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Review Article

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Governance challenges to protect globally important ecosystem services of the Antarctic and Southern Ocean

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Abstract

Antarctica and the Southern Ocean (A&SO) has a unique environment that plays an important role in the Earth's life-support systems. It has no indigenous human population but hosts around 5000 researchers and is visited by more than 100 000 tourists per year. In this paper, we describe the biophysical processes that create the region's ecosystem services, outlining their related governance systems within the Antarctic Treaty System (ATS), and show the global distribution of the ecosystem service beneficiaries. These services clearly support populations across the world but are endangered by anthropogenic activities, which the current place-based ATS is not empowered to control. We discuss whether it is possible to use insights from Elinor Ostrom's work on managing the commons, including her eight core design principles and the idea of Common Asset Trusts, to better harness efforts to protect ALL of the region's ecosystem services. We note that many existing arrangements associated with the ATS are already well-aligned with Ostrom's design principles but need to be expanded to better protect the globally important ecosystem services produced by A&SO.

Keywords: Antarctic governance; anthropogenic climate change; climate regulation; common asset trusts

Introduction

Despite the fact that the resources of the Antarctic and Southern Ocean (A&SO) have been exploited since the mid-1600s (Trathan and Reid 2009), the region remains remote and relatively pristine. It provides numerous ecosystem services (ES) to the planet, including climate control, scientific research, fisheries, tourism, aesthetics, and other critically important cultural values (Grant et al. 2013, Cavanagh et al. 2016, Deininger et al. 2016, Chown and Brooks 2019, Pertierra and Hughes 2019, Gogarty et al. 2020, Bax et al. 2021, Cavanagh et al. 2021, Pertierra et al. 2021, Steiner et al. 2021, Dietz and Koninx 2022). The collective value of these ES has been conservatively estimated at more than USD 180 billion per annum (Stoeckl et al. 2024)—a critical concern being that anthropogenic activities occurring elsewhere in the world are impacting the physical, chemical, and biological processes that create and sustain these globally significant services. The Southern Ocean is becoming warmer (Gille 2002, Swart et al. 2018, Meredith et al. 2019, Auger et al. 2021) and acidified (McNeil and Matear 2008, Pachauri et al. 2014, Pörtner et al. 2019). The Antarctic Ice Sheet and sea ice are melting, with the sea-ice coverage for 2023 the lowest on record (Siegert et al. 2023). Habitats for marine and terrestrial biodiversity are shrinking (Constable et al. 2014, Lee et al. 2017, Convey and Peck 2019), and across the globe the frequency and magnitude of extreme events (e.g. storms, heat waves) are on the rise (Meucci et al. 2020, Masson-Delmotte et al. 2021, González-Herrero et al. 2022).

A substantial body of literature considers issues relevant to the governance of the Antarctic region and the governance framework that sits under the Antarctic Treaty System (ATS) (Hemmings 2012, Dodds et al. 2017, Dodds 2019, Haward and Jackson 2023, Mancilla and Jabour 2023), which was originally signed in 1959 by 12 states and which has now grown to 57 states, 29 of which have decision-making rights. Attention has been paid to the formal and informal institutional arrangements that govern activities impacting some of the region's critically important ES, including the role of the Scientific Committee on Antarctic Research (SCAR; Bastmeijer and van Hendel 2009); the role of Marine Protected Areas (MPAs) and Protected Area Planning (Bastmeijer and van Hendel 2009, Sylvester and Brooks 2020, Boothroyd et al. 2023); the robustness of self-regulatory arrangements in the tourism sector (Haase et al. 2009); and the management of the krill, toothfish, and other fisheries through the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) in relation to other ES (Constable et al. 2000, Constable 2011, Grant et al. 2013).

Whilst existing governance arrangements address current challenges with varying degrees of success (Rothwell 2021), they were not designed with any consideration of how actions outside the region might impact Antarctica's environmental values and the services it provides to the planet. Nor would it be appropriate for the reach of the Antarctic Treaty to extend further north than its current boundary. Nonetheless, this exposes a fundamental problem for the Antarctic Treaty Consultative Parties (ATCP) (Stephens 2019, Roberts 2023). Notwithstanding their adoption of additional instruments to accommodate emerging environmental and resource pressures (1972 CCAS, 1981 CCAMLR 1991 Madrid Protocol), human activities that contribute to global warming are threatening the very place that ATCP seek to protect. At least part of the problem relates to the fact that the characteristics of ES provided by the region make them inherently difficult to govern and protect.

This paper focuses on key ES of Antarctica and the Southern Oceans. It is structured as follows. First, we describe our overall approach (section 'Approach'). We then provide background on the current ATS (section 'Governance of A&SO'). In the 'Ecosystem services of A&SO' section, we briefly outline the current state, risks and threats, and governance arrangements of key ES. These include: a suite of inter-related regulating and maintenance services that contribute to the global ocean conveyor belt so critical to nutrient cycles whilst also helping to regulate climate and sea level; commercial fishing (an example of a provisioning service); tourism (a type of cultural service); and science/research (another cultural service). In the 'Beneficiaries of A&SO Ecosystem services' section, we use maps to show the global distribution of the ecosystem service beneficiaries, and in the 'Governance for the future' section, we highlight vulnerabilities in current governance arrangements, discussing whether it is possible to use insights from Elinor Ostrom's work on managing the commons, including her eight core design principles and the idea of Common Asset Trusts (CATs), to better protect some of the region's most 'valuable' ES.

Approach

This paper is an outcome from a 6-day face-to-face workshop, involving 19 experts from across diverse disciplines, that was held in Hobart, Tasmania, Australia, in May 2023. The first day comprised a series of 'Antarctic and Southern Ocean' presentations that provided an overview of core ecological, chemical, physical, social, and economic issues relevant to the region's ES. Ideas on how to synthesize these diverse insights towards a cohesive end to generate information that could support managers/governance were adaptively developed during the remaining 5 days of the workshop. These 5 days involved plenary discussions (at the beginning and end of each day where ideas were shared and blended) and 'working groups' (with each focused on a particular subset of issues). By the end of the workshop, a rough outline of this paper had been drafted, and groups of authors were allocated the task of contributing material (references and text) for different sections. Post-workshop, the working groups undertook targeted literature reviews and drafted text, with the final paper developing through an iterative process that involved synthesizing and linking contributions from each group.

The literature discussed in this paper was identified by first compiling references from the authors' own multidisciplinary expertise (mostly compiled during the workshop) and by following up references and citations from related reviews, particularly those that had discussed ES in the region (Grant et al. 2013, Deininger et al. 2016, Pertierra and Hughes 2019, Pertierra et al. 2021, Solomonsz et al. 2021, Steiner et al. 2021). Between June and December 2023, the working parties also undertook additional targeted searches on key themes identified during the workshop, using Google Scholar, Scopus and the Web of Science.

Governance of A&SO

Antarctica has been described as a 'global commons' (Kennicutt et al. 2019, Brooks et al. 2020) alongside the high seas, the atmosphere, and outer space, but its status is in fact unique under international law. The region is governed by the Antarctic Treaty, which was originally signed in 1959 by 12 states. This number has now grown to 57 states, with 29 of these having decision-making rights. The continent is still subject to seven historical sovereignty claims, which were placed in abeyance under the Antarctic Treaty (Art IV) yet remain a point of underlying tension. This has led to perceptions of Antarctica being managed by a 'club' dominated by Western States (Haward and Jackson 2023)—a view which, when aired during ongoing UN General Assembly debates (1982–2000), raised legitimate questions about the operation of the ATS. Such challenges have been largely resolved with an increasingly diverse membership to the ATS—although the (original) claimant states still dominate discussion (Dudeney and Walton 2012), and critics have highlighted inequities associated with the two-tier system (Mancilla 2019).

