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Research article

Loss of research and operational equipment in Antarctica: Balancing scientific advances with environmental impact

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ABSTRACT

Antarctica has been subject to widespread, long-term and on-going human activity since the establishment of permanent research stations became common in the 1950s. Equipment may become intentionally or inadvertently lost in Antarctic marine and terrestrial environments as a result of scientific research and associated support activities, but this has been poorly quantified to date. Here we report the quantity and nature of equipment lost by the UK's national operator in Antarctica, the British Antarctic Survey (BAS). Over the 15-year study period (2005–2019), 125 incidents of loss were reported, with c. 23 tonnes of equipment lost of which 18% by mass was considered hazardous. The geographical distribution of lost equipment was widespread across the BAS operational footprint. However, impacts are considered low compared to those associated with research station infrastructure establishment and operation. To reduce environmental impact overall, we recommend that, where possible, better use is made of existing research station capacity to facilitate field research, thereby reducing the need for construction of new infrastructure and the generation of associated impacts. Furthermore, to facilitate reporting on the state of the Antarctic environment, we recommend that national Antarctic programmes reinvigorate efforts to comply with Antarctic Treaty System requirements to actively record the locations of past activities and make available details of lost equipment. In a wider context, analogous reporting is also encouraged in other pristine areas subject to new research activities, including in other remote Earth environments and on extra-terrestrial bodies.

1. Introduction

The Antarctic Treaty System designates Antarctica, including all land, ice and sea south of the 60° south latitude parallel, as a 'natural reserve, devoted to peace and science' (see: https://www.ats.aq/index_e.html). However, delivering the potentially conflicting aims of providing effective conservation and facilitating scientific discovery within the same geographical area presents a challenge for Antarctic policymakers and environmental managers (Tin et al., 2009; Aronson et al., 2011; Hughes et al., 2013; Leihy et al., 2020).

Antarctic research has delivered scientific advances across many research disciplines, some of which have been of global significance. The quantity and spatial distribution of research activities across Antarctica is likely to further increase with the greater need to understand Antarctica's role in the Earth system. The current human footprint on the continent may expand further and intensify as more nations accede to the Antarctic Treaty and develop science programmes in order to demonstrate 'substantial scientific research activity' in Antarctica, which is a prerequisite for the attainment of consultative status to the Antarctic Treaty and the right to participate in the governance of the region (Gray and Hughes, 2016; Pertierra et al., 2017; Leihy et al., 2020).

Antarctic research and associated support and logistic activities can have negative impacts upon the natural environment, including through the emission of greenhouse gases (Pertierra et al., 2013; Crossin et al., 2020), disturbance or displacement of wildlife (Coetzee and Chown, 2015), destruction of habitat (Pertierra et al., 2018; Brooks et al., 2019; Cannone et al., 2021), the introduction of non-native species (Frenot et al., 2005; Chown et al., 2012; Hughes et al., 2015, 2019; McCarthy et al., 2019) and the release of pollutants into the atmosphere and

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Table 1
Major infrastructure abandoned or lost in the Antarctic environment.[a]

Infrastructure type	Examples	References
Research stations	Between the mid-1950s and the late 1980s entire abandoned stations built on floating ice shelves became buried in snow, were abandoned and eventually calved off the ice sheet into the sea (e.g., the UK's Halley I, II, III and IV stations on the Brunt Ice Shelf) (see Fig. 1a). Halley VI is mounted on skis and can be moved to avoid being lost due to calving events; this was first tested over a three-year period that commenced during the 2015/2016 season. The Environmental Impact Assessment for the eventual planned removal of Halley VI estimated that 39 tonnes of buried and irretrievable steelwork, electrical & optical fibre cable, waste piping and general waste will be left behind.	Aronson et al. (2011); Clarke et al., 2005
	A series of stations operated by the South African National Antarctic Expedition (SANAE) were located on the Fimbul Ice Shelf. SANAE I, II, and III stations were occupied by South Africa from 1962, 1971 and 1979, respectively, with abandoned stations replaced by a new station as they became buried. The stations are thought to have calved off into the Antarctic marine environment. In 1997 the current station, SANAE IV, was located on rock on the nunatak Vesleskarvet.	Cooper and Headland (1991).
	The Georg von Neumayer Station was constructed by Germany on the Ekström Ice Shelf during the 1980/81 summer season. Due to snow burial, the station was abandoned in 1992 and was replaced by Neumayer II Station. In 2009, Neumayer II Station was replaced by Neumayer III Station which was constructed on a platform that can be raised by hydraulic columns, so keeping the station above the accumulating snow.	Gernandt et al. (2007); Wesche et al. (2016).
	Argentina installed the meteorological hut 'Teniente Luis Ventimiglia' on Peter I Island in 1971. Later attempts to find the hut failed, but given the conditions at the site where it was established, it is assumed that the hut became buried in the snow, collapsed and was lost to the sea.	Fontana (2018)
	The US constructed five research stations on the Ross Ice Shelf, close to the Bay of Whales, between 1929 and 1958 (Little America I, II, III, IV and V). The stations have likely been lost to the marine environment as a result of ice shelf calving events. For example, Little America III broke off in 1963 and in 1987 the iceberg B-9 carried away the remnants of the Little America V.	Scambos and Novak (2005); Keys et al. (1990).
	The Russian Druzhnaya 1 Station was originally located on the Filchner Ice Shelf in 1976. In 1986, the large iceberg A-23 A (c. 100 km across) calved off the ice shelf, taking the station with it. Members of the Soviet Antarctic Expedition were able to land on the iceberg by helicopter from the vessel Kapitan Kondratyev to salvage the most valuable equipment from the station.	Shabad (1986)
	Base Sorbal was constructed of >40 tonnes of supplies by Argentina on April 2, 1965 on the Filchner Ice Shelf to support expeditions to the South Pole from the Weddell Sea. It was closed October 28, 1968 due to accumulating snow and station damage due to ice movement. The station was temporarily reopened in November 1983, but efforts to relocate it in 1997 were not successful and the station was considered lost to the environment.	Fundación Marambio, 2023
	The abandoned US/Australian Wilkes Station, situated on Clark Peninsula in the Windmill Islands, East Antarctica, c. 3 km from Casey Station (Australia), was established in 1959 and operated until 1969, when it was abandoned. In some cases, surplus supplies sent to the station were not moved from their landing positions and became covered in snow and were lost (Clark and Wishart, 1989). Waste has been recorded at 536 locations and efforts have been made to clean up the site.	Clark and Wishart (1989); Fryirs et al. (2013).
	Several field huts and station buildings, constructed by national Antarctic programmes in the Bunger Hills, East Antarctica from the 1950s–1980s, have not been maintained and are in a poor state of repair. An apple hut being transported as a helicopter sling load from MV *Nella Dan* to Edgeworth David Base was dropped accidently and smashed somewhere over the ice shelf or Edisto Ice Tongue during the establishment of the base in Bunger Hills.	Gore et al. (2020)
Logistical support infrastructure	Artificial ice piers have been constructed to allow resupply of McMurdo Station since 1973 and are constructed with steel cable, mesh, pipe, bollards and wooden poles embedded in a sheet of ice. A typical ice pier at the McMurdo Station measures 168 m long, 76 m wide, 6 m thick, and is covered by gravel to provide a non-slip working surface. An ice pier has a normal life span of 1–10 years, after which the surface materials are removed and the pier is either cut loose or towed offshore. The materials lost to the environment include the materials used in the construction of the ice pier that cannot be removed prior to disposal, and generally consist of c. 4000 m of 25 mm diameter steel cable, 45 m of eight-inch steel pipe and 45 m of 12-inch steel pipe, all of which remain embedded in the ice because removal is technically infeasible, and are lost to the environment. The United States Environmental Protection Agency determined that the disposal of artificial ice piers poses a very minimal adverse risk to the marine environment and represents small quantities of unrecoverable non-ice materials.	United States Environmental Protection Agency, 2023.
Waste disposal sites near stations	Up until the 1990s, waste generated at many Antarctic stations was dumped in local landfill sites or disposed onto sea ice, from where it would be lost when the ice broke up. The legacy of earlier waste disposal practises may only come to light following investigation. For example, a survey of the seabed near McMurdo Station (Ross Sea) found tractors, storage sheds, pipeline, hose, and numerous fuel drums with up to 16% of the seafloor covered with anthropogenic debris.	Lenihan et al. (1990); Crockett and White (1997)
	At Fildes Peninsula, King George Island, South Shetland Islands, the remains of open waste burning and open waste dumps, including hazardous items, were recorded. In one incident, a variety of unsorted material (construction waste, insulation material, cardboard, paint cans, batteries, fire extinguishers) were inappropriately stored outside for several years without measures to prevent distribution by wind, resulting in large amounts of lighter-weight waste materials being dispersed over the southern part of Fildes Peninsula and into Maxwell Bay (see Figure 8 in Braun et al. (2012)).	Braun et al. (2012)
	The waste disposal site at the Australian Casey Station, East Antarctica, operated between 1965 and 1986 on the foreshore of Thala Valley. Initial removal of c. 150 tonnes of waste in 1995/96 may have mobilised remaining pollutants. Therefore, subsequent efforts to clean up the site included the removal of waste and the treatment of contaminated water.	Stark et al. (2006)
	The UK Fossil Bluff Field Station is situated on Alexander Island adjacent to George VI Ice Shelf. The station was constructed in February 1961 and was occupied in the winters of 1961, 1962 and 1969–75, after which it has been operated as a summer-only station. During the 1960s, all waste generated at Fossil Bluff, including physical, chemical and biological hazards, was deposited in a dump on the surface of the ice shelf. The dump remained on the surface of the ice shelf and was removed in 2003.	Plato and Shears (2003); Hughes and Nobbs (2004)

