ecosystems	Actions to reduce impacts on vegetation and fauna, such as marking roads, limiting sampling and increased observation distances to wildlife.
Fuel use reduction and management	Plans for fuel reduction at stations, protocols and actions to manage spills (e.g., use of drums instead of tanks, raised pipelines and double-walled tanks).
Using renewable energies and efficient technologies	Using cutting-edge and efficient technologies for vessel design and station construction, including the use of wind and solar energies and automatization of fieldwork.
Educating, creating awareness	Outreach and informal education and interpretation activities, educational material for personnel, cleaning campaigns, briefings to staff and voluntary codes of conduct.
Recycling, separating and removing waste	Removal of temporary equipment and tools used for research activities, recycling, separating and removal of waste ensuring final disposal.
Reducing or reusing resources	Reusing materials for construction and reducing debris at stations. In tourism, practices to reduce or reuse resources (e.g., not using plastics, using reusable boots and jackets).
Enhancing collaboration	Collaborations among researchers, NAPs and tour operators, such as citizen science, agreements on the shared use of facilities and collaborative research teams.
Inaction	Refraining from conducting/implementing research activities in the field, the development of new constructions and the increase and diversification of tourism operations.
Environmental management	
Complying with regulations and procedures	All practices conducted by science and tourism stakeholders to comply with policy instruments and regulations.

Table 2 Environmental management and environmental stewardship practice categories for tourism and science operations.

EM and ES practice categories	Science	Tourism	Total	Examples of shared practices of both operations
Minimizing impacts on flora, fauna and ecosystems	14	23	37	Implementing boot, clothing and equipment decontamination protocols before and after going to the field. Setting specific restrictions considering potential impacts of activities on wildlife (e.g., unmanned vehicle use).
Fuel use reduction and management	14	6	20	Limiting spill risk by having mobile refuelling hoses (stations) and over-board valves in vessels
Using renewable energies and efficient technologies	6	9	15	Introduce renewable energy generation at stations and vessels (e.g., wind turbines for electricity) Implementing a dynamic anchoring system to remain in a set position without dropping an anchor.
Educating, creating awareness	10	3	13	Developing a wide range of work procedures and protocols, in pocket-size publications, written in different languages and in a style that is under-standable to non-experts. Involving tourists in research activities like collecting data or supporting field activities (e.g., citizen science) and providing information about research to tourists and the general public.
Enhancing collaboration	5	3	8	Use of vessels to support research, shared use of facilities, equipment for research, medical facilities
Reducing or reusing resources	5	2	7	Implementing water and heat recycling and reusing systems for stations and vessels Reducing single-use plastics. Switching food packages from glass jars to paper containers.
Recycling, separating and removing waste	3	1	4	Separating waste properly for removal from Antarctica and disposal in a destination with recycling available at port reception facilities.
Inaction	2	0	2	
Complying with regulations and procedures[a]	9	16	25	Conducting EIAs of research activities and completing post-season reports. Complying with formal regulations and procedures: the Environmental Protocol and national, environmental impact assessments and self-regulatory instruments.
Total	68	63	131	

[a] This is the only category referring to environmental management practices.

environmental impact categories, while doing justice to the nature of the practices. The categorization was performed by two researchers to increase reliability and minimize subjectivity.

Relating environmental practices to environmental impacts

To evaluate whether environmental practices address the most pressing environmental impacts, we first identified environmental impacts attributable to tourism and science operations. The starting point for this part of the analysis was two recent literature reviews on environmental impacts in Antarctica (Tejedo et al. 2022; Liggett et al. 2023). Together, these form a comprehensive examination of environmental impacts related to tourism activities. To include literature concerning the impacts of science and its associated logistical operations in Antarctica, we performed a complementary literature search in two leading databases: Web of Science and Scopus. We used the following Boolean string: TITLE-ABSTRACT-KEYWORDS "Antarc*science impacts" OR "Antarc*National Programs" OR "Antarc*science support" OR "Antarc*science impacts" OR "Antarc*social impacts" OR "Antarc*cult*impacts." A total of 68 peer-reviewed articles, reviews, books and book chapters published from 2010 to 2023 were included in our appraisal. The impacts found in this literature were organized into categories adapted from a recent inventory of environmental impacts of polar research and logistics (Elshout et al. 2023), with a few amendments (Table 3).

Our survey instrument consisted of an online Qualtrics form in English, which was pre-tested by our research team. Surveys were administered to a group of Antarctic experts (n = 17) who were selected based on their specific knowledge of Antarctic tourism issues and active participation in research and decision-making processes in the Antarctic Treaty fora. A balanced representation of the social and natural sciences was ensured. For each of the environmental impact categories, participants were asked to assess the impact that the use of 11 science and tourism types of facilities (e.g., infrastructure, vehicles, equipment; Table 4) has in terms of scale (local, regional, continental), duration (transitory, semi-permanent, permanent) and severity (low, moderate, high).