The focus on core ideas of peace and science has seen the Treaty endure and adapt to evolving geopolitical circumstances. The Treaty arose as a Cold War solution to disputes over claims and ongoing security concerns—essentially a peace treaty that enshrined scientific research as the 'currency of credibility' in the continent's governance (Kaye et al. 2011). Since that time, the addition of further instruments—including the Convention on the Conservation of Antarctic Seals (CCAS, 1972), the Convention on the Conservation of Antarctic Marine Living Resources (CAMLR Convention, 1980), and the Protocol on Environmental Protection to the Antarctic Treaty (Madrid Protocol, 1991)—has expanded the ATS so that this place-based governance system elevates environmental protection alongside the recognition of the freedom of scientific research. While there are no end dates to the instruments, there are review provisions, as is common in international law. Further annexes to the Madrid Protocol have addressed specific issues such as waste disposal and marine pollution as they have arisen.

While many commentators have emphasized the stability and resilience of the ATS to accommodate emerging geo-political changes during its 60-plus years of operation (Haward and Jackson 2023), questions have properly been asked whether a Treaty formed in 1959 can continue to adapt and respond to current challenges (Rothwell 2021). Commentators (Hemmings 2017, Rothwell 2021) have outlined these challenges, which include: tensions and impasses within CCAMLR decision making, especially around MPAs, raising issues around the efficacy of the consensus-based process; long delays in ratification of particular measures and annexes; ambiguity around so-called 'grey zone' activities in which military and scientific uses blur; the impact of climate change; the increased heterogeneity of parties since 1959, amid a changing international order in which China is taking a more influential role; and growing disharmony among the consultative parties. The 44th ATCM (2022) in Berlin saw an unprecedented walk-out of many parties in protest over Russia's invasion of Ukraine; this also occurred during the 2022 CCALMR meeting.

Rothwell (2021, p. 356) concludes that 'while the Antarctic Treaty System has enjoyed enormous success, the global international order is currently experiencing a backlash against some aspects of international law and institutions which is partly driven by a concern from some states that certain global institutions and mechanisms are no longer appropriate and are in need of reform, modification or even alternate frameworks. It would therefore be inappropriate to become complacent about the Antarctic Treaty System and the challenges that it faces. It is within this context that we consider another challenge for Antarctic governance—that of safeguarding ALL of the region's valuable ES.

ES of A&SO

Several recent publications highlight the importance of and discuss issues relevant to the region's ES (Grant et al. 2013, Deininger et al. 2016, Pertierra and Hughes 2019, Pertierra et al. 2021, Solomonsz et al. 2021, Steiner et al. 2021). A key subset of those services has been conservatively estimated to provide at least USD 180 billion per annum (Stoeckl et al. 2024), and it is on that subset of services that our discussion focuses: a suite of interrelated regulating and maintenance services; commercial fishing, tourism, and science.

Regulating and maintenance services

Overview

The A&SO regulate the Earth's climate through multiple processes, some of them being interlinked (ocean ventilation, heat and carbon storage, albedo, and sea level regulation). The Southern Ocean plays a crucial role in the climate system via ocean ventilation, where upwelling and mixing of different water bodies around A&SO provides a significant window for the atmosphere-deep ocean exchange (Williams et al. 2023). As the main reservoir of global carbon dioxide (CO_2) is in the deep ocean and the principal connection of that reservoir with the surface and atmosphere is in the Southern Ocean, the area has a direct influence on the climate system via its physics, chemistry, and biological processes (Watson et al. 2014). These dynamic processes see anthropogenic carbon and heat sequestered from the atmosphere and redistributed over the global oceans via large-scale flows involving the Antarctic Circumpolar Current (ACC), neighbouring subtropical gyre circulations, and vertical overturning circulation (Morrison et al. 2015). As the largest ocean current on the planet, the ACC is one of the dominant features of the Southern Ocean. By connecting the Atlantic, Pacific, and Indian Oceans' basins, the ACC allows the redistribution of heat, freshwater, carbon, and nutrients around the globe—see Fig. 1. The seasonal formation of sea ice around Antarctica initiates the transport of Antarctic bottom water, a cold and dense water mass that sinks to depth. This process, which takes place in four main regions along the Antarctic coast, is key for the global ocean circulation (Talley 2011, Ohshima et al. 2013). These large currents directly affect marine ecosystems, cloud formation, and regional weather patterns, as well as our global climate.

These interconnected processes collectively provide a suite of interconnected regulating services, which, using the Common International Classification of Ecosystem Services (CICES) version 5.2 include regulation of the chemical condition of salt waters by living processes (2.3.5.2); regulation of chemical composition of atmosphere and oceans (2.3.6.1); maintenance and regulation by inorganic and natural chemical and physical processes of fresh or salt waters (5.2.2.1) and atmosphere (5.2.2.2); maintaining or regulating nursery populations and habitats or breeding grounds (2.3.2.3); maintaining or regulating refuge habitats (2.3.2.4); and maintaining or regulating feeding grounds (2.3.2.5). The economic value of these interrelated services has been estimated at approximately USD 179 billion per annum (Stoeckl et al. 2024), with some specific contributions described briefly below.

- The Southern Ocean is the largest oceanic sink of atmospheric CO_2 and is currently responsible for 40% of anthropogenic CO_2 uptake (Terhaar et al. 2021). This carbon sink, ranging between 0.1 and 2.5 Pg C yr^{-1}, is due to both the dissolution of CO_2 in seawater and phytoplankton growth. There is high variability in the carbon sink as it results from spatially and temporally varying processes, with outgassing from carbon-rich waters upwelled water on the southward side of the ACC and atmospheric CO_2 drawn down by subduction of waters to the north of the ACC (Williams et al. 2023). The amount sequestered in this way varies due to the strength and form of the interaction of surface circulation and the winter mixed layer, leading to localized regions of enhanced subduction (Williams et al. 2023). Other climate active gases are also regulated by the Southern Ocean, such as methane (CH_4) and nitrous oxide (N_2O) or dimethyl sulfide (DMS, a cooling gas). Like CO_2, the Southern Ocean acts as a sink for CH_4 and N_2O, therefore mitigating their greenhouse effect.
- The global oceans absorb 90% of the excess heat produced on Earth by greenhouse gas emissions, acting to regulate the excess heat from rising global temperatures (Von Schuckmann et al. 2020, Huguenin et al. 2022). The Southern Ocean is responsible for 35%–43% of this heat uptake (over the top 2000 m) (Frölicher et al. 2015, Shi et al. 2018). The Southern Ocean also emits DMS produced by phytoplankton which, when released into the atmosphere, leads to cloud formation and cools the climate.

Figure 1. Map of Ocean Currents and Gyres that connect Antarctica and adjacent Southern Ocean to Global Populations with Antarctic Treaty Boundary. By connecting the Atlantic, Pacific, and Indian Ocean basins, the ACC allows the redistribution of heat, freshwater, carbon, and nutrients around the globe. Data sources: Ocean currents: ArcGIS.com, 2016, Major Ocean Currents; Antarctic Treaty Area Boundary: Esri 2014 World Latitude and Longitude Grids.

