



Ecosystem services in Antarctica: Global assessment of the current state, future challenges and managing opportunities

L.R. Pertierra^{a,*}, F. Santos-Martin^b, K.A. Hughes^c, C. Avila^d, J.O. Caceres^e, D. De Filippo^f, S. Gonzalez^g, S.M. Grant^c, H. Lynch^h, C. Marina-Montesⁱ, A. Quesada^j, P. Tejedo^k, T. Tin^l, J. Benayas^k

^a Dept. Biology, Geology, Physics and Inorganic Chemistry, Rey Juan Carlos, University, Mostoles 28933, Spain

^b Dept. of Environmental and Chemical Technologies, Rey Juan Carlos, University, Mostoles 28933, Spain

^c British Antarctic Survey, Cambridge CB3 0ET, United Kingdom

^d Dept. of Evolutionary Biology, Ecology and Environmental Science, University of Barcelona, Barcelona 08028, Spain

^e Department of Analytical Chemistry, Complutense University of Madrid, Madrid, 28040, Spain

^f Dept. of Bibliometrics and Documentation, Carlos III University, Getafe 28903, Spain

^g State Meteorological Agency (AEMET), Barcelona, 08005, Spain

^h Dept. of Ecology and Evolution, Stony Brook University, New York 11794, United States

ⁱ Dept. of Analytical Chemistry, University of Zaragoza, Zaragoza 50009, Spain

^j Dept. Biology, Autonomous University of Madrid, Madrid 28049, Spain

^k Dept. Ecology, Autonomous University of Madrid, Madrid 28049, Spain

^l Independent Consultant, Chambery 73000, France

ARTICLE INFO

Keywords:

Polar heritage
Antarctic science
Antarctic tourism
Southern Ocean provisioning
Climate regulation

ABSTRACT

Antarctic ecosystem services are rich and diverse and include global climate modulation, biodiversity and habitat protection, cultural heritage, scientific knowledge, education and recreation as well as the extraction of marine living resources. However, environmental protection studies have rarely examined the full complement of Antarctic values recognized in the Antarctic Treaty or Antarctica's other natural benefits as ecosystem services (ES). Moreover, the existing limited number of ES studies have focused primarily on the biophysical modeling of the service providing units, with little focus on evaluating the balance between Antarctica's intrinsic vs. economic values (e.g., opportunity cost, payment for services and bequest), or societal perceptions on the Antarctic ES teleconnections with global issues. Here, we systematically identify the ES dimensions present in Antarctica through an expert elicitation combined with scientific literature review. We then map their spatial overlap and examine the existing trends of usage over the various stages of ES utilization in the continent. Lastly, we conduct a preliminary evaluation of the resulting trade-offs from their respective increased utilization. Our results show that Antarctica's ES are currently facing substantial challenges to remain sustainable. In marine ecosystems, fish and krill stock provisioning may put at risk the maintenance of habitats and biodiversity regulation. In turn, cultural values centered around terrestrial ecosystems, face a three-way conflict between the increasing demand for tourism opportunities, the region's rich and diverse scientific interests and the vast wilderness and bequest values. To appropriately conserve Antarctic ES for future generations, we discuss how different ES framework tools could be developed and adapted to the Antarctic Treaty policy context.

1. Introduction

The Ecosystem Services (ES) framework provides the link between (natural) ecosystems and human wellbeing (social), with the services, acting as the 'bridge' between the human world and the natural world

(Braat and de Groot, 2012). Antarctica (the area south of latitude 60°S), despite often being visualized as a largely 'frozen continent' without any permanent human population, harbours an enormous richness of (i) local ES directly linked to in-situ activities, (ii) regulatory ES that are indirect and concern ex-situ global societies and (iii) bequest services

* Corresponding author.

E-mail address: luis.pertierra@gmail.com (L.R. Pertierra).

<https://doi.org/10.1016/j.ecoser.2021.101299>

Received 17 November 2020; Received in revised form 3 May 2021; Accepted 4 May 2021

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concerning future generations. Overall, these ES present unique opportunities for a mixed formula of utilization and long-term preservation (Kennicutt et al., 2019). However, Antarctic terrestrial and marine ES remain to be systematically assessed, mainly as a result of the history and legal particularities of the continent, but also in part due to the existing lack of supporting scientific knowledge and advice, from a socio-ecosystemic perspective, under the ES framework (see Pertierra and Hughes, 2019). Nonetheless, the vast flow of ES from Antarctica to the Earth systems and global societies in the form of provisioning (e.g., marine living resources), regulating (e.g., atmospheric circulation, cryospheric balances, nutrient cycling) and cultural (e.g., scientific knowledge, cultural heritage, education and recreation) demands such recognition and scientific attention.

The urgency of this issue is particularly concerning when we consider the historical utilization of Antarctic ES and the increasing human pressure placed upon the region (Leihy et al., 2020). Currently, human transient or semi-permanent populations and related activities in the continent and offshore waters act as local ES beneficiaries, being largely present in the form of fishing and research vessels, permanent scientific bases and cruises from tourist operators (Tin et al., 2019, Lynch et al., 2010). Altogether, they generate a human footprint that cannot be considered as insignificant (Brooks et al., 2019; Pertierra et al., 2017a, 2017b). Consequently, the Antarctic ES providing units, i. e., the biotic and abiotic natural elements of ecosystems that provide multiple services (e.g., krill, penguins, ice-sheets, etc.), demand strategic management in order to satisfy all ES local and global beneficiaries and to achieve long-term sustainable use.

In a global context, the ES concept has been recognized by the United Nations (UN) as a successful framework to promote and monitor progress towards delivery of the Sustainable Development Goals (IPBES, 2019). However, it is important to note that the Antarctic continent is not under the jurisdiction of the UN or any single country, but is under a separate system of international governance, through the Antarctic Treaty System (1959). Additionally, there has been some suggestion that Antarctica, or parts of it, could be considered as an applicable region to fall under the scope of the Marine Biodiversity of Areas Beyond National Jurisdiction (BBNJ) Resolution of the United Nations (2017), but this issue has not been resolved (Nickels, 2020). Therefore, methodologies to define, quantify and manage ES developed in other parts of the globe may be relevant tools for Antarctica, to contribute to the safeguarding of Antarctic values and associated ES. However, in order to provide any theoretical or practical application, the concept of ES needs to be amended to function in accordance within Antarctica's unique history and isolation from most human activities, which has been driven by the continent's distinct geographic and climatic conditions, as well as the prevailing system of international governance operating through the ATS.

The ATS includes the Protocol on Environmental Protection to the Antarctic Treaty (also known as the Madrid Protocol or Environmental Protocol (EP); signed in 1991, and entered into force in 1998), which sets out a framework for the comprehensive protection of the continent, conservation of the region's natural values, and designates Antarctica as a 'natural reserve, devoted to peace and science'. The EP established the Committee for Environmental Protection (CEP), the role of which is to provide advice on environmental protection to the Antarctic Treaty Consultative Meeting (ATCM). Another key instrument of the ATS is the CCAMLR: Convention on the Conservation of Antarctic Marine Living Resources (CAMLR Convention, 1982), which was developed to ensure adequate conservation of marine life in the Southern Ocean. In the Antarctic Treaty System context, an ES framework can offer a valuable tool whereby different structural and functional elements of the ecosystems (e.g., net primary productivity and biomass) and the socio-cultural context (e.g., benefits and beneficiaries) are fully acknowledged and integrated in the decision-making process. ES were inherently recognized at the very start of the Antarctic Treaty through the concept of Antarctic values, which over time have been categorized as scientific,

historical, wilderness, aesthetic and intrinsic values (ATS 1959, ATS 1991). However, where several ES co-exist, some studies have raised concerns that conflicting activities are being undertaken by ES beneficiaries. For example, in the terrestrial systems at the relatively scarce ice-free areas, Braun et al. (2012) described the clash of conservation, scientific and logistic interests in Fildes Peninsula, King George Island (see also Convey, 2020). Pertierra et al. (2018) noted the conflict between science and conservation activities in geothermal ground on Deception Tejedó et al. (2016) raised the issue of cumulative trampling by visitors degrading the natural values of Barrientos Island (i.e., recreation conflicting with conservation). To date, such conflicting relationships between these values have not been explicitly addressed as ES trade-offs.

Following other ES methodologies used globally and guided by Antarctic experts' assessments, this work systematically reviews the socio-ecological components of Antarctic ecosystems, including the substantial roles played by the Southern Ocean and ice masses. ES methodologies could offer practical approaches to map and assess ES and trade-offs, and ultimately assist in the sustainable management of Antarctica. Despite existing international agreements under the ATS, currently, provisioning, regulating and cultural services are under pressure from climate change and increasing human activity in the region (Convey and Peck, 2019, Siegert et al., 2019). However, as recognition of the high value of Antarctic ecosystems increases (Chown et al., 2015), application of ES methodologies becomes particularly relevant. For these reasons, we see this examination of trends and trade-offs in utilisation of Antarctica ES as a first step towards increasing our knowledge of ES in the region with a view to assisting Treaty Parties in developing additional tools for the future management of the region.

2. Materials and methods

2.1. Study area

The scope of the study focussed on the landmasses and near-shore marine environment within the Antarctic Treaty area. A detailed investigation into the ES of the broader Southern Ocean was beyond the scope of this study. However, given the strong spatial and temporal relevance of the Southern Ocean in shaping Antarctic ES, we often refer to scientific advances concerning Southern Ocean marine ecosystems and their connectivity with coastal and inland ecosystems.

2.2. Identification of Antarctic Ecosystem services

To conduct this assessment of Antarctic ES, all the major ES applicable to Antarctica were systematically identified following the Common International Classification of Ecosystem Services (CICES v5.1, Haines-Young & Potschin 2018). For this purpose, a group of 12 experts with complementary backgrounds in Antarctic natural and social sciences was gathered to cover the diverse range of disciplines from within the Antarctic academic community (including terrestrial and marine biologists, environmentalists, geologists and geophysicists, meteorologists and climatologists), assisted with two experts in Ecosystem Services Assessment theory. We acknowledge that the expert group cannot provide a complete representation of the diversity of views among the 'Antarctic community', particularly in the range of values and perceptions (but see Nash et al. (2019) and Brasier et al. (2020)) and so we focused in assembling a comprehensive skillset to enable characterization of the functional aspects of the prevailing ES.