For further analysis, "local," "transitory" and "low" were assigned a score of 1; "regional," "semi-permanent" and "moderate" were assigned a score of 2 and "continental," "permanent" and "high" were assigned a score of 3. As a result, mean scores ranged from 1 to 3, subdivided into "low" (1 to 1.67), "intermediate" (1.67 to 2.33) and "high" (2.33 to 3) scores. In a separate question, participants were asked to rank the environmental impact categories according to the significance of science and tourism contribution: the least significant was assigned a score of 1, and the most significant a score of 7. Data were collected from 20 November 2023 to 20 January 2024. The data were analysed by employing descriptive statistics. To associate the environmental impact categories with practices, we developed a table that connects the environmental impact categories (columns) with all the environmental management and environmental stewardship practices (rows) found in our document appraisal (Supplementary material).

Results

Environmental management and stewardship practices

After removing duplicates and aggregating similar practices, a total of 131 environmental management and environmental stewardship practices remained, of which 119 were unique to one environmental practice category, whereas the remaining 12 featured in multiple categories. We subsequently subdivided the 131 practices into nine categories of operational practices (Table 1, Supplementary material). A similar number of practices were identified for science and tourism operations: 68 and 63 respectively (Table 2). The category "complying with regulations and procedures" was classified as the only one concerning environmental management since the practices in this category relate to compliance with policy instruments.

The environmental stewardship practice category "minimizing impacts on flora, fauna, and ecosystems" contains the largest number of practices implemented in the field by science and tourism operations, followed by the category "fuel use reduction and management." The

Table 3 Environmental impact categories identified.

Impact category	Impacts included
Soil degradation	Mechanical–physical alteration, chemical pollution, rubbish/litter and changes in soil biota.
Water pollution	Sewage dumps, vessel discharges, oil spills, chemical pollution, microplastics and marine debris.
Wildlife and flora disturbance	Disturbance of marine and terrestrial species, noise and light pollution, collisions, ethological changes, physiological responses and trampling.
Loss of wilderness	Perceived loss of solitude conditions, presence of people, buildings, artifacts and equipment.
Atmospheric and greenhouse gas emissions	Emission of CO_2 and other air pollutants and greenhouse gas emissions.
Landscape and geomorphological modifications	Graffiti, removal of materials (e.g., legacy waste) and presence of paths and roads.
Introduction of non-native species and diseases	Introduction of multicellular organisms (mostly invertebrates and plants), microorganisms, viruses and pathogens.

Table 4 Types of infrastructure supporting tourism and research activities in Antarctica.

Infrastructure type	Examples of infrastructure
Terrestrial infrastructures	Roads, station buildings, hangars, storages
Air infrastructures	Land runways, heliports, airstrips
Marine infrastructures	Floating dock, piers, jetties
Research and commercial vessels	Tourism and NAPs vessels
Research and commercial aircraft	Helicopters, small aircraft, and planes
Support research and commercial terrestrial vehicles	Vehicles, trucks, snowmobiles, motorbikes, buses
Support research and commercial marine vehicles	Zodiacs, marine unmanned vehicles, small research vessels
Temporal research infrastructures and equipment	Refuges, camping areas, weather balloons, drones, cameras, tags
Deep field tourism expeditions infrastructures	Camping areas, toilets, tents, shower, kitchens, storages
Non-motorized terrestrial activities	Trekking, hiking, wildlife observation
Non-motorized marine activities	Kayaking, diving, swimming

practice categories "use of renewable energies and efficient technologies" and "educating, creating awareness" are in the middle bracket in terms of the overall number of practices. Smaller numbers of practices were found for "enhancing collaboration" and for the waste and resource management categories. Concerning the practice category "inaction," just two declarations of intent were found concerning the non-construction of new infrastructures. Whereas the total number of practices found for science and tourism is similar, the differences between categories are striking. Science dominates most categories, including education and fuel use reduction, whereas tourism has relatively large numbers related to minimizing impacts on nature and using renewable energy. Tourism also has almost twice as many practices in the environmental management category of "complying with regulations and procedures."

Environmental impacts and experts' assessment

The review of the literature on the environmental impacts of science and tourism operations in Antarctica yielded seven impact categories (Table 3).

The expert ranking of the impact categories by level of significance yielded four different ranks (Fig. 1). The highest-ranking category pertains to the "introduction of non-native species and diseases" (median rank: 6), followed by "landscape and geomorphological modifications" and "atmospheric and greenhouse gas emissions" (median rank: 5), "water pollution, wildlife and flora disturbances" and "loss of wilderness" (median rank: 4) and finally "soil degradation" (median rank: 3.0).

Science and tourism operations were regarded as having permanent impacts of high severity concerning the "introduction of non-native species and diseases." The impacts of research and commercial aircraft and vessels, and terrestrial, air and marine infrastructures have a continental scope. Note, however, that the impact of non-motorized marine and terrestrial activities was assessed as local and of moderate severity (Fig. 2a).