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Table 1 (*continued*)

Infrastructure type	Examples	References
Research, fishing and tourist vessels	In January 1989 the Argentinian Navy transport ship ARA *Bahia Paraiso*, ran aground close to Palmer Station (US) on Anvers Islands, Antarctic Peninsula, and subsequently capsized. Two Agusta/Sikorsky ASH-3D Sea King helicopters onboard were lost. The wreck was drained of fuel and oils, but c. 150,000 gallons of fuel is estimated to have been released into the sea and surrounding shoreline.	Kennicutt (1990); Ruoppolo et al., 2013; Richardson (2020)
	On December 13, 2010, the Korean fishing vessel *No. 1 In Sung* sank in the Ross Sea with several fatalities. On the April 21, 2013, the Chinese fishing vessel *Kai Xin* sank off the coast of Antarctica near the Bransfield Strait.	ASOC, 2012; Ruoppolo et al., 2013; Henao (2013)
	In 2007, the polar cruise ship MV *Explorer* was damaged by ice and sank close to the South Shetland Islands. In 2012, MV *Mar Sem Fim*, an expedition charter yacht was crushed by ice and also sank nearby.	Ruoppolo et al., 2013
Aircraft	Aircraft are an integral part of the logistics of many Antarctic national programmes. Numerous accidents have occurred, some of which having resulted in fatalities. Patterson (2013) compiled a list of 40 aircraft accidents, predominantly of US aircraft, during the period 1929–2013. While some aircraft were recovered, this was not always possible.	Patterson (2013)
	The most significant aviation accident in Antarctica occurred when a DC-10 aircraft operated by Air New Zealand crashed into Mt Erebus during a sightseeing flight on November 28, 1979, resulting in 257 fatalities. Much of the aircraft debris and the bodies of some of those who died could not be recovered, and consequently, the crash area was declared a tomb and designated as an Antarctic Specially Protected Area (ASPA 156, Lewis Bay, Mt Erebus, Ross Island).	ATS (2013)
	A Russian plane dating from the early 1960s lies at a depth of *c.* 12 m in Algae Lake close to Oasis Station, Bunger Hills, East Antarctica (D. Andersen, personal communication 1999). The environmental impact on the lake is not known.	D. Andersen, pers. comm. 1999; cited in Gore et al. (2020).
Overland vehicles	Numerous overland vehicles have been lost or abandoned due to mechanical failures or accidents when moving over crevassed ground or sea ice. On some earlier occasions, obsolete vehicles have been abandoned, e.g., a 17 m long Antarctic Snow Cruiser, an M2A2 light tank and a T3E4 Gun Carrier were left at Little America III in February 1941.	Camenzuli et al., 2015; COMNAP, 2002; Scambos and Novak (2005)
	During the Commonwealth Trans-Antarctic Expedition, vehicles were abandoned as the fuel ran out and supplies could be carried by fewer vehicles.	Fuchs (1958)
	Two derelict, rusted steel-tracked *vezdekhod* vehicles have been abandoned at the Oasis Station, Bunger Hills, East Antarctica. One of the vehicles is known to have been submerged in and then recovered from Lake Polest. Broken vehicle lead-acid batteries have also found in the area.	Gore et al. (2020)
Field depots	Field depots of fuel, food and equipment are established in often remote locations to support future work or for safety reasons. Depots established on ice need to be raised regularly to avoid burial and loss; however, unexpected incidents, such as the widespread reduction of Antarctic activities during the COVID-19 pandemic, may prevent timely action, causing depots to be lost. Depots on ice-free ground may be subject to damage caused by wind, water, solar radiation and interference from wildlife.	Hughes et al. (2011); Hughes and Convey (2020);
	Spills at fuel depots may have substantial, but often unquantified, environmental impacts. For example, in 1989, a spill of 260,000 L occurred on Williams Field on the Ross Ice Shelf, 13 km from McMurdo Station, of which only 100,000 L was recovered, the rest eventually reaching the sea.	Wilkness (1990)
	To support scientific research logistics, the British Antarctic Survey established a fuel depot near the Abbott Ice Shelf, Ellsworth Land. The depot, which comprised 43 drums of fuel and 34 empty drums, was last raised above the accumulating snow on December 1, 2012. Given the high rate of accumulation in the area, and that more than decade has passed since it was last raised, it is likely that this depot is buried under many metres of snow. It is not known if it will be possible to relocate and raise this depot.	Nicholas Gillet, pers. comm.
Field huts and refuges	Field huts and refuges can be constructed to support research near sites of scientific interest, e.g., near concentrations of wildlife. However, in some cases, once the scientific activity ceases, the huts may not be removed or adequately maintained, resulting in structural degradation and local pollution. For example, the refuge situated within ASPA 117 Avian Island, Marguerite Bay, Antarctic Peninsula, on the northwest shore of the island, is currently in a poor state of repair; the roof has collapsed, and wood and timber are being dispersed to the local environment. Similarly, BAS was recently alerted to the need for repairs to the hut at Cape Geddes, South Orkney Islands, which had not been visited by BAS for some time.	ATS, 2018; Martin and Rae (2016).

[a] Abandoned or lost infrastructure associated with whaling or sealing industries have not been included, due to the potential associated historic values (e.g., Richardson, 2020).

terrestrial and marine environments (Bargagli, 2008; Tin et al., 2009; Aronson et al., 2011; Waller et al., 2017). While the majority of human impacts in Antarctica resulting from national science programmes have been associated with research station construction, operation and resupply (Tin et al., 2009; Crossin et al., 2020), a sub-set of these impacts can also occur due to the inadvertent loss or intentional abandonment of equipment and infrastructure in the natural environment, often beyond station footprints.

1.1. International agreements

Parties to the Antarctic Treaty that operate scientific programmes in the Antarctic Treaty area recognise the need to minimise human impacts on the Antarctic environment. In demonstration of this, the Protocol on Environmental Protection to the Antarctic Treaty was agreed in 1991 and entered into force in 1998. Annex III to the Protocol concerns 'Waste disposal and waste management' (https://www.ats.aq/e/waste.html) and states that '*The amount of wastes produced or disposed of in the Antarctic Treaty area shall be reduced as far as practicable so as to minimise impact on the Antarctic environment and to minimise interference with the natural values of Antarctica, with scientific research and with other uses of Antarctica which are consistent with the Antarctic Treaty*'. Annex III also states that each Party shall, as far as is practicable, '*prepare an inventory of locations of past activities (such as traverses, field depots, field bases, crashed aircraft) before the information is lost, so that such locations can be taken into account in planning future scientific programmes* …' (Article 8 (3)). While every effort should be made to reduce the possibility of polluting the Antarctic environment, activities, including some undertaken after the Protocol entered into force, have resulted in substantial impact (see Table 1 and Fig. 1). At some locations, complications arise where the requirement for clean-up coexists with the desire to preserve potentially valuable heritage items (Camenzuli et al., 2015; Hodgson-Johnston et al., 2017).

Through Annex I to the Protocol 'Environmental Impact Assessment'

(EIA) (https://www.ats.aq/e/eia.html), the acceding Parties have agreed to perform an EIA for all activities planned to take place within the Treaty area, with the level of assessment required depending upon the anticipated degree and duration of environmental impact (Bastmeijer and Roura, 2008; Hemmings and Kriwoken, 2010). For Parties, and in particular those that have enacted the Protocol into their domestic legislation, it is during this process that any plans to intentionally leave equipment in the Antarctic environment are considered by the national competent authority (usually a representative of the national government). At this point, further efforts should be made to identify measures to mitigate any environmental impacts.