In order to characterize and evaluate ES in Antarctica, the experts were first asked to identify any potentially applicable ES listed under the CICES classification. Additionally, the emerging literature on the matter of Ecosystem Services conceptualization around Antarctic values (as defined within the ATS framework) was examined. Publications that were indexed in the ISI Web of Science (<https://www.accesowok.fecyt.es/>) before the end of 2020 that specifically focussed on the topic of ES

in the Antarctic region were reviewed. A study was considered relevant if it met the following criteria: (1) the study area was located in Antarctica (above 60°S latitude), (2) the study explicitly focused on ES, and (3) it used biophysical, socio-ecological or socio-economic techniques for mapping or assessing ES. The keywords used in the search process were ‘Ecosystem Services’ and ‘Antarctic’. Similarly, we searched for any published ES-related reports and/or papers considered at the Antarctic Treaty Consultative Meetings. This was done by searching the Antarctic Secretariat Meeting Documents Archive for documents that included the term ‘Ecosystem Services’ that explicitly mentioned ES Assessment nomenclature (see: <https://www.ats.aq/deVAS/Meetings/DocDatabase?lang=e>). Lastly, additional relevant publications from the rich literature on Antarctic values were taken into consideration as they directly related to one or various ES dimensions. Since we could not take account of all contributions individually, we also analysed the production of publications on Antarctic values as a whole (see network analysis of published terms). The final list of prevailing ES in Antarctica, identified by experts, is provided in Table 1.

2.3. Assessing the status and trends of Antarctic Ecosystem Services.

Once the final list of ES in Antarctica was defined, the past levels, present status, and on-going trends in the level of their utilisation were examined. First of all, prominent sites of active engagement in the use of ES were spatially mapped, with the focus on the Antarctic Peninsula as the region with the highest concentration of human activities. Then, information summary panels were generated with time series data on the status and trends of the utilization of different ES categories at the whole continental level.

2.3.1. Regulating services

The main providing units and services reported in the Antarctic literature are described around the four bio-physical Earth systems present in the continent (see Fig. 1). To demonstrate climatic trends, we show the annual temperature, time series and climate trends recorded at three meteorological stations located on the western side of the Antarctic Peninsula (i.e., at Bellingshausen (62°S, 58°W), Vernadsky (65°S, 64°W) and Rothera (67°S, 68°W) Research Stations) since the 1970 s. Data were retrieved from the SCAR (Scientific Committee of Antarctic Research) Met-READER repository (Turner et al., 2004).

Regarding biosphere regulation the rich phytoplankton and zooplankton of the ocean support the Antarctic ecosystem and their dynamics are reflected in trophic chains (Roberts et al., 2011; Moy et al., 2009). Penguins are recognized as sentinels of the Southern Ocean marine environment given their position as major predators in the Antarctic trophic chain, serving as good indicators of the rate and nature of changes on Antarctic ecosystems (Boersma, 2008; Humphries et al., 2017). For this purpose, we examine the historic trends of the regional meta-population of two contrasting *Pygoscelid* species (*Pygoscelis papua* –

gentoo penguin, and *P. adeliae* – Adelie penguin) breeding on the Antarctic Peninsula. Data were retrieved from MAPPD website (<http://www.penguinmap.com/>).

2.3.2. Provisioning services

Extraction of marine living resources during fishing and seal and whale hunting activities comprise the main historical provisioning services in Antarctica. The most recent history and evolution of the extraction of Antarctic living resources are shown using information obtained from CCAMLR annual fishery reports taken from the CCAMLR website (<https://www.ccamlr.org/es/>). Specifically, we examined marine biomass provisioning trends within Antarctic waters since the 1970s as the first year with available annual statistics. Earlier provisioning stages around past seal and whale hunting are also discussed alongside their ecological impact on the current state of Antarctic ES and their strong influence in shaping the ATS/CCAMLR biodiversity conservation frameworks.

In absence of summary statistics of utilization trends the emerging bioprospecting services and freshwater provisioning systems are briefly discussed.

2.3.3. Cultural services

The range of socio-cultural features that are related to Antarctic local human activities and/or indirectly linked with modern societies were explored.

First, we examined the historical development of cultural heritage and conservation within the Antarctic Treaty System. With regard to the identification of cooperation and conservation actions (bequest services), we examined the historical trends in the cumulative number of countries that became signatories to the Antarctic Treaty and to the Environmental Protocol, using data obtained from the Antarctic Treaty Secretariat website (www.ats.aq). Data on Antarctic Specially Protected Areas (ASPAs), or earlier equivalent protected area designations, were retrieved from the protected area management plans (<https://www.ats.aq/e/protected.html>). Additionally, policy papers concerning topics that were relevant to the conservation of Antarctic values and related ES features were examined within the Antarctic Treaty Secretariat website repository using a set of relevant keywords to count the number of reports for each topic. These terms included: ‘climate’, ‘tourism’, ‘science’, ‘education’, ‘wilderness’, ‘biological prospecting’/‘bioprospecting’ and ‘historic’. With regard to intrinsic values, we briefly discuss the social elements that fall beyond direct interests and activities in the continent, but are featured in the Antarctic Treaty System in the form of aesthetical and wilderness values.

Secondly, in order to examine the intellectual gains resulting from NAPs (National Research Programs) providing scientific services in Antarctica, the record of historical scientific production was analysed as a whole. Published literature can be taken as a proxy indicator of knowledge acquisition but this naturally does encompass several other

Table 1

List of Antarctic features linked to Ecosystem Services and involved active stakeholders (not to be taken as beneficiaries).

Antarctic features	Stakeholder	ES Categories	Ecosystem Services (according to CICES 5.1 classification)
Atmosphere	All parts	Regulating	Gaseous flows (e.g. climate regulation), Maintenance, Mediation, Filtration (pollutants)
Cryosphere	All parts	Regulating	Liquid flows, Maintenance (e.g. Sea level balance), Mediation, Filtration (pollutants)
Geosphere	All parts	Regulating	Mass flows, Maintenance (e.g., Soils Quality, Habitats) Mediation (sequestration of wastes and nuisances of anthropogenic origin), Dilution, Regulation of flows (e.g. permafrost)
Biosphere	All parts	Regulating	Maintenance of Lifecycles, Nursery Populations and Habitats, Pest and Disease Control, Bio-remediation)
Biodiversity	Bio-prospecting research industry	Provisioning	Genetic
Living Resources	Fishing industry	Provisioning	Biomass Extraction
Surface Waters	NAP	Provisioning	Nutrition, Materials
Policy & Conservation	ATS, CCAMLR & SCAR	Cultural	Heritage, Bequest, Symbolic, Existence, Educational, Sacred, Cultural, Aesthetic
Science	NAP & SCAR	Cultural	Scientific, Educational, Experiential, Cultural Physical
Tourism	IAATO	Cultural	Recreational, Experiential, Educational, Cultural, Physical

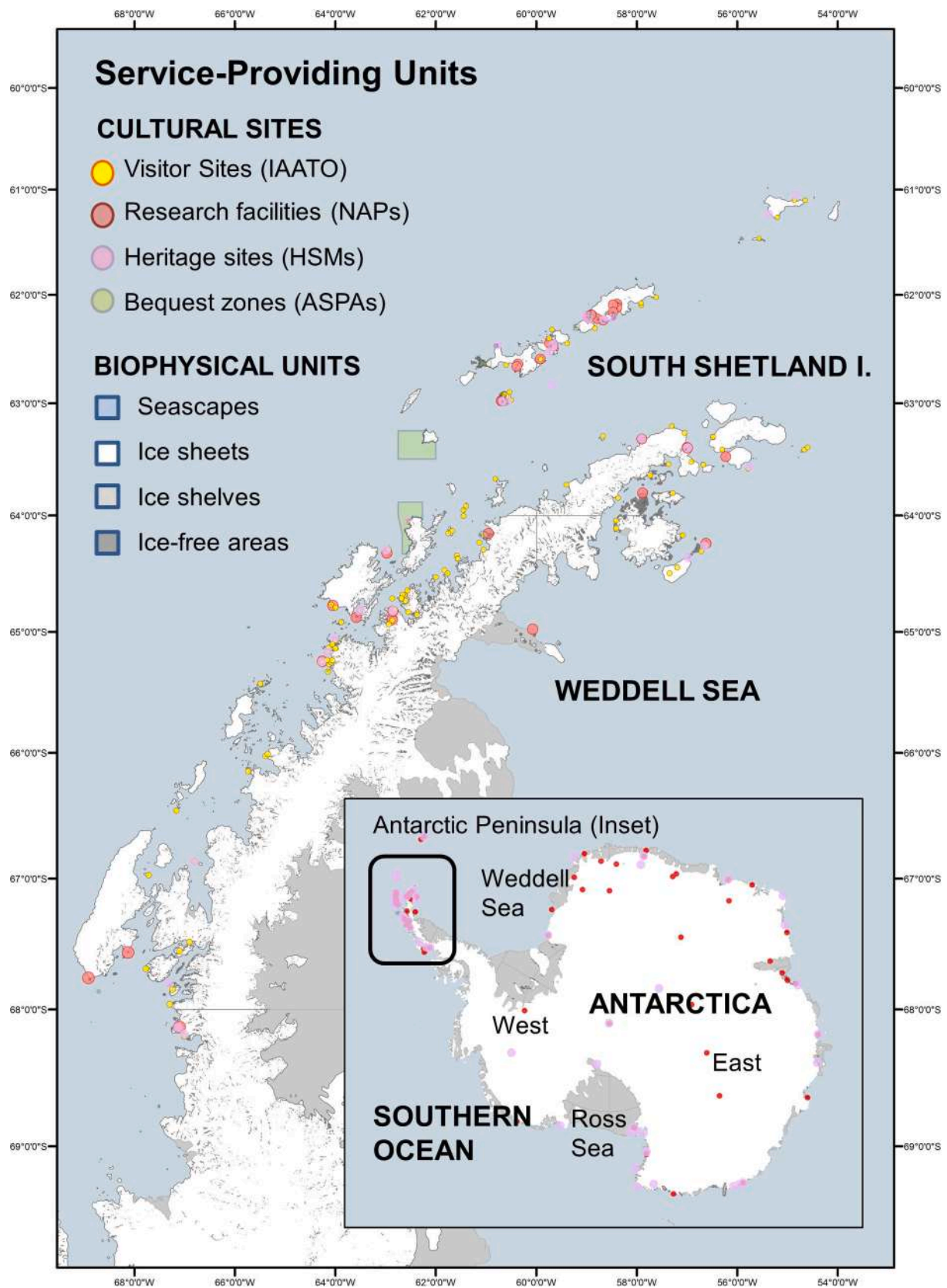


Fig. 1. Spatial mapping of ecosystem services in the study area. Map of Antarctica and the Antarctic Peninsula (inset) with the spatial distribution of biophysical units and cultural activity sites. Terrestrial sites with cultural human activities in the Antarctic Peninsula are displayed as circles: areas influenced by research (red circles, 5 km in diameter), tourist sites (yellow circles, 2.5 km in diameter), historic sites (purple circles, 1 km in diameter) and protected areas (green polygons of variable size). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