"Landscape and geomorphological modifications" (Fig. 2b) by terrestrial and air infrastructures were assessed as being local, but permanent and of high severity. The impact of temporal research infrastructures (e.g., summer field camps) was evaluated as semi-permanent and low severity. The impact of research and commercial vessels and aircraft was assessed as semi-permanent with low severity, even though the scope of the impacts may be regional or continental. Finally, non-motorized terrestrial activities were regarded as causing a local, transitory impact of low severity. For most of the activities, the effect that vessels and aircraft have on "atmospheric and greenhouse gas emissions" (Fig. 2c) is considered to be semi-permanent and of a continental scale, with a high severity (higher for aircraft than vessels). In the case of terrestrial and air infrastructure, the duration was evaluated as permanent.

Regarding "water pollution" (Fig. 2d), research and commercial cruise vessels and aircraft, terrestrial infrastructures, and marine vehicles supporting science and tourism were assessed as having a regional effect. Opinions were divided about the duration and severity of impacts caused by the various science and tourism operations. However, non-motorized marine activities were assessed by most as having local, transitory and low-severity impacts. "Wildlife and flora disturbances" were mostly assessed to be local (Fig. 2e). The impacts of

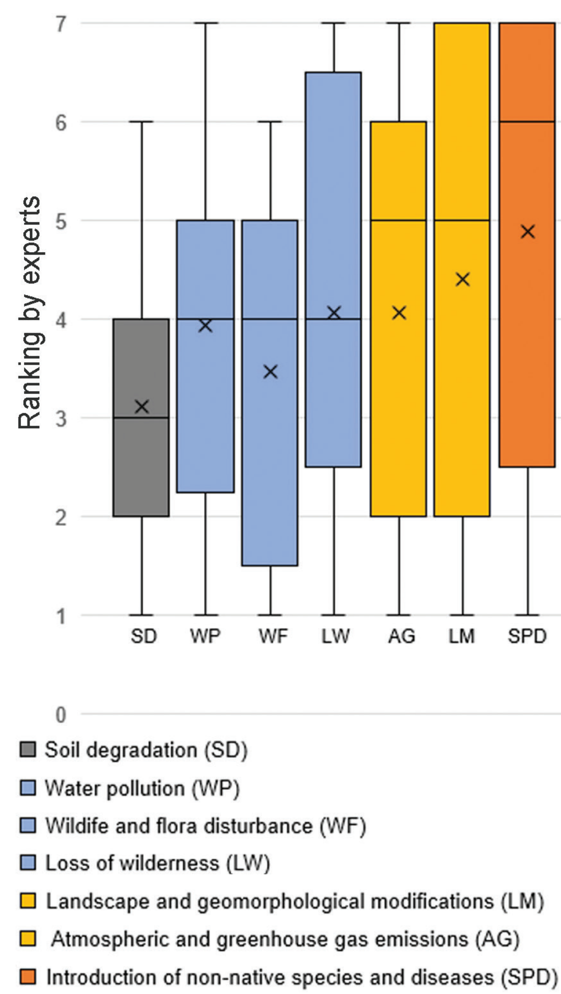

Fig. 1 Ranking of environmental impact categories concerning science and tourism operations according to experts (n = 17). The horizontal lines within the bars denote the median rank assigned, × denotes the mean rank and the bars denote the range of ranks assigned.