While impacts are often mitigated through the EIA process, they are rarely eliminated, often resulting in a decline in environmental quality in the affected area. Furthermore, as an increasing number of nations have engaged in Antarctic research, the scale and scope of research activity has increased, with the result that environmental degradation has intensified, including at sites of multiple operator activity (e.g., Fildes Peninsula, King George Island), and also spread over a larger spatial area (Chwedorzewska and Korczak, 2010; Braun et al., 2012; Pertierra et al., 2017; Brooks et al., 2019; Convey, 2020). The greatest impacts have generally been reported from the vicinity of Antarctic research stations, particularly those (the large majority) located in coastal ice-free areas where the interests of humans, wildlife and ice-free ecosystems come into direct conflict (Hughes et al., 2011; Braun et al., 2012; Pertierra et al., 2018; Leihy et al., 2020).

As one of the fundamental principles of the Protocol, Antarctic Treaty Parties have agreed '*to preserve the value of Antarctica as an area for the conduct of [such] research*' (Article 3 (3)); however, increasing levels of national governmental operator activity may have a negative impact upon the value of some Antarctic marine and terrestrial environments for scientific research (Tin et al., 2009). Questions have been raised regarding the capacity of the Antarctic Treaty System to manage effectively increasing cumulative impacts and the expanding footprint of humans including associated research infrastructure (Brooks et al., 2019; Convey et al., 2012; Chown and Brooks, 2019; Convey, 2023).

1.2. British Antarctic Survey organisational footprint

The British Antarctic Survey (BAS) delivers internationally important scientific research on climate, upper atmospheric physics, earth sciences, oceanography and marine and terrestrial biology. Research papers produced by BAS scientists have been cited over 300,000 times and each year the organisation produces up to c. 400 peer-reviewed publications (Beverley Ager, pers. comm.). BAS currently operates one (until recently two) research vessel, the *RRS Sir David Attenborough*, five aircraft, five research stations and two seasonal deep-field support facilities and multiple deep-field research camps in the Antarctic region across South Georgia, the South Orkney Islands, the Antarctic Peninsula and the Brunt Ice Shelf. It sends c. 500 personnel to Antarctica each year to support c. 70 station-based and deep field research projects. The organisational footprint over the Antarctic continent extends across an area of roughly 8 million km^2, in addition to the area of the Southern Ocean around the Antarctic Peninsula, Weddell Sea, South Georgia and the South Sandwich Islands (see Fig. 2a). BAS makes every effort to remove all wastes from Antarctica, with the exception of sewage waste for which disposal into the marine or ice environment is permitted under Annex III to the Protocol. BAS has a comprehensive waste management handbook (see https://www.bas.ac.uk/for-staff/polar-predeployment-prep/intro-guidelines-and-forms/preliminary-environmental-assessment/) and currently recycles >80% of waste generated in Antarctica (BAS, 2022).

In this study, we report the approximate quantity, diversity and geographical distribution of scientific and logistical materials and equipment lost through BAS operations in the Antarctic and the Southern Ocean region during the period 2005–2019. We consider the potential implications for the natural environment and provide recommendations for environmental managers and Antarctic policymakers.

2. Methods

2.1. BAS lost equipment database

In an effort to comply with the Protocol (Annex III, Article 8 (3)), during the period 1996–2005, a record was kept of scientific equipment and experimental markers lost specifically in the vicinity of Rothera Research Station, Adelaide Island, Antarctic Peninsula. After reviewing these data, the BAS lost equipment database was established in January 2005 to record equipment that was left in Antarctica intentionally or lost inadvertently by those undertaking logistical and scientific activities. The database does not record pollution events, such as intentional, unavoidable or accidental release of sewage/greywater, fuel or atmospheric pollutants into the Antarctic environment, as these are generally recorded by other means. The lost equipment data were recorded as part of the BAS incident reporting system and the organisation's post-field season review process. For the purposes of this study, the Antarctic region was considered as the Antarctic continent including the Antarctic Peninsula (and associated Antarctic ice sheets), the South Shetland Islands and South Orkney Islands, as well as South Georgia and the South Sandwich Islands and the surrounding marine environment. South Georgia and the South Sandwich Islands do not lie within the area of Antarctic Treaty governance, but activities undertake in these regions form an integral element of BAS operations and were therefore included in this study. Data collected within the BAS lost equipment database includes: the name of the item, the quantity lost, the environment in which the item was lost (marine, terrestrial or research station), the approximate weight, whether it was hazardous, whether it was abandoned intentionally or lost accidently, the location (including coordinates) and the date the item was lost. Whether the item was lost in direct support of a scientific activity (i.e., an activity that directly resulted in the collection of scientific data such as the use of an Autonomous Underwater Vehicle (AUV) or establishment of remote environmental data loggers) or operational activity (i.e., an activity that supported research being undertaken, but did not generate research data, e.g., maintenance of a building) was also noted. Items were considered hazardous if they included material that may be harmful to the environment, including alkaline or lithium batteries, drilling fluid, fuel, lubricants, etc.

2.2. Lost weather balloons

As part of the study, other BAS datasets were analysed for information on the potential loss of equipment. To inform meteorological forecasts and models, weather balloons are launched approximately daily from Rothera Research Station year-round, and at Halley Research Station during the summer. At Halley, year-round launches halted following the 2016 winter, after which launches took place only during the summer. The number of balloon launches from both stations is estimated as c. 8800 balloons over the 18-year period 2004–2022. Once the balloon reaches an altitude of several kilometres (controlled by the amount of helium), it bursts and the remains of the balloon and the radiosonde fall to earth and are lost. The radiosonde, and the balloon to which it is attached, is tracked by the satellite-based Global Positioning System (GPS). The last recorded position of each balloon track represents the approximate location where the balloon debris and radiosonde fell to Earth. Such data were collected for the 1188 balloons launched from Rothera Research Station between May 10, 2017 and June 20, 2022.

3. Results

3.1. Rothera Research Station pilot study (1996–2005)

The pilot study established to record lost scientific equipment at Rothera Research Station between 1996 and 2004 recorded the losses of 82 plastic cloches and seven other experiment markers. In general, the plastic cloches were blown away by strong winds. In some cases, the fixings that secured the cloches to the ground had been removed by local skuas (*Catharacta maccormicki*). These data are not included in the remainder of the analyses presented.

3.2. Lost item type

Table 2 shows the number of lost items, number of reported incidents (where each incident may include multiple items) and approximate weight of lost items categorised into the type of equipment lost (e.g., marine scientific equipment, land/ice-based scientific equipment, logistical equipment, etc.) and whether the items contained hazardous materials. Of the 125 incidents reported, 70% of incidents represented equipment lost in the marine environment, 25% losses in the terrestrial environment and 5% losses within station boundaries. This pattern was reflected in the total weight of material lost in each environment, with losses to the marine environment, terrestrial environment and within station boundaries of 62%, 25% and 13%, respectively. However, more individual items were lost to the terrestrial environment (57%) than the marine environment (30%) reflecting the greater mean weight of individual items lost at sea. The lowest number of individual items were lost at stations (13%).

Overall, of the 23,032 kg of material lost, 24% was operational equipment and 76% was scientific equipment. Fig. 3 shows the numbers of items lost for each weight category, with most items falling into the 10–100 kg weight range. Items containing hazardous materials accounted for 18% of the total weight of lost equipment, with 75% of incidents concerning hazardous material relating to scientific activities compared to only 21% of reports relating to operational activities. In total, 96 of the 749 items lost during the study period contained lithium or alkaline batteries that ranged in weight from 10 g to 20 kg. Lost equipment that contained other hazardous materials included an ice core drill, associated cabling and drilling fluid that was lost to the environment on four occasions, reflecting the technical challenges of operating complex scientific equipment in remote Antarctic environments.

