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What are the real environmental impacts of Antarctic tourism? Unveiling their importance through a comprehensive meta-analysis

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ABSTRACT

Human activities in Antarctica were increasing before the COVID-19 pandemic, and tourism was not an exception. The growth and diversification of Antarctic tourism over the last few decades have been extensively studied. However, environmental impacts associated with this activity have received less attention despite an increasing body of scholarship examining environmental issues related to Antarctic tourism. Aside from raising important research questions, the potential negative effects of tourist visits in Antarctica are also an issue discussed by Antarctic Treaty Consultative Parties.

This study presents the results of a meta-analysis of scholarly publications that synthesizes and updates our current knowledge of environmental impacts resulting from Antarctic tourism. A first publication database containing 233 records that focussed on this topic was compiled and subjected to a general bibliometric and content analysis. Further, an in-depth content analysis was performed on a subset of 75 records, which were focussed on showing specific research on Antarctic tourism impacts. The main topic, methods, management proposals, and research gaps highlighted by the respective authors of these 75 publications were assessed. The range of research topics addressed, the methods used – including the application of established research designs from the field of environmental impact assessment –, and the conclusions reached by the study authors are discussed. Interestingly, almost one third of the studies did not detect a direct relationship between tourism and significant negative effects on the environment. Cumulative impacts of tourism have received little attention, and long-term and comprehensive monitoring programs have been discussed only rarely, leading us to assume that such long-term programs are scarce. More importantly, connections between research and policy or management do not always exist. This analysis highlights the need for a comprehensive strategy to investigate and monitor the environmental impacts of tourism in Antarctica. A first specific research and monitoring programme to stimulate a debate among members of the Antarctic scientific and policy communities is proposed, with the ultimate goal of advancing the regulation and management of Antarctic tourism collaboratively.

1. Introduction

The modern era of Antarctic tourism is commonly regarded to have commenced in the 1960s, when annual commercial expedition cruises to this region began (Headland, 1994; Crosbie and Splettstoesser, 2011). Since then, and until the disruptions caused by the COVID-19 pandemic in the 2020-21 season, Antarctic tourism had significantly increased and diversified. A total of 74 401 tourists visited Antarctica during the 2019-20 season, representing a 134% increase from the 2010-11 season (International Association of Antarctica Tour Operators, 2021). The

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expanding Antarctic tourism sector within one of the world's largest remaining wildernesses, increasing operational capacity of vessels to access new sites, and the synergies with other global issues (e.g., climate change, biological invasions, global pollutants, COVID-19) make it essential to take a strategic approach to regulating Antarctic tourism, and in fact, any human activity in the Antarctic.

Presently, human activities in the Antarctic Treaty area and their environmental impacts are mainly regulated through the 1991 Protocol on Environmental Protection to the Antarctic Treaty, also known as the Madrid Protocol ("the Protocol" hereafter), which entered into force in 1998. Tourism is expressly mentioned in the Protocol as one of the human activities that are regulated by this agreement.

Article 3 (1) of the Protocol mandates that *"regular and effective monitoring shall take place to allow assessment of the impacts of ongoing activities, including the verification of predicted impacts"*. This implies that Antarctic Treaty Consultative Parties (ATCPs) consider the management of Antarctic tourism to be within their purview, which is a commitment that was reaffirmed in Resolution 7 (2009). This document outlined the 'General Principles of Antarctic Tourism' and called for scientific research and evidence to support Antarctic tourism regulation and management. This call was reiterated by the Committee for Environmental Protection (CEP), when they emphasized the need for monitoring environmental impacts caused by Antarctic tourism, particularly cumulative impacts, in their 2012 comprehensive state-of-knowledge review of Antarctic tourism (CEP, 2012).

Antarctic tourism operators have shown a strong commitment to environmental protection. The International Association of Antarctica Tour Operators (IAATO), founded in 1992 and currently counting more than 100 members, advocates and supports safe and environmentally responsible private-sector travel to the Antarctic. IAATO states that they strive for tourism operations to have "*no more than a minor or transitory impact*" on the Antarctic environment, and that their members are to comply with all regulatory mechanisms – binding as well as hortatory – agreed by the ATCPs, the International Maritime Organization (IMO) and other applicable international and national agreements (IAATO, 2021).

Three decades ago, some scholars suggested that the environmental impacts of Antarctic tourism may be insignificant compared to (a) the adverse effects caused by the construction of Antarctic bases and the waste generated in this process, or (b) the harvesting of marine resources by the fishing industry (Hall, 1992). However, according to many researchers, the potential environmental impacts arising from human activities in the Antarctic in general, and tourism in particular, represent an important but under-researched matter (Stewart et al., 2005, 2017). A high concentration of tourist sites, alongside scientific stations, in ice-free coastal areas is thought to potentially cause more significant adverse environmental impacts since these sites possess most of Antarctic terrestrial biodiversity (Convey, 2011).

Antarctic tourism activities are concentrated during the austral summer between November and March though operations extend into October and April. In this period, from an operational perspective, access to the Antarctic continent is aided by sea-ice thaw. From an ecological perspective, the Antarctic tourism season corresponds with the peak breeding season for several Antarctic wildlife populations, increasing the chance of direct human-wildlife conflicts and adverse impacts on endemic fauna and flora. Therefore, it is important to carefully review the character and magnitude of any negative effects arising from tourism and other human activities in the Antarctic and to weigh their benefits against their environmental costs.

While scholarly publications have explored the types of environmental impacts arising from human activities in the Antarctic, including tourism, fishing, and national operator activities (e.g., Chen and Blume, 1997; Tin et al., 2009; Coetzee and Chown, 2016), few studies have focused specifically on the impacts of tourism. Among the latter are two technical reports that have been devoted to Antarctic tourism. The first report presented the proceedings of a workshop on cumulative environmental impacts of commercial ship-based tourism in the Antarctic Peninsula area (Hofman and Jatko, 2000). The second report was the comprehensive review of tourism matters, including tourism impacts and management (CEP, 2012). Almost a decade later, an updated review of advances in knowledge regarding this issue is warranted.

After a period of little advancement in the study of tourism impacts in Antarctica, this research topic has been growing in importance in recent years (Stewart et al., 2005). Several key texts published in the mid-1990s have mentioned Antarctic tourism impacts (e.g., Headland, 1994; Hall and Johnston, 1995), but since then the number of scientific publications exploring the matter of, or need for greater research on, Antarctic tourism impacts has been steadily increasing. Meanwhile, the topics and issues explored by Antarctic tourism scholars have diversified (Stewart et al., 2017).

Nowadays, research on the impacts resulting from Antarctic tourism operations is a priority issue for the Antarctic scientific community as exemplified by the growing interest in polar tourism research by policy makers and tour operators themselves (Stewart et al., 2005; Netherlands and New Zealand, 2019). This has encouraged research on the growth and diversification of Antarctic tourism (Liggett and Stewart, 2017; Carey, 2020), observations relating to an increasing pace of climate and environmental changes in the region putting pressures on native biodiversity, the potential consequences of regional warming for the establishment of non-native species (Liggett et al., 2017; Convey and Peck, 2019), and cautionary recommendations relating to uncertainties around tourism activities and development as a result of the COVID-19 pandemic (Hughes and Convey, 2020; Barbosa et al., 2021).

Interest in a detailed review of human impacts arising from Antarctic tourism is also stimulated by Antarctica's geopolitical peculiarities as global commons (Buck, 2017) governed by a consensus-based system with decision-making rights currently held by 29 ATCPs. This makes governance a complex matter, with reached decisions limited to the common denominators that the different Parties can agree upon,. Secondly, Article 2 of the Protocol designates Antarctica as *"a natural reserve, devoted to peace and science"*, which requires the protection of Antarctica from adverse impacts caused by human activities on behalf of humankind.

Within this context, the aim of the current study was to update and synthesize our current knowledge of the environmental impacts resulting from Antarctic tourism by undertaking a meta-analysis of scholarly publications, addressing the following set of research questions:

1. What adverse environmental impacts are being associated with Antarctic tourism operations?
2. What research methods have been adopted to assess the negative consequences of the presence of tourists in the Antarctic?
3. How can the results obtained be applied to improve Antarctic tourism management by the Antarctic Treaty System (ATS)?

2. Research methods

This bibliometric meta-analysis followed the guidelines on *Preferred Reporting Items for Systematic Reviews and Meta-Analyses* (PRISMA) (Moher et al., 2010), which divide a structured assessment of publications into four distinct phases: identification, screening, eligibility, and included works. It has been utilised previously with a focus on polar tourism issues by Demiroglu and Hall (2020). In this study, a fifth phase was added involving an in-depth content analysis of the selected works to the PRISMA approach (Fig. 1).