intellectual and educational activities (e.g., PhD training, environmental monitoring, policy making, etc.). The analysis facilitated the identification and visualization of the dominant ES Providing Units featured in the Antarctic literature. We evaluated total scientific output relating to Antarctica (intellectual gains) through a broad query in the ISI Web of Science databank. All manuscripts available for the 1980–2017 periods with the keyword ‘Antarctic’ in the title or summary, were retrieved and displayed in a timeline chart. We did not include production from an earlier timeframe given the arbitrary digitalization of older grey literature and greater omissions of contributions published in non-English language. The examination of the number of countries involved in the production of science on Antarctica was done by selecting two contrasted periods: (i) 1980–1989 (also, coincidentally pre-EP); and (ii) 2010–17 (post-EP). The main clusters of related information (established through repeated use of words) were identified with the software VosViewer 1.6 (Van Eck and Waltman, 2010) and interpreted to allow the visualization of the main areas of knowledge gained. A network graph was produced with the main terms used in the literature. The resulting six clusters were named with reference to the main keywords featured within them.

Trends in recreational services were quantified using tourist statistics retrieved from the International Association of Antarctica Tour Operators (IAATO) website (www.iaato.org). Total count data on the annual number of visitors and visitor landings were plotted.

Lastly, trade-offs between actively utilized ES were assessed through an expert elicitation among the constituent co-authors. This was done by asking the experts to rank the degree of conflict between current services utilization from 0 (none or synergistic), 1 (minor), 2 (moderate) and 3 (major). Mean scores were represented in an enneagram.

3. Results

The summary identification of ES in Antarctica by the experts indicated a remarkably diverse range of contributions by nature to people by a ‘frozen’ continent typically depicted as harsh and barren (Table 1). Abiotic regulatory services in the continent are present and important in their indirect contribution to Earth systems. All the cultural services are represented, although sacred and religious sites are few in number and operated by a small number of NAPs (e.g., Chile and Russia). Notably, there are two major categories of biotic provisioning that were absent for the continent, as the area lacks cultivated biomass and reared animals, with only wild animals being utilized currently (and restricted to the marine ecosystem).

The literature review reveals that a total of five original research academic publications and two editorial/perspective letters explicitly covered the topic of ES in Antarctica (Bax et al., 2021; Cavanagh et al., 2021; Deininger et al., 2016; Grant et al., 2013; Neumann et al., 2019; Pertierra and Hughes, 2019; Verbatsky 2018). Albeit, several other studies contribute to our knowledge of ES and are examined in their respective sections, below. Nonetheless, regarding the published works specifically applying elements of the ES framework to the region, we observe that they do not cover the totality of services that have been identified as relevant for Antarctica. The marine ecosystems of Antarctica, and by extension the entire Southern Ocean, have distinctive biophysical features (e.g., animals harvested to provide nutrition in the form of fish and krill fisheries) that bring diverse interests and perspectives concerning the management of provisioning versus regulating services (Grant et al., 2013; Deininger et al., 2016; Neumann et al., 2019). In turn, the ice-free terrestrial ecosystems have largely been utilised for the provision of cultural services in the form of research: stations grounds, recreation: tourist visitor sites, and conservation: Historic Sites and Monuments (HSMs) heritage sites and ASPA bequest zones, leading to questions being raised regarding the necessity for redirecting the benefits from recreational activities to conservation (Verbatsky, 2018; Pertierra and Hughes, 2019).

A map of the Antarctic continent displays areas with multiple values

that provide ES (see Fig. 1). The main biophysical formations are shown, i.e., ice, ice-free areas and ocean seascapes. Important socio-cultural sites are also shown, including tourist visitor sites, protected areas, historical sites and areas subject to the direct influence of research stations. A broad range of ecosystem services exists within Antarctica. However, their spatial distribution across the continent is highly heterogeneous: abiotic regulating services are predominantly located within ice-covered areas, while cultural services are typically seasonal, spanning the austral summer, and found mostly in ice-free areas (but also include year-round stations on ice). In contrast, the Southern Ocean supplies most of the provisioning services but also a broad range of cultural and regulating services.

In the following sections, we present the history, status and trends of all the identified ES, arranged within each of the three ES categories (provisioning, regulating, cultural) following the CICES v5.1 classification (Haines-Young and Potschin 2018).

3.1. Regulating services

As a result of its unparalleled and gigantic cryospheric ice sheet and ice shelf reservoir, its strong polar atmospheric circulation front and its vast, cold and deep surrounding ocean the southern continent of Antarctica plays a major global service in the regulation of the Earth’s climate and the life supporting systems (Fig. 2). The Antarctic continent contributes to the regulation of global temperature and regional climates and it is considered to be a tipping element in the Earth’s climate system (Lenton et al., 2008). It also contains over 70% of the world’s freshwater, with the state of its ice masses influencing global sea level, air mass movement and ocean current circulation. Moreover, the continent’s ice-free areas (estimated to be between 21,745 and 45,886 Km²; Burton-Johnson et al., 2016; Terauds et al., 2012) together with the vast extent of shallow marine and benthic habitats, harbour biodiversity that also sustains a variety of cultural and provisioning services.

3.1.1. Atmospheric circulation in Antarctica and the polar front (Services: Gaseous flows, e.g., climate regulation)

As a major global heat sink, the frozen Antarctic continent and the Southern Ocean play a major role in the Earth’s Climate System (Frölicher et al., 2015). The reorganization of atmospheric circulation, on a millennial time scale, can produce abrupt climate change events that can have a global impact by overturning the ocean’s meridional circulation. As a consequence, changes in the Antarctic climate are not restricted to the continent but may have repercussions globally. For example, an expansion of the southern polar cell 8000 years ago, may have resulted in a decrease in precipitation in equatorial Africa (Stager and Mayewski, 1997). Moreover, the Antarctic continent also plays an important role on shorter (annual to centennial) time scales, via the Southern Annular Mode (SAM), which is a major factor determining patterns of variability in Southern Hemisphere weather systems (Spensberger et al., 2019; Thompson and Solomon, 2002). Lastly, Antarctica’s carbon storage through seafloor sequestered by marine ecosystems (blue carbon) has been recently recognized as an increasingly important regulating ecosystem service (Bax et al., 2021).

Changes in atmospheric circulation affect the Antarctic continent via many physical and functional factors. The state of the Antarctic cryosphere is linked closely with global climate change and variability (Oliva et al., 2017). On a regional scale, climate regulation plays a role in ecosystem structure and function. In the maritime Antarctic, milder temperatures contribute to the presence of increasingly numerous deglaciated areas compared to most other parts of Antarctica (the notable exception being the McMurdo Dry Valleys) that support well-developed moss and lichen communities, liverworts, and two vascular plants. Since the mid-20th Century, the Antarctic Peninsula has experienced some of the most rapid regional warmings on Earth (Vaughan et al., 2003) with substantial impacts upon both the physical environment and native biota (Siebert et al., 2019). This warming may induce a

