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The value of Antarctic and Southern Ocean ecosystem services

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Antarctica and the Southern Ocean provide numerous ecosystem services that benefit people globally, but many are 'invisible' to markets and to some decision makers. A subset of these services – Antarctic tourism, commercial fisheries, and a suite of inter-related regulating services – are conservatively valued at ~US $180 billion annually, highlighting their importance.

Antarctica and the Southern Ocean (A&SO) are undergoing rapid environmental change: sea ice reached an all-time observational low in 2023, the Antarctic ice sheet has lost substantial mass, the Southern Ocean has become warmer and more acidic, and endemic marine biodiversity has diminished. These changes threaten the core physical, chemical and biological processes that create and sustain numerous ecosystem services that A&SO provide, including regulating services (climate control), provisioning services (fisheries) and cultural services (scientific research and tourism).

The value of such ecosystem services has been estimated for various ecosystems (including forests, grasslands, coastal areas, coral reefs and other marine systems), with global net benefits totalling ~US $145 trillion annually[1–3]. However, assessments of polar systems are limited. Ecosystem service values of the Arctic have been estimated at ~US $290 billion annually[4], suggesting that values for A&SO might also be high. Yet, while the supporting biophysical functions (and to some extent, social mechanisms) underpinning A&SO's services are increasingly understood, little is known about their economic value. Accordingly, prioritizing actions and devising supporting strategies is challenging and, given the rapid and ongoing anthropogenic changes, urgently needed.

Here, we outline and estimate the monetary value of a subset of A&SO's ecosystem services – fisheries, tourism and a suite of inter-related regulating and maintenance services. We acknowledge arguments about the ethics of valuation and the danger that it might lead to commodification and degradation, but note that valuation can help raise awareness of otherwise 'invisible' services, garnering support for improved governance.

Regulating and maintenance services

A&SO regulate the Earth's climate through multiple physical, chemical and biological processes that link ocean CO_2 uptake to water mass transport, ice melt, albedo, methane (CH_4) retention and the distribution of heat, freshwater, carbon and nutrients around the globe. Of considerable importance is the ventilation, sequestration and storage of CO_2 and heat from the atmosphere into the Southern Ocean via atmosphere–ocean–biosphere interactions. This CO_2 and heat is subsequently redistributed over the global oceans via large-scale flows involving the Antarctic Circumpolar Current, neighbouring subtropical gyres and vertical overturning circulation[5]. Thus, A&SO are central in regulating global CO_2 concentrations and related processes.

The economic value of these regulating services can be quantified as the global social and economic damages that are avoided by them. It is calculated by multiplying different estimates of the annual carbon sequestered by the Southern Ocean (1.28, 1.95 and 7.34 Mt CO_2 per year)[6–8] by different estimates of the social cost of carbon (SCC; 22.00, 92.18 and 98.33 USD per tonne of CO_2); see Supplementary Information. Using the range of carbon sequestration and SCC estimates as a measure of uncertainty provides a low valuation of US $28.16 billion, a medium valuation of US $175.98 billion, and a high valuation of US $721.72 billion per year (Table 1).

These estimates seemingly focus on CO_2, but associated damages (such as infrastructure loss due to sea level rise) are embedded within most estimates of the SCC; even if the Southern Ocean's carbon sequestration rates are unaffected by climate change[9], inter-related changes (in ice melt and sea level rise, for instance) will reduce the 'value' of these regulating services – fewer damages are avoided. Low estimates of SCC often include only a subset of potential impacts and so underestimate total social costs. Although conservative, these values are broadly comparable with the estimated US $23 billion–$1 trillion annual economic damages associated with Antarctic ice sheet melt[10] and the US $49–$416 billion annual value associated with albedo and CH_4 retention in Arctic permafrost[4].

Data limitations prevent quantifications of other regulating and maintenance services (including the filtering of airborne wastes, nuisances and noise). However, while these aspects can be of considerable value in ecosystems adjacent to large populations, they are unlikely to be substantial for Antarctica.