A database of 592 publications (up to December 2020) was compiled. Suitable publications for this database were identified by searching two leading academic bibliometric databases – Clarivate's *Web of Science (WoS)* and Elsevier's *Scopus* –using the following Boolean string (1):

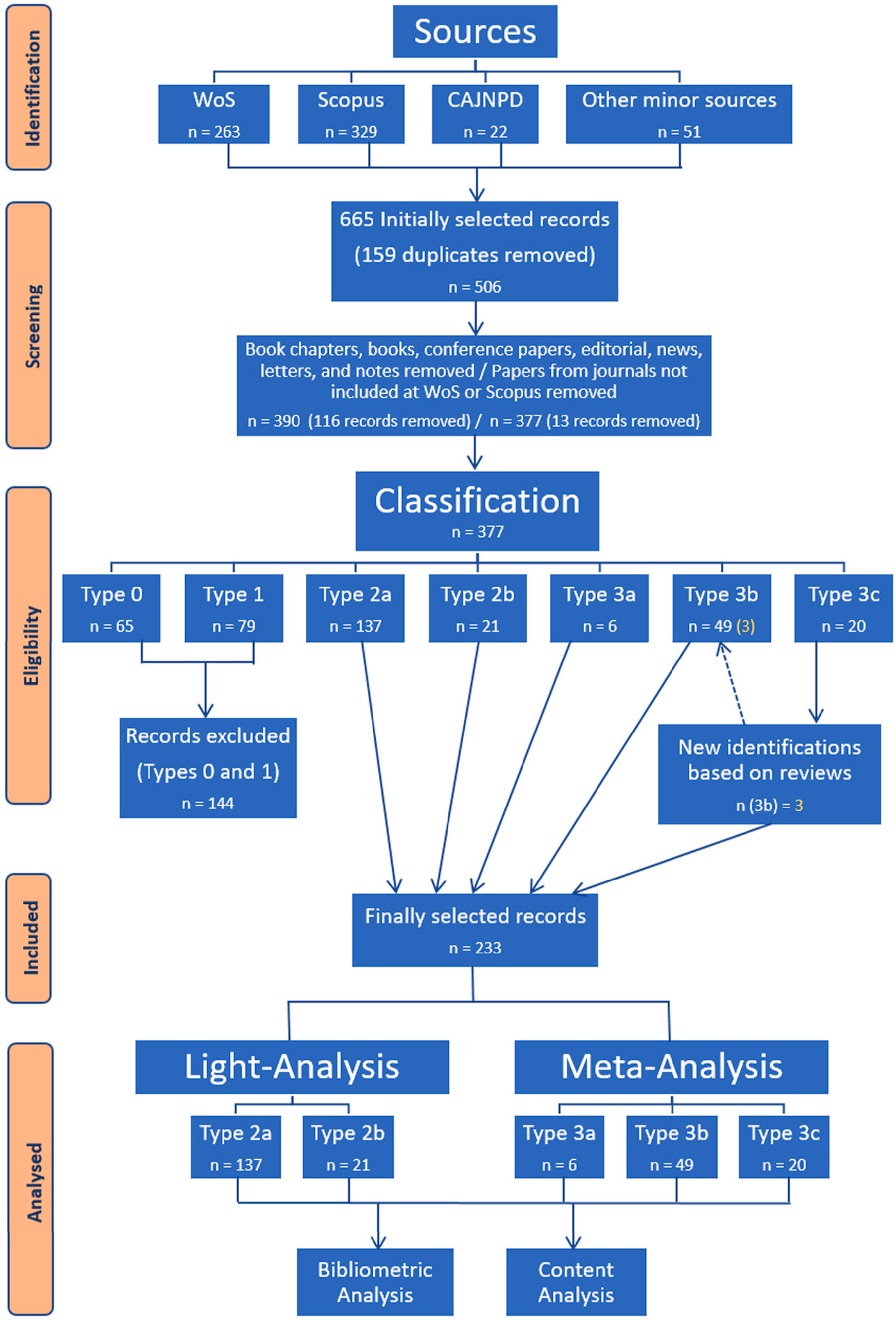

Fig. 1. Flow diagram depicting the five-phase methodology for systematic review of Antarctic tourism impacts documents.

TITLE-ABSTRACT-KEYWORDS ("Antarctic tourism" OR "tourism Antarctic*" OR "Antarctic* touris*" OR "Antarc* touris* impact" OR "impact* tourism* antar*") (1)

Following this initial search, then the database was expanded by a targeted search of other secondary sources, including *Google Scholar*, the *China Academic Journal Network Publishing Database (CAJNPD)*, and the authors' personal collections. The Google Scholar search was undertaken in four languages (English, Spanish, French, and German), using the following query string (2).

Antarctic tourism impact / Impacto turismo antártico / Impact tourisme antarctique / Antarktis Touris(mus/tik) umweltbelastung (2)

The query that we used in CAJNPD (3) was:

TOPIC-TITLE-KEYWORDS (南极旅游) (3)

This search returned 263 individual records in *WoS*, and 329 in *Scopus*. 24 additional publications were identified in *Google Scholar*, 22 in *CAJNPD*, and 27 from the authors' personal collections or specialized in Science or Biology databases (24 and 3 records, respectively). The reference lists of all identified publications were also searched for additional relevant records that reported research on potential environmental impacts arising from Antarctic tourism operations. The latter scan of the reference lists identified only three additional publications, indicating that our prior online database search, along with the publications added from our personal collections, had resulted in a comprehensive database.

Any duplicates from the publication database thus built were then removed. In total, 159 duplicate records were removed. In addition, any records not classified as research articles (i.e., books, book chapters, conference papers, conference review, letter, news, technical reports, and notes), or not published in indexed journals (*WoS*, *Scopus*, or *CAJNPD*), were also removed, resulting in a final database containing 377 records.

Publications then were assigned to one of the following seven categories:

Type 0: Tangential publications that focus on other regions of the world outside the Antarctic but make mention of Antarctica, or the broader Antarctic region, as a case study or for the sake of comparison.

Type 1: Publications that refer to Antarctic tourism specifically but are not evolving around Antarctic tourism as a central topic of discussion.

Type 2a: Publications that consider Antarctic tourism from a theoretical perspective and may discuss tourism development, management or regulation, governance matters or operational aspects.

Type 2b: Publications presenting research on socio-psychological issues related to Antarctic tourism, including learning, changes in perception, attitudes, awareness or knowledge, tourist experiences, aspirational values, or citizen-science projects. It is noteworthy that positive impacts of Antarctic tourism were explored by some of the papers in this category.

Type 3a: Publications discussing adverse environmental impacts related to tourism affecting the Antarctic (e.g., plastics, global pollutants) and arising from human activities outside the Antarctic.

Type 3b: Publications examining direct interactions between tourism and the Antarctic environment (e.g., wildlife, soils, contamination, water, non-native species, flora, trampling, penguins, colonies, mammals) or assessing tourism impacts originating from activities within the Antarctic.

Type 3c: State-of-knowledge review papers summarizing present knowledge on Antarctic tourism impacts but not presenting original data on environmental impacts.

Following this categorisation, all Type 0 and Type 1 records (144 in total) were excluded from further analyses resulting in a reduced database containing 233 records. Consequently, we analysed the records for temporal trends to show the evolution of scholarly interest in relation to Antarctic tourism matters by article types. The language of the relevant publications was also assessed in these 233 records.

Type 2b records were subjected to a high-level content analysis that identified and described the main issues discussed in these publications. Type 3 records were subjected to a thorough content analysis that considered the publication outlet (i.e., the journal in which a study was published), the impact factor of the respective journals, the main topics of the article, any relevant management/policy proposals, and any research gaps or needs identified by the authors. For Types 3a and 3b publications, the study design and methods employed and, where primary data were collected, the spatial and temporal scale as well as sites for data collection, the variables and covariates analysed, impacts identified, statistics applied, and the main conclusions and recommendations reached by the authors were examined. The content analysis for Type 3c records examined potential Antarctic tourism impacts identified and the study framework (i.e., global, by contaminant, by environment, by taxonomic group, or by region).

3. Results

3.1. General bibliometric analysis

Early descriptive scholarly works explored Antarctic tourism activities in the 1980s (e.g., Reich, 1980), but publications examining some of the potential environmental impacts arising from the presence of tourists in Antarctica only entered the scene in the 1990s (Fig. 2). There has been also a rise in the number of documents dedicated to the description of the governance of Antarctic tourism (Type 2a articles), and those dedicated to the human dimensions of this activity (Type 2b articles) over the last 30 years. The numbers of Type 3a and 3c articles also increased, but mainly over the last decade only.

Most of these works were published in English. Of 233 articles included in the final database, 205 were in English (88%). Chinese (17 articles, 7.3%) and Spanish (6 articles, 2.6%) were the next most common languages. The presence of relevant indexed publication in languages other than English, support the need to use different data sources, including databases in different languages, to comprehensively assess knowledge generated in relation to a research topic of international interest such as this one.