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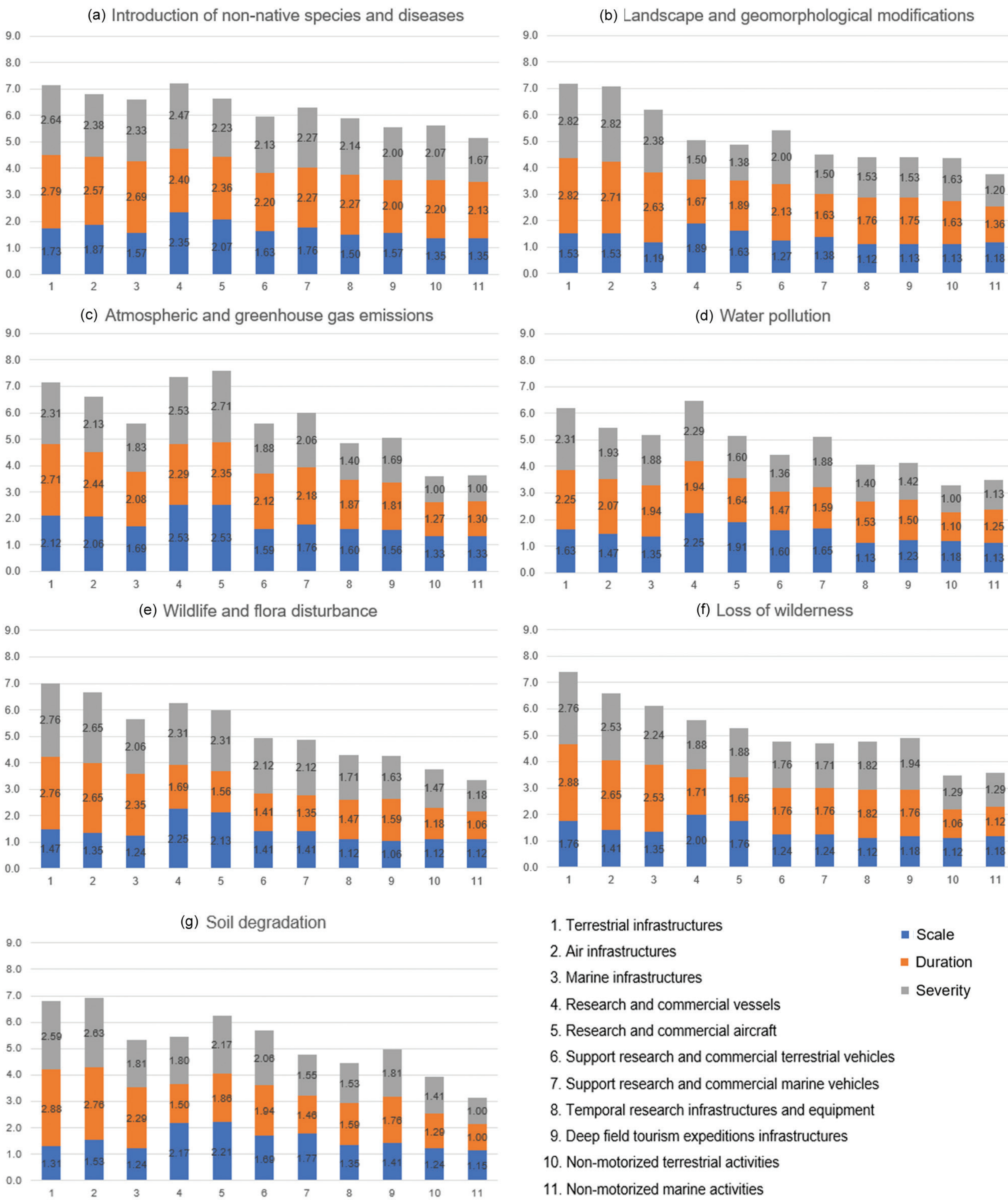

Fig. 2 Expert assessment of the significance of the impacts of 11 types of facilities and vehicles with respect to seven environmental impact categories. The subcategories of significance relate to scale, duration and severity, with values as follows: 1 (local, transitory, low severity), 2 intermediate (regional, semi-permanent, moderate severity) and 3 (continental, permanent, high severity). Combined mean scores (based on the mean values shown in each column segment) range from 3 to 9.

research, commercial and supporting vessels, aircraft and terrestrial vehicles were considered to have a regional scope; to a lesser degree, that was also the case for terrestrial and air infrastructure. According to the experts, terrestrial and air infrastructures, research and commercial vessels and aircraft have a permanent impact on "wildlife and flora disturbances," whereas non-motorized marine and terrestrial activities cause transitory impacts. The experts differed on the duration and severity of the impacts caused by the other operations and activities assessed. "Loss of wilderness" (Fig. 2f) was assessed as being a high-severity, permanent impact on terrestrial and air infrastructures. Research and commercial vessels were assessed as having a regional effect, while non-motorized marine and terrestrial activities were seen as causing a low-severity, transitory "loss of wilderness."

"Soil degradation" (Fig. 2g) was assessed to be a local-scale impact for most operations evaluated, with semi-permanent to permanent duration, and low to high severity. The impacts of terrestrial and air infrastructures were assessed to be permanent and of high severity, whereas those of non-motorized terrestrial activities were seen as transitory and low severity.

Linking environmental practices with environmental impacts

Most of the environmental stewardship practices in science and tourism could be confidently associated with one of the seven types of environmental impacts. However, most of the environmental management practices about "complying with regulations and procedures" relate to various impact categories and were therefore mostly categorized as cross-cutting, along with most of the environmental stewardship practices of "educating, creating awareness" and "enhancing collaboration." The rest of this section focuses on the environmental impact categories associated with the remaining categories of environmental stewardship, specifically those related to science and tourism.

The largest number of environmental stewardship practices for science and associated logistical operations address impacts of "soil degradation" through "fuel reduction and management" practices and "minimizing impacts on flora, fauna, and ecosystems" (Fig. 3). There is also considerable attention to addressing atmospheric and greenhouse gas emissions through various stewardship practices, such as "using renewable energies and efficient technologies" and "reducing fuel use." Less attention is spent on the impact categories of "wildlife and flora disturbance," "loss of wilderness," "landscape and geomorphological modifications" and, particularly, the "introduction of non-native species and diseases." Each of these impact categories is addressed by only a few stewardship practices. Overall, the impact categories addressed through environmental stewardship practices in science reflect an emphasis on terrestrial activities that concern logistical operations of research stations.