Provisioning services

In addition to critical roles in the ecosystem, particular marine species also have substantial value in fisheries[11], contributing to their ecosystem services. Antarctic toothfish and krill, for example, are used as food for humans, high-value pharmaceuticals and food supplements. Considering tonnes of toothfish and krill caught in the Antarctic region managed by the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR), the value of these fisheries is estimated at approximately US $370 million per year (Table 1); values range between

Table 1 | Summary of a subset of ecosystem service values in Antarctica and the Southern Oceans, $billions USD per annum

Service	Medium	Min	Max
Antarctic Tourism	0.82	0.13	1.50
Fish captured in commercial fisheries: Antarctic and Patagonian toothfish, Antarctic krill	0.37	0.08	0.67
Regulating services that are inter-related to CO_2 uptake	179.30	28.26	721.72
Totals	180.49	28.47	723.89

US $80 million and US $670 million depending on assumptions made about ex-vessel prices, profit margins and consumer surplus (Supplementary Information). The Antarctic Circumpolar Current and neighbouring subtropical gyres transport Antarctic krill and nutrients, thus supporting other global fisheries[12]. The additional value of these benefits is in the range of US $260 million to US $5.44 billion per annum but is not included in the estimates above (Supplementary Information).

Several other provisioning services are also important in A&SO, including freshwater resources, ornamental resources or other raw materials, and medicinal and/or genetic resources, but data limitations prevent economic assessments of their value. Although transport costs suggest that Antarctic freshwater resources are unlikely to be of substantial economic value, genetic resources might be, as suggested for a marine area north of Scotland where the option value of deep-sea organisms has been estimated at US $75 per household per annum[13]. Extrapolating the Scottish estimates globally (even if only across OECD countries), suggests a large value. Accordingly, the US $370 million estimate of provisioning value is likely an underestimate.

Cultural services

A&SO also provide cultural services in the form of tourism. Antarctic tourism has increased markedly, rising from ~8,000 to 105,000 tourists between the 1993–1994 and 2022–2023 seasons[14]. Shipborne tourism predominates, with 98% of tourism voyages visiting the Antarctic Peninsula in the summer and shoulder months (October–April). The value of the Antarctic tourism industry is estimated at approximately US $820 million, ranging from US $130 million to US $1.5 billion (Table 1) depending on assumptions made about the cost of cruises, profit margins and the consumer surplus accruing to visitors (Supplementary Information).

As with regulating and provisioning services, there are other cultural service values that cannot be quantified. Of note is the science undertaken within Antarctic research stations and under broader international programs. However, this research might have helped avoid economic damage – reports of ice melt and likely associated increases in sea levels might have encouraged the construction of sea walls to protect livelihoods and infrastructure – hence providing a monetarily valuable service. Symbolic, 'existence' or 'bequest' values are also important, but to the best of our knowledge, they have not been assessed for Antarctica. Using another iconic region (the Great Barrier Reef) as an analogue, however, suggests these non-use values might be as high as US $140 per household per annum[15].

Governance

Only some of these ecosystem services are governed through the Antarctic Treaty System (ATS). When the Antarctic Treaty was first adopted in 1959, ecosystem services were not taken into consideration. The ATS has since evolved to incorporate a suite of related instruments including the Convention on the Conservation of Antarctic Seals (CCAS, 1972), CCAMLR (1980), and the Protocol on Environmental Protection to the Antarctic Treaty (Madrid Protocol, 1991). Some of A&SO's ecosystem services discussed above are governed under the ATS, but not to the extent required to protect them all into the future; the ATS regulates activities which take place within A&SO (including fishing, tourism and research), whereas most of the human activities that impact the climate and the processes that underpin A&SO's ability to provide regulating and maintenance services occur outside the region. The efforts of the Treaty parties to safeguard Antarctica as a place with unique environmental, cultural and scientific values are undermined by forces beyond their remit.

Summary

Collectively, a subset of A&SO's ecosystem services – fisheries, tourism and a suite of interrelated regulating services – are valued at ~US $180 billion per year (Table 1). Rapid climate-related changes are occurring, and the magnitude of these ecosystem service values underscores the importance and urgency of finding better ways to manage the anthropogenic activities that are reducing the ability of A&SO to provide them into the future. In light of the value of A&SO's regulating and maintenance services – and that of other 'icy' regions – their protection is a global imperative. One achievement of the ATS has been its ability to evolve over the past 60 years to add instruments that address emerging issues. With more support, the ATS might also be able to adapt and evolve to protect all of the region's ecosystem services – not just those that can be protected by looking at A&SO.

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Competing interests

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