3.2. Publications examining social dimensions of Antarctic tourism

The study of Type 2b documents (SM1), i.e., those focused on human dimensions of Antarctic tourism, shows that most of the published research discusses perceptions of tourists, scientists, or support staff regarding Antarctica and its values, wilderness, or tourist activities (8 articles). The second most prominent cluster of articles analyses the experiences, characteristics, and motivations of tourists (5 articles). Authors of both of these clusters of publications most commonly utilise questionnaire surveys, but a number of different qualitative techniques have also been used and include the study of travellers' blogs, autoethnographies using researchers' self-reflective writings, and semi- or unstructured interviews. Less common topics included in our Type 2b category are the potential for tourists to be Antarctic ambassadors (2 articles), Antarctic heritage (2), tourism development and management

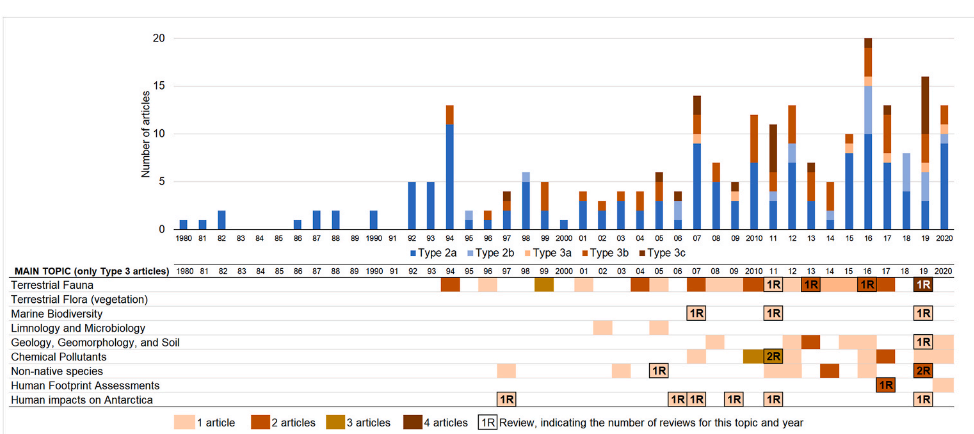

Fig. 2. Trends in the articles about Antarctic tourism and its impacts. Upper graph: articles by year (1980–2020) and type. Table below: main topic for each Type 3 article.

(2), and citizen science in relation to Antarctic tourism operations (2).

3.3. Publications examining Antarctic tourism impacts

Roughly 39% of the 75 Type 3 articles that specifically analyse the impacts of Antarctic tourism (SM2) have been published in polar journals (*Polar Biology*, 15 articles; *Antarctic Science*, 6; *Polar Record*, 5; *Polar Research*, 3) (SM3). Other Type 3 articles were published in conservation-focussed journals (*Biological Conservation*, 3) or management journals (*Journal of Environmental Management*, 3), with the remaining 32 Type 3 articles published in a mix of polar journals with lower impact factors, generalist publications, or other journals specializing in tourism, management, environmental matters, and certain types of ecosystems or taxonomic groups. Within these 34 publications, Q1 and Q2 journals are the most common (SM4), with an increase in the number of publications in Q1-journals in the last decade. As is known, Q index defines the rank of a journal. For example, Q1 indicates the journal is ranked among the top 25% journals in the same area of research.

Most of the early publications exploring tourism impacts focused on penguin-human interactions (Fig. 2, Table below), with 30 relevant articles over 40 years. Penguins are one of the main tourist attractions, are widely distributed on the continent with high abundance at a number of locations, are easily accessible to researchers, and most importantly, are an umbrella species selected as bioindicators for environmental monitoring and conservation decisions that benefit a larger ecological community (Houstin et al., 2021).

Other topics receiving greater scholarly attention over time include research on chemical pollutants (13 articles), non-native species (10), and soil degradation (8). Chemical pollution and the potential introduction of non-native species are matters that have received much international attention in recent years as they are considered global drivers of ecosystem change. Soil degradation is another internationally fundamental problem that is equally pertinent in Antarctica since a large part of the terrestrial biota is concentrated in a few ice-free areas, primarily around the coast but also in nunataks and the McMurdo Dry Valleys.

In contrast, damage to Antarctic vegetation by tourists has so far received limited consideration by field scientists. While many articles have cited the adverse effects of trampling as a potential impact of tourism (e.g., Chen and Blume, 1997; Tin et al., 2009), only very few empirical studies have been developed to date. Much research on this topic corresponds to experimental studies not specifically designed to evaluate the consequences of tourism, but of researchers doing fieldwork (e.g., Pertierra et al., 2013). Actual data on trampling and footpath development by Antarctic tourists are rare (e.g., Tejedo et al., 2016). This is reflected in Fig. 2, which highlights that no article has been identified as having vegetation as the central topic studied. The same holds true for limnology, another area rarely studied from an Antarctic tourism impacts perspective. However, the scarcity of bodies of freshwater at sites frequented by Antarctic tourists explains the absence of such research in an Antarctic tourism context.

The effects of tourist activities on marine ecosystems have been addressed mainly through review studies often focussed on tourism in parts of the world outside the Antarctic region (e.g., Erbe et al., 2019). Microbiologists have published some research that focused on the role of tourists as vectors for the dispersal of microorganisms, e.g., via their boots (Curry et al., 2002), and on managing the risk of introducing or dispersing microorganisms in the Antarctic through the use of disinfectants (Curry et al., 2005). Finally, a couple of articles focussed on the examination of the human footprint in the Antarctic (Pertierra et al., 2017; Leihy et al., 2020) drawing on historical and spatial records of the distribution of Antarctic tourists, researchers and science support staff, and other visitors.

3.4. Identified impacts

An in-depth analysis of the 75 Type 3 articles allowed to identify a wide range of potential and measured impacts arising from Antarctic tourism activities (Table 1). For the sake of analytical clarity, 3 large groups of activities were chosen: land-based, ship-based, and airborne activities. Table 1 shows that actual negative impacts have only been confirmed as arising from tourism activities in a very limited number of cases, which were largely focussed on effects on soil and vegetation (due to trampling), disturbance of macrofauna (mainly penguins and seabirds, but also in relation to some marine mammals), the potential introduction of non-native species, and pollution (e.g., marine debris or greenhouse gases). However, in many cases the magnitude of these impacts on Antarctic ecosystems has not been adequately quantified.

Potential negative environmental impacts resulting from Antarctic tourism discussed in Type 3a and 3b articles (Fig. 3) include chemical pollutants; impacts on geology, geomorphology, and soil; limnological and microbiological consequences; and social impacts/human dimensions. For other topics, i.e., terrestrial fauna and non-native species, there is more variability in the results since numerous studies within these topics have not been able to prove that the presence of tourists generates negative impacts on the component of the environment analysed.

The research approach taken by the authors of the 55 Type 3a and 3b articles was examined to understand the levels of rigour and comprehensiveness the reported study results were based on (Table 2). Most of the undertaken research so far has either utilised empirical field-based observations or a mix of primary methods, but dedicated long-term monitoring studies of tourism impacts are still very rare. Personal observations were used in 18% of the studies. On a number of occasions, researchers used a range of different primary methods for verification purposes.

Logistical limitations linked to the difficult conditions in the field often mean that researchers resort to using simple and widely used sampling protocols for data collection, making measurements and observations that are relatively quick and easy to obtain in the field, although laboratory analyses of the taken samples in field can be complex, costly and time-consuming (e.g., eDNA, massive parallel sequencing, mass spectrometry, etc.).

Sixty percent of the studies analysed undertook component analyses of a set of parameters, applying a state-of-the-environment approach. 29% of the studies catalogued used impact-control designs (i.e., by comparing areas or colonies with and without tourism), and 22% drew on time-series of monitoring data. Repeated observation over time, or better yet, long-term monitoring using consistent sampling protocols, are vastly superior when trying to identify significant relationships between the presence of visitors and their impacts on the environment. Before-and-after studies are still rare (9%) because of the logistical complexity required to carry out this type of research and because researchers often lack comparable pre-visitation data. This is a disadvantage since it would be useful to combine such before-and-after studies with annual, or biennial, review studies to determine the resilience of Antarctic ecosystems, in terms of their capacity to recover from tourist activities. 20% of the studies analysed used mixed-methods approaches (i.e., 11 articles). Full BACI designs (Before-After-Control-Impact), which are ordinarily applied in environmental impact assessments, are notably absent in the analysed works. They could enable an improved identification of any adverse impacts resulting from Antarctic tourism operations (SM5).

The study sites in the Type 3a and 3b articles analysed largely correlate with areas frequented by tourists, that is, the South Shetland Islands (42%) and the Antarctic Peninsula (35%). The Ross Sea region has received less scholarly attention, except in relation to impacts on soils, which is the focus of several studies (e.g., Ayres et al., 2008; O'Neill et al., 2013, 2015). Regardless of the respective study sites, it should be noted that most of the papers analysed drew on data obtained

Table 1
Environmental impacts by tourism activity, impact class, and impacts category. Some selected references are showed. For each impact, we point out the spatial range of the effects (G = global; L = local) and if it is a confirmed or probable impact caused by tourism activity (+ = proved, ? = theoretical). Although the relationship between a specific impact and a tourist activity has been proved in an article, it does not mean that such impact occurs on all occasions or that its effects are more than minor or transitory.