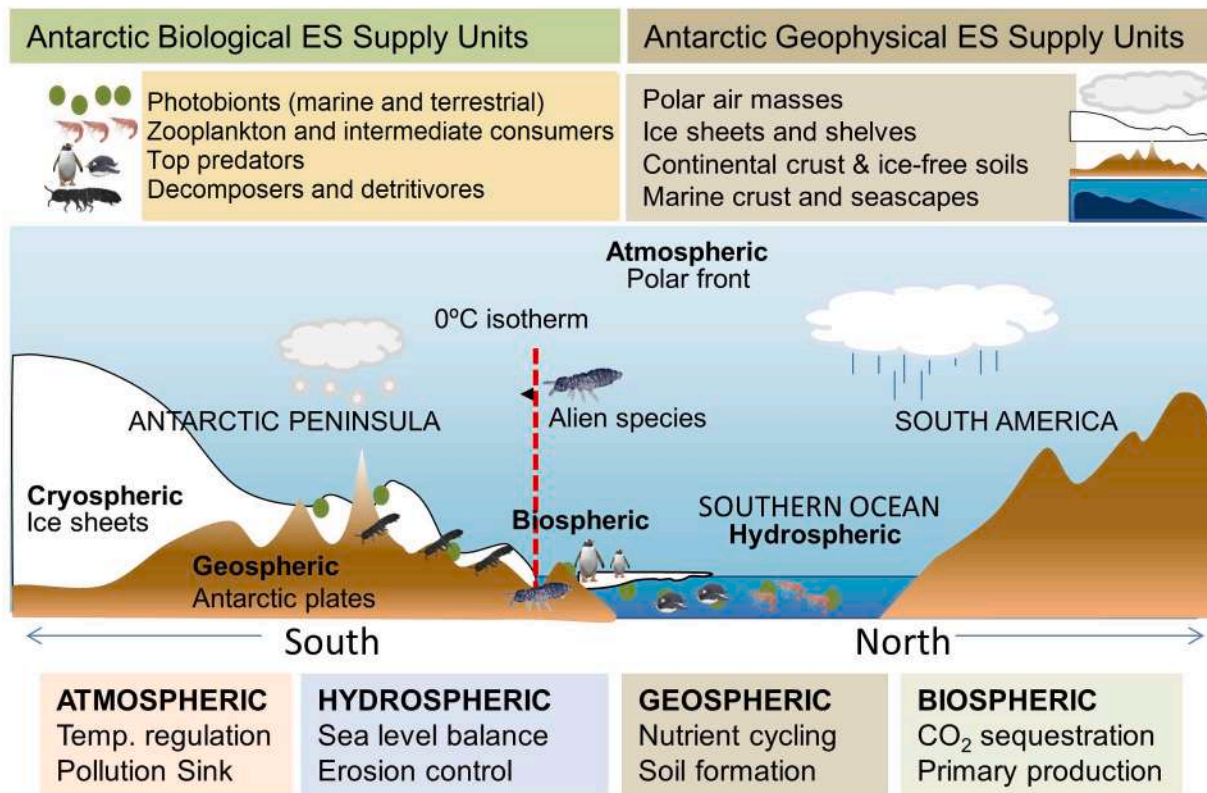


Fig. 2. Visual display of biotic and abiotic regulating services in Antarctica. The visual schematic panel displays the main biotic and abiotic components of Antarctica that provide regulating services.

“greening” of ice-free areas, but may also make the establishment of non-native species more likely (Avila et al., 2020; Hughes et al., 2020).

3.1.2. Antarctic cryosphere (Services: Liquid and mass flows, e.g., sea level balance)

Antarctica represents the largest reservoir of fresh water on Earth, albeit in frozen form, that maintains ocean salinity levels and drives ocean circulation (Liggett et al., 2015). Changes in the Antarctic cryosphere could lead to perturbations in energy balance, runoff, and ecosystem activities (Levy et al., 2018). Antarctic ice sheets are an essential driver in the global climate system, but are vulnerable to climate change (Frederikse et al., 2020). Understanding the variability of Antarctic ice loss is key to the development of future climate models (Donat-Magnin et al., 2020).

One of the main consequences of Antarctic continental ice sheets' flow is global sea level rise. Future sea level changes will have an effect on the height and frequency of extreme flooding events (Frederikse et al., 2020). Rising sea levels increase the risk of flooding in coastal zones, many of which are economically and ecologically important. Additionally, these low lying and often fertile areas are home to many millions of people and may provide food upon which large populations depend (Hallegatte et al., 2013). Decisions on the viability of coastal erosion mitigation measures (e.g., sea walls) are based on sea level rise projections, and uncertainties related to the accelerated disintegration of the Antarctic ice sheets directly impacts upon these decisions (Oppenheimer and Alley, 2016). During the period 1992–2017, the Antarctic continent was responsible for 7.6 ± 3.9 mm of the global mean sea level rise, driven mainly by increased ice discharge into the ocean (Shepherd and Ivins, 2017). This input is expected to increase further over the next one hundred years and beyond (Edwards et al., 2019).

3.1.3. Ice-free areas (Services: Maintenance of Soils, quality and Habitats, Mediation of wastes and uses of anthropogenic Origin, regulation of Flows)

Antarctic ice-free ground represents a minor part of the extent of the continent (Lee and Terauds, 2017). However, it is vital for terrestrial ecosystems and as a breeding or haul out site for marine birds and mammals, as well as for human activities such as research facility construction and tourist visitation. In particular, the Antarctic Peninsula hosts most of the visited ice-free ground, but local areas in East Antarctica and the Ross Sea region (and the McMurdo Dry Valleys, in particular) also sustain concentrated human activities (Pertierra et al., 2017a, 2017b). Importantly, soils in ice-free ground are generally poorly developed and represent a scarce ES providing unit that needs to be preserved.

The permafrost and soil-organic layers contribute to climatic regulation through thermal buffering and carbon sequestration processes (Hrbáček et al., 2020). Permafrost affects biogeochemistry and geomorphological dynamics in the terrestrial ecosystems of the maritime Antarctic. It stores frozen water and other naturally occurring (Hg, CO₂, CH₄) and anthropogenically released (Pb, As) elements (Hrbáček et al., 2020). Furthermore, permafrost may be a sink for organic and inorganic compounds, especially persistent organic pollutants (POPs) and heavy metals. Potapowicz et al. (2019) suggest that the ongoing increase in Antarctic temperatures could affect rates of soil organic matter turnover in the terrestrial ecosystems, as well as CO₂ emissions, as it has been demonstrated in the Arctic.

Despite the fact that Antarctica is physically isolated from nearby continents by the Southern Ocean, the region is impacted by anthropogenic pollutants, both from local and remote polluting sources (Marina-Montes et al., 2020). Antarctica is considered a trap for atmospheric aerosols (Eisele et al., 2008). In particular, some elements such as lead and other heavy metals have been detected in the area (Cáceres et al., 2019). Some of these elements are known for being toxic inorganic

contaminants that can persist in the food chain for large periods of time by bioaccumulation, thereby negatively affecting Antarctic environment and ecosystems. Additionally, POPs have been found at substantial concentrations in air, snow, seawater, biota and sediments in the Antarctic region (Corsolini et al., 2006; Casal et al., 2019).

3.1.4. Antarctic terrestrial and marine biodiversity (Services: Maintenance of Lifecycles, Nursery populations and Habitats, Pest and Disease Control, Bio-remediation, Aesthetic)

Global biodiversity is facing critical changes and Antarctic biodiversity is also affected by these threats (Chown et al., 2015). Antarctic biodiversity is strongly linked to global regulating services (e.g., climate regulation and supporting primary production), largely driven by its vast cryosphere and the remarkably high primary productivity of the marine ecosystems of the Southern Ocean (Grant et al., 2013). In turn, the harsh environmental conditions limit the productivity of terrestrial ecosystems and as most freshwater bodies are not impacted by mega-fauna, they are typically oligotrophic. Nonetheless, some elements of the terrestrial environment, such as snow algae or microbial mats, still provide an important carbon sink (Gray et al., 2020). When considering pollutant cycling along biological systems, it is worth noting the bioaccumulation effect on food chains where top predators such as colonial bird species (e.g., penguins) ultimately transport nutrients and pollutants from sea to land (Santamans et al., 2017; Bokhorst et al., 2019). Lastly, there are no pollinators servicing terrestrial environments, with native plants relying on abiotic means for reproductive dispersal. The arrival of non-native species poses a substantial threat to the native biodiversity and associated ES (Hughes et al., 2020). Consequently, biosecurity measures have been and continue to be approved by the ATCM and implemented, to varying degrees, by NAPs and tourist operators in order to reduce the risk of inadvertent introduction of non-native species (Hughes et al., 2020).

Fig. 3 (upper panel) shows the changes in abiotic conditions related to the regional climate warming in the Antarctic Peninsula over several decades. In turn, population dynamics among key components of the Antarctic ecosystems such as penguin species (lower panel) are also

changing, suggesting on the cascade effects from the alteration of abiotic and biotic regulating factors.

3.2. Provisioning services

3.2.1. Fishing and hunting. (Services: Biomass extraction)

Antarctic ecosystems have been subject to harvesting activities since humans first arrived on the continent c. 200 years ago (Fig. 4 timeline, Table S1). The earliest visitors sought to obtain benefit from fur seal hunting in the South Shetland Islands (Pearson et al., 2009; Dibbern, 2009). However, this fur sealing industry proved to be the first example of the unsustainable use of Antarctic marine living resources, which continued through the 19th and 20th centuries with the sequential and largely uncontrolled exploitation of elephant seals, whales and finfish (Nicol et al., 2007). Following the agreement of a series of international regulatory conventions between 1946 and 1982 (Table S1 timeline), the supply of provisioning services (harvesting of seals, whales, krill and finfish) is now highly regulated or prohibited in Antarctic waters and coastal environments. In addition to this high level of regulation, the lack of any permanent population means that provisioning services are almost entirely used by remote rather than local beneficiaries.

Sustainable harvesting of marine living resources is allowed under the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR, 1982), within a comprehensive regulatory framework, including precautionary catch limits, open and closed areas and seasons, environmental regulations and protected areas. The main species harvested are Antarctic krill (*Euphausia superba*), Patagonian toothfish (*Dissostichus eleginoides*), Antarctic toothfish (*D. mawsoni*), and mackerel icefish (*Champsocephalus gunnari*). The relative size of national Antarctic fishing industries, among the main nations involved can be seen in Fig. 3.

