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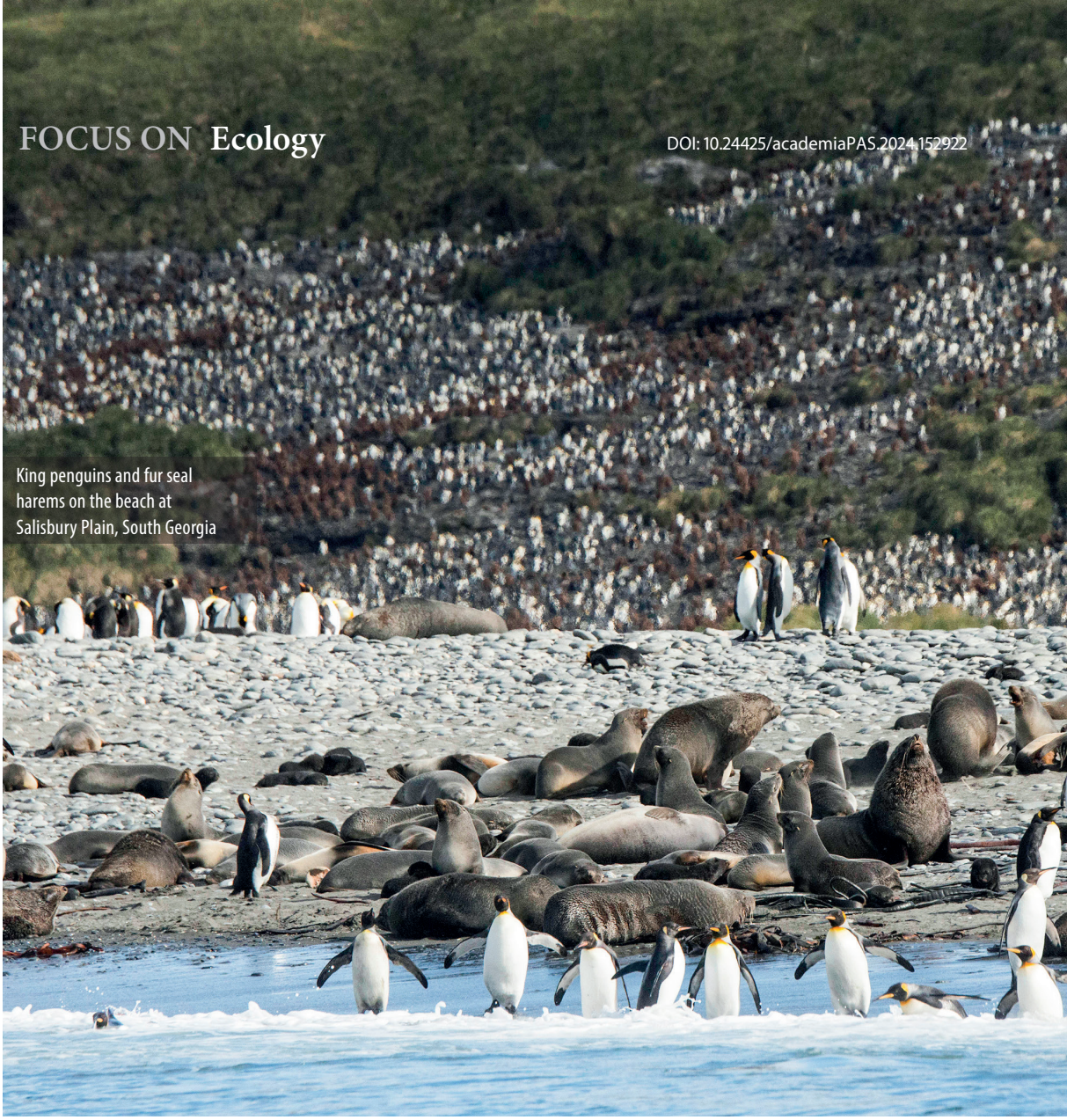

King penguins and fur seal harems on the beach at Salisbury Plain, South Georgia

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South Georgia: Paradise Regained?

Isolated islands function as natural ecological laboratories, where both the negative and positive impacts of human activity on the environment are plain to see.

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South Georgia, the largest island in the sub-Antarctic region, is a haven for millions of birds (with 29 species nesting here) as well as for numerous marine mammals, including elephant seals and Antarctic fur seals. Remarkably, an estimated 95% of the global Antarctic fur seal population, nearly five million individuals, originate from South Georgia. The surrounding waters are teeming with life, drawing humpback whales that migrate from their breeding grounds off Brazil to feast in this nutrient-rich environment.

The island's coastlines, which are increasingly being exposed as the glaciers retreat, are fertilized by guano from the abundant wildlife, fostering surprisingly lush vegetation for such latitudes. South Georgia is home to 25 native vascular plant species, a similar number of introduced species, along with around 125 mosses, 85 liverworts, and 200 lichens.