Activity	Impact class	Impact category	Selected references	Range	Impact
Tourism Environmental Impacts					
Land-based: onshore activities	Soil degradation	Compaction/compression	Tejedo et al. (2012, 2016)	L	+
		Denudation/visual disturbances/reduced soil albedo	O'Neill et al. (2013)	L	+
		Footpath erosion	Tejedo et al. (2016)	L	+
		Negative effects on soil fauna	Ayres et al. (2008), McInnes and Pugh (2013)	L	+
		Alteration of nutrient availability and pH conditions	O'Neill et al. (2015), Tejedo et al. (2016)	L	?
		Alteration of microbial activity	Tejedo et al. (2016)	L	+
		Changes in soil moisture/snow/permafrost	Tejedo et al. (2016)	L	+
	Lakes, freshwater pods, and streams degradation	Water quality alteration	Kariminia et al. (2012)	L	?
		Alteration of food web and local communities	Frenot et al. (2005)	L	?
	Vegetation damages by trampling	Plant cover decrease	Chen and Blume (1997), Cajiao et al. (2020)	L	+
		Reduced vigour	Cajiao et al. (2020)	L	+
	Disturbance to macrofauna	Reduced breeding success, recruitment, or population abundance	Woehler et al. (1994), Trathan et al. (2008)	L	+
		Increased predation	Chen and Blume (1997)	L	?
		Eggs, pups or nest desertions	Chen and Blume (1997), Pfeiffer and Peter (2004)	L	+
		Disruption of reproductive and other social behaviours	Coetzee and Chown (2016), Ropert-Coudert et al. (2019)	L	?
		Increase in energetic or time costs by altered behaviour and stress from interaction, or physiological negative effects	Burger and Gochfeld (2007), Barbosa et al. (2013)	L	+
	Introduction of non-native species	Alteration of food web and local communities	Frenot et al. (2005), Molina-Montenegro et al. (2012)	L	?
		Inter and intra-region transfers	Fuentes-Lillo et al. (2016), McCarthy et al. (2019)	L	?
		Diseases and zoonosis	Curry et al. (2002, 2005), Bonnedahl et al. (2005)	L	+
	Other impacts	Pollution by vehicles (e.g. snowmobiles)	Tin et al. (2009)	G	?
		Water consumption and pollution during camping and station visits	Kariminia et al. (2012)	G	?
		Rubbish and litter	Amelung and Lamers (2007), Kariminia et al. (2012)	L	?
		Visual presence of people	Amelung and Lamers (2007)	L	?
		Degradation of heritage sites/graffities	Kariminia et al. (2012), Tin et al. (2014)	L	?
		Noise from drones undermining other tourists experience	Leary (2017)	L	?
		Damage to geomorphological features	Tin et al. (2014)	L	?
		Landscape modification (recreational paths)	Brooks et al. (2019)	L	+
		Disruption of scientific research	Aronson et al. (2011)	L	?
		Souveniring and removal of historic artefacts	Amelung and Lamers (2007), Tin et al. (2014)	L	?
Ship-based activities in the marine environment	Direct effects	Accidental collisions of seabirds for light attraction	Chen and Blume (1997)	L	?
		Damage to benthic communities by anchoring	Aronson et al. (2011)	L	?
		Ice damages	Kariminia et al. (2012)	L	+
		Direct injures or death by ship strikes in marine mammals	Leaper and Miller (2011)	L	+
		Consequences of groundings and sinkings	Liggett et al. (2011), Kariminia et al. (2013)	L	+
	Emissions and chemical pollution	Sewage dumps	Amelung and Lamers (2007), Aronson et al. (2011)	G	?
		Greenhouse gases, particulates, and other emissions	Farreny et al. (2011), Cabrerizo et al. (2016)	G	+
		Fuel spills and leaks	Tin et al. (2009), Aronson et al. (2011)	G	?
		Anti-fouling toxins from ships hulls	Woehler et al. (2014)	G	?
		Albedo alteration by dispersion of dust/particles	Convey and Peck (2019)	L	?
	Disturbance to marine mammals	Habituation	Leaper and Miller (2011), Erbe et al. (2019)	L	?
		Stress from interaction	Williams and Crosbie (2007), Erbe et al. (2019)	L	?
		Disruption of feeding, reproductive and other social behaviours	Erbe et al. (2019)	L	?
		Avoidance and displacement from feeding areas or migration routes	Williams and Crosbie (2007)	L	?
		Auditory masking, hearing threshold shifts, death	Williams and Crosbie (2007), Erbe et al. (2019)	L	?
	Non-native species	Alteration of food web and local communities	Frenot et al. (2005)	L	?
		Inter and intra-region transfers		L	?

(continued on next page)

Table 1 (*continued*)

Activity	Impact class	Impact category	Selected references	Range	Impact
		Diseases and zoonosis	Lewis et al. (2003), Smith and Richardson (2011) Grimaldi et al. (2011), Woehler et al. (2014)	L	?
	Marine debris	Entangles seals: infections, inability to evade predators, starvation due to an impaired ability to catch prey, death	Do Sul et al. (2011), Woehler et al. (2014)	L	?
		Negative effects in seabirds: injures in gastrointestinal tract, infections, starvation, decrease feeding stimulus, contamination by organic pollutants, entangled individuals are unable to fly feed or evade predators, death	Do Sul et al. (2011), Ibañez et al. (2020)	L	+
		Plastic particles from laundry and personal care products introduced in the environment	Woehler et al. (2014), Waller et al. (2017)	G	+
	Other impacts	Disruption of scientific research	Aronson et al. (2011)	L	?
Airborne: air transport, overflights and helicopter operations	Direct effects	Collision and strike injure	Woehler et al. (2014), Hughes et al. (2019)	L	?
	Disturbance by noise	Temporal displacement, mass panic, death, etc.	Tin et al. (2014)	L	?
	Emissions and chemical pollution	Greenhouse gases, particulates, and other emissions	Amelung and Lamers (2007)	G	?
		Fuel spills and leaks	Amelung and Lamers (2007)	G	?
		Albedo alteration by dispersion of dust/particles	Convey and Peck (2019)	L	?

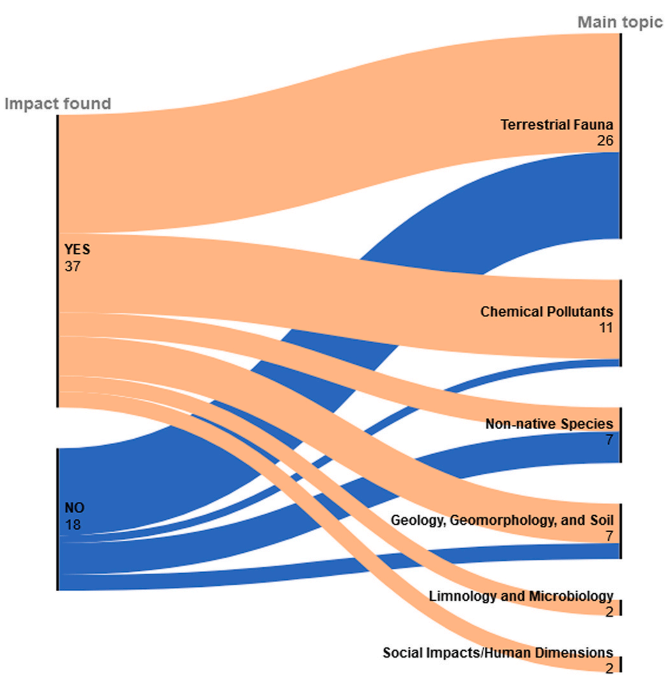

Fig. 3. Impact found by main research topic addressed in Type 3a and 3b articles.

from a number of locations (46%). A few researchers undertook regional studies (4%) or considered the entire Antarctic continent (7%).

When examining the location of study sites further, many studies were conducted at frequently visited tourist sites (66%), in Antarctic Specially Protected Areas (ASPAs) (40%), or in the vicinity of bases or stations (33%), probably due to these sites' easier access for researchers.

The majority of the field studies specifically included a longitudinal aspect, with data collected over a few years (56%), which makes sense considering that many funded projects are designed to extend over 2–3 field seasons. However, studies involving opportunistic data collection and less than two months in the field also featured strongly (33%). Given the difficult and expensive logistics required for Antarctic fieldwork, the prevalence of opportunistic data collection is not surprising. Regarding impact detection, long-term studies are preferable (SM6).

Finally, it is worth noting that the difficulties in establishing causal links between the presence of tourists and negative environmental impacts resulting from tourist visits might be due to almost half of the articles (49%) not using hypothesis testing, thus precluding any statistical inferences. The study authors are generally cautious and do not categorically associate tourism with possible negative environmental effects (SM6). In fact, 33% of the reviewed studies could not conclusively link tourism activities with any specific environmental impacts.

3.5. State-of-the-art literature reviews

Most of Type-3 review articles (N = 20, marked with a box in Fig. 2) followed a generalist approach to identify potential environmental impacts resulting from the presence of tourists in Antarctica, especially in the case of articles published up to 2010. Since then, a greater number of reviews have been published with more specific foci on particular ecosystems (e.g., marine environment), taxonomic groups (e.g., penguins or whales), or environmental problems (e.g., non-native species).