Figure 4 presents how environmental stewardship practices in tourism relate to the various impact categories. Here, "atmospheric and greenhouse gas emissions" represent the

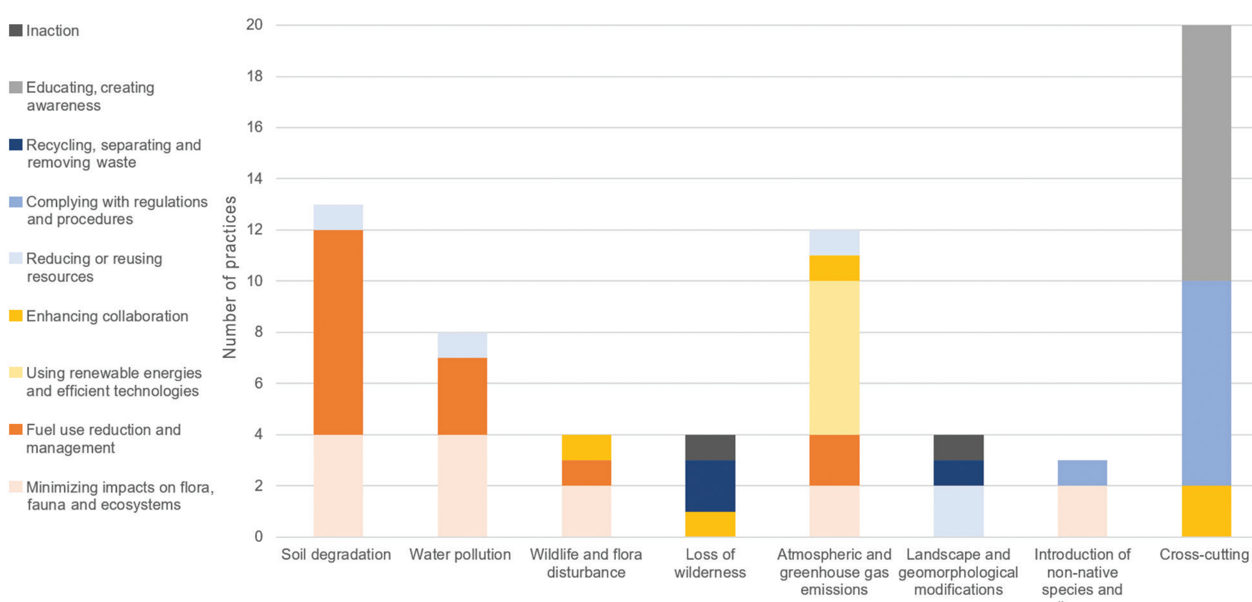

Fig. 3 Environmental management and environmental stewardship practices associated with science operations, displayed by environmental impact category.

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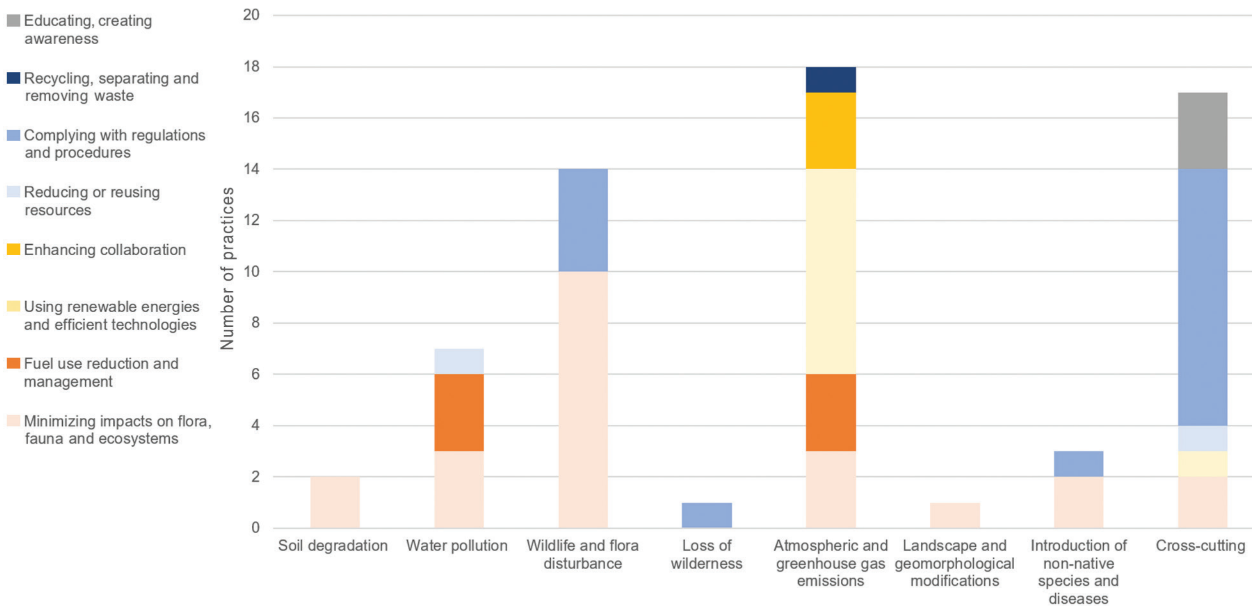

Fig. 4 Environmental management and environmental stewardship practices associated with tourism operations, displayed by environmental impact category.

impact category most strongly addressed by stewardship practices, which include "using renewable energies and efficient technologies," "reducing fuel use" and "enhancing collaboration." "Wildlife and flora disturbance" is a second impact category that is well-covered by tourism practices, not only by "complying with regulations and procedures," but also through additional environmental stewardship practices aimed at "minimizing impacts on flora, fauna, and ecosystems." Tourism has only a few practices addressing "soil degradation," "loss of wilderness" and "landscape and geomorphological modifications," even fewer than science.