3.2.2. Biological prospecting (Services: Genetic materials)

Based on the studies and reports reviewed, it was found that Antarctic biodiversity is a source of many unique natural bioelements such as genetic material and biochemical compounds that are inherent,

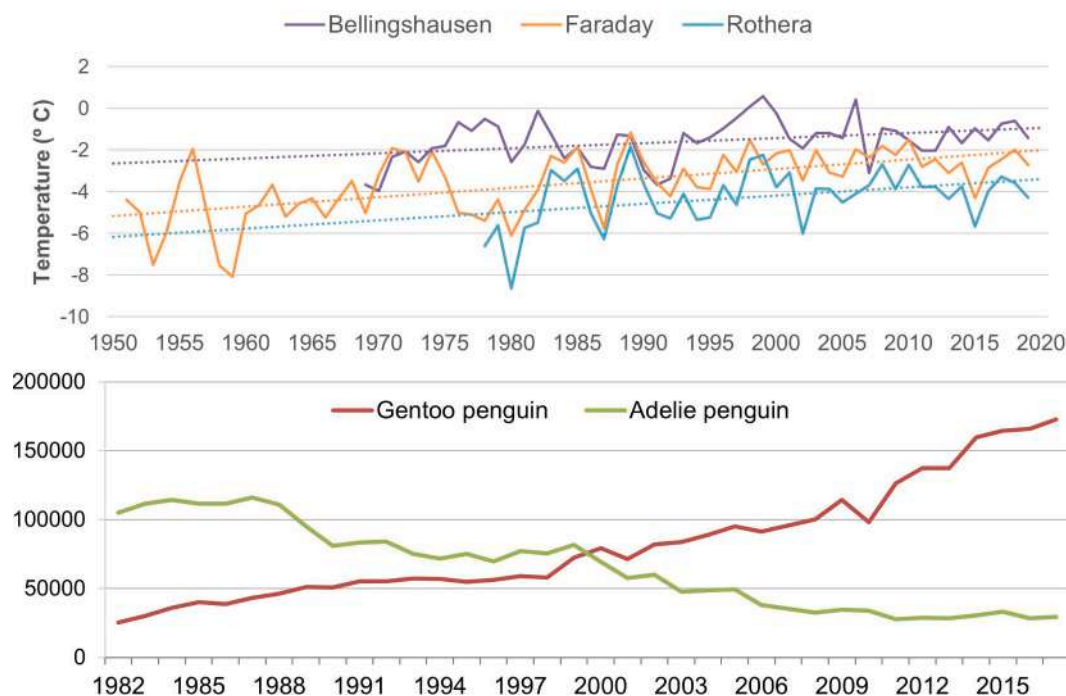


Fig. 3. Indicator trends of sentinel biotic and abiotic elements of regulating services in Antarctica. Upper graph: Mean annual temperature time series from research stations in the Antarctic Peninsula show the climatic warming trends in the region. Lower graph: Time series for the meta-population of two penguin species (bio-sentinels) in the Antarctic Peninsula are shown as an indication of species population changes in the region.

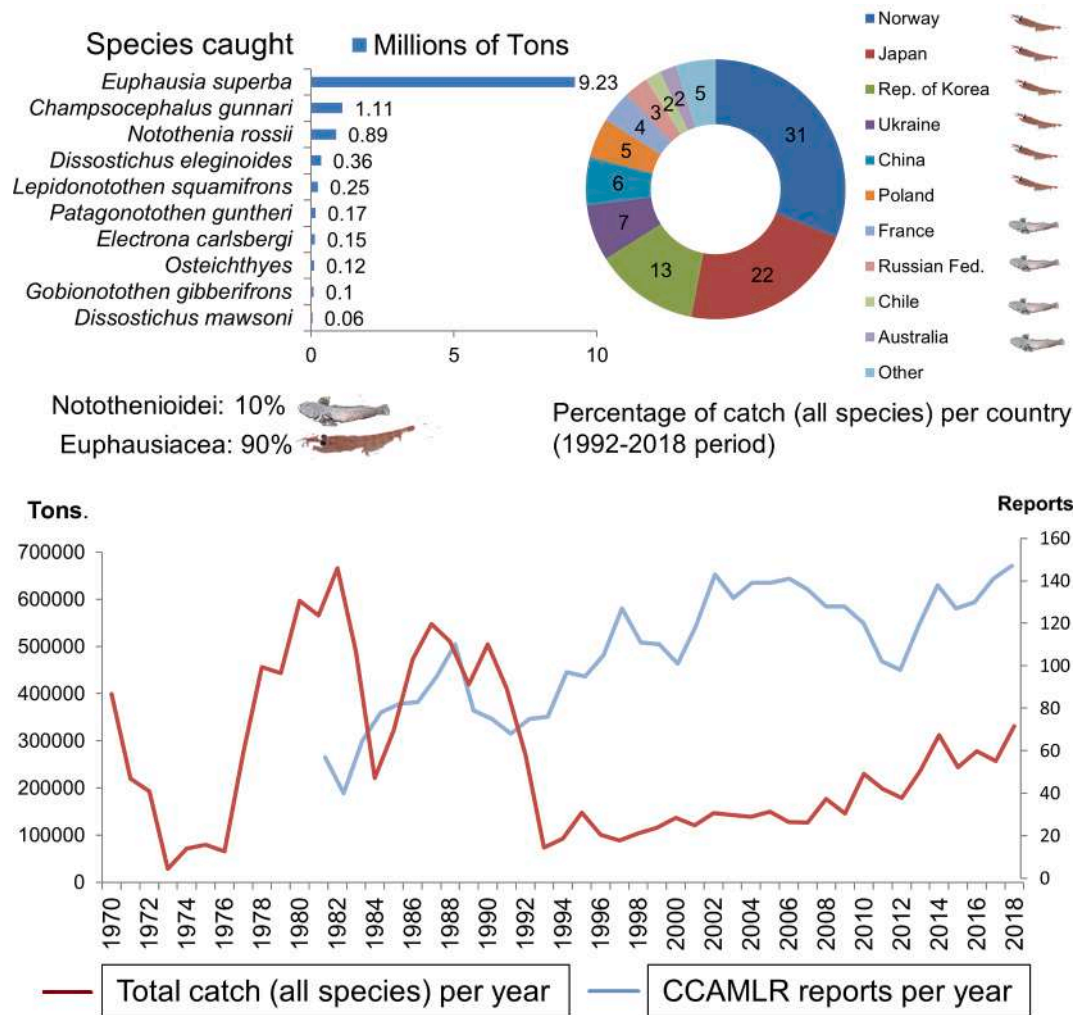


Fig. 4. Historical record of biomass provisioning in Antarctica. Top left graph: main species exploited in millions of tons and relative contribution per animal group. Data source: <https://www.ccamlr.org/es/>. Top right chart: distribution of marine living resources catches per nations involved in Antarctic marine living resources biomass extraction. Lower graph: total catch (tons) per year by all nations and the total number of presented to meetings (as a rough indicator of nations' engagement in fisheries management).

produced or accumulated by biological groups including invertebrates, microorganisms, algae, and vascular plants (Hemmings and Rogan-Finnemore, 2005). These natural products are likely the result of evolutionary pressures, such as predation or competition in a rather unique environment, and may include structurally diverse compounds with specific biological activities (Avila et al., 2008). In marine areas endemism is common, ranging from 45 to 75% of species depending on the taxonomical group (Griffiths, 2010), and thus, the chances of finding new species and novel natural compounds are high. As a consequence, Antarctica and the Southern Ocean hold a huge potential for bioactive compound discovery, based on their untapped biochemical diversity. Biological prospecting in Antarctic coastal areas has been undertaken during recent decades by many research groups using different methods and strategies (Avila, 2016), with increasing attention been paid to the topic in the general literature (see some earlier discussions in Hughes and Bridge, 2010). In recent years, this field has gained further attention, with some discovered bio-products considered potentially useful as precursors of active molecules for the design of new pharmacological drugs, as anticancer agents, antimicrobial compounds or as antifouling agents (e.g., Taboada et al., 2010; Figuerola et al., 2014).

3.2.3. Surface waters supply (Services: Drinking and non-drinking purposes)

Water utilization is allowed under the Antarctic Treaty as no forms of water are considered a mineral resource (hence its inclusion here as a provisioning service). Many research stations use energy to take freshwater from nearby water bodies, although some coastal stations use desalination plants. Most freshwater in Antarctica persists in the form of ice or snow, and the utilization of liquid water is often restricted due to either an insufficient supply of natural reservoirs or holding tanks, or limited filtering capabilities to make the water potable. In the long-term, this may result in friction between potential users, as some stations have to share water supplies (e.g., the stations located on Fildes Peninsula, King George Island). Once used, water is returned to the local environment, although it may be contaminated with non-native faecal microorganisms and chemical pollutants (Tin et al., 2019; Hughes and Thompson, 2004). Regulations on the provisioning of freshwater focus on the protocols for sewage water treatment to reduced environmental pollution. The requirements can be considered weak, with maceration only required once more than c. 30 people are residing on station (Environmental Protocol 1998, Annex III). In turn, measures for the rational use of water supplies have not yet been regulated, which is a concern in light of an increase in water demand due to a growth in research station numbers, and potential future changes in water quality

and availability, including as a consequence of local environmental change. No ex-situ freshwater exploitation has been conducted (so far) through the tethering and removal of large icebergs by ships; however, this possibility might be considered by nations as a mitigation against future potential scenarios of desertification and water scarcity.

3.3. Cultural services

Shared utilization of cultural services in Antarctica between AT signatory nations, such as the sustained collaborative research (Kennicutt et al., 2019), is perhaps nowadays the dominant reason for the prevailing internationalization of human activities in the continent. Still, the full extent of cultural services has not always been recognised. Attempts to quantify Antarctic cultural services are scarce and are mostly limited to quantifying the production of scientific outputs. Antarctic ecosystems provide a series of ES to visitors including: (1) scientific knowledge, which contributes to Antarctic science, (2) the aesthetic value of the landscape and its role in inspiring art and literature, (3) strictly recreational and tourist leisure activities, (4) educational or environmental awareness activities that generate a cultural identification and a feeling of attachment to the continent through its vast cultural heritage, (5) psychological well-being and cognitive benefits at the individual level, derived from direct contact with wilderness, (6) bequest values for future generations in terms of the maintenance of an exceptional environment and, (7) a spiritual, inspirational and/or religious value for modern societies (Grant et al., 2013; Neumann et al., 2019).

3.3.1. The Antarctic Treaty system (Services: Heritage, Bequest, Symbolic, Scientific, Existence, Educational, Cultural, Aesthetic)

Early exploration of the continent revealed the immense ecological value of Antarctica. This latent value was first communicated to 19th and then 20th century societies, and generated a desire to understand more of this vast and remote wilderness (see more in spiritual services), while simultaneously raising disputes between nations concerning territorial claims. This interest came in parallel with (or was rooted in) the desire to expand provisioning activities, which were more closely related to the direct economic gains of national industries and promoted by the pioneer nations in the continent in their desire towards exploring extra food security systems and access to future resources (in part linked

to territorial claims). Consequently, several early expeditions made attempts to understand more of the continent through, for example, circumnavigation or reaching the geographic South Pole (Walton, 2013). As a result, many early activities in Antarctica are framed within the idea of ‘adventure’ and ‘heroism’, which is marked physically by historical landmarks across the continent, many of which are preserved as HSMS. From the 1900s onward, nations increasingly realized the value of the continent, and sought to claim territory, marking their physical presence with the establishment of an increasing numbers of research stations.