3.6. Management proposals and research gaps

Type 3a and 3b articles identify a range of suitable management responses and research gaps that were summarized in Tables 3 and 4. Most frequently mentioned management measures include: 1. implementing long-term monitoring, 2. improving biosecurity protocols, 3. strengthening environmental impact assessments, 4. applying active remediation actions, and 5. developing educational programs for different Antarctic tourism stakeholders. The most common identified research needs include: 1. evidence-based research that is of direct relevance and use to decision-makers, 2. research on cumulative impacts and the interaction between impacts and different global drivers of change, 3. studies developing more complex, and yet robust, models that take into consideration multiple environmental variables simultaneously to enable a comprehensive visualization of possible changes in Antarctic ecosystems, especially where they relate to human visitation, and 4. more comprehensive longitudinal regional and continental-scale studies of human impacts.

4. Discussion

4.1. Challenges when compiling the database of scientific papers

Searches in academic publication databases using keywords generate large lists of results, but not all of the resulting outputs are relevant. Consequently, a careful screening is required to remove irrelevant results. This is a straightforward task with medium-sized result sets (<1000) but can become untenable for larger datasets. Other bibliometric studies focussed on Antarctic-related research have also encountered this problem (Dastidar and Persson, 2005; Dastidar, 2007;

Table 2
Research methods used in the impact articles (Types 3a and 3b). N = 55 articles. A single result correspond with one category, meanwhile multiple results can correspond to combinations of two (2x), three (3x) or four (4x) categories. When an article has multiple categories, single percentages do not sum 100% due to mixed-methods approaches taken by these studies.

Criteria	Categories		Type of result	
Impact articles				
Primary methods	Field experiments: 7	12.7%	Single: 36	65.5%
	Field survey of resource conditions: 45	81.8%	2x: 15	27.3%
	Visitor/staff/crew/guides survey: 2	3.6%	3x: 4	7.3%
	Personal observations: 10	18.2%		
	Historical records: 6	10.9%		
	Spatial analysis: 6	3.6%		
	Modelling: 6	10.9%		
Complexity of the methodology	Simple direct measurement (on-site): 38	69.1%	Single: 31	56.4%
	Complex direct measurement (on-site): 8	14.5%	2x: 21	38.2%
	Simple lab measurement (ex-situ): 13	23.6%	3x: 3	5.5%
	Complex lab measurement (ex-situ): 18	32.7%		
	Not applicable (or not described): 5	9.1%		
Study design	Baseline inventory or assessment	60.0%	Single: 44	80.0%
	Before-after comparison	9.1%	2x: 10	18.2%
	Control-Impact comparison	29.1%	3x: 1	1.8%
	Repeated monitoring	21.8%		
	Personal observations/other situations	1.8%		
Spatial scale	Antarctic Peninsula	34.5%	Single: 51	92.7%
	Shetland Islands	41.8%	2x: 4	7.3%
	Continent	3.6%		
	Ross Sea Region	10.9%		
	All the Antarctica	10.9%		
	Not applicable	5.5%		
Spatial design	Site-Multiple	45.5%	Single: 55	100.0%
	Site-Single	38.2%		
	Regional	3.6%		
	All the Antarctica	7.3%		
	Not applicable	5.5%		
Type of site	Protected area[a]	40.0%	Single: 30	54.5%
	Visited/touristic site	65.5%	2x: 12	21.8%
	Base or station	32.7%	3x: 6	10.9%
	Other sites	36.4%	4x: 7	12.7%
	Not applicable	7.3%		
Temporal scale	Short-term (2 months or less)	30.9%	Single: 55	100.0%
	Data from an entire season	7.3%		
	Data from an entire year	3.6%		
	Data from multiple years	58.2%		
Impact found	Yes: 37	67.3%	Single: 55	100.0%
	No: 18	32.7%		
Statistics/p-value	Yes: 28	50.9%	Single: 55	100.0%
	No: 27	49.1%		

[a] Protected areas = ASPA (Antarctic Specially Protected Area), ASMA (Antarctic Specially Managed Area), IBA (Important Bird Area), MPA (Marine Protected Area), HSM (Historic Site and Monuments).

Aksnes and Hessen, 2009; Stefenon et al., 2013). In the current case, roughly a quarter of the articles that the search of indexed journals yielded only referred to Antarctica indirectly but did not focus on Antarctic tourism or its impacts (Type 0 or 1 articles in our analysis).

Twenty percent of the articles classified as Type 3 have been added manually from the authors' personal collections. This highlights a recurring problem in massive bibliographic searches: search engines have limited reliability when the goal is to identify all publications related to a highly specific knowledge area. Hence, it is important to combine different information sources (complementary databases, technical reports and 'grey literature', and references included in the reviews) and consult subject matter experts to create as comprehensive a database as possible. This approach also allows for a correction of thematic and idiomatic biases and the underrepresentation of publications from non-English speaking countries in *WoS* and *Scopus* (Mongeon and Paul-Hus, 2016). The search terms used might also result in misidentifications as the current search terms might not have been included in the publication title, abstract, and keywords. Comprehensive reviews such as those by Headland (1994), Hofman and Jatko (2000), Tin et al. (2009), Bauer (2011), and CEP (2012), also helped to check the quality of the database.

4.2. *Issues related to the definition of tourism impact*

A number of scholarly publications discuss the results of studies on the environmental impacts caused by scientists and their activities in the field and not those originating from tourism. This analysis did not include these publications, but we note that it is difficult, if not impossible, to link a negative environmental effect exclusively to one or another type of Antarctic visitor. In fact, research usually considers the impact caused by humans visiting the Antarctic without distinguishing between tourists and researchers or support personnel from National Antarctic Programs (e.g., Tejedo et al., 2016; Cajiao et al., 2020). This is because most people who visit Antarctica at one time or another engage in tourism activities (Braun et al., 2012), either visiting locations in the vicinity of the bases for leisure activities or accompanying scientists on their field work not only to offer field support but also to visit and enjoy unique sites and their scenery or wildlife.

Besides, the fact that an impact exists does not mean that it is significant, critical, extensive, or indicative of a conservation issue. The global carbon footprint of Antarctic tourism aside, often, negative impacts resulting from the presence of tourists are local or limited to a few individual animals, without affecting the viability of entire populations or without significantly affecting the values of a specific site. Sometimes,

Table 3
Management proposals by type.

Proposed in Types 3a and 3b articles	Proposed in Type 3c articles
Yes:30 54.5% No: 25 45.5%	Yes:18 90.0% No: 2 10.0%
Grouped proposals – All Type 3 articles (No. of articles proposing it)	References
Management proposals	
Increase research and improve (long-term) monitoring (14)	Chen and Blume (1997); Micol and Jouventin (2001); Frenot et al. (2005); ; Williams and Crosbie (2007); Dimitrov et al. (2009); Farreny et al. (2011)Leaper and Miller (2011); González-Alonso et al. (2017); Waller et al. (2017); Convey and Peck (2019); Hughes et al. (2019); McCarthy et al. (2019); Sutilli et al. (2019)
Strengthen the application of biosecurity procedures to avoid the introduction of non-native species (14)	Chen and Blume (1997); Curry et al. (2002); Lewis et al. (2003); Curry et al. (2005); Frenot et al. (2005); Tin et al. (2009); Aronson et al. (2011); Grimaldi et al. (2011); Huiskes et al. (2014); Fuentes-Lillo et al. (2016); Convey and Peck (2019); Hughes et al. (2019); McCarthy et al. (2019); Cajiao et al. (2020)
Strengthen existing regulation, international cooperation and stakeholder coordination (9)	Chen and Blume (1997); Grimaldi et al. (2011); Leaper and Miller (2011); Waller et al. (2017); Convey and Peck (2019); Erbe et al. (2019); Hughes et al. (2019); McCarthy et al. (2019); Ropert-Coudert et al. (2019)
Improve environmental impact assessment processes (8)	Chen and Blume (1997); Amelung and Lamers (2007); Farreny et al. (2011); Pertierra et al. (2017); Brooks et al. (2019); Erbe et al. (2019); Hughes et al. (2019); McCarthy et al. (2019)
Concentrate impacts, e.g., on established paths for repeated visits, areas subjected to high use levels, or small sections of the breeding colonies (7)	Chen and Blume (1997); Pfeiffer and Peter (2004); Burger and Gochfeld (2007); Ayres et al. (2008); Tejedo et al. (2012); O'Neill et al. (2013); Tejedo et al. (2016)
Apply active remediation for detected impacts, including the quick removal of non-native species after their detection (6)	Chen and Blume (1997); Frenot et al. (2005); Smith and Richardson (2011); Molina-Montenegro et al. (2012); O'Neill et al. (2013); McCarthy et al. (2019)
Develop and run educational programmes or environmental briefings on certain critical environmental issues to staff, visitors, researchers, tourists, and environmental managers (6)	Farreny et al. (2011); Braun et al. (2012); Convey and Peck (2019); Hughes et al. (2019); Cajiao et al. (2020)
Improve visitor and operator guidelines (6)	Frenot et al. (2005); Coetzee and Chown (2016); Leary (2017); Erbe et al. (2019); Hughes et al. (2019); McCarthy et al. (2019)
Apply the Precautionary Principle where scientific data are limited (5)	Chen and Blume (1997); Tin et al. (2009); Naveen et al. (2012); Tejedo et al. (2016); Dunn et al. (2019)
Review and strengthen the Antarctic Specially Protected Areas network and its criteria (5)	Leaper and Miller (2011); Braun et al. (2012); Leary (2017); Pertierra et al. (2017); Leihy et al. (2020)
Emphasise the need for greater caution when interacting with wildlife (e.g., reducing proportion of colony and determining approach distance for species) or vegetation (5)	Martín et al. (2004); Pfeiffer and Peter (2004); Leaper and Miller (2011); Coetzee and Chown (2016); Lee et al. (2017)
Propose/design management decisions for specific conditions (5)	Giese (1996); Burger and Gochfeld (2007); Coetzee and Chown (2016); Hughes et al. (2019); Ropert-Coudert et al. (2019)
Apply an adaptive management approach; Use monitoring to inform management/conservation plans (4)	Acero and Aguirre (1994); Coetzee and Chown (2016); Ropert-Coudert et al. (2019); Cajiao et al. (2020)
Utilise zoning tools that allow for temporary closures, e.g., in locations experiencing erosion, with vulnerable biotypes altered by trampling, or at times when wildlife is breeding (4)	Burger and Gochfeld (2007); Tin et al. (2009); Tejedo et al. (2012); Ropert-Coudert et al. (2019)
Improve technologies, or police behaviours, to reduce environmental pollution (3)	Amelung and Lamers (2007); do Sul et al. (2011); Waller et al. (2017)
Use a dispersion strategy when a very low pressure is expected in areas affected by trampling (2)	Tejedo et al. (2012); O'Neill et al. (2013)
Introduce emission compensation schemes (1)	Amelung and Lamers (2007)
Ensure transparency of regulatory decision-making processes (1)	Erbe et al. (2019)
Make available public databases for the sharing of research and data (1)	Erbe et al. (2019)
Focus management on major threats and more vulnerable species (1)	Ropert-Coudert et al. (2019)
Monitor emerging threats and take proactive actions (1)	Ropert-Coudert et al. (2019)