- The 'whiteness' of Antarctica's ice sheet (Albedo) and sea ice to this point has acted to help buffer heating as it reflects a significant amount of sunlight back into space. This protects the planet from further warming (see, e.g. Perkins 2019).
- The Antarctic Ice Sheet holds 80% of the world's ice, with ice continuously accumulating on top of the Antarctic continent and ice melting along the coast. The East Antarctic Ice Sheet holds 52 m of potential sea level rise,

compared with 3–4 m in the West Antarctic Ice Sheet (Fretwell et al. 2013).

- Through the formation of Antarctic bottom water along the Antarctic coast, the Southern Ocean is a major contributor to the global ocean conveyor belt, a process by which large currents mix the ocean from top to bottom and transport nutrients from one region to another. This conveyor means the A&SO has an underappreciated role in the global ocean's nutrient cycles. Approximately 50% of all oxygen comes from phytoplankton, and ∼25% of global marine primary production is in the Southern Ocean (Fisher et al. 2023). A considerable proportion of the oxygen produced in marine systems is used by marine life so more specific attribution of the size of this ecosystem service is challenging. However, ocean model experiments suggest that the supply of nutrients from the Southern Ocean accounts for about three quarters of biological production north of 30°S (Sarmiento et al. 2004) with many fisheries relying on Antarctic nutrients (Solodoch et al. 2022).
- These nutrients are estimated to support from 20% to 75% of global fisheries (Moore et al. 2018). At the lower 20% level, this generates net benefits of ∼2.31 billion USD per annum (Stoeckl et al. 2024).
- The area offers a refuge and feeding ground for a diverse and abundant marine life, ranging in size from microscopic algae to the largest animals on the planet, e.g. the Antarctic blue whale. The Southern Ocean also provides important feeding grounds for migratory species such as whales, including the Humpback whales (*Megaptera novaeangliae*) (Riekkola et al. 2018, 2019), which travel to breeding areas in South America, southern Africa, Australia, New Zealand, and the Pacific; on both feeding and breeding grounds they are an important resource for tourism (Orams 2002). The same can be said for southern right whales (*Eubalaena australis*).

Trends/risks

Anthropocentric activities undertaken outside the A&SO are impacting processes and may reduce the ability of the region to continue to provide those globally important regulating and maintenance services, with much evidence of recent change. For example, the transfer of CO_2 from the atmosphere into the Southern Ocean has strengthened in recent years (Landschützer et al. 2015, DeVries et al. 2017), although large uncertainties remain on the capacity of the Southern Ocean to absorb (or emit) climate active gases in the future (Willis et al. 2023). It is also possible that entirely new processes will emerge as the ocean responds to climate change and/or to changes in emissions. For example, in a study designed to consider long-term ocean carbon storage, some model simulations predict unanticipated large scale carbon releases, even up to 50 years after stabilizing emissions (a carbon 'burp') (Oschlies 2021).

The contribution that the Southern Ocean makes to heat uptake has also changed—strengthening in recent years (Talley 2011, Huguenin et al. 2022). This is due to the unique geographic properties of the Southern Ocean, as strong westerly winds blow uninterrupted by land masses, pushing cold surface water northward while absorbing vast amounts of heat before sinking to depths at about 45°S.

While the state of the East Antarctic Ice Sheet is ambiguous, the West Antarctic Ice Sheet has been melting quicker than new snow can replace it since the 1990s, contributing to global-mean sea-level rise (Otosaka et al. 2022). As land ice melts, the Antarctic continent rebounds [by around 4.1 cm per year; Barletta et al. (2018)] and local sea levels fall while in contrast, other parts of the globe experience significant increases in sea level, often above the global mean (Fox-Kemper et al. 2021). This geographic variation in land motion and relative sea levels occurs immediately as an 'elastic' process, with an additional delayed 'viscous' response of the mantle playing out over decades to millennia. A continued shrinking of the Antarctic Ice Sheet will thus have severe ramifications for the sea levels globally and therefore for coastal populations, infrastructures, and wetlands (Glavoic et al. 2022). Changes to the region's albedo, either through the loss of ice and snow and/or pollution of their surface with dust or soot, have large regional and global implications by accelerating ocean warming and ice melt even further.

In addition, Antarctic bottom water is becoming fresher, warmer, and less dense in some regions (Rintoul 2007, Jacobs and Giulivi 2010, Purkey and Johnson 2012, van Wijk and Rintoul 2014, Menezes et al. 2017, Aoki et al. 2020, Silvano et al. 2020) slowing down the global conveyor belt (Li et al. 2023 and references therein) and possibly reducing the pace and magnitude of nutrient transport elsewhere on the planet. Observations have suggested that Antarctic bottom water production has recently slowed by 30% in two of the four basins (Gunn et al. 2023, Zhou et al. 2023), with further slowdown possible in coming decades (Li et al. 2023). Models considering the consequences of forecast changes in Southern Ocean nutrient export indicate that the projected potential 25% drop in global primary production would lead to a 20%–60% drop in fisheries production, depending on the region. This occurs even as local production within the Southern Ocean is projected to increase (Leung et al. 2015, Fu et al. 2016, Moore et al. 2018, Ryan-Keogh et al. 2023) through a loss of sea ice, a temperature-mediated increase in phytoplankton productivity and nutrient trapping.

Notably, the waters west of the Antarctic Peninsula have also seen large changes in sea-ice extent and associated ecosystems. Phytoplankton growth has decreased by 12% overall between 1978 and 2006 in this region (Montes-Hugo et al. 2009). Climate driven habitat change is also impacting species higher in the food web (Bestley et al. 2020). Significant reductions in Antarctic krill biomass could generate 'knock-on' impacts in other sectors—e.g. krill-dependent predators, such as penguins, seals, and whales may be displaced or even decline in numbers (Melbourne-Thomas 2020), with consequent economic decline for industries and destinations that rely on these iconic species for tourism (Paterson et al. 2015).

Governance

As evidenced in the Helsinki Declaration, the ATCPs have expressed deep concern about the potentially devastating impacts from Antarctic ice-sheet loss that could be irreversible. They have further recognized the critical role of the A&SO in the global climatic system and recognize the objectives and principles of the United Nations Framework. They recognize associated efforts to tackle climate change, support global efforts to reduce carbon footprints, and strongly encourage those who operate within the A&SOs (e.g. Antarctic tour operators, researchers, and fishers) to identify ways of working towards 'net zero'. That said, the ATS does not have the remit to directly control activities undertaken outside the Treaty area (the boundary of which is shown in Fig. 1), even when those activities are impacting the A&SO.

Commercial fisheries

Overview

The Antarctic toothfish (*Dissostichus mawsoni*), the Patagonian toothfish (*Dissostichus eleginoides*), and krill (*Euphausia superba*) are caught in these waters and used in a variety of different ways. Antarctic toothfish are highly prized by high-end restaurants, sometimes referred to as 'white gold'; krill are prized as high-value pharmaceuticals (krill oil tablets are mainly used for omega-3) and as food supplements improving the [perceived] quality of farmed salmon (the astaxanthin from krill is used to ensure pink flesh and improve the health of fish) (Stachowiak and Szulc 2021). The economic value (formally *net benefits)* of Antarctic commercial fisheries (toothfish and krill), a type of provisioning service [codes (1.1.6.1 and 1.1.6.2 under CICES 5.2)] has been estimated at approximately USD 370 million per annum (Stoeckl et al. 2024).

Trends/risks

Toothfish and krill populations appear relatively stable and are conservatively fished, but the fisheries operate in an integrated and complex environment: changes in one part of the system, even small, may have significant impacts elsewhere. There is some evidence that krill densities have decreased and contracted southward in parts of the Atlantic sector, towards the colder waters of the Antarctic Peninsula (Atkinson et al. 2019), although this is contested (Cox et al. 2019, Candy 2021). Models project a marked decline in krill population biomass under all climate scenarios by 2100, independent of fishing pressure (Testa et al. 2022).