Mindful of the scientific value of the continent (see intellectual services section) and in a geopolitical environment of increasing tension between claimant states, the nations with an interest in Antarctica sought to reach consensus and agreed upon the peaceful and shared use of Antarctica for science under the Antarctic Treaty (1959). The ATS is an exceptional forum for international diplomacy. Antarctica represents the only landmass on Earth that is managed internationally. The capacity of the system to prevent conflicts cannot be measured directly, but can be seen in terms of the development of international agreements that are intended to safeguard the use of Antarctic ES. The ATS provides a framework for nations to cooperate in peace, where all decisions are made through consensus. The ATS has proven to be robust enough to safeguard the interests, and in many cases active presence, of the (currently) 54 Antarctic Treaty Parties for c. 60 years (i.e., since the Treaty entered into force in 1961) (see Fig. 5), with governance through the normally annual ATCM provisions.

The EP established the CEP to provide advice on environmental issues to the ATCM. The EP provides the means to sustain Antarctic ES through the recognition and protection of Antarctic values. The values to be protected are classified around six categories: environmental, scientific, historical, wilderness, aesthetic and intrinsic. The Antarctic Protected Areas System provides a mechanism for the designation of ASPAs, ASMAs (Antarctic Specially Managed Areas) and HSMS which can be used to protect sites containing outstanding values (ASPAs), to facilitate cooperation and avoid conflict in areas used by several stakeholders (ASMAs) or protected sites of historic or cultural value (HSMS) (see Fig. 5).

Conservation policies, in the form of Measures and Resolutions, have also been developed within this system. An examination of ATCM/CEP

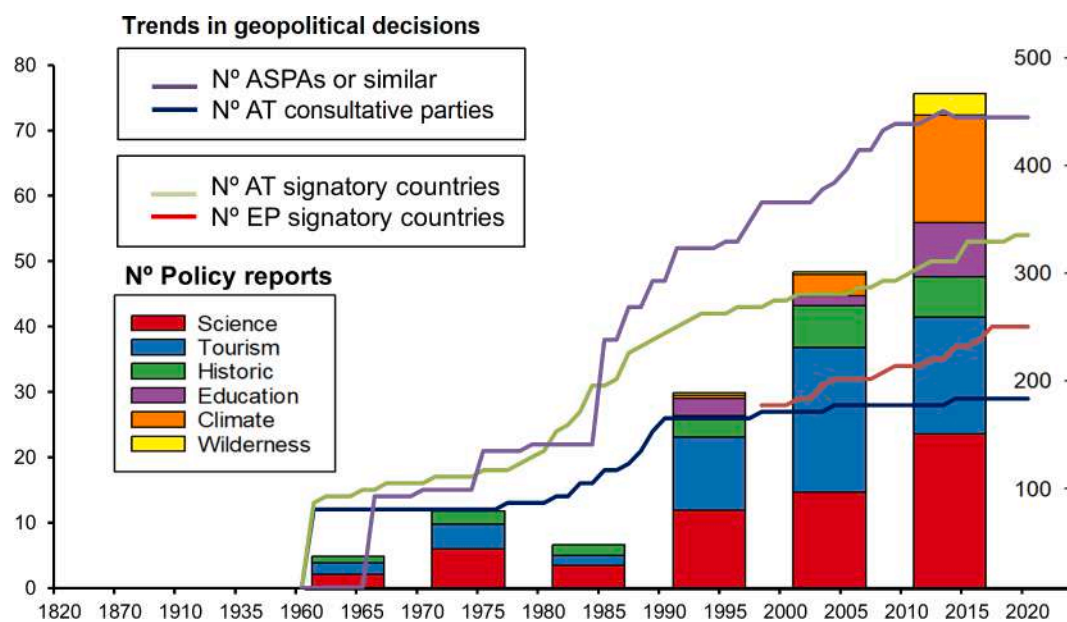


Fig. 5. Heritage and bequest services from the antarctic treaty. The main chart shows the number of participant nations in the Antarctic Treaty over time as well as the cumulative designation of protected areas (ASPAs). The histogram shows the cumulative number of Antarctic Treaty Consultative Meetings policy papers published per decade (1961–2019) relating to different ES.

policy papers (Fig. 5) shows a long history of policies aimed at safeguarding scientific values (for example, with the agreement of a mechanism to establishment of Specially Protected Areas in 1964). Another long-running topic of discussion within the ATS concerns tourist activities and how Antarctic recreational activities can be managed more appropriately. It is worth noting that educational services have been promoted by AT parties in recent years. Moreover, in recent decades there has been a greater awareness of the impacts of climate change in Antarctica, and particularly since the publication of the SCAR Antarctic Climate Change and Environment (ACCE) Report (Turner et al., 2009). Lastly, the bequest values of Antarctica are starting to gain more attention with a focus on protecting wilderness (Leihy et al., 2020) and the designation of inviolate areas within protected areas (Hughes et al., 2013). These developments result from an increasing and wider recognition of ES in Antarctica, but also a more precise identification of current and future threats. Based on our systematic literature review and data collection we identified an increasing trend of awareness and interest in the preservation of cultural ES since the Antarctic Treaty entered into force, as demonstrated by a steady increase in the number of policy papers published on the Antarctic region of relevance to cultural ES (Fig. 5).

Socio-ecosystem conceptualizations also face the challenge of evaluating the intrinsic wilderness, aesthetics and symbolic values values of Antarctica. Antarctic wilderness values relate to the absence of human infrastructure, and the associated silence and remoteness of unimpacted areas, with the whole continent been seen as a bastion of wilderness on Earth (Brooks et al., 2019). However, recent examinations of historical footprint in the continent suggest that the Antarctica is less untouched than previously realized (Hughes et al., 2011; Leihy et al., 2020). Aesthetic values relate to human perceptions of the region's beauty. Without first-hand experience of Antarctica, the world's population gets its understanding of the region from books, images, films, and even advertisements (Nielsen, 2017). Surveys and interviews conducted in some countries report that members of the public value Antarctica's environment, especially as a wilderness, and are against the exploitation of its mineral resources (Salazar, 2013; Shabudin et al., 2016; Tin et al., 2019; Peden et al., 2016; Bastmeijer and Tin, 2015). Symbolic values refer to the feats and achievements that inspire humanity. In this context, Antarctica has been variously represented as: a backdrop for feats of heroism, endurance and transformation; a blank space for Utopian visions; a vast, cold, indifferent desolation, set apart from the rest of the world; a world wilderness park for peace and science; the last pristine wilderness that, despite its geographical isolation, is intimately connected with global human activities; fragile; and threatened by anthropogenic pollution and climate change (Glasberg, 2012; Nielsen,

2019; McClintock, 2012; Schilat et al., 2016; Shortis, 2016; Leane, 2018).

3.3.2. National Antarctic programs research (Services: Scientific, Educational, Physical, Experiential)

The current regulatory system for Antarctica, the ATS, was initiated following the success of the International Geophysical Year (1957–58). The SCAR was established initially in 1958 as a body to promote Antarctic science and, once the Treaty was agreed, to also provide impartial scientific advice to the ATCM to assist in its policy-making. Scientific production has grown over the years both in number of total annual publications and the number of countries involved in Antarctic research (Fig. 6).

Over the years, scientific research knowledge concerning Antarctica, or knowledge of global relevance gained within the region, has made a substantial contribution to knowledge (e.g., the discovery of ozone depletion in the stratosphere above Antarctica; Farman et al., 1985). Furthermore, research within the region has produced globally important research on climate change and sea level change (with much of it contributing to documents presented to policy-makers working outside the Antarctica context (IPCC, 2019)). The study of Antarctic biodiversity has led to advances in biogeography, biochemistry, microbiology, physiology and evolutionary biology, which has been made possible, in part at least, by the low levels of human impact within the region. Antarctica contains outstanding palaeontological and geological heritage that has revealed past Earth processes and paleoclimates (Hughes et al., 2016). Antarctica is also selected for upper atmospheric, astronomical and cosmological observations and measurements due to the thin and clean atmosphere, relative to many other areas of Earth. Finally, the continent provides a unique environment to study human health and physiological response under isolation and extreme environmental conditions. Primary topics researched their relation to ES can be seen in Fig. 7.

3.3.3. Antarctic tourism and recreational activities (Services: Entertainment, Experiential, Educational, Cultural, Physical)

Antarctic tourism is recognised as a legitimate activity under the ATS (Bender et al., 2017). Tourism makes use of the recreational and, to some degree, the educational services of the continent, and the IAATO encourages safe and environmentally responsible operations within the continent (<https://iaato.org/>). However, unregulated visits also occur, by yachts (private and commercial) in particular, with reports of occasional damage to the historical heritage and environmental values of the region (e.g., Wordie House HSM 62 as noted by United Kingdom (2010)). Within the cultural services, tourism is perhaps the easiest

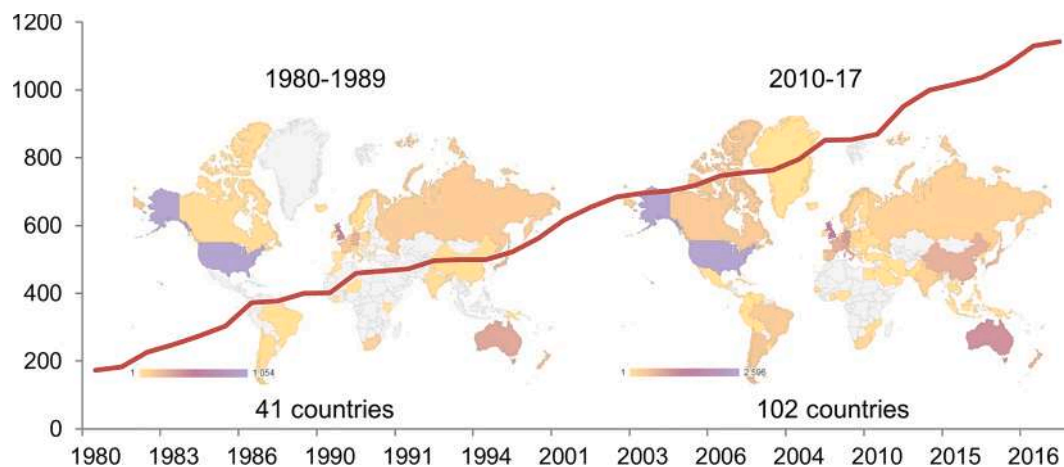


Fig. 6. Trends in scientific services relating to antarctic research. Total annual production (academic publications per year), number of countries and production per country is shown for two periods (1980–89 and 2010–2017) in the background of the timeline chart.