3.3. Geographical distribution

Fig. 2b–d shows the distribution of lost equipment across the study region during the period 2005–2019. Fig. 2b shows the quantity of items lost at each location, with, for example, high values often being attributed to the loss of multiple smaller items during a reported incident, such as bamboo poles and marker flags. Fig. 2c shows the weight of equipment lost at each location, with higher values in the marine environment being a consequence of the intentional but unrecoverable release of metal weights overboard for the purpose of securing oceanographic equipment and, on the continent, with the loss of large volumes of ice core drilling fluid. Fig. 2d shows the number of incidents reported within each 50 $\times$ 50 km grid across the area of operation, with each incident potentially involving the loss of more than one item. The highest number of incidents was reported in and around Rothera Research Station, but other areas of regular (e.g., Halley, Signy, King Edward Point and Bird Island research stations) or short-term intense (e.g., the Pine Island and Thwaites Glaciers; Kirkham et al., 2019) activity also produced multiple reports. It was also apparent that low levels of losses occur more generally throughout the area of BAS operations, as indicated by the scattered yellow boxes in Fig. 2d.

During the study period, 13% of equipment items were lost in the vicinity of research stations, with the majority (87%) being lost in the field in either the marine (30%) or terrestrial environments (57%). Much of the equipment was lost within areas where BAS has a high level of logistical operation (e.g., permanent field camps or sites of major short-term scientific activity). For example, the highest number of items lost (187) was from Halley Research Station, where items can be blown away in high winds if not adequately secured, or buried in snow. Several additional incidents of windblown equipment loss have been recorded, including a single incident in which 175 empty oil drums were lost in high winds during the winter.

3.4. Intentional vs. accidental loss of equipment

Overall, 9% of reported incidents of lost equipment were intentional (i.e., included in planning in the associated EIA for the project), compared with 91% unintentional (for examples, see Fig. 1 and Table 3). A wide diversity of items was lost accidently, ranging from protective hard hats to AUVs, to fuel drums. Equipment intentionally lost to the environment included air-dropped projectile 'javelins' designed to deliver GPS devices and other instruments to inaccessible locations, such as crevassed glacier surfaces (Fig. 1f), the loss of buried thermistors to detect snow and ice temperatures, and a proportion of electronic devices deployed on wildlife to track them (Fig. 1d and e). Some tracker types are deployed with an expectation that subsequent retrieval would be unlikely, particularly those capable of remote communication of positional information (e.g., communication of GPS position via satellite). Other tracker types are deployed with the intention of retrieval when the animal later returns to the deployment location, which may be up to a year later. In some cases, retrieval was not possible for reasons including the animal not returning to the deployment location, evading capture, already shedding its tracker or the researcher responsible for retrieving the tracker being uplifted from the field earlier than planned meaning that retrieval was not possible.

3.5. Lost weather balloons

Fig. 4 shows the approximate landing locations of the 1188 weather balloons and attached radiosondes launched from Rothera Research Station between May 10, 2017 and June 20, 2022. Following launch, the weather balloons and tethered radiosondes are irretrievable and once they have completed their data collection (i.e., when the balloon bursts) their precise position is no longer recorded and they are lost to the environment. Balloons travelled predominantly to the east, blown by strong westerly winds, with some reaching distances of up to 250 km from the launch location. Of the balloons launched from Rothera Research Station, most fell on the Antarctic Peninsula, with a smaller proportion falling on the Larsen Ice Shelf, and the remaining falling into the ocean to the west of the Peninsula or to the east into the Weddell Sea.

3.6. Lost equipment reported by other means

By far the biggest recent loss of equipment was associated with the decommissioning of Halley V Research Station that commenced in 2012 and the movement of the Halley VI Research Station which was completed during the 2016/17 season (see Table 4). Although parts of Halley V station were designed to be raised annually to keep the station buildings above the accumulating snow, a large proportion of the station infrastructure was located within buried tunnels which could not be removed. Similarly, the relocation of Halley VI station resulted in the abandoning of buried cabling and pipework. At the time, data on the loss of these items were not recorded within the lost equipment database, but were documented through the EIA process.

Fig. 1. Examples of equipment lost intentionally or inadvertently to the Antarctic environment. (a). Halley III Research Station was constructed on the Brunt Ice Shelf but, once buried by accumulating snow, was abandoned to fall into the sea (credit: A. Alsop, 1993). (b). Halley IV Research Station one year after completion and already showing signs of burial (credit: D. Allan, 1984). (c). Camping equipment in the field may be blown away during storms if not adequately secured (credit: D. Vaughan). (d and e). Small wildlife geolocators can be lost if not retrieved from the animal (credit: R. Phillips). (f). Air-dropped projectile 'javelins' designed to deliver Global Positioning System (GPS) devices and other instruments to inaccessible places in Antarctica, such as crevassed glacier surfaces (credit: K. Hughes). (g). On occasions, technical difficulties during ice core drilling have resulted in the loss of the drill and/or cable, while on other occasions the fluid left in the borehole has not been retrieved (credit: R. Mulvaney). (h). Oceanographic equipment can be attached to moorings comprised of heavy objects such as repurposed iron train wheels (credit: P. Enderlein). The oceanographic equipment is generally retrieved but the mooring is not recovered and remains on the seabed. (i). Debris, thought to be scientific equipment, exposed following the retreat of ice on South Georgia (credit: Jennifer Black). (j). Abandoned Soviet caboose found in the remote Lassiter Coast, southern Antarctic Peninsula (credit: J. Johnson). The metal plaque attached to the caboose read 'USSR Gravimetric Station No. 6 GUGK 1981' (k). Autonomous underwater vehicles (AUVs) can occasionally lose power and/or become flooded resulting in their loss either at the sea surface, within the water column or seabed (credit: K. Hughes).

4. Discussion

4.1. Geographic distribution of lost equipment

Our study showed that BAS logistical and research activity has resulted in low-level loss of equipment across the organisation's area of operation, with higher levels of loss in areas of more intense or longer-term activity, such as in the vicinity of research stations. The lost equipment database recorded the loss of items (including electrical batteries, wastes containing heavy metals and fuel drums) that the Protocol (in Annex III, Article 2 (1)) lists as specific waste items that should be removed from the Antarctic Treaty area. The data showing the distribution of weather balloon and radiosonde debris further reveal the cumulative impact of regular scientific activities (Fig. 4), with the dispersal of irretrievable 'scientific litter' across a wide spatial area around the launch site at Rothera Research Station that could affect marine, terrestrial and ice environments. These impacts are not limited to the British Antarctic Survey, as the activities leading to the types of losses recorded are commonly carried out by many national Antarctic operators. For instance, Brooks et al. (2018) reported that 27% of the total environmental incidents reported by Australian Antarctic Division (AAD) personnel were beyond the boundaries of Australian stations and highlighted the potential of field activities to spread environmental footprint and impact.