This extraordinary biodiversity thrives on an island just 165 km long and 35 km wide, thanks to its location in krill-rich waters. Antarctic krill, a small crustacean vital to the Southern Ocean ecosystem, serves as the primary food source for penguins, whales, seals, and fish. Krill swarms are carried to South Georgia from the Antarctic Peninsula by the Antarctic Circumpolar Current, the most powerful ocean current on Earth.

Having no permanent residents and with strict legal protections covering the island and its surrounding waters, South Georgia is largely untouched by human activity. Visitors are limited to scientists and tightly regulated tourist groups arriving by ship. The island has no airport, no hotels, or no industry, ensuring minimal human impact and preventing the spread of invasive species.

However, South Georgia's ecosystems were not always so pristine. In the nineteenth century, rampant hunting nearly wiped out the fur seals. In 1915, a single individual was found on the island – and promptly killed. Whaling, too, left its mark. Several whaling stations, employing hundreds of workers, operated on the island during the early twentieth century. Over 175,000 whales were hunted and processed into oil before the industry became unprofitable, with the last station in Grytviken closing in 1966. The environmental consequences of human activity were nevertheless severe. Rats, accidentally introduced by humans, devastated the bird colonies, while reindeer, intentionally brought to the island, decimated the native vegetation. Humpback whales ceased visiting the area's fjords.

But today, these degraded ecosystems have significantly recovered. South Georgia therefore stands as a testament to nature's resilience – when humans not only step back but also actively support restoration efforts. The reindeer herds have been removed, and the island underwent what was probably the world's largest rat eradication campaign. Ongoing efforts are targeting invasive plant species, such as dandelions, which thrive in the island's conditions. South Georgia's recovery showcases the transformative power of successful conservation efforts. It serves as a living

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A core from King Edward Cove showing a well-oxygenated upper sediment layer deposited in the early twenty-first century

example of how ecosystems can heal when given the opportunity and the right interventions. This "paradise regained" is a symbol of hope for the natural world.

Tiny Giants

We conducted field research in this remarkable region in late 2019, funded by a grant from Poland's National Science Centre (NCN). At present, Poland does not have a research vessel suitable for studying the Southern Ocean. The days when the Henryk Arctowski Polish Antarctic Station in the South Shetland Islands was regularly supplied by Polish-flagged ships ended decades ago. To carry out our project, we chartered a small research yacht, the *Saoirse*, operated by a highly experienced and dedicated crew. While this approach had its limitations, it also offered significant advantages. It provided flexibility, allowed us to access shallow coastal waters that larger ships cannot reach, gave us the adventure of sailing through the infamous "Roaring Forties" and "Furious Fifties" (southern latitudes) and, importantly, kept costs relatively low.

One goal of the expedition was to document the distribution and typical habitat conditions of foraminifera – single-celled microorganisms, whose fossilized remains in sediments are widely used to reconstruct past environmental conditions. We gathered extensive samples, which enabled us to describe three new genera and four new species of foraminifera, as well as six new species of their close relatives from the genus *Gromia*. Using molecular clock analysis, we linked key evolutionary events in *Cassidulinidae* foraminifera to periods of Antarctic climate warming approximately 15 and 5–7 million years ago. During these warmer periods, related populations from Antarctica, South Georgia, and areas north of the Drake Passage likely came into contact, leading to interspecies hybridization. With current warming in the sub-Antarctic and Antarctic Peninsula regions, a similar scenario could unfold in the near future.

Another objective of our expedition was to study ecosystem changes in South Georgia over the twentieth and twenty-first centuries. We focused on the fjords near former whaling stations and examined changes that occurred during and after their operation. In key areas of Cumberland Bay, located in the island's central region, we collected short marine sediment cores. These samples allow us to reconstruct environmental conditions during the peak of the whaling industry (1904–1966) and in the years since its decline. We wanted to understand whether – and how quickly – the delicate ecosystem of the bay recovered after a period of intense industrial activity, which was unparalleled in the Southern Ocean.

WOJCIECH MAJEWSKI

Hundreds of fur seals during the breeding season on the beach near the abandoned buildings of the Stromness whaling station, famous as the final point of Sir Ernest Shackleton's heroic journey with his companions in 1916

Revival

The most intriguing results came from a sediment core collected in King Edward Cove, the natural harbor of Grytviken, South Georgia's longest-operating whaling station. The age of the sediments was determined by analyzing the lead isotope ^{210}Pb. Sediments from the whaling station's operational period showed elevated levels of certain heavy metals, petroleum-derived compounds from coal burning, and organic waste from human activity. These pollutants dropped sharply in sediments dating to the years immediately after the station's closure.