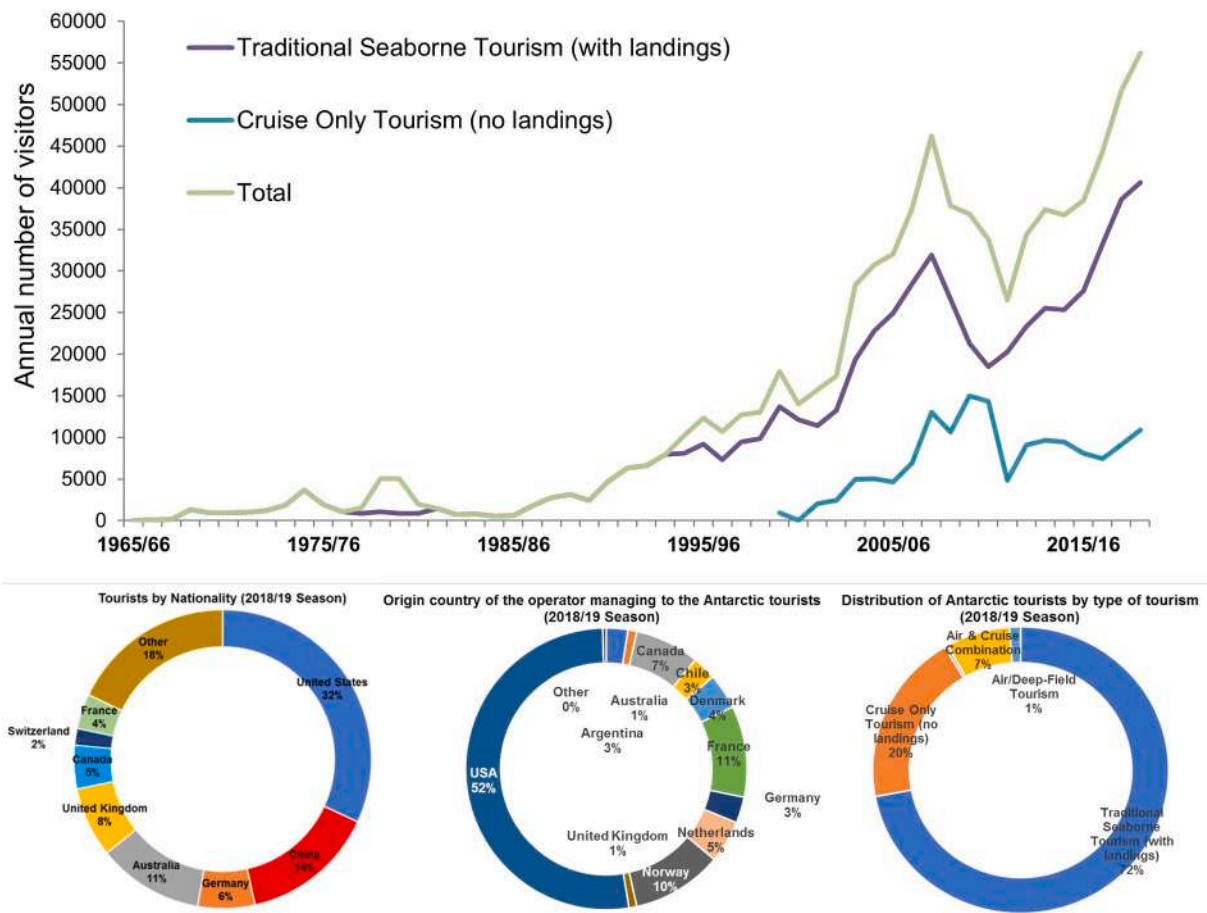


Fig. 8. Recreational and experiential services from the tourism industry. Trends of tourist activities/logistics are shown in the main graph. Total data include other less numerous forms of tourism, such as overflights, air and cruise combination, or land-based activities with air support. Lower charts show the range of visitor nationalities, operator nationalities and tourism types.

from the general trend of an increase in utilization, which has been observed for all ES types, and the potential impacts caused to ES resulting from cumulative use. Conflicts between stakeholders with interests in particular ES are increasingly observed, and inevitably, the values are subjected to spatial trade-offs (Tejedo et al., 2016; Pertierra et al., 2018). Our study has observed a net growth for all activities, thus presumably leading to an associated intensification of trade-offs over time (e.g., Fildes Peninsula, King George Island, as an important gateway to Antarctica, but also an important location for Antarctic biodiversity and biological communities). Fig.9 provides a conceptual panel detailing potential trade-offs between Antarctic Ecosystem Services. Here we can observe that in terrestrial systems several trade-offs are detected between cultural services and in particular, when involving recreational activities. In turn marine systems only face a major clash between biosphere regulation and marine living resources provisioning. Interestingly, a positive note to take from the assessment is the perceived peaceful coexistence of several ES, also pointing the need to prioritize managing efforts on mediating in the few conflicting ones.

Overall, future policy development on biodiversity conservation and protection of ES would benefit from strategic planning that accounts for all ES and impacts, in particular, with regard to their spatial extent, intensity and temporal trends. ES mapping and assessment would help to identify priority areas for conservation and management, taking into consideration their value and vulnerabilities. Mapping overlapping ES at a local scale would help to further identify occasions where values co-exist, thereby bringing new tools to manage any potential conflict between stakeholders. In this regard, future assessments will be challenged from the appropriate identification of the trends and the local

conservation status of the service-providing units; e.g., in the given penguin species example by considering the regional intraspecific diversity (see Tyler et al., 2020, Pertierra et al., 2020). Minimising conflict between ES beneficiaries is essential through the development of appropriate regulation and management tools. For example, the identification and designation of carrying capacities for a particular area may restrict the magnitude of permitted activities to sustainable levels and also contribute to limiting cumulative impacts. Socio-cultural studies on stakeholder's views and perceptions remain few in number, but such research may offer key opportunities to establish sustainable goals. Lastly, intrinsic economic valuations can assist with the identification of the non-monetary market value of certain ES and further promote their adequate consideration and inclusion in decision-making processes. Overall, the range of ES tools highly applicable to Antarctic ES study and management can be divided in three groups:

(I) Biophysical ES spatial mappings Improvements in spatial and temporal data provide opportunities to develop more detailed biophysical ES assessments for Antarctica. Mapping biophysical ES has commenced in marine ecosystems, although this cannot be said for terrestrial systems. This can be attributed to the different categories and history of utilization of dominant ES in each domain. Whereas cultural ES in terrestrial systems have until now been more easily instrumentalized by the ATS values and the Environmental Protocol, marine living resources ES were under substantial pressure from a much earlier time, but have also been more closely managed by CCAMLR. Nonetheless, with regard to the emerging trade-offs highlighted in this study between cultural values in terrestrial systems, new systematic conservation planning tools are currently being considered to model the