Tourism coincides with science, however, on the limited number of environmental stewardship practices addressing the "introduction of non-native species and diseases," the impact category that the experts considered most significant. Overall, the impact categories addressed by stewardship practices in tourism correspond with the international debates and discourse on the main impact categories of tourism.

Discussion

In this study, we identified and assessed a range of environmental practices in science and tourism aimed at reducing and mitigating environmental impacts (Fig. 5). We distinguished environmental management practices—those that are part of binding and non-binding policy instruments—and environmental stewardship practices—which are self-initiated voluntary practices that go beyond compliance with current policy instruments.

We asked a group of experts to scrutinize science and tourism operations and assess the scale, duration and severity of their environmental impacts. The "introduction of non-native species and diseases" was evaluated as the most significant impact category, echoing concerns of the scientific community (Lee et al. 2022). Despite the efforts introduced by NAPs to prevent unintentional introductions, their activities carry the most significant risk (Siegert et al. 2023), which may be associated with the presence of introduced and invasive species in the Peninsula region, where most science and tourism operations are located (Hughes et al. 2015). In sharp contrast with the great significance that the experts attach to this impact category stands the small number of environmental stewardship practices addressing it: only 6 out of 131. It is important to note, however, that the small number of practices does not necessarily imply limited effectiveness. Despite longstanding concerns about the introduction of non-native species and diseases, the strict policy instruments to prevent introductions of any non-native species and development of comprehensive biosecurity guidelines along with environmental stewardship practices may be so effective that no further practices are needed (Hughes & Convey 2010; Hughes et al. 2020).

In shared second place were the impact categories of "landscape and geomorphological modifications" and "atmospheric and greenhouse gas emissions." Although terrestrial infrastructure was assessed as having predominantly localized impacts, particularly regarding "landscape alterations and geomorphological modifications," it

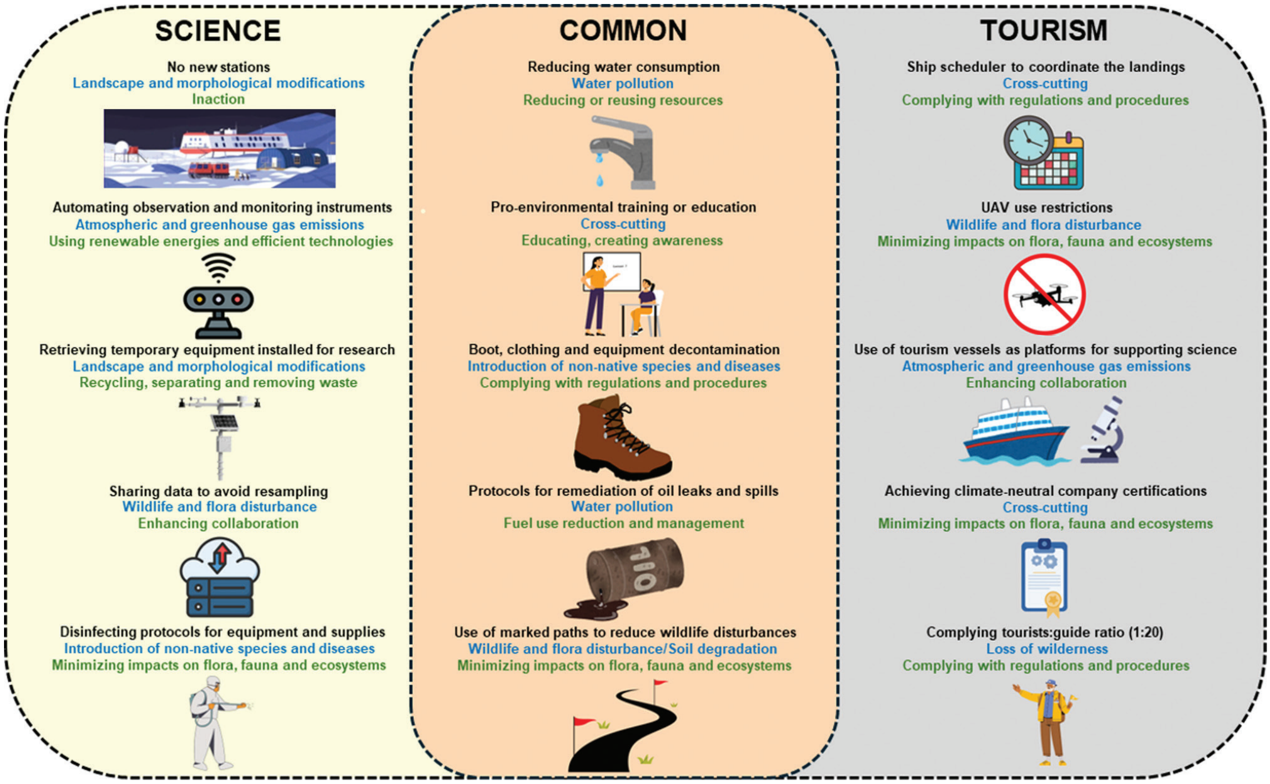

Fig. 5 Examples of environmental practices corresponding to science and tourism operations, with the practices themselves in black, the associated practice categories in blue and the environmental impact categories addressed in green.