Future populations are likely to become increasingly uncertain. Some of this uncertainty is associated with the recovery of Antarctic fur seals (Forcada et al. 2023) and humpback whales (Zerbini et al. 2019, Jackson et al. 2024), which may alter ocean productivity and impact other species (e.g. chinstrap, Adélie, and macaroni penguins); these uncertainties interact with and thus exacerbate uncertainty about the impacts of climate change (Trathan 2023a).

Major upheavals in the region's physical systems mean that even under what appears to be conservative management, the stocks may be subject to undesirable levels of cumulative pressure. Should the fisheries fail, there would clearly be a direct financial impact on those fisheries and a somewhat less direct impact on the purchasers/consumers of those fish—with losses in associated ES (Stoeckl et al. 2024). Notably, if krill stocks were to fail or become markedly depleted, there could also be 'knock on' impacts in other fisheries or ecosystems outside the Southern Ocean, as a result of effort-shift and/or a pivot to source the same biological compounds from another source (Atkinson et al. 2004, Testa et al. 2022).

Governance

The toothfish and krill fisheries are managed in a precautionary, ecosystem-based manner under CCAMLR. Fishing areas and seasons are set by agreement, and a total allowable catch is set for each season by area. There are also strict measures in place to manage bycatch, particularly for species of conservation concern (Kock et al. 2007), as well as vessel monitoring systems, a catch documentation scheme and procedures for reporting catch and effort. Ongoing management challenges for CCAMLR include restoring populations of seals and whales that are still recovering from the legacy of overexploitation (Grant et al. 2021), and the management of targeted species, whose stocks may relocate in response to climate and other changes. This could require CCAMLR to engage more frequently with other Regional Fishery Management Organizations.

The toothfish fishery management has been criticized in some circles, and CCAMLR harvest control rules are being challenged (Trathan 2023a). The Antarctic krill fishery is currently operating well under the catch limit set by CCAMLR [about two-thirds of the CCAMLR catch quota (Cappell et al. 2022)]. The current precautionary catch limit for krill is based on an acoustic survey undertaken in 2000; newly proposed catch limits have been questioned, given marked uncertainties around climate, current stocks, future ecosystem states, and the absence of appropriate systems for monitoring biomass (Trathan 2023b).

Tourism

Overview

Antarctic tourism is a type of cultural service, with the latter formally described in CICES V5.2 as comprising: elements of living and geophysical systems that enable activities promoting health, recuperation, or enjoyment through active or immersive interactions (3.1.1.1, 6.1.1.1) passive or observational interactions (3.1.1.2, 6.1.1.2) that are resonant in terms of culture or heritage (3.2.1.3, 6.2.1.3) or that enable aesthetic experiences (3.2.1.4, 6.2.1.4). The economic value (formally *net benefits)* of Antarctic tourism has been estimated at approximately USD 820 million per annum (Stoeckl et al. 2024).

The International Association of Antarctic Tour Operators (IAATO) provides data on tourism in this region, used here to describe recent tourism in this region (International Association of Antarctic Tour Operators 2023). More than 104 000 tourists travelled to A&SO during 2022–2023 (International Association of Antarctic Tour Operators 2023). Shipborne tourism predominates, with 98% of tourism voyages visiting the Antarctic Peninsula; a small fraction of tourist visits are to the Ross Sea region south of New Zealand, or the interior of the continent. Just under a third of visitors travelled on large (>500 passenger) cruise ships, which are prohibited from landing (on the continent or nearby islands) under IAATO bylaws. The remaining tourists travelled on smaller vessels which are permitted to land at certain sites and ferry passengers to these sites in small inflatable boats/tenders. There are currently 50 tourism operators (with 60 vessels) that travel to A&SO. These operators are mostly based in Europe, North America, and Australia. Between 2014 and 2022, the US, China, Australia, the UK, and Germany have been the key sources of passengers, although since the COVID-19 pandemic Chinese passenger numbers have fallen dramatically. The A&SO offers incredible experiences for tourists, including unique beauty, photo opportunities (e.g. of scenery and wildlife), and experiential interactions (e.g. polar plunge, kayaking, and camping).

Trips are often promoted as 'expeditions', tapping into the sense of adventure (encountering harsh conditions), fulfiling dreams (bucket list tourism), producing a sense of achievement (e.g. passengers visiting their seventh continent), providing an opportunity for social bonding, and providing the chance to learn about wildlife and the environment (Picard and Zuev 2014, Vila et al. 2016, Cajiao et al. 2022).

Trends/risks

Antarctic tourism numbers have been increasing for several decades, from just under 8000 in 1993–1994. Since 2013, the number of tourist operators has increased from 39 to 50, and the number of tourism vessels operating in the region has risen from 45 to 60 (International Association of Antarctic Tour Operators 2023). As a trade association, the International Association of Antarctica Tour Operators cannot seek to regulate the number of operators or visitors to Antarctica. The ATS has recently indicated an interest in addressing the growth of the industry as part of the development of a systematic framework for managing and regulating tourism and other non-governmental activities (Antarctic Treaty Secretariat 2024).

The activities undertaken by tourists have diversified over time, with high-octane alternatives on offer including scuba-diving, submersibles, and heli-skiing (International Association of Antarctic Tour Operators 2023). Like the growth in tourist numbers, diversification of activity has been a source of concern (Cordero et al. 2022, Clemence 2023, Liggett et al. 2023). Central to this concern is the environmental impact of the Antarctic tourism industry.

Antarctic vessels produce a significant carbon footprint: Researchers have estimated that the average Antarctic tourist voyage produces more carbon per capita than the average world citizen in a whole year (Farreny et al. 2011). Some operators apply carbon offsets, and others have introduced hybrid ships. Other impacts include the potential for wildlife disturbance, injury or death, the risk of introducing invasive species or disease (from shoes and clothing or ship discharges), landscape disturbance, and pollution (Tejedo et al. 2022, Liggett et al. 2023). Socio-cultural impacts include disruption to research and the disturbance of historic sites, as well as (more positively) pro-environmental behaviours, increased environmental awareness, and support for researchers (Liggett et al. 2023).

Governance

Tourism ship operators based in states that are party to the Antarctic Treaty must apply for a permit from their National Competent Authority. In the absence of ATS measures, environmental protections have been agreed via an industry body, the International Association of Antarctica Tour Operators (IAATO), which has a clearly articulated set of bylaws, that seek to ensure *safe and environmentally responsible travel to the Antarctic.* (The complete set of by-laws can be accessed and downloaded from https://iaato.org/.) In 2024, all SOLAS passenger vessels undertaking commercial tourism operations in the region were members of IAATO (IAATO 2024). Some yachts that are not part of this association also travel to the region each year, but the number of yacht-based visitors is small relative to cruise visitors. Recently, members of IAATO pledged to voluntarily reduce emissions (compared with 2008) by 50% by 2050 (somewhat short of the Net Zero target called for in Trathan 2023a.), an ambition that requires them to submit fuel usage data from 2023 (International Association of Antarctic Tour Operators 2022).

The fact that at present, neither IAATO nor the ATS have authority to control or limit the number of visitors who can travel to A&SO is concerning given the variety of ways in which visitors can impact specific sites. What the precise tourism carrying capacity of the continent, or of sites frequented by visitors is, however, unknown. In May 2024, the ATCP did agree to 'develop a comprehensive and consistent framework for the regulation of Antarctic tourism and other non-governmental activities' with a Working Group to guide the discussions (Antarctic Treaty Secretariat 2024).