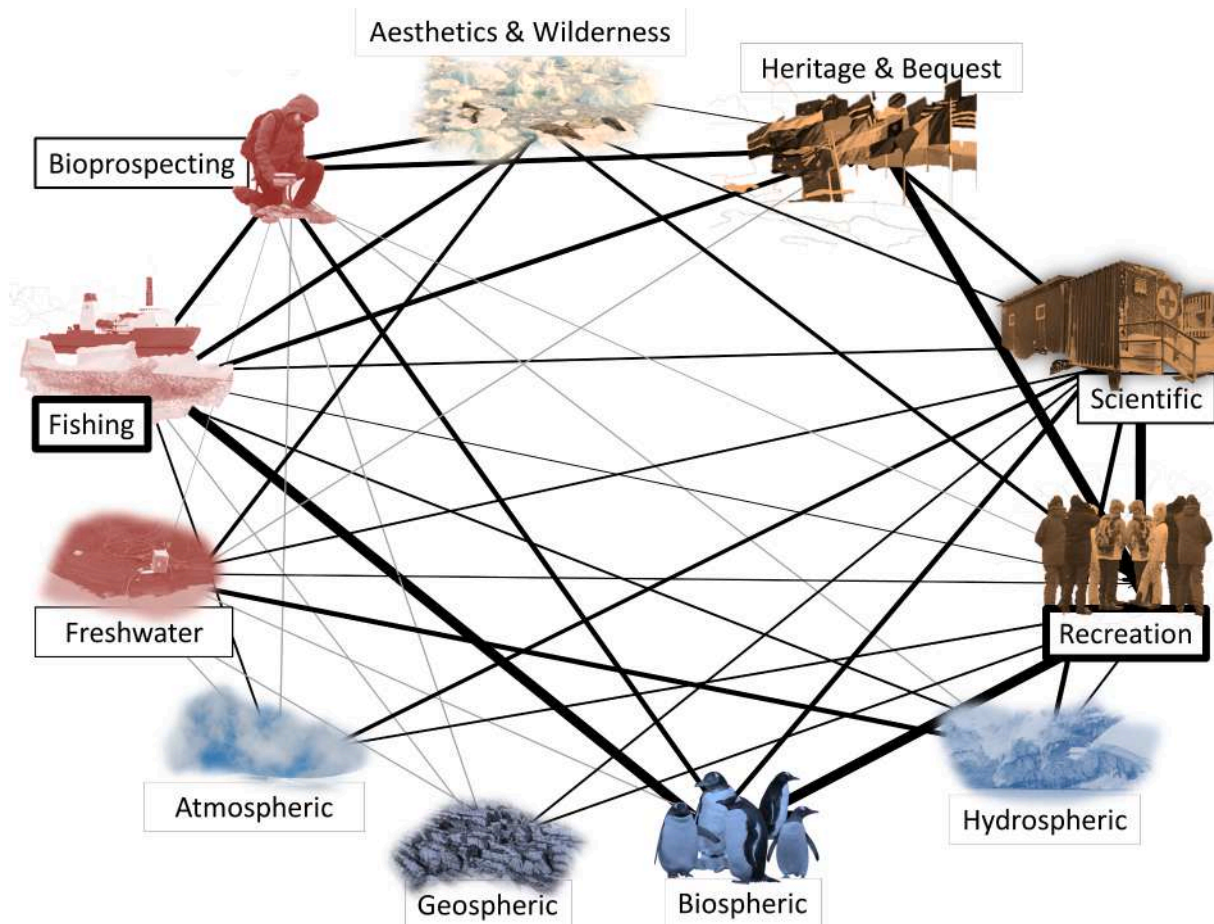


Fig. 9. Conceptual panel of ecosystem services trade-offs. Evaluation of trade-offs between the main ecosystem services operating in Antarctica. Line size represents the mean relative magnitude of the conflict in intervals from none or synergistic (no line), minor (thinner and greyer lines) and major trade-offs (thicker and darker lines) from the levels of interference individually assigned by the experts. Self-conflicting trade-off levels resulting from the cumulative utilization of each service are represented in their respective label boxes in form of outline sizes.

division of predominantly ice-free areas into sites for science, tourism and conservation of representative terrestrial ecosystems (SCAR and IAATO, 2019). Simultaneously, marine zoning systems in the form of new marine protected areas (MPAs) and Vulnerable Marine Ecosystems (VMEs) are also discussed annually. As a result, focused assessments have already examined ES providing units on ocean seascapes around marine ecosystems in the Southern Ocean above 60°S (Grant et al., 2013, Deininger et al., 2016, Neumann et al., 2019). In turn, there have been some attempts to examine the overlap of cultural activities in terrestrial systems (e.g., Chown et al. 2012, Pertierra et al., 2017a, 2017b; Brooks et al., 2019). Enhanced data availability for biotic and abiotic features would facilitate more refined assessments at various spatial scales and improve strategic area protection (Shaw et al., 2014; Hughes et al., 2016b; Hughes and Grant, 2017). Undoubtedly, increased international coordination of geospatial information resources would drive the more rapid and comprehensive delivery of ES assessments.

(II) Socio-cultural ES perceptions and public participation Increasingly we understand the key role Antarctica plays within the Earth system, and yet global ES assessments fail to incorporate this important natural space. A broader appreciation of the contribution Antarctica ES make to humanity may further reinforce existing desires to protect this remote continent. For these reasons, the socio-ecological disciplines and, in particular, the ES formula of visual interpretation panels of socio-ecosystems functioning (e.g., Fig. 2 on the variety of regulation services) can be used in raising further awareness among stakeholders and the general public on the ES value of Antarctica. This could be particularly helpful should societies wish to launch campaigns relating to climate

change and the reduction of CO₂ emissions, by bringing more attention to the key importance of preserving the Antarctic cryosphere due to its role in maintaining global climate and sustaining life on Earth.

Overall, Antarctic intrinsic values are widely considered as remarkable. Some authors refer to Antarctica as a wonderland, a sanctuary that challenges humans to think about our moral duties and rights on this planet and in the universe; it represents the possibilities for peace and a human–environment relationship that is characterized by restraint and humility (Rolston, 2002; Tin, 2017; Shortis, 2019; Cole, 2005). However, not all public perceptions are aligned with that perspective and, in order to preserve intrinsic values, Antarctic conservation faces the challenge of meeting different socio-cultural perceptions. In response, ES conceptualizations can help offer a relatable picture of nature's contribution to people in the form of the various benefits to humankind.

It has been suggested that experiential activities in Antarctica provide an educational value. Recreational activities can be used to engage tourists in the conservation of this region by making them 'ambassadors' for Antarctica, and encouraging their international promotion of the area as a continent dedicated to peace and science (Vila et al., 2016). The educational dimension, including the need for conservation, experienced by Antarctic tourism, provides a unique opportunity to enhance advocacy for the continent. However, the validity of such claim remains to be fully tested (Alexander et al., 2019). In this context, dedicated socio-cultural ES assessments would provide a better account of both the costs and benefits of experiential activities.

The absence of local Antarctic beneficiaries contrasts starkly with the increasing number of beneficiaries located outside the continent,

including the tourism and fishing industries as well as the NAPs. However, indirect and future (bequest) beneficiaries have a 'silent' voice that remains to be addressed. For instance, climate action is becoming a growing demand by today's societies, which raises questions concerning the key role of Antarctica's cryosphere in global climate regulation and the actions necessary to preserve its essential contribution. No specific socio-cultural studies concerning remote human awareness of ecosystem services have been undertaken in Antarctica under the ES conceptualization, even though some pioneering works on societal perceptions have been undertaken that provide the opportunity to examine views and attitudes towards the benefits of Antarctica to humankind (Salazar, 2013; Shabudin et al., 2016; Tin et al., 2019; Peden et al., 2016; Bastmeijer and Tin, 2014).

(III) intrinsic vs. Economic ES valuations, with recognition of non-monetary values. In the absence of a native human population in Antarctica, where economic resources could be reinvested, economic forces such as the tourism and fishing industries have removed wealth from the Antarctic region and transferred it to either peripheral gateways or distant societies linked to the nations of the operators (Verbitsky, 2018). Consequently, recent voices have called for specific action, such as the monetization of recreational services and reinvestment in efforts to protect the environment (Lee and Hughes, 2010; Verbitsky, 2018). In turn, carbon neutral policies such as the use of formulas to reinvest wealth generated in Antarctica in offsetting the impact of the fishing industry are currently under consideration in CCAMLR. Additionally, Antarctic scientists and NGOs have advocated for the designation of an extended strategic protected area network in order to safeguard the region's natural values and ensure better representation and wider protection of species and other natural features, albeit, leading to probable further restriction to local human activities (Shaw et al. 2014, Leihy et al., 2020). Overall, the protection of Antarctic ES services will rely upon achieving a sustainable equilibrium between costs and the benefits of utilization (including externalities).

Estimates of the intrinsic and/or economic value of ES remain difficult to undertake and address (but see Table S2). However, payment for ES has been discussed with regard to tourism (Lee and Hughes, 2010; Netherlands and New Zealand, 2019). The contribution of Antarctica to the regulatory services of the Earth system is widely known, but detailed valuations remain to be conducted. Nonetheless, there is a growing consideration of the economic and societal value from Antarctica's blue carbon from benthic ecosystems, estimated to be around 1–2 billion US\$ (Bax et al., 2021). This recent study reinforces the idea that it may become much more economically important for global societies to preserve the integrity of the seafloor in the long term against the immediate benefits from intensive resource extraction.

In terrestrial systems cultural activities have notable market too. The economic size of the tourist industry has not been officially reported, but it could exceed US\$ 500 million per year if the cost of a typical visit and the numbers of tourist visiting in recent years are taken into consideration. Prices for traditional seaborne cruises are often above US\$8,000, although there is a wide range of prices, depending upon the company, time of the season, length of the cruise, amenities on the vessel, location and size of the cabin selected, availability/use of helicopter trips and other factors. However, as noted earlier, future short to medium-term trends have become highly uncertain due to the potential impacts of the COVID-19 pandemic.

Lastly, new resources resulting from biological prospecting research and the so-called 'blue biotechnologies' are considered an emerging economic sector that remains to be fully regulated under the ATS. In the short term, economic impacts have to be considered in terms of research activities and the commercial enterprises involved. In the medium to long term, commercialization of Antarctic bioactive products could generate economic impacts in the fields of anti-cancer drugs, compounds to counter neurodegenerative diseases, antimicrobial agents, antiviral drugs, antifungal agents, antiparasitic drugs, enzymes (protease inhibitors, etc.), antioxidants (skin protection) and chemicals with many

other potential applications. In order to obtain benefits from natural products, while still conserving biodiversity by keeping sampling/harvesting to an absolute minimum, it is crucial to be able to synthesize the bioactive compounds in the laboratory. Further work by the Antarctic Treaty Consultative Meeting may help to identify and develop necessary measures to regulate such activities in Antarctica.

5. Conclusions

Antarctic Ecosystem Services are rich and diverse, covering a broad range of categories. The Antarctic cryosphere and atmospheric circulation are vital for global climate regulation. Marine ecosystems have high primary productivity, with a rich biodiversity providing a broad source of potential bioprospecting materials, while also sustaining a large biomass of fish stocks which are currently exploited within regulated catch limits. Marine and terrestrial ecosystems support a wide variety of cultural services that have developed following earlier (and on-going) exploration, diplomacy and conservation. Antarctic ES are diversifying and being increasingly utilised, with global awareness of their importance increasing in both public and governance fora. However, these trends impose growing challenges for safeguarding their sustainable use in the longer term. An expanding body of scientific literature exists that records the increase in human impacts within Antarctica, while policymakers have discussed protection of Antarctica through the ATS for many years. However, to date, the ES provided by Antarctica have not been adequately considered or described in a manner (1) that allows them to be considered in comparison with ES provide in other regions globally, or (2) that reveals their crucial role in supporting the continued operation of human societies across the planet. The Ecosystem Services Assessment framework provides additional tools and opportunities to identify and manage Antarctic Ecosystem Services, which may help safeguard the continent, to the benefit of humankind, both now and into the future.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecoser.2021.101299>.

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