is worth noting that NAP infrastructure exerts substantial pressure and irreversible changes on ice-free and coastal areas. Brooks, Jabour et al. (2019) calculated that the total building footprint across Antarctica was 0.393 km^2, mainly located in coastal ice-free areas (81%). While these ice-free areas represent only approximately 0.5% of Antarctica's total area, they contain critical ecosystems that support diverse and significant flora and fauna (Terauds et al. 2012). As discussed by Hughes et al. (2013) the ongoing increase in Antarctic scientific activities could lead to the permanent loss of ecosystem values due to the construction of logistical facilities, unregulated collection of geological specimens or oversampling for scientific purposes. Science and tourism were assessed as having continental and permanent effects on the impact category of "atmospheric and greenhouse gas emissions," particularly due to the presence of infrastructures and the mileage made by a large number of vessels. No tourism destination in the world ranks higher than Antarctica in terms of its per-passenger contribution to CO_2 and greenhouse gas emissions (Farreny et al. 2011; Li et al. 2022; Cajiao et al. 2025).

Environmental stewardship practices tackling the impacts of "atmospheric and greenhouse gas emissions" include the introduction of "renewable energies and efficient technologies" in science and tourism operations. The shift towards renewables is ongoing but it has substantial challenges. For science operations, the dismantling of old fossil fuel-based infrastructure leads to a significant waste stream, the disposal of which may be unaffordable for some countries. Windmills and solar panels are subject to controversy because of the costs and carbon footprint associated with their transportation, as well as their environmental and visual impacts (Teetz et al. 2003; Tin et al. 2010; Tian et al. 2020). Similarly, we found an important number of environmental stewardship practices in tourism related to the energy transition. Some examples include the design of more efficient vessels, renewable fuels, onboard wind turbines and heat and water recycling systems. It is worth noting, however, that despite the positive effects of such technologies and practices on relative environmental performance, greenhouse gas emissions have only increased in absolute terms. Energy efficiency gains are vastly outpaced by the growth of transport volumes (for tourism transport, see e.g., Gössling & Peeters [2015]).

In shared third place are the impact categories of "disturbances to wildlife and flora," "water pollution" and "loss of wilderness." Regarding the first, experts assessed science and tourism as having a local effect with transitory duration, which resonates with earlier studies conducted for distinct species, at various locations and under different stressors (Coetzee & Chown 2016). In most cases, results show that human disturbances are local and transitory and are not the only variable affecting populations (Holmes 2007; Dunn et al. 2019; Tejedo et al. 2022). Stewardship and precautionary practices have nevertheless been recommended (Coetzee & Chown 2016), and increasing numbers of those have seen the light, especially in the context of tourism operations (IAATO n.d.). The emphasis of tourism operations on wildlife disturbance is not surprising given the primary focus on wildlife motivations and experiences (Cajiao et al. 2022).

Impacts on "water pollution" were assessed as having a local, transitory effect of low severity. This is somewhat at odds with the increasing concerns raised in the literature about sewage, persistent heavy metals, microplastics and oil spills associated with an increasing Antarctic fleet (Ruoppolo et al. 2013; Tort et al. 2017; Griffiths et al. 2017). The impacts of human activities on wilderness values—a cornerstone of Antarctica's conservation—are subject to ongoing academic debate (Leihy et al. 2020), in part because the intangible nature of the wilderness construct makes it difficult to assess what a "loss of wilderness" entails (Summerson & Bishop 2012).

The impact category of the least significant concern was "soil degradation." The experts considered the impacts of science and tourism operations on soil degradation as local and of low severity, even though their duration can be semi-permanent. This resonates with past research that argues that even though trampling can cause semi-permanent impacts, it is limited to specific locations where intense human activities take place (O'Neill 2017; Brooks, Tejedo et al. 2019). Despite the limited extent of soil degradation, we found numerous environmental stewardship practices in science operations (tourism operations are less commonly land-based) addressing it, including many station-specific actions to contain and manage fuel spills. In fact, an intriguing hypothesis is that the success of the many practices contributed to the expert assessment of soil degradation being of limited importance. This hypothesis could be subjected to further research.