Science and research

Overview

Science and research are recognized as a type of cultural service, described in V5.2 of the CICES as: Elements of living and geophysical systems that enable scientific investigation (3.2.1.1, 6.2.1.1) education and training (3.2.1.3, 6.2.1.2)—and this service is core in A&SO. There are 82 scientific research stations in Antarctica, operated by 30 nations with over 5000 researchers (Council of Managers of National Antarctic Programs 2017, Hughes et al. 2018, Leihy et al. 2020). More than one-half of the stations operate year-round (Hughes et al. 2018), with the USA, Argentina, Russia, Chile, the UK, and Australia supporting the largest populations of researchers (Elzinga et al. 2017).

The financial expenditures associated with the research provide a financial stimulus to the home ports and cities from which operations are based. Antarctic fishers and tourism operators also provide significant in-kind support to research, e.g. contributing to observer programs, collecting and sharing data, and providing free berths (Taylor et al. 2020, Cappell et al. 2022, Otosaka et al. 2022, Orheim et al. 2023). Enhanced international coordination and advances in autonomous platforms have also resulted in progress towards sustained observations of the region. Between 2009 and 2019, the Southern Ocean community deployed over 5700 observational platforms south of 40°S (Newman et al. 2019). However, investment and expenditure may not be good indicators of value: It is possible to spend money on research that has little impact, and some research that costs little may generate significant global benefit. We are not aware of any research that has estimated the true economic 'value' of Antarctic science, but the insights generated from Antarctic research are globally significant (Table 1).

Other indicators also help to shed light on value (Fioramonti 2014). We undertook some additional rudimentary analysis of research undertaken in Antarctica and in several other 'iconic' and environmentally sensitive places (the Arctic, the Great Barrier Reef, and Galapagos), finding that Antarctic research is some of the most cited research globally (Appendix A). To the extent that higher citations suggest higher impact, this highlights the critical and impactful importance of research undertaken in the region.

Trends/risks

It has been acknowledged that research stations and researchers working in the field can damage these fragile ecosystems (Pertierra et al. 2013, Cordero et al. 2022). Brooks et al. (2019) argue that research stations—those being constructed, those in operation, and those that are abandoned—cause 'the

Table 1. A non-exhaustive selection of globally relevant insights generated by A&SO research.

- Antarctic research discovered the Antarctic Ozone Hole (first detected from data collected at Halley Bay station in 1981–1983 and subsequently confirmed via satellite measurements), and linked its presence conclusively to chlorofluorocarbon emissions, leading to the Montreal Protocol on Substances that Deplete the Ozone Layer (Farman et al. 1985).
- Antarctic ice cores have revealed that there have been major fluctuations in the Earth's climate over the last 800k years, with evidence that Australia experienced a multi-decadal scale drought during the last 2000 years (Udy et al. 2022, Thomas et al. 2023).
- Antarctic research has improved our understanding of biological adaptation to extreme environments—e.g. polar gigantism (massive polar marine invertebrates) and antifreeze in icefish blood. Physiological and genetic studies of these extreme and unusual features have been an important contribution to broader understanding of how species are adapted to extreme environments globally (and what this means for climate change vulnerability etc).
- The Census of Antarctic Marine Life (a large-scale international collaboration) and follow-on projects have pioneered new understandings of the evolution and diversity of life and changed our understanding of levels and patterns of biodiversity in polar regions (Schiaparelli et al. 2013, Brasier et al. 2019).
- Antarctic research has improved development of technologies for ecosystem observations in remote and hard-to-access environments—e.g. ARGO, seal-mounted sensors and cameras—with applicability to remote observations in other parts of the ocean.
- CCAMLR is now widely recognized as a leading international organization in developing best practice in the ecosystem approach to managing fisheries (and arguably the first conservation-centred convention). Fisheries science underpinning the CCAMLR ecosystem approach, together with lessons learnt about impediments to implementing EBFM, have significance for broader transition to ecosystem approaches in other regions (Constable 2011).
- Monitoring sites within MPAs may be able to provide early warning systems for tipping points and provide additional insights into how climate change is influencing ice sheet dynamics, etc.
- Indigenous knowledge and science relating to A&SO ecosystems stretches back tens of thousands of years and is captured in Indigenous stories of connection (Hird 2022, van Uitregt et al. 2022, Wehi et al. 2022).

most prominent human impacts on a wide range of environmental values'. Impacts include potential introduction of species (Hughes et al. 2020), soil contamination from fuel spills (Brown et al. 2023), black carbon pollution (Cordero et al. 2022), pathogens in sewage and wastewater (Stark et al. 2016), and ecological disturbance due to infrastructure (Brooks et al. 2019). With substantive scientific research being the key criterion for a Treaty signatory to become a Consultative Party, there is a risk of proliferation of stations. Hemmings (2011) points to the very low number of facilities shared between nations as evidence that 'national autonomy' trumps cooperation between scientific programs.

Governance

The central tenet of the AT is freedom of scientific investigation (Art 1) with a commitment to sharing freely scientific observation and results (Art II). Research activities are assessed under the Madrid Protocol (like tourism activities), which provides some oversight of potential environmental impacts. Noted on the organization's website (https://scar.org/), the SCAR plays an important role in coordinating international scientific research relating to the Antarctic region (including the Southern Ocean), as well as on the role of the Antarctic region in the Earth system (Summerhayes 2008). SCAR is a thematic organization of the International Science Council and provides independent scientific advice to the Antarctic Treaty Consultative Meetings and to other organizations such as the United Nations Framework Convention on Climate Change (UNFCC) and the Intergovernmental Panel on Climate Change (IPCC) (Walton 2011). Other global programmes that play various roles in the coordination and dissemination of scientific observations, modelling, and data for the Southern Ocean region include the World Meteorological Organization, the Southern Ocean Observing System and Integrating Climate, and Ecosystem Dynamics, which is a regional program of Integrated Marine Biosphere Research.

There are arrangements and instruments in place (including via CCAMLR and the Madrid Protocol) to help manage/minimize impacts from Antarctic Research Stations (Hughes et al. 2018). The management and remediation of contamination associated with research sites and stations has presented a challenge in the past (due to cold and isolated conditions); the station on Southern Thule is an example of an abandoned station with no cleanup, and there are heavy metal toxicities at various stations left from earlier occupation. However, recent investments by nations in new remediation technologies mean that current and legacy impacts and contaminants can now be managed much more effectively (Hodgson-Johnston et al. 2017, Stark et al. 2023).

Beneficiaries of A&SO ES

Figure 2 shows the global distribution of people who benefit from A&SO ES. Panel A (top left) considers science and research, showing the total number of citations that publications that focus on Antarctica and/or the Southern Ocean have obtained by the author's country of affiliation. To the extent that affiliated countries support their Antarctic scientists because they benefit from that research, this suggests that the science and research undertaken in this part of the world benefits people throughout the world, most notably those from North America and Europe. We also note the likelihood of spillover benefits to other countries—including those without Antarctic and/or Southern Ocean science programs.

Panel B (top right) focuses on Antarctic tourism, showing both the origin of visitors to this region and the departure ports of tourism vessels that travel there. The majority of Antarctic tourists (beneficiaries of that ecosystem service) originate from North America, although people from around the world clearly benefit from the Antarctic experience. Countries that host the ships that carry these tourists (Argentina, Chile, New Zealand, and Australia) also benefit from the economic activity that is generated by the Antarctic tourism industry. South Africa also benefits from Antarctic tourism; cruise ships are not hosted here, but Antarctic flights are.