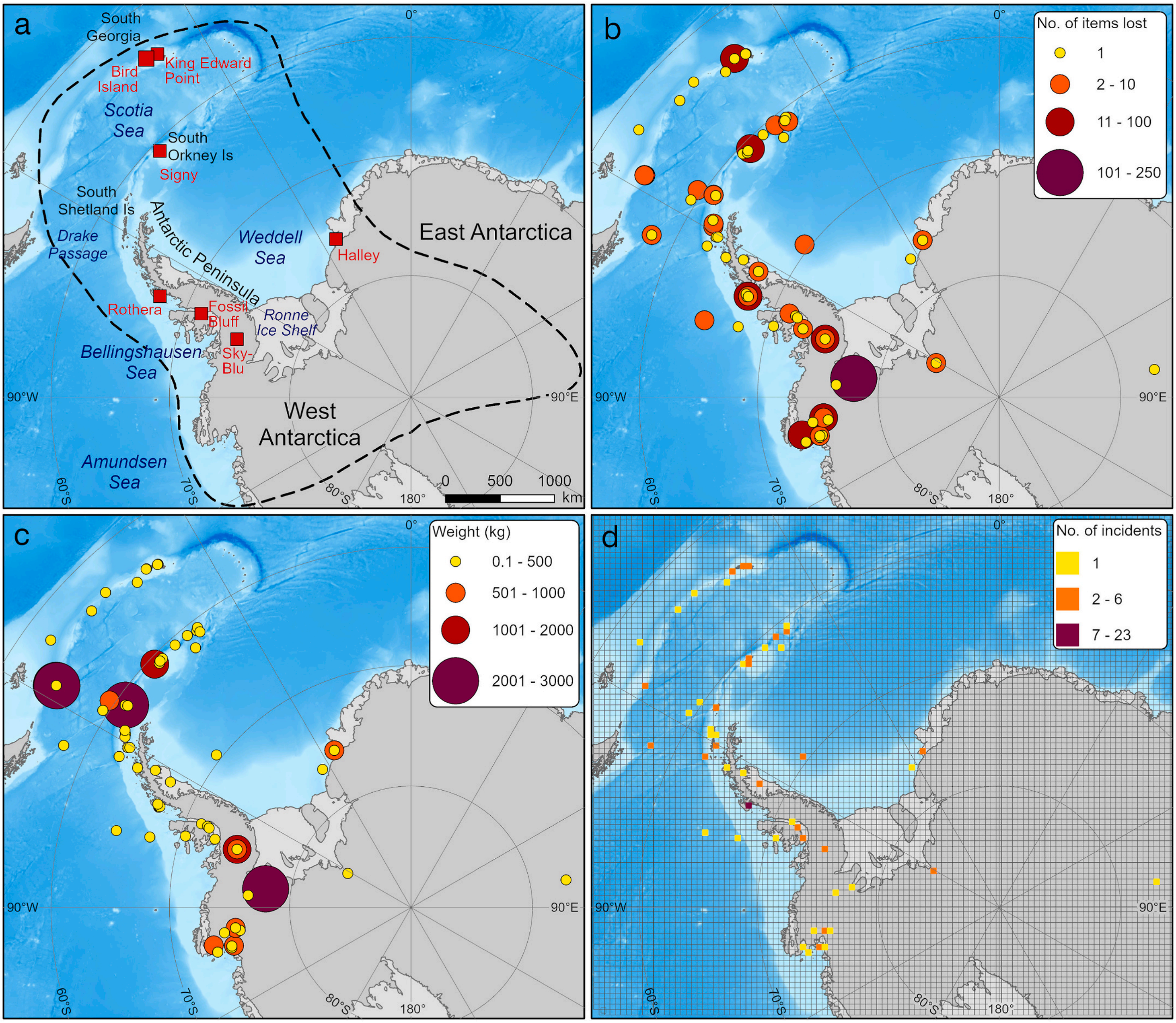

Fig. 2. (a) The approximate operational footprint of the British Antarctic Survey (BAS) in the Antarctic region (dashed line). BAS research stations and permanent field facilities are denoted by red squares. (b) The quantity of items lost at each location. (c) The weight of items lost at each location. (d) Hotspots of equipment loss within the Antarctic region (2005–2019). Each grid square represents an area of 50 × 50 km and the colour indicates the number of incidents reported within the area.

4.2. Equipment losses by BAS and other national Antarctic programmes

Over the 15-year study period, 125 reports were made of BAS equipment lost in the Antarctic environment. Where practical, efforts are generally made to search for and recover equipment that is lost inadvertently, but in many cases these are unsuccessful. Direct comparisons with other national Antarctic programmes are difficult due to a lack of equivalent information. However, Brooks et al. (2018) reported that, during a 6.2-year period (Dec 31, 2009–Feb 18, 2016), 195 environmental incidents were recorded by AAD personnel, of which 24 concerned waste dispersal (most others related to minor fuel spills or biosecurity incursions). They suggested that the large number of reports, many of which had inconsequential impacts, suggested a high level of awareness and an effective reporting system. The AAD's operation is of roughly equivalent scale to that of BAS, although it is likely that AAD's incidents concerning waste dispersal may not have included all intentional or inadvertent losses due to scientific and logistic activities. Nevertheless, allowing for the longer time-period (15 years cf. 6.2 years), BAS had over twice as many reports of lost items on average per year, which suggests a roughly comparable level of reporting. We recognise that the reports submitted by BAS personnel are likely to provide only an indicative level of incidents, as the reporting system is unlikely to have captured all equipment lost over the time period.

In total, c. 32 national Antarctic programmes (of various scales of operation) are present within Antarctica. Quantities and types of equipment lost by programmes may depend upon the number and type of logistical platforms used, the type and quantity of logistic and science activities undertaken, the footprint of operations and the level of training given to personnel concerning the importance of minimising inadvertent equipment losses. It is likely that each year several tonnes of equipment, including a proportion containing hazardous materials, are lost in the Antarctic environment at locations in the vicinity and remote from existing research stations across the continent (COMNAP, 2002). Given the scale of the Antarctic continent (14 million km^2) and Southern

Table 2
Equipment lost to the environment by the British Antarctic Survey within the Antarctic region (2005–2019).

		Operational activity		Science activity		Total
		Hazardous	Non-hazardous	Hazardous	Non-hazardous	
Research Stations[a]	No. of incidents	2	4	0	0	6
	No. of items	21	74	0	0	95
	Weight (kg)	1004	1917	0	0	2921
Marine Environment	No. of incidents	3	26	22	37	88
	No. of items	4	39	108	73	224
	Weight (kg)	2	1683	2136	10,489	14,310
Terrestrial and ice environment	No. of incidents	2	3	16	10	31
	No. of items	6	69	46	309	430
	Weight (kg)	125	897	766	4013	5801
Total	No. of incidents	7	33	38	47	125
	No. of items	31	182	154	382	749
	Weight (kg)	1131	4497	2902	14,502	23,032

[a] No science equipment was recorded as lost at research stations, as scientific activities were mostly undertaken beyond the station areas or within the station buildings.

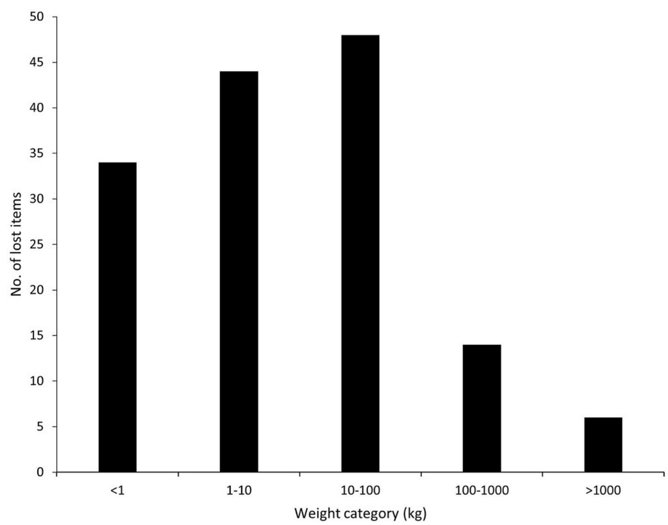

Fig. 3. Equipment lost to the Antarctic environment by the British Antarctic Survey (2005–2019) categorised by estimated weight.

Ocean (>20 million km^2), the loss of these quantities of equipment might seem insignificant compared to pollution elsewhere on the planet. However, the losses may become more problematic in locations where multiple national programmes operate, such as the South Shetland Islands, Larsemann Hills, Bunger Hills or McMurdo Dry Valleys, due to cumulative impacts, including from earlier times when environmental standards were lower prior to the entry into force of the Protocol (Burgess et al., 1992; Braun et al., 2012; Talalay and Pyne, 2017; Gore et al., 2020; Convey, 2020; Chignell et al., 2021). The general improvement in environmental standards now put in place by most national Antarctic operators means that current levels of equipment losses may be minor in comparison with losses associated with historic practices (see Table 1 for examples).

The Antarctic Treaty System recognises that scientific equipment can be deployed in the field and, on occasions, fail to be collected, with many Antarctic Specially Protected Area (ASPA) management plans (see: https://www.ats.aq/devph/en/apa-database) containing instructions to clearly identify the owner of left equipment, including a date for expected removal, so that action can be taken if not removed in a timely manner. Similarly, SCAR is aware of the issue of lost equipment, and has published codes of conducts for scientific field research in Antarctica with recommended steps to address this issue (see: https://www.scar.org/policy/scar-codes-of-conduct/). Researchers are advised to effectively mark equipment left in the field, label scientific experiments and include a removal date to help indicate whether the experiment needs to remain *in situ* or can potentially be removed. They go on to suggest that steps are taken to avoid irretrievable burial of items and, for equipment that cannot be retrieved, '*the location of such equipment, and any disturbance related to its use, should be recorded and reported with a high degree of accuracy*' (SCAR, 2021).

4.3. Examples of scientific field equipment lost in Antarctica

The scientific literature contains may reports of the loss of equipment, including drilling equipment for use in ice and rock, remotely piloted marine and airborne vehicles, scientific balloons and wildlife tracking devices, during Antarctic fieldwork (examples are provided in Table 5). Occasionally, however, lost equipment has been rediscovered; for example, after being deployed in the Drake Passage in 2011, and being recorded missing in 2013, deep ocean measuring equipment was found 14,000 km away on a beach in Tasmania in 2018 (NOC, 2018). In another example, a 4.5 m high mast and associated data logging equipment, installed at an inland site in the southern Antarctic Peninsula, was completely buried when researchers returned to the site two years later, and was only relocated using ground penetrating radar (Arthern et al., 2010). The researchers noted the risks of equipment and data loss when installing equipment in an area of high snow accumulation.