The environmental stewardship practice of "inaction" features only twice: two declarations of intent to limit the increase of NAP infrastructure. Crossin et al. (2020) have emphasized the environmental impacts caused by the operation of stations and have also called for reflection on the need to expand research facilities and the management of waste coming from logistical operations and research. For tourism operations, no practices of inaction were identified. Despite recurring debates among the scientific community and policy-makers regarding the limitation of operations (e.g., fixed length of season, carrying capacity, limitation in the number of visited sites; Bastmeijer et al. 2023), we have been unable to identify any industry-initiated practices or actions specifically aimed at halting the increase and diversification of Antarctic tourism.

Most of the environmental stewardship practices that we identified were implemented by one single actor. Some practices, however, enhanced "collaboration" among stakeholders operating in the same area at the same time. Commercial vessels are increasingly supporting scientific activities by promoting and facilitating citizen science projects (e.g., the FjordPhyto project) while also transporting researchers to remote locations (Cusick et al. 2020). Lamers et al. (2024) recently raised the question of whether the emerging combinations of science and tourism practices in the polar regions always lead to positive environmental outcomes, a question that requires further research in the Antarctic context.

Our research supports the view that environmental management and environmental stewardship practices are fundamentally different, but that over time some stewardship practices have been institutionalized and turned into management. For example, environmental stewardship practices in tourism, such as visitor site guidelines, have transitioned into environmental management practices as they were initially adopted as part of self-regulation and later incorporated into internationally agreed-upon formal Antarctic policy instruments (Haase et al. 2009; Lamers et al. 2012). In a similar vein, science-related logistical operations developed a series of environmental stewardship practices to address and improve the management of resources, going far beyond the formal policy instruments. An example of this is fuel management and the prevention of oil spills.

Limitations and further research

Our analysis and results rest on several key choices and assumptions. The expert assessment of the significance of different impact categories was performed by highly knowledgeable individuals but it remains subjective. Our aggregation of environmental stewardship practices also contains an element of subjectivity. In addition, environmental practices are dynamic and constantly evolving (Lamers et al. 2024). Therefore, the resulting list of environmental management and stewardship practices is not intended as an exhaustive inventory of science and tourism environmental practices in Antarctica. The current analysis is based on various written reports or paper records of actual environmental management and stewardship practices of Antarctic science and tourism operations. Particularly for Inspection Reports, we recognize that the rigid structure and set questions of the reports may cause additional practices to go unnoticed and unreported. We acknowledge the fact that we have merely counted numbers of practices, without assessing the significance and effectiveness of these practices in tackling environmental impacts. Therefore, the number of practices should not be used as a proxy for the effectiveness of environmental management. More ground-truthing work is warranted to empirically analyse environmental stewardship practices in the field.

Conclusions

Environmental management and environmental stewardship practices make a substantial contribution to reducing or avoiding the environmental impacts that human activities have in Antarctica. We identified environmental stewardship, almost equally divided between science and tourism operations. A plurality of practices relate to the reduction of atmospheric emissions, many in the context of the energy transition. Other impact categories that are addressed by many stewardship practices are wildlife disturbance, water pollution and soil degradation. The number of practices does not align with the most significant impacts. Although the number of practices does not necessarily reflect the effectiveness of the measures taken, it can at least indirectly give an idea of the level of concern by the stakeholders relating to the impact category. Experts identified the introduction of non-native species as the most significant impact of science and tourism in Antarctica, but only a few practices address it. Conversely, many practices relate to soil degradation, for example, to prevent oil spills, whereas experts assessed this impact category as the least significant of all seven categories considered.

At first sight, self-initiated environmental stewardship practices may seem insignificant in comparison to formal Antarctic Treaty System policies, but over time they can be influential in policy-making. Science and tourism stakeholders can borrow successful practices from each other and contribute to Antarctica's management and conservation in the process. As stewardship practices become more common, they can be adopted by policy-makers and end up being codified in Antarctic Treaty System regulations. Looking at what tourism does in terms of environmental stewardship practices could greatly contribute to the development of the comprehensive framework for tourism in Antarctica, now an ongoing process led by ATCPs.

Environmental stewardship is also used as a vehicle for collaboration among stakeholders. Science and tourism share infrastructure, facilities, transport vehicles and platforms, for example, to transport tourists and researchers, support citizen science projects or reduce costs by making better use of existing capacity. Limiting the construction of new infrastructure and facilities is also the goal of an often overlooked environmental stewardship practice: inaction. The practice of refraining from action opens up whole new avenues for reflection: reflection by NAPs on the need to continue expanding infrastructures in Antarctica and reflection by the tourism sector on the need to increase the number of cruise vessels and sites available for visitation or to further diversify activities (e.g., to include extreme adventure). We encourage NAPs and tour operators to consider inaction as a suitable and feasible environmental stewardship practice.

Environmental stewardship practices have been a key element for tourism and science operations in Antarctica, but there is also a need to transition to more comprehensive management. Self-initiated environmental stewardship practices are useful for stakeholders who want to do the right thing in situations—as today's—in which they need to adapt to fast-changing circumstances and want to distinguish themselves from others. The adoption of comprehensive environmental management practices and the implementation of environmental stewardship practices should go hand in hand to protect Antarctica as a natural reserve, a continent devoted to peace and science.

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