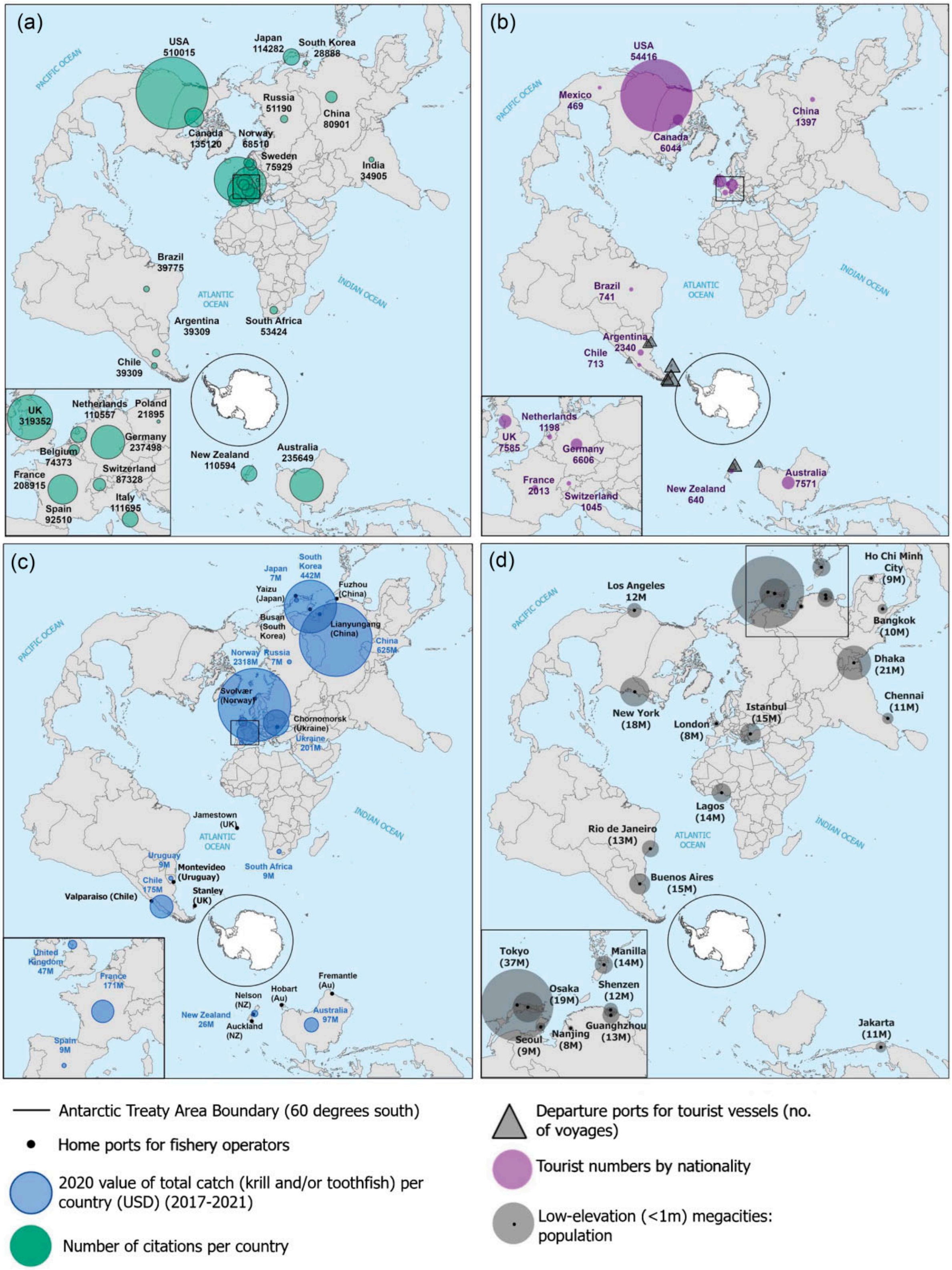

Figure 2: Map showing beneficiaries of the ES that are provided by the Antarctic and adjacent Southern Ocean. The coloured circles show the location of direct beneficiaries: the larger the circle, the larger the relative number of beneficiaries. Panel A—science and research, numbers are total Scopus citations from top 2000 articles published 2008–2003 by country of affiliation of authors (Table A2); Panel B—tourism, numbers are total visitors during the 2022–2023 season by nationality of visitor; Panel C—Antarctic krill and toothfish fisheries, numbers are estimated value of catch by country within the 5 year period 2017–2021; Panel D—low elevation megacities, numbers are populations of cities with elevations <1 m above sea level. Data sources: citations Table A2 (Appendix A); tourist numbers (Appendix B); tourist vessel numbers: McCarthy et al. (2022); combined value of total catch (Appendix C); population of low elevation megacities (Appendix D); Antarctic Treaty Area Boundary: Esri 2014 World Latitude and Longitude Grids.