these impacts reflect a lack of effective management and could be solved easily through specific interventions. The Protocol assumes that any human activities generate an impact simply because they are physically present. This text also endeavours for human impacts to be as minor and transitory as possible to ensure that, once the visitors leave, the ecosystem can recover naturally without the need for additional restoration efforts.

It should be noted that not all effects resulting from the presence of tourists are negative. The review of Type 2b publications also identifies a number of positive consequences of tourism (see e.g., Lamers and Amelung, 2012; Powell et al., 2012; or Alexander et al., 2019). The benefits of tourism discussed in the above publications can be categorised as follows: 1. supporting the conservation of sites of archaeological and historical interest, 2. providing funding for research stations, e.g., via the sale of souvenirs, 3. science support, 4. logistical support to National Antarctic Programs, 5. creating greater environmental awareness among tourists through bespoke lectures, and educational experiences, 6. creating Antarctic ambassadors, 7. resulting in health benefits, 8. contributing to the early detection of epizooties, and, 9. indirectly improving compliance with environmental guidelines and codes of conduct through peer monitoring and mere presence (with the threat of being reported) by other visitors, including individual adventure tourists and National Antarctic Programs. Any of the above benefits must be considered when undertaking a comprehensive analysis for tourism and its consequences. However, most of these effects are benefits to humans, not to the Antarctic environment itself.

4.3. Trends in environmental-impact research in relation with tourism

Antarctic tourism has received increasing attention from the international scientific community, especially in the last decade, and Antarctic tourism research has reached a certain degree of maturity. Since Smith and Splettstoesser's (1994) special issue on Antarctic Tourism almost three decades ago, tourism has positioned itself as a significant human activity in the polar regions expanding and intensifying its activities, and not surprisingly, aligned with this growth an increase in tourism research was witnessed (Stewart et al., 2017). After an initial period of exploratory, and largely descriptive, studies, tourism research is now showing clear signs of progress, incorporating more innovative and sophisticated data collection and analysis techniques (e.g., considering molecular data, physiological indicators, genetics, etc.), and often including environmental data to distinguish natural variability from

Table 4
Research gaps and needs by type.

Proposed in Types 3a and 3b articles	Proposed in Type 3c articles
Yes:24 43.6% No: 31 56.4%	Yes:16 80.0% No: 4 20.0%
General – All Type 3 articles (No. of articles proposing it)	References
Research gaps and needs	
New studies are necessary for certain species, sites or contaminants (16)	Chen and Blume (1997); Clayton et al. (1997); Curry et al. (2002); Lewis et al. (2003); Bonnedahl et al. (2005); Frenot et al. (2005); Dimitrov et al. (2009); Aronson et al. (2011); do Sul et al. (2011); Coetzee and Chown (2016); Brooks et al. (2019); Convey and Peck (2019); Erbe et al. (2019); Hughes et al. (2019); McCarthy et al. (2019); Ropert-Coudert et al. (2019)
Cumulative effects and interactions with other drivers of change (such as climate change or non-native species) are poorly understood or assessed (6)	Chen and Blume (1997); Amelung and Lamers (2007); Tin et al. (2009); Tejedo et al. (2011); Coetzee and Chown (2016); Pertierra et al. (2017)
Human impacts on a regional or continental scale are rarely examined (6)	Chen and Blume (1997); Bonnedahl et al. (2005); Tin et al. (2009); Tejedo et al. (2011); Hughes et al. (2019); McCarthy et al. (2019)
Investigation into the effectiveness of remediation of disturbed sites or impact mitigation options (3)	Brooks et al. (2019); Convey and Peck (2019); Erbe et al. (2019)
Lack of connection research-management: monitoring not designed to contribute to management (2)	Acero and Aguirre (1994); Tejedo et al. (2011)
The protection of Antarctica's wilderness and aesthetic values should be reinforced (2)	Chen and Blume (1997); Tin et al. (2009)
International policy or research efforts are insufficient (2)	Molina-Montenegro et al. (2012); Waller et al. (2017)
Low availability of studies because are internal reports and other types of 'grey literature' (2)	do Sul et al. (2011); Leary (2017)
In many cases it remains unclear if less than minor or transitory impacts (1)	Chen and Blume (1997)
Antarctic Treaty policy is unclear about whether non-indigenous species should be removed. Therefore, research on this topic should be taken into account for decision making (1)	Smith and Richardson (2011)
There is an important taxonomic disparity in the information available for different Antarctic sites (1)	Cajiao et al. (2020)
Research-specific – All Type 3 articles (No. of articles proposing it)	References
Data are insufficient to prove the initial hypothesis, or there are gaps in data availability and uncertainties (11)	Ciaputa and Sierakowski (1999); Amelung and Lamers (2007); Williams and Crosbie (2007); Tin et al. (2009); Leaper and Miller (2011); Tejedo et al. (2012); González-Alonso et al. (2017); Pertierra et al. (2017); Waller et al. (2017); Erbe et al. (2019); McCarthy et al. (2019)
Environmental covariates or more data should be recorded to better explain results (9)	Woehler et al. (1994); Curry et al. (2005); Trathan et al. (2008); Graf et al. (2010); Kukučka et al. (2010); Coetzee and Chown (2016); Dunn et al. (2019); McCarthy et al. (2019); Ibañez et al. (2020)
The research is limited to the impacts in Antarctica itself (3)	Amelung and Lamers (2007); Tin et al. (2009); Leaper and Miller (2011)
More tourism-typologies or groups should be included in future research (e.g., independent expeditions, staff, etc.) (2)	Amelung and Lamers (2007); Farreny et al. (2011)
Apply robust experimental designs to minimize sources of variability in effects (1)	Coetzee and Chown (2016)
Use innovative methodological advances for minimizing disturbance in future research (remote sensors, remote operated vehicles, etc.) (1)	Coetzee and Chown (2016)
There are non-studied key factors (e.g. soil functional gene expression, microbial community structure) (1)	Tejedo et al. (2012)

tourism impacts (e.g., Kukučka et al., 2010; Zhang et al., 2014). Tourism impacts are also related to global change, such as greenhouse gas emissions (Amelung and Lamers, 2007; Farreny et al., 2011), biological invasions (Frenot et al., 2005; Huiskes et al., 2014; McCarthy et al., 2019), or global pollutants (Eijgelaar et al., 2010; Cabrerizo et al., 2016). The indirect and cumulative impacts from tourism industry have only recently attracted more research attention, and monitoring programmes are far from comprehensive (Lamers et al., 2012).

4.4. Environmental impacts resulting from tourism activities

Regardless of its complexity, the diversification of analytical techniques touched on in the previous section made it possible to improve the identification of different types of impacts associated with tourism activities. In addition, researchers have increasingly explored new issues such as microplastics, pharmaceutical residues, bacterial pathogens, marine debris, or anthropogenic hydrocarbons, thereby widening the spectrum of impacts assessed.