Smaller items of research equipment are also regularly lost to the environment, but these losses (and especially items such as CTD bottles, cloches, sample bags and containers, marker posts/flags, etc.; see Tables 3 and 5) may be less frequently reported in the academic literature (Anfuso et al., 2020). At some locations, including those where scientific activities were undertaken during earlier times when environmental standards where less stringent than today, the level of impact resulting from scientific activities can be substantial. In one study undertaken during the early to mid-2000s, Brazilian researchers reported that 38% of debris found around the Admiralty Bay Antarctic Specially Managed Area (ASMA) (King George Island, South Shetland Islands) was associated with research activities and 22% was associated with scientific experiments (Sander et al., 2009). German researchers working on Fildes Peninsula (King Geoge Island, South Shetland Islands) observed broken installations of long-term experiments left in place for at least one or two seasons (Braun et al., 2012). Researchers working within ASPA No. 126 (Byers Peninsula, Livingston Island, South Shetland Islands) reported that many nations had established camps in the area in recent years and, although the camps were largely removed, it was possible to identify the locations of some by the presence of litter/waste and disturbed ground (Pertierra et al., 2013). Researchers had also left meteorological stations, sensors, plots, cairns and markers, some of which appeared not to have been maintained regularly and might, in

Table 3
Examples of items typically lost as a result of BAS activities within different Antarctic environments.

Antarctic environment	Examples of items lost	Weight[a]	Quantity[b]	Hazardous components[c]	Likely fate/environmental impact
Marine	Iron ballast weights	●●●	●●	No	May provide solid substrate on seabed for colonisation (Fig. 1h)
	CTD and cable	●●●	●	No	"
	Plastic water sampling equipment	●	●	No	Dispersal around Southern Ocean
	Oceanographic floats (e.g., Argo floats)	●●●	●	Yes	"
	Ship operational equipment (e.g., hard hats)	● - ●●	●●	No	"
	Autonomous underwater vehicles (AUVs)	●●●	●	Yes	May sink or float. Potential release of metals and leachates (Fig. 1k)
	Wildlife trackers (e.g., GPS loggers)	●	●●	Yes	Small – negligible impact (Fig. 1d and e)
Terrestrial & freshwater	Irretrievable bolts for attaching scientific equipment to rock	●	●●●	No	Slow corrosion. Potential impact to wilderness and aesthetic values
	Plastic cloches	●	●●	No	Plastic littering of terrestrial environment,
	Scientific monitoring equipment	● - ●●	●●	Yes	Release of metals and leachates
	Scientific equipment lost to freshwater bodies	● - ●●	●	Yes	Release of pollutants into lakes
	Loss of packaging material	●	●	No	General littering
	Station structural material (e.g., cladding)	●●	●	No	Potential injury to wildlife
Cryosphere	Ice borehole drill fluid	●●●	●	Yes	Impact hard to predict, but may depend on the drilled environment and the level of dilution/dispersal. Potential contamination of sub-glacial water bodies (Fig. 1g).
	Buried thermistor cables in bore holes	●●	●	Yes	Will likely remain frozen for 100s-10,000 s years, before release to the ocean
	Iced-in marker poles	●●	●●●	No	"
	1900 m of hot water drilling hose and nozzle	●●●	●	No	"
	Empty 205 l fuel drums	●●	●●●	No	Buried or blown into marine environment (Fig. 1c)
Atmosphere[d]	Weather balloons and radiosondes	●	●●●	Yes	Lost to the marine or terrestrial environments. See Fig. 4.
	Balloon-mounted upper atmospheric monitoring equipment	●●	●	Yes	Lost to the environment
	Lost Remotely Piloted Aircraft Systems (RPAS)	●●	●	Yes	Lost to the environment

[a] Typical weight: <1 kg (●), 1–100 kg (●●), >100 kg (●●●).
[b] Quantity: 0–10 (●), 11–100 (●●), >100 (●●●).
[c] Hazardous components may include hydrocarbons, alkaline and lithium batteries, etc.
[d] Items released into the atmosphere will pollute the environment when they return to Earth.

effect, have been abandoned. Gore et al. (2020) reported that scientific debris left in the vicinity of research station buildings in the Bunger Hills, East Antarctica, included gas cylinders, hundreds of empty steel fuel drums and derelict equipment including an unserviceable boat previously used for research purposes on lakes. Windblown debris was abundant up to several kilometres downwind of the research stations and bases. It remains to be seen whether developments in the research methods employed (e.g., recovery of borehole fluids; Triest et al., 2014), the sustainability of scientific equipment (e.g., increased biodegradability of radiosonde components) and enhancement of the platforms from which research equipment is deployed (e.g. new research vessels; Rogan-Finnemore et al., 2021) can substantially reduce the impact and likelihood of equipment loss during Antarctic research activities.

4.4. Lost equipment reporting within the fishing and tourism industries

National operators are not the only sources of lost equipment in Antarctica. Substantial losses by the fishing industry and other shipping sources contribute to the dispersal of materials across the Southern Ocean and the accumulation of debris on Antarctic and sub-Antarctic shorelines, despite efforts by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) to eliminate littering at sea (Convey et al., 2002; Ivar do Sul et al., 2011; Waluda et al., 2020; Finger et al., 2021). Fishing industry losses in the Southern Ocean should be reported to the Working Group on Fish Stock Assessment of CCAMLR (Grant et al., 2021).

The Antarctic tourism industry, which has recently surpassed the visitor number high reached before the COVID-19 pandemic with 104,076 visitors during the 2022/23 season (Hughes and Convey, 2020; IAATO, 2023), also loses equipment during activities at coastal locations (predominantly in the Antarctic Peninsula region) and at inland sites (e.g., Union Glacier, Ellsworth Mountains and Which-a-way Camp, Dronning Maud Land) (Tejedo et al., 2022). The International Association of Antarctica Tour Operators (IAATO; the primary tourism industry body) has a reporting system for such events. Ongoing minor losses by the tour companies and their clients, such as personal equipment, clothing items, litter, etc., may become more noticeable at locations of high tourist visitation (e.g., see the list of locations with Site Guidelines for Visitors at: https://www.ats.aq/devAS/Ats/VisitorSiteGuidelines) although efforts are made by tour guides to remove litter and lost items and to educate their clients, not least to preserve the impression of an 'Antarctic wilderness' that the industry promotes. IAATO have placed a moratorium on the use of Remotely Piloted Aircraft Systems (RPAS) by tourists largely due to the potential impacts on wildlife but, before this was enacted, there was report of an RPAS piloted by a tourist having been lost in a crevasse at Waddington Bay (IAATO, 2015).

4.5. Implications for the natural environment of lost equipment

Little work has been done to determine the fate of items lost or discarded in the Antarctic environment, although this may depend largely upon the characteristics of the receiving environment and the material