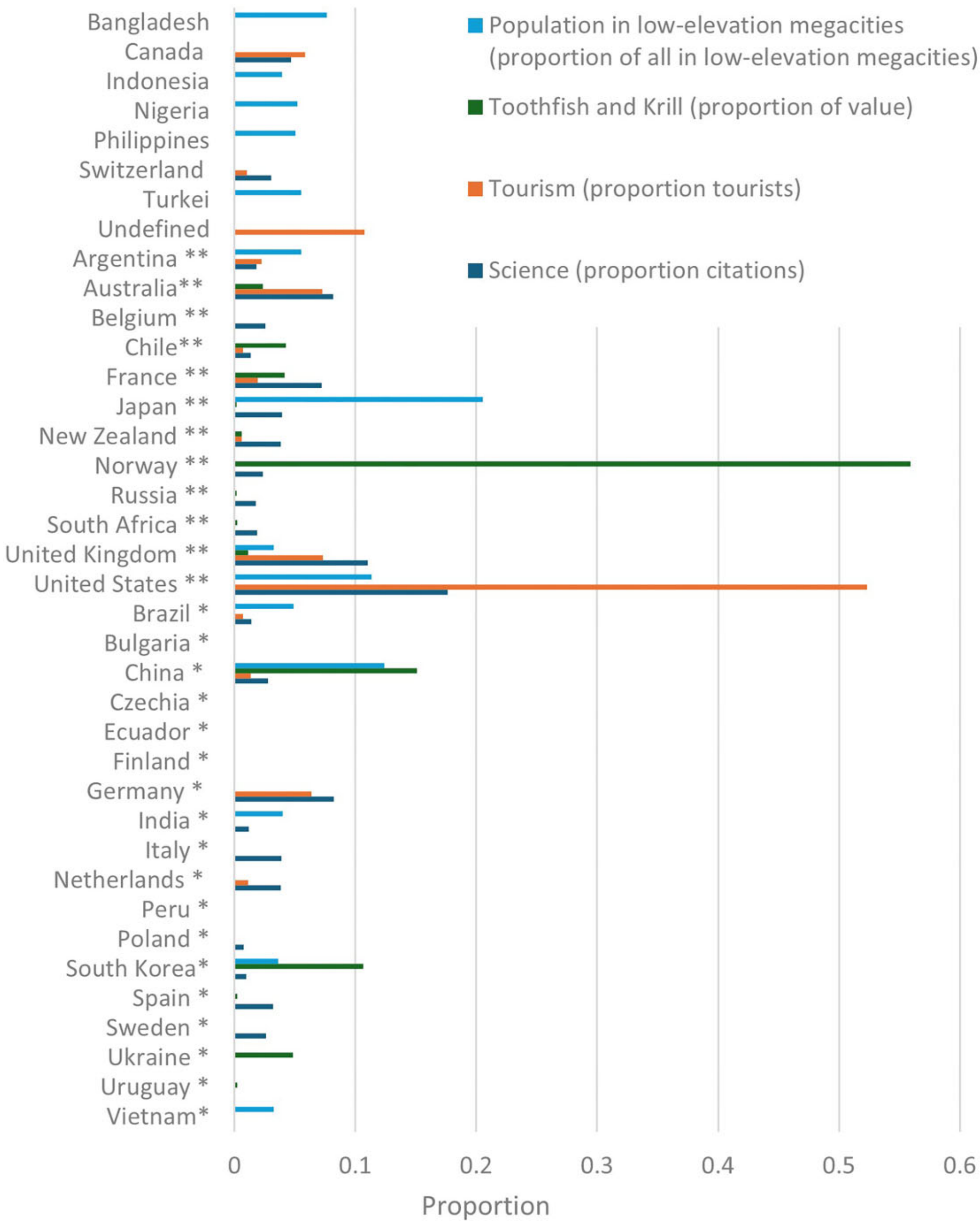

Figure 3: Individual countries that benefit from the ES that are provided by the Antarctic and adjacent Southern Ocean. * denotes Antarctic Treaty Parties; ** denotes original signatories to the Antarctic Treaty. Data sources: citations Table A2 (Appendix A); tourist numbers (Appendix B); tourist vessel numbers: McCarthy et al. (2022); combined value of total catch (Appendix C); population of low elevation megacities (Appendix D).

Panel C (bottom left) provides information about the distribution of commercial fishing beneficiaries, showing estimates of the value of fish harvested in the Southern Ocean, differentiated by the country in which Antarctic fishing vessels are registered. The largest beneficiary of these provisioning services is Norway, while other countries in Asia, Europe, South America, and Oceania also enjoy significant benefits from fisheries resources in the Southern Ocean.

Panel D, Fig. 2 shows the location and population of the world's low-elevation megacities—used here to demonstrate the global distribution of (some of the) beneficiaries of regulating and maintenance services, which, amongst other things, control climate and sea levels. People across the world benefit from the services, but it is arguably people in low-lying regions who benefit most: they are not only vulnerable to changes in climate but also to sea level rise. Evidently, it is not only those who live in the low-lying islands of the South Pacific who are vulnerable to sea-level rise and extreme (marine) events such as typhoons: more than 275 million people, across most continents inhabit low-elevation mega-cities (Appendix D), a large portion of which are in Asia.

Figure 3 shows the proportion of each broad type of benefit received by individual countries, using * to identify countries that are part of the ATS. Benefits are distributed across numerous countries although there are a few that receive disproportionately large shares of some services: Norway, e.g. receives almost one-half of the harvest value associated with toothfish and krill, and US citizens account for more than one-half of all Antarctic tourists. Most relevant to issues of governance, there are many countries that are not signatories of the Antarctic Treaty that benefit from the region's ES through commercial fishing, tourism, science, and/or regulating services that manage climate and sea level (e.g. Bangladesh, Canada, Indonesia, Nigeria, the Philippines, Switzerland, Türkiye, and Vietnam). There are also several countries that are signatories to the treaty, who do not reap significant benefits from the four ES considered here (Czechia, Ecuador, Finland, and Uruguay)—although we note there are numerous other ways those countries could be benefiting from A&SO, including through other ecosystem and non-ES. Evidently, there is a disjuncture between those who are signatory to the Antarctic treaty, and those who benefit from the region's ES.

Governance for the future

The ATS only has the remit to control or influence activities undertaken in Antarctica and (parts of) the Southern Ocean—each map in Fig. 2 has a circle at 60° south that approximately coincides with that area (noting CCAMLR has slightly different boundaries). Activities being undertaken outside these boundaries are impacting the ability of A&SO to provide ES that benefit people all over the world. The most 'valuable' of the services at risk are those that have the characteristics of 'public goods', which are inherently difficult to govern and protect (Appendix E).

A success of the ATS has been its ability to evolve over the past 60 years to include more instruments addressing living marine resources and fisheries (CCAMLR, 1980); seal conservation (CCAS, 1972); and environmental protection, including a ban on mining activities (Madrid Protocol, 1991). However, Article VI of the Treaty defines the treaty area as 'the area south of 60° latitude', while CCAMLR has defined northern borders that approximately align with the Antarctic Convergence. The place-based activities associated with fisheries, tourism, and science are matters falling within the remit of the Treaty System, human activities occurring outside the treaty area are not within its scope.

Under Article IX of the Antarctic Treaty, Parties may consider and formulate 'measures in furtherance of the principles and objectives of the Treaty', but the ATS does not seek to regulate the external actions of Parties and their citizens, nor the actions of non-parties. This jurisdictional limit is recognized in Article 3 of the Madrid Protocol. Other international instruments create obligations to reduce greenhouse emissions: The United Nations Framework Convention on Climate Change (1994), the Kyoto Protocol (2005), and the Paris Agreement (2016) have led to agreement on the need to limit temperature increases and take national action within each state's own jurisdiction. Regime interplay plays an important role here—McGee and Haward (2019, p. 78) note that, going forwards, 'the Antarctic Treaty System will likely require a new level of institutional resilience in interacting with other regimes within the Antarctic regime complex'. Nevertheless, as the Montreal Protocol (1987)—which resulted in shrinkage of the ozone hole above Antarctica—demonstrates, instruments that shape human activity outside the Antarctic region can have a big impact on the continent itself.

The ATS provides an invaluable framework that can be leveraged to help address today's challenges. However, the Treaty System does not have at its disposal legally enforceable mechanisms to protect the region from the actions taking place elsewhere in the world by parties or non-parties. A core challenge in the Anthropocene is thus to consider how to best support what has, in the past, proven to be a remarkably effective treaty system so that it can address emerging issues. Arguably, the most significant modern day threats to A&SO relate to various inter-related, *cascading*, tipping points (Kubiszewski et al. 2024) which could markedly impact all of the region's ES.

One approach is to conceptualize the governance problem not solely as that of needing to govern activities that are undertaken at a particular place (in this case, the Antarctic region) but rather of needing to govern activities that impact the region's ES. Several ideas for giving the Antarctic Treaty parties more power or more responsibility in regards to climate change have been raised. These include: through official participation in the UNFCCC discussions, an idea that Australia unsuccessfully raised in 2012 (Stephens 2019); or, more provocatively, to tie power within the ATS not to scientific activity but to parties' efforts to minimize their contribution to climate change and hence ice-melt within their own national boundaries (Roberts 2023). Needed, is a holistic approach to governing activities undertaken around the world that affect climate and people/places globally. Evident from Figs 2 and 3: protection of A&SO from the damages associated with anthropogenically induced climate change would also protect and benefit other people and places across the globe.

A long and significant body of literature considers ways in which to manage assets and/or places that create benefits for all (Bromley 1992, Barnes 2006, Bollier 2007, Bollier and Helfrich 2014). In some countries (e.g. New Zealand, India, and Ecuador—Tanasescu 2017), this has led to rivers being granted the legal rights of people—which effectively prioritizes ecocentric values (these arguably include *existence* values, which are a type of cultural service, categorised variously in CICES v5.2 with codes 3.4.2.1, 3.4.2.2, 6.4.2.1, and 6.4.2.2.) above all other types of ES. It also removes any explicit or implied obligation of nature to provide services to humans that may lead to its own detriment. See also Poelina et al. (2019) for related perspectives from Australian Aboriginals in the Kimberley, Northwestern Australia. This general idea has been aired for Antarctica to ensure that Antarctica could at its own behest (via guardians) institute proceedings before courts and tribunals regarding any adverse effects of transboundary harm on the continent and require them to take any injury to Antarctica into account when granting any relief (Daya-Winterbottom 2023). However, the question remains of which body would speak for Antarctica's rights.