Empirical research has confirmed specific impacts that were classified as impacts potentially caused by tourism activities, such as the alteration of stress hormones in animals (Barbosa et al., 2013), or collision of vessels with whales (Leaper and Miller, 2011). Other impacts, such as plastic contamination (do Sul et al., 2011), exist but have yet to be adequately quantified. Other impacts remain theoretical, such as the contribution of tourism to the establishment of non-native species in Antarctica (Frenot et al., 2005), since a direct and causal relationship has not yet been unequivocally proven. It is clear, however, that the presence of non-native species influences Antarctic ecosystems (e.g., Molina-Montenegro et al., 2012).

Environmental impacts of tourism activities are often site-, stage-, activity- and species-specific, not just in the Antarctic but in many natural areas worldwide that are visited by humans (Marion et al., 2016; Monz et al., 2021). Therefore, it is very difficult, and even inappropriate, to argue that tourism always has negative effects on certain species or environmental variables or is the only cause of an environmental problem. Other factors such as tourist numbers, the resilience or vulnerability of the ecosystem, the existence of rest periods or temporal closures allowing respectively species or ecosystem recovery, the influence of global problems (such as overfishing, climate change, or ocean pollution and acidification), or the introduction of environmentally-focussed codes of conduct, can strongly affect the extent and severity of the impact. Nevertheless, the negative impacts of human activity and presence in the Antarctic are additive and are likely to be further confounded by some, or all, of the aforementioned global problems, leading to an even more pronounced effect on endemic flora and fauna, perhaps critically in some cases (Monz et al., 2021). The impact of global pollution is well documented in the case of microplastics. Local sources of this pollutant do not explain concentrations reported for the Antarctic, which are likely to have a non-Antarctic origin. The levels of microplastics released in the region from ships and scientific research stations are likely to be negligible at the scale of the Southern Ocean, with the larger amounts of microplastics originating from other parts of the World. Nevertheless, pollution may be significant on a local scale, mainly in the Northern Antarctic Peninsula (Waller et al., 2017).

4.5. From research to management

The management measures proposed in the publications dedicated to assessing the impacts of Antarctic tourism were analysed. However, establishing direct links between research and actual management processes is not always easy (Hughes et al., 2018; Cajiao et al., 2021). An example of successful science-policy interaction where environmental impacts are concerned is the case of Barrientos Island in the Antarctic Peninsula Region. Here, research by the Ecuadorian and Spanish National Antarctic Programs on the effects of trampling on fragile moss carpets resulted in scientific publications and policy papers that were presented at several Antarctic Treaty Consultative Meetings (ATCMs), which have consequently led to improvements of the Visitor Site Guidelines for Barrientos Island (Cajiao et al., 2020, and references therein). Unfortunately, this is not the norm, and many evidence-based recommendations made in relevant scientific publications have not turned into regulatory mechanisms adopted by the ATS. Management and regulation need to be more strongly connected with, and informed by, the science focussed on identifying impacts generated by human visitation in Antarctica to ensure that, overall, tourism will yield net benefits for Antarctic environmental values.

4.6. Broadening the focus: the need for a strategic vision

Management and policy decisions regarding Antarctic tourism require valid and detailed information on the actual impacts, operational circumstances, and the global context in which the tourism industry operates (Lamers et al., 2012). The current study has revealed a lack of data on the long-term effects of tourism development, cumulative impacts and the absence of scientific studies that quantify the negative effects of certain impacts. The latter might be due to logistical and operational constraints of Antarctic fieldwork and the reluctance of funding agencies to support monitoring research (see Hughes et al., 2018). So far, as this bibliometric study has highlighted, Antarctic tourism research has largely been undertaken through small individual projects, focusing on a limited number of sites, for short periods of time, and without a coordinated research agenda, offering only limited evidence of environmental impacts (see also Stewart et al., 2005), with

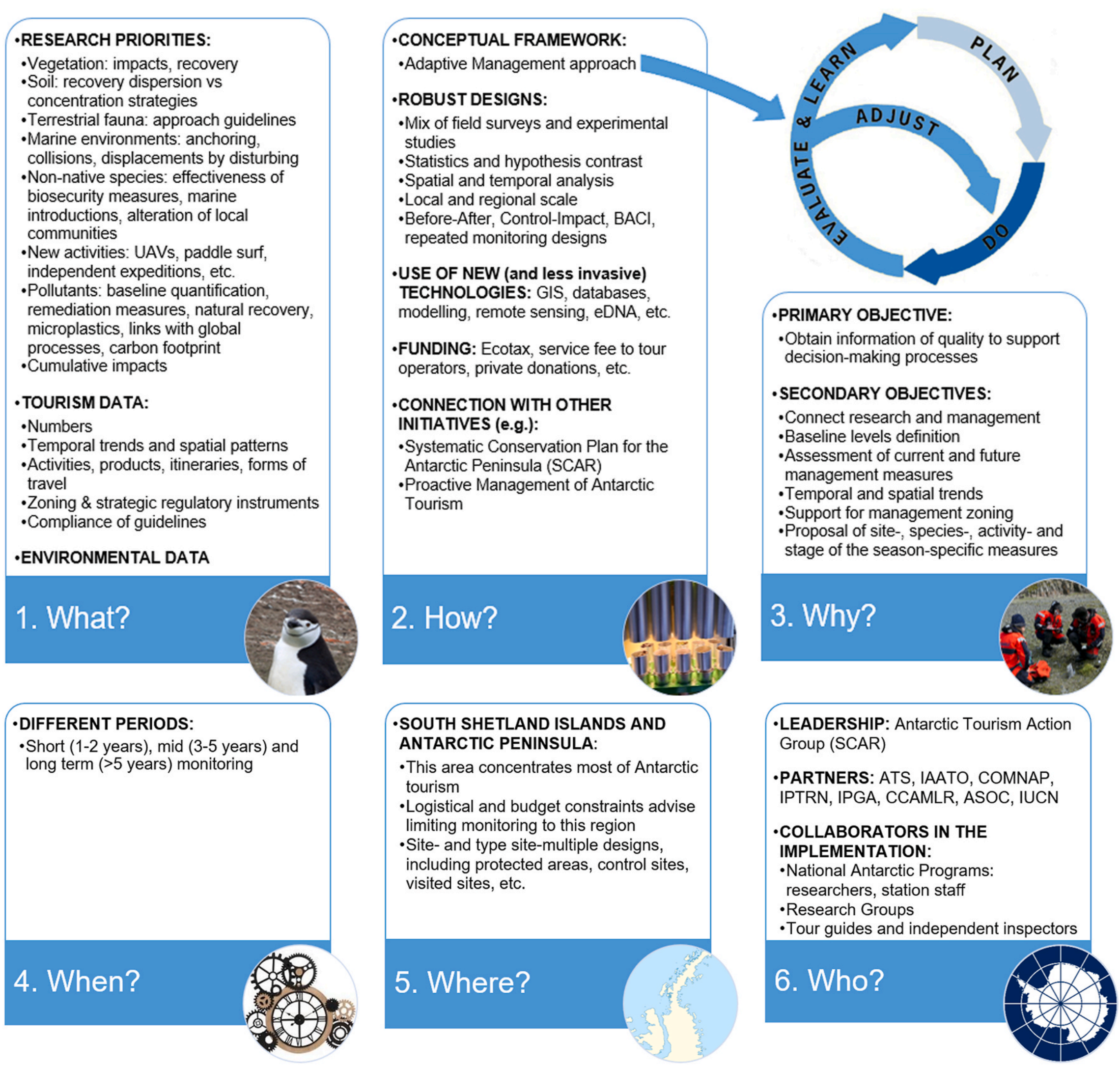

Fig. 4. Scheme for implementing the proposed strategy of strengthening research and monitoring of tourism environmental impacts in Antarctica. Each box corresponds to one of the six basic questions that a monitoring project should answer.

some notable exceptions listed in Table 1. Clearly, a call for proposals is needed, and the related funding, for a strategic and systematic research and monitoring programme focussed on environmental impacts of tourism in Antarctica. Such an ambitious research and monitoring programme brings along significant logistical, political, financial and governance challenges. The basic components of such a research and monitoring programme are outlined in Fig. 4, but a transdisciplinary working group with experts from different knowledge fields should be established to further develop this initiative. However, it is expected that the cornerstones of such a research and monitoring programme proposed in this paper will stimulate discussion in the Antarctic community, including amongst managers, decision makers, researchers, tour operators, support staff, and the media.