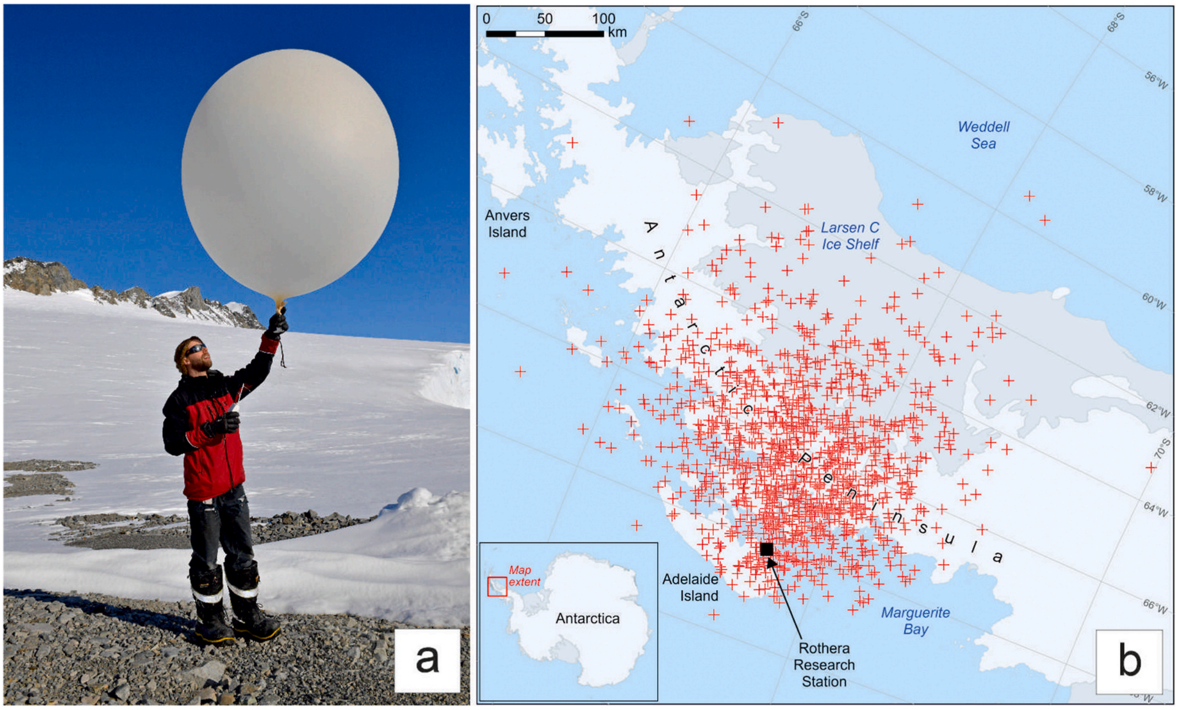

Fig. 4. (a). The launch of a meteorological balloon comprising a latex balloon and attached radiosonde. (b). Map showing the last known positions, and therefore approximate landing positions, of the 1188 radiosondes released from Rothera Research Station, Adelaide Island, Antarctic Peninsula, between May 10, 2017 and June 20, 2022.

Table 4
Material lost to the Antarctic environment following the closure of sequential UK research stations at Halley Bay, Brunt Ice Shelf. The remains of Halley I, II, III, IV and V and the material left at the initial site of Halley VI have been or will be lost to the ocean following periodic calving of the ice shelf.

Station Name	Date constructed	Date closed	Approximate weight of material left at site	Notes	References
Halley I	Jan 1956	Early 1968	>246 tonnes	The weights of individual buildings are provided in Smith (2005). Buried buildings were not removed.	Smith (2005); Martin and Rae (2016)
Halley II	Jan–Mar 1967	1973	100s of tonnes?	Seven buildings, each 22 × 6 × 4 m. The buildings were not removed.	Smith (2005); Martin and Rae (2016)
Halley III	Early 1973	1984	100s of tonnes?	Comprised c. 84 m of 9 × 5.5 m Armco metal tubes, inside which internal buildings were constructed. Site partially cleaned up in 1991. Buried buildings were not removed. A portion of ice shelf containing the station calved off in 1993 (see Fig. 1a).	Smith (2005); Martin and Rae (2016)
Halley IV	Jan 1983	Feb 1992	100s of tonnes?	Comprised c. 120 m of 9 m diameter plywood tubes with double story internal buildings. Buried building were not removed. Site partially cleaned up during 1992/93 season.	Smith (2005); Martin and Rae (2016)
Halley V	Jan 1989 (fully operational 1992)	2012	>400 tonnes	In contrast to earlier stations, part of Halley V was built on metal stilts and regularly raised above the snow. Lost material predominantly comprised the buried steelwork for the c. 500 m of under-ice tunnels, cabling, steel building legs and some plywood structures. All hazardous material were removed. The ice shelf upon which Halley V was located calved off in Jan 2023 (iceberg A81).	Smith (2005); Downie et al. (2007); Neil Cobbett, pers. comm.
Halley VI (initial location)	Commenced Dec 2007, occupied from end of 2012 and officially opened Feb 2013	N/A	c. 120 tonnes	Due to instabilities in the ice shelf, Halley VI was moved 23 km further from the shelf edge during the 2016/17 season. Left material included buried steelwork, timber, cabling and mast foundations.	Bradley and Clarke (2016)
Halley VI (current location)	Station re-located during 2016/17	N/A	39 tonnes (predicted)	The draft Environmental Impact Assessment for the deconstruction and removal of Halley VI predicted buried steelwork, electrical and optical cabling and pipework would be left at the site when the station was decommissioned.	Gilbert (2021).

from which the lost items are constructed. At sea, most dense items (e.g., iron weights used as moorings) will rapidly sink at the location in which they were deployed or lost and may then potentially provide a hard substrate for subsequent colonisation by benthic species. In the years before the Protocol entered into force, it was common practice for national Antarctic operators to deposit drummed waste on sea ice adjacent to research stations and wait for the ice to break up and float out to sea, allowing the waste to eventually sink to the sea floor (Lenihan et al., 1990; Tin et al., 2009; Bartlett, 2023; see Table 1). In contrast, buoyant items, including floats, buoys, some AUVs and some objects made of wood or plastic, may float for prolonged periods (decades) resulting in potential dispersal across a wide area of the Southern Ocean (Clarke

Table 5
Examples of scientific equipment lost to the Antarctic environment.

Scientific equipment type	Examples	Reference
Sample containers	During beach litter survey work at Admiralty Bay, King George Island, South Shetland Islands, researchers found a wide range of litter items, including a plastic centrifuge tube which are commonly used by field researchers for storing collected samples.	Anfuso et al. (2020)
Weather stations	Following the deployment of a network of Automatic Weather Stations (AWS) around the continent by US researchers, the AWS unit at Cape Adams could not be relocated and was probably buried in the snow and was assumed to be lost.	Holmes et al. (1993)
Wildlife trackers and sensors	Wildlife trackers are routinely lost following deployment. For example, Australian researchers tracked breeding cape petrels, Antarctic petrels and southern fulmars from colonies located in the northwest of Hop Island near Davis Research Station and reported that few loggers were recovered at the end of the breeding season.	Dehnhard et al. (2021)
	Deployment of time depth recorders (TDRs) to record leopard seal dive data at Cape Shirreff, Livingston Island, South Shetland Islands resulted, in one case, in the loss of seven out of 14 deployed instruments.	Krause et al. (2016)
Automatic underwater vehicles (AUV)	AUVs have been lost on a number of occasions, with loss considered more likely when operating under sea ice or, to an even greater degree, under an ice shelf.	Loh et al. (2020)
	In 2012, researchers from the United Kingdom lost a Seaglider SG522 underwater glider in the Weddell Sea due to incorrect parameters set by the AUV operator.	Brito et al. (2014)
	On February 16, 2005, the AUV 'Autosub', operated by the UK National Oceanography Centre, was lost due to a mechanical failure, 17 km into an ice cavity beneath the Fimbul Ice Shelf.	Strutt (2006)
Remotely piloted aircraft systems (RPAS)	Remotely piloted aircraft have crashed in Antarctica on many occasions. In one example, a long-range unmanned aircraft system (wingspan: 3 m; weight: 15 kg; range: >1000 km) undertaking survey over Terra Nova Bay polynya crashed on the sea ice on its return flight to Pegasus Runway	Knuth et al. (2013)
	On January 25, 2011, a large (c. 3 m wingspan) RPAS that was designed for aeromagnetic surveys was lost in the vicinity of Marsh Airfield, King George Island, likely as a result of a failure in the satellite guidance system, while a second RPAS was lost a year later in the vicinity of Penguin Island, possibly due to icing.	Funaki et al. (2014)
Thermistors and other sensors in ice	Experimental equipment is often intentionally frozen into ice to record physical parameters. In most cases, subsequent removal is generally impossible or not practicable and the devices are lost to the environment. For example, a sensor string (c. 761 m) containing a pressure sensor and 30 thermistors was deployed in a hole generated by hot water drilling that extended into cavity below the Whillans Ice Stream.	Begeman et al. (2020)
	An international team deployed a range of instruments at two sites on Johnson Glacier, Livingston Island, South Shetland Islands, using a hot water drill to produce the boreholes.	Sugiyama et al. (2019)
	Thermistor strings and other sensors are also commonly deployed in sea ice.	Richter et al. (2022).
Ice drilling equipment and borehole fluids	Since the late 1950s, for example, numerous drills and drill cables have been lost by researchers from the Soviet Union and later the Russian Federation when deep drilling into ice in the vicinity of Lake Vostok, East Antarctica.	Vasiliev et al. (2007)
	During an unsuccessful attempt to take samples from sub-glacial Lake Ellsworth in 2012, UK researchers lost a 340 m umbilical hose and the attached submersible borehole pump in the ice above the lake.	Siegert et al. (2014)
	At the initial stage of the drilling of a borehole in the Minna Bluff piedmont glacier by US researchers, part of the auger cutting head broke off at the bottom of the hole, so the hole was abandoned and the auger string was retrieved.	Goodge et al. (2021)
	Due to technical issues, UK researchers were unable to fully retrieve the borehole fluid from a borehole drilled on the Skytrain Ice Rise in during the 2018/19 season, contrary to the environmental impact mitigation measures outlined in the associated environmental impact assessment.	Mulvaney et al. (2021)
Geological drilling equipment	Geological drilling in the McMurdo Dry Valleys and McMurdo Sound over several decades has resulted in the loss of drill heads, casings, fluid and logging equipment.	Talalay and Pyne (2017)
Explosives	Detonated explosives in ice can act as a seismic source for geophysical research activities. Once deployed in a borehole in the ice, occasionally the explosives will fail to detonate. Under these circumstances, recovery is not safe and the explosives are abandoned. This occurred during geophysical research projects on the Rutford Ice Stream (BEAMISH project) and in ice above sub-glacial Lake CECs.	Smith et al. (2021); R. Clarke, pers. comm.
	Due to restrictions on transportation, at the end of the research projects, excess explosives are routinely detonated in the field, resulting in local pollution.	Ensminger and Blasing (1995)
Scientific balloons	Scientists participating in the Japanese-American Cosmic-ray Emulsion Chamber Experiment (JACEE) recorded the loss of a large (up to 1 million m^3) helium-filled balloon with a c. 110 kg gondola containing measuring equipment in the Ross Sea.	Wilkes, 1998
	It has been estimated that ~5000 meteorological balloons are released over Antarctica annually and lost to the environment.	Steve Colwell, pers. comm.