Other ideas may also be worth considering. With no ownership rights and no formal management processes, public goods (like the regulating and maintenance services provided by A&SO) are vulnerable to degradation and depletion (Hardin 1968, Feeny et al. 1990). But public goods *can be* effectively managed providing that governance processes ensure compliance with established rules, and agreements and several scholars have outlined core design principles for effective governance to promote resilience (Berkes et al 1989,Feeny et al. 1990, Ostrom 2008, Biggs et al. 2012, Atkins et al. 2019).

Table 2. Elinor Ostrom's 8 core design principles for sustainable commons management, with a generalized version (Atkins et al. 2019), description of the basic function of each principle in the context of CATs and assessment of the extent to which current governance arrangements conform to each (weak, medium, and strong; blended colours reflect mixed assessments across various ES).

Ostrom's principle (Generalized version) *Function*	Degree to which current governance arrangements conform to each of the principles in general, and for specific ES				
	ATS in general	Tourism	Fishing	Science	Regulating services
1. Clearly defined boundaries (shared identity and purpose) *Defines group and establishes property rights*	medium	medium	medium	strong	weak
2. Proportional equivalence between benefits and costs (equitable distribution of contributions and benefits) *Ensures effectiveness by balancing individual and collective interests*	weak	weak	weak	weak	weak
3. Collective choice arrangements (fair and inclusive decision-making) *Ensures effectiveness by balancing individual and collective interests*	medium/strong	strong	medium	medium	strong
4. Monitoring (monitoring agreed behaviours) *Ensures effectiveness by balancing individual and collective interests*	medium/strong	medium	medium	medium	strong
5. Graduated sanctions (graduated responding to helpful or unhelpful behaviour) *Ensures effectiveness by balancing individual and collective interests*	weak/medium	weak	medium	medium	weak
6. Conflict resolution mechanisms (fast and fair conflict resolution) *Ensures effectiveness by balancing individual and collective interests*	weak/medium	medium	medium	medium	weak
7. Minimal recognition of rights to organize [authority to self-govern (according to principles 1–6)] *Ensures effectiveness while supporting engagement*	strong	strong	strong	strong	weak
8. Polycentric governance [collaborative relations with other groups (using principles 1–7)] *Connects to other spatial and temporal scales*	strong	strong	strong	strong	medium

Costanza et al. (2021) list Ostrom's and Atkin's generalized principles, discussing the intended function of each while noting that being able to address all principles does not guarantee success.

Although tourism is, arguably, not a pure public good, researchers have used Ostrom's design principles to evaluate the advantages and disadvantages of the IAATO's self-regulation of Antarctic tourism, as an intended contribution to the 'institutional development of the Antarctic tourism regulatory regime' (Haase et al. 2009, p. 426; see also Arvanitidis and Almyriotou 2021). This leads to the larger question of whether Ostrom's design principles could provide ways to evaluate and design governance systems that are able to better support ATCPs to protect the complete range of ES that are provided by the region into the twenty-first century. Table 2 synthesizes core ideas from the preceding discussion to coarsely assess the extent to which existing ATS governance systems match those principles on a three-point scale: weak, medium, and strong (Table F.1, Appendix F provides notes justifying the assessment). Existing governance arrangements are relatively well aligned with Ostrom's design principles although alignment is generally weak for principles 2 and 5, while generally strong for principles 7 and 8. Commercial fishing, tourism, and science are also better aligned than the interrelated suite of regulating services provided by the A&SO to the world.

While re-defining and/or detailing a governance system that might more adequately support the A&SO's regulating services is well beyond the scope of this paper, we highlight one system that embodies Ostrom's design principles that might be useful here, the concept of the CAT. Trusts are widely used and have well-developed legal mechanisms to protect and manage assets on behalf of specific beneficiaries—even when beneficiaries are diverse and geographically dispersed as is the case here. Moreover, there are numerous and diverse examples of their use or proposed use around the world at multiple geographic scales, including National Trusts (England, Wales, Scotland, and Ireland); Costa Rica's system around the payment for ES; Vermont's CAT proposal; and the global scale—Earth atmospheric trust (Costanza et al. 2021). While Antarctica is in the unique position of being governed through the ATS rather than falling under one national jurisdiction, it may be possible to leverage insights from these applications to explore ways of better supporting the Treaty System to continue to do that which it has been tasked to do. Individual nations could, for instance, approach their policy in the region using CAT principles, using this to guide their actions and set a pro-environmental example for others, leading to positive outcomes for the region. The key insight from the work on CATs is that assets (in this case A&SO) should be managed to maintain and enhance their health, wellbeing, and value. We have highlighted that that value includes ES that have so far been underappreciated.

One obvious difficulty with such an approach is the need to complement the ATS not undermine it. But the ATS already conforms to many of Ostrom's design principles and can be thought of as at least approximating a CAT (Table 2 and Appendix F). Participation has increased to 57 nations (Consultative and Non-Consultative) from the original 12 in 1959, and the Treaty System has proven to be robust in navigating emerging challenges such as inclusivity of nations and the spectre of mining leading to the Madrid Protocol. The ATCPs will understandably be protective of a regime that was not only remarkable for its time but remains an example of international cooperation in present day. Noting the reality of international relations, and the often incremental development of international agreements, one option is to introduce the benefits of Common Area Trusts framing and design principles to the twin forums—the UNFCCC Conference of Parties and the ATCM—with the aim of facilitating a shared understanding of what a CAT means, the extent to which the current system already embodies many of the design principles, and securing agreement on shared goals on action to protect Antarctica's regulating services. A CAT can and does mean different things depending on which discipline you approach it from, and international and interdisciplinary dialogue to reach common ground would itself be a significant achievement, particularly if Ostrom's design principles guide the dialogue.

Concluding comments

The ATS shares key features with a CAT: Stakeholders have come together and devised rules and norms to protect a globally important asset—the A&SO. Our paper clearly highlights other things that need attention if Antarctica, the surrounding oceans, and the global populations that are inextricably linked to it are to continue to be protected. Most notably, existing governance arrangements that are specific to commercial fishing, tourism, and research are reasonably well aligned with Ostrom's design principles. However, arrangements are less well aligned for—and thus less able to protect—regulating and maintenance services. The ATS has, over the last 60 years, proven its ability to adapt and evolve to face new challenges. With more support, we contend that it may also be able to adapt and evolve to protect ALL the region's ES. It may also need to incorporate new mechanisms, incentives, policies, and instruments to understand, manage, and enforce the protection of this extraordinarily valuable region.

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Author contribution

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Supplementary data

Supplementary data is available in the appendices at *ICES Journal of Marine Science* online.

Conflicts of Interest: The authors have no conflicts of interest to declare.

Data availability

The datasets were derived from sources in the public domain, including Antarctic Treaty Area Boundary: Esri 2014 World Latitude and Longitude Grids; Ocean currents: ArcGIS.com, 2016, Major Ocean Currents; Combined value of total catch (toothfish & krill) USD (2018–2021), homeports of fishing vessels: CCAMLR Statistical Bulletin 2022, Vol 34; Tourist numbers: International Association of Antarctic Tour Operators 2023, and Tourist vessel numbers: McCarthy et al. (2022).

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