The proposed research and monitoring programme would build on the research priorities identified in the current meta-analysis (Table 4), including a number of priority research topics that should be addressed in the near future as these are the topics where there are the most significant knowledge gaps. It must include the evaluation of cumulative impacts, which has long been recommended by the CEP and ATCM. The first international cumulative impact workshop took place in 1996 but little progress has been made since then (O'Neill, 2017). So far, only limited empirical evidence exists to conclusively identify the magnitude of cumulative impacts arising from tourism operations (Stewart et al., 2005; Lamers and Amelung, 2012; Carey, 2020). In addition to data about the impacts themselves, it is also required information on Antarctic tourism. This should include annual tourism statistics, site visit records and spatial data on tourist mobilities – within the Antarctic but also to the Antarctic – to establish spatial and temporal patterns of use. These are important indicators that will help to quantify tourism impacts. While some of these data have been shared by IAATO, they are not necessarily in a high enough resolution or suitable format to model tourism impacts. Basic environmental data is also necessary to ensure that natural variability can be considered in models and that tourism impacts can be separated from other processes. Currently existing databases and interactive maps – such as the SCAR Antarctic Digital Database, the Antarctic Secretary Maps for Antarctic Protected Areas and Visited Sites, or the SCAR Composite Gazetteer of Antarctica – could be used towards this end.

The *Adaptive Management* approach proposed by Williams et al. (2009) lends itself as a theoretical framework for the assessment of tourism impacts. It is a structured, iterative approach that enables robust decision making, with an aim of reducing uncertainties over time via systematic monitoring. The advantages and disadvantages of applying an Adaptive Management approach to Antarctic tourism are discussed in greater detail in Cajiao et al. (2021), this being the conceptual framework chosen for this proposal.

Experimental studies are needed to isolate the effects of tourism and study issues such as the system's resilience (requiring temporal analysis and repeated monitoring), its vulnerability, or impacts resulting from a range of tourist behaviours and activities. Research designs derived from environmental impact assessments can be of help in undertaking such experimental studies, given the extensive experience of this professional discipline in studying and quantifying impacts.

Impact monitoring must also include multiple locations with different environmental variables, and ideally including a range of locales, such as frequently visited tourist, specially protected areas, and unvisited control sites. It is not necessary to replicate the same methods across all chosen sites. It is likely to be more effective and efficient to employ site-specific research designs in the most suitable locations (sentinel sites) that can then be transferred to other sites with similar characteristics. When designing monitoring procedures, non-invasive technologies should be prioritized, with data being obtained with minimal alteration of the environment.

Any Antarctic tourism research and monitoring strategy should be aligned with, and linked to, current initiatives such as the Systematic Conservation Planning (SCP) for the Antarctic Peninsula developed jointly by the Scientific Committee on Antarctic Research (SCAR) and IAATO. The objective of the SCP project was to establish conservation priorities and primary management goals by identifying and geolocating the values of science, biodiversity, and tourism in the region using integer linear programming in order to the aim at enabling integrative, evidence-based site management that considers all activities (science and tourism) and all known biodiversity features, such as breeding seabird colonies, vegetation, and invertebrates in the area (IAATO and SCAR, 2019). Through the identification of a network of tourist sites which should be subjected to focussed impact monitoring (sentinel sites), both the impacts of tourism and the success of the SCP could be monitored synergistically at a regional scale.

Equally, the funding options for this programme should be identified. A collaborative Dutch research project titled "*Proactive Management of Antarctic Tourism*" currently assesses the viability and effects of a potential eco-tax for Antarctic tourism to, *inter alia*, fund monitoring studies, something that has been discussed by other scholars (Verbitsky, 2015) and also, on several occasions, by the ATS but has not been applied so far due to the complexities of the Antarctic regime. Other possible sources of funding for monitoring projects include service fees for tour operators (Kariminia et al., 2012) or private donations, but their implementation is as equally problematic as that of a tourism eco-tax.

Any robust Antarctic tourism impact monitoring study aimed at generating knowledge to support decision-making processes and enable evidence-based tourism regulation and management (as the primary goal) needs to also address a set of secondary research objectives. These secondary research objectives include: 1. the definition of reference values for different pollutants, 2. an assessment of the effectiveness of management measures currently applied, and, 3. an analysis of temporal and spatial trends for Antarctic tourism. Addressing these research objectives will then allow formulate targeted recommendations of regulatory and management measures, both general and adapted to specific activities or sites.

The monitoring of tourism activities should integrate different research projects and opportunities of varying lengths and employing different research designs in accordance with the availability of funding and logistics. Short-term experimental studies can provide concrete answers to highly specific and clearly defined research questions. More ambitious and complex studies are necessary to assess the possible cumulative impacts of tourism (Hofman and Jatko, 2000). Specifically, long-term data are indispensable in efforts to determine if changes detected at tourist sites are due to natural variability, climate-change effects, fishery-related effects, scientific research or support activities, or tourism activities. The significant drop in tourist activity in the Antarctic due to the COVID-19 pandemic provides a unique opportunity to develop a baseline against which future environmental impacts of Antarctic tourism can be evaluated.

It is proposed employing a research and monitoring programme for Antarctic tourism impacts that integrates the principles outlined above in the Antarctic Peninsula region and the South Shetland Islands, where most Antarctic tourism is concentrated and many frequently visited tourist sites are located (IAATO, 2021). In addition, this region has the largest concentration of research stations on the Antarctic continent which might make it easier to set up feasible long-term monitoring projects. It also has a less inhospitable climate, outstanding terrestrial biodiversity (that we have more in-depth knowledge of), and greater vulnerability to climate change and biological invasions (Siegert et al., 2019).

This monitoring programme could be implemented by the recently created *Antarctic Tourism Action Group* (Ant-TAG). It harnesses the range of expertise in the SCAR's Standing Committee on the Humanities and Social Sciences (SC-HASS) and related Standing Committees on tourism topics (https://www.scar.org/science/ant-tag/home/). This Action Group should manage the establishment of a broad group of experts for this task that would include researchers from different National Antarctic Programs, station staff (who could undertake basic monitoring tasks at visit or control sites close to their bases), tour guides (who could act as early identifiers of tourism impacts through specifically created communication channels), and independent observers accompanying tourist cruises and evaluating the compliance of Antarctic tourism guidelines by tourists and operators. The group would being responsible for translating research and monitoring results into management recommendations and proposals for specific sites and providing guidance on tourism regulation and management to the SCAR, who would inform the CEP and the ATS. This initiative must integrate all Antarctic tourism stakeholders, including the ATS, COMNAP (Council of Managers of National Antarctic Programs), IAATO, IPTRN (International Polar Tourism Research Network), IPGA (International Polar Guides Association), CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources), ASOC (Antarctic and Southern Ocean Coalition), and IUCN (International Union for Conservation of Nature). The Ant-TAG could facilitate the coordination of research planning, the sharing of data and logistics support, the establishment of standard research monitoring protocols, and collaboration around data analysis and reporting between these stakeholders.

5. Conclusions

Progress has been made with respect to advancing our understanding of the environmental impacts of Antarctic tourism in recent years, which is reflected in a greater number of publications in indexed journals. These studies have become more scientifically rigorous, advancing from largely descriptive studies toward employing more elaborate research designs and data analysis. However, many of the gaps identified in previous reviews remain, and new gaps have been identified by the current bibliometric review study. The absence of a regional tourism monitoring strategy for the Antarctic Peninsula, the area where most Antarctic tourism is concentrated, stands out. Neither common protocols for monitoring nor methods for cumulative impact assessment have been developed thus far. The knowledge about the human impact on Antarctica continues to grow steadily, but the quantification of the contribution of the tourism industry remains largely unknown. Numerous studies analysing impacts arising from National Antarctic Programs activities have been developed as these are often easier to fund, logistically support and permit, but, so far, tourism impacts can only be inferred by analogy, without in-situ verification. As these impact studies are not specific to tourism, the validity of transferring their conclusions to tourism activities is questionable. In any case, these studies only identify possible impacts – they do not confirm them.

Properly identifying tourism impacts in Antarctica is an ambitious and complex undertaking. A two-pronged approach combining long-term impact monitoring and targeted shorter-term experimental studies is needed to detect potentially adverse tourism impacts on Antarctica and to support the evidence-based management and regulation of Antarctic tourism. Species-specific, activity-specific, and location-specific studies should be developed to assess and quantify Antarctic tourism impacts. At the same time, the precautionary approach should be applied to tourism regulation and management, especially in those cases where it remains unclear whether impacts are less than minor or transitory.

Unfortunately, Antarctica can no longer be considered pristine. Human presence in the Antarctic has significantly increased and diversified over the last decades. The COVID-19 pandemic has created an opportunity to reassess how humans engage with the Antarctic and to examine the consequences of a decrease in tourist pressure on Antarctic environments. The temporal shutdown of tourism activities, and many Antarctic research and base operations, in the 2020/21 season can be used to develop and launch strategic tourism impact research to be implemented in line with the anticipated recovery of tourism activities in 2021/22 and beyond. Antarctic tourism is expected to return eventually in full force and expand further, and the international community must be prepared to safeguard one of the last wild places on our planet.

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Author contributions

Pablo Tejedo: Conceptualization, Methodology, Validation, Investigation, Formal analysis, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision. **Javier Benayas:** Conceptualization, Methodology, Investigation, Writing - Review & Editing. **Daniela Cajiao:** Methodology, Investigation, Writing - Review & Editing. **Yu-Fai Leung:** Methodology, Investigation, Writing - Review & Editing. **Daniela de Filippo:** Investigation, Formal analysis, Writing - Review & Editing; **Daniela Liggett:** Investigation, 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.114634.

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