Interestingly, no foraminiferal microfossils were found in the sediments from the whaling era, suggesting that the seafloor environment at the time was nearly *anoxic* (devoid of oxygen). This likely resulted from the decomposition of whale carcass waste, which consumed much of the available oxygen in the water. This finding raised the question of whether the bay was entirely devoid of life during this period – a pos-

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The research yacht *Saoirse* moored at the former whaling station in Grytviken (December 2019). The expedition included Christine Ellard, Andrew Gooday, Maria Holzmann, Michael Kean, Greg Landreth (first captain), Keri Pashuk (second captain), Jan Pawłowski, Piotr Rozwalak, Witold Szczuciński, and Wojciech Majewski, the expedition leader.

sibility hinted at in Ernest Shackleton's vivid descriptions of the area around the nearby Stromness station during his famous Imperial Trans-Antarctic Expedition.

Our ability to reconstruct these historical ecosystems was enhanced by analyzing ancient environmental DNA – the genetic material left behind by past organisms, preserved in sediments. Although such DNA is often highly degraded, fragments can still be recovered and their sources identified. This work revealed that during the anoxic period, the seafloor was in fact inhabited by a relatively diverse community of annelids, mainly polychaetes, a group typically associated with ecologically degraded environments.

As pollution levels decreased and oxygen conditions improved, foraminifera rapidly recolonized the seafloor. These populations were dominated by agglutinated forms and displayed notable diversity, suggesting a sudden improvement in environmental conditions. This recolonization happened quickly, without the transitional stages often observed in Scandinavian fjords, where communities evolve gradually from pollution-adapted species to those typical of normal conditions. However, it is worth noting that while the environmental degradation during the whaling era was severe, it was likely confined to the immediate vicinity of the whaling stations.

In contrast to the swift recovery of foraminifera, larger benthic (bottom-dwelling) organisms in King Edward Cove adapted more slowly. Environmental DNA analysis and sediment dating suggest that their recovery may have taken up to a decade. It was only then that cnidarians, such as anemones and hydroids, reappeared, indicating that conditions had stabilized by the 1980s and 1990s.

Ubiquitous humans

After 2000, however, another shift occurred. Oxygen levels in the sediment increased again, prompting a rapid response from foraminifera, this time

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Collecting sediment samples from the seabed in front of one of the world's fastest-retreating glaciers (approximately 450 m per year) – the Neumayer Glacier, located in the western arm of Cumberland Bay

WOJCIECH MAJEWSKI

The British Antarctic Survey station at King Edward Cove, with the buildings of the former Grytviken whaling station visible in the background

predominantly species with calcareous shells. Multicellular organisms responded more slowly; cnidarians, such as anemones and hydroids, virtually disappeared, replaced by nematodes. This change was an unexpected discovery and may be linked to ongoing climate change. Around South Georgia, this manifests as a gradual rise in average annual air temperature of 0.14°C per decade, increased rainfall, and stronger winds. However, these trends affect a broad region, and the changes observed in sediment cores from other parts of Cumberland Bay do not always align with – or sometimes even run counter to – those observed in the relatively shallow King Edward Cove.

What has changed most noticeably in King Edward Cove in recent decades is the growing impact of human activity – this time from tourism. Since the early 2000s, the annual number of visits by large cruise ships to South Georgia has risen from fewer than 30 to nearly 80 between 2017 and 2020. Grytviken is a key stop for most of these tours, and this increased traffic is likely responsible for changes in the cove's ecosystem, primarily due to more frequent and intense mixing of its waters. For now, these effects appear limited. King Edward Cove is a small area with a significant capacity for regeneration, as shown by its rapid recovery from the severe degradation caused by the whaling era.

The remarkable recovery of South Georgia's ecosystem in recent decades is an undeniable success. However, with the slow recovery of Antarctic whale populations, which play a critical role in regulating krill numbers, the Southern Ocean's food web remains in transition. In some areas, fur seal densities are now higher than before the nineteenth-century hunting era, likely due to increased krill availability.

The long-term stability of this ecosystem, however, remains uncertain, as threats undoubtedly persist. Invasive plant species continue to spread on the island, and climate change is likely to accelerate the expansion of introduced species. The ongoing warming could alter both the island's terrestrial and coastal ecosystems, and it may also impact the patterns of ocean currents that transport krill, although in the Scotia Sea region – culminating in South Georgia – these currents are partly shaped by seafloor topography.

The loss of Antarctic sea ice now being observed, further threatening krill reproduction. Meanwhile, the rising pressure from tourism, as evidenced by our data, poses the risk of introducing new invasive species or reintroducing old ones – not reindeer, but rodents remain a significant concern. It remains an open question, therefore, whether the recovered natural paradise of the sub-Antarctic's largest island truly has been regained for good.

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