et al., 2005; Ivar do Sul et al., 2011; NOC, 2018).

For items lost in areas of permanent ice, it is considered likely that most will quickly become buried in snow where they may remain largely unchanged for many years, if not decades or more. Ice flow will eventually transport the items to the continent fringe where the encapsulating ice will break off creating icebergs that will likely disperse across the Southern Ocean. This was the fate of several generations of previous research stations constructed on floating ice shelves, such as successive Halley stations on the Brunt Ice Shelf (see Table 4), and at some time the same may be true of the last resting place and memorial of Scott's fateful South Pole expedition. Only once the ice melts will the item be released into the sea, potentially centuries after it was originally lost, depending upon location. Under some circumstances, items previously lost under accumulating snow may re-emerge, possibly as a result of ice-retreat due to climate change (Hughes and Nobbs, 2004; Lee et al., 2017). For example, sub-Antarctic South Georgia is an area subject to rapid climate change and, during the 2022/23 summer season, old batteries and metal debris thought likely to be associated with earlier scientific research activities re-emerged from beneath snow and ice on Glacier Col (see Fig. 1i).

Items lost in ice-free areas, such as parts of the Antarctic Peninsula or the McMurdo Dry Valleys, may be blown into lakes or subject to wind erosion if partially buried in sand or soil (Moorhead et al., 1999; Priscu and Howkins, 2016; Hawes et al., 2023). Fluctuation in air temperature and the effects of solar ultraviolet radiation may have detrimental effects on some materials, such as plastics, should they experience prolonged exposure, while wood and other organic materials may be subject to microbial degradation under appropriate environmental conditions (Lacerda et al., 2019; Björdal and Dayton, 2020).

The effects of hazardous materials on Antarctic environments and biota are also little understood but, depending upon the amount of material lost, are likely to have detrimental impacts upon only a localised area. Hazardous chemicals released into the ocean may become rapidly dispersed and diluted, depending upon the environmental conditions. However, in terrestrial environments the often limited and/or sporadic availability of liquid water may result in only slow leaching of contaminants into the immediate vicinity over a prolonged period, with potentially serious consequences for the local biota (Stark et al., 2003; Fryirs et al., 2013). Some lost items may be composed of wood or paper, which could introduce partially or fully available organic carbon into otherwise low carbon environments. Loss of items made of organic materials may also have the potential to disperse non-native species including microorganisms into Antarctic environments (e.g., mouldy wood; see Hughes et al., 2018). Materials lost at sea, including fishing gear, may have particularly serious consequences for wildlife, with mortality of seabirds and marine mammals resulting from ingestion of or entanglement in marine debris (Waluda and Staniland, 2013; Ryan, 2018; Phillips and Waluda, 2020; Waluda et al., 2020).

4.6. Balancing scientific advances with environmental impact

Although potentially controversial, the benefit of undertaking any research project or other activity in Antarctica may need to be balanced against the environmental impact and, in some cases, the irreversible change it may cause (Pertierra et al., 2013). Under the current rules of the Protocol (Annex I), all activities in Antarctica, including scientific research, must have been subject to an EIA. However, while the Protocol stipulates the appropriate level of EIA (depending upon whether the activity is likely to have an impact that is assessed as less, equal to, or greater than 'minor or transitory'), it says little about how to assess whether the likely level of impact upon the Antarctic environment of the project is justified by the potential research benefit, given the reality that all research is not of an equivalent value and/or quality (see Jabour, 2019, for a more comprehensive discussion). In general, environmental managers are not in a position to assess the scientific merits of any given project and, therefore, judge whether the likely scientific benefits justify the identified environmental impacts. Furthermore, most research projects are funded by national science funding bodies before any EIA has been undertaken and the likely impacts upon the environment have been considered in full. Under these circumstances the options for environmental managers to suggest substantial changes to the project in order to minimise environmental impact may be limited, and they may not have the authority to prevent a project proceeding, even if they do identify that it may have a particularly high level of environmental impact.

4.7. Loss of scientific equipment in comparison with other impacts

Our study has shown the degree to which undertaking scientific research results in the loss of equipment in the Antarctic environment for one national Antarctic operator, the British Antarctic Survey. However, as mentioned earlier, BAS is only one of c. 32 national Antarctic programmes operating in the region, and the environmental standards employed and level of losses experienced by other programmes are not known, making extrapolation of these data difficult (but see the earlier reporting provided by COMNAP (2002)).

The level and impact of equipment losses, and impacts of Antarctic research more generally, must be balanced against the scientific, policy and societal benefit that the associated research delivers (Bentley et al., 2021). The Antarctic Treaty System itself acknowledges that all science is not equal through its recognition that 'best available science' should be used for decision-making (Article 10 of the Protocol). Therefore, if environmental impacts are to result from research, then scientific benefits should be maximised. Perhaps inevitably, there is a wide diversity in the quantity and quality of research outputs across the Treaty Parties (see Dastidar and Persson, 2005; Dastidar, 2007; Dudeney and Walton, 2012; Ji et al., 2014; Gray and Hughes, 2016; Xavier et al., 2017; González-Aravena et al., 2023; Karatekin et al., 2023). With science considered the 'currency of credibility' within Antarctica and the political sensitivities associated with the demonstration of 'substantial scientific research activity' within the region (Haward, 2017; Roberts, 2023) there may be a reluctance by some Parties to publicly scrutinise the quality of their research outputs, or develop metrics to indicate whether or not the scientific benefits outweigh the environmental costs (Giffoni and Vignetti, 2019).

If impacts of equipment losses in the field are placed in the context of those resulting from the construction and operation of scientific research stations, they could be considered insubstantial (Crossin et al., 2020; see Fig. 5). For example, the construction of research stations on permanent ice is a logistical challenge and, over several decades, a conservative estimate suggests that BAS has lost more than 1000 tonnes of station infrastructure and equipment associated with the successive Halley Research Stations (Table 4). German, Russian, US, French, Italian, Argentinian and South African national Antarctic programmes have lost/abandoned stations situated on areas of permanent ice or ice shelves in the past. It is not known how many thousands of tonnes of material have been released into the Antarctic environment as a result.

Station construction on ice-free ground has often resulted in wildlife displacement, destruction of terrestrial habitat and local pollution (Tin et al., 2009). Brooks et al. (2019) showed the disturbance footprint around research stations located on ice-free ground to be > 5,200,000 m^2, which resulted in a visual footprint similar in size to the total ice-free area of Antarctica. Furthermore, human impacts were disproportionately concentrated in some of the most sensitive environments. When considering equipment lost by AAD in recent years, Brooks et al. (2018) concluded that the cumulative environmental impact of the programme over the six-year study period played a smaller role than the impact and increase in footprint resulting from planned activities and those undertaken before the Protocol entered into force. There have been calls for national Antarctic programmes to limit construction of new research stations, and their associated environmental impact and, where possible, use capacity at existing research stations to deliver their research activities (Gray and Hughes, 2016), although the operational and geopolitical practicalities of achieving this have, as yet, proved largely insurmountable. Notably, Kim and Jung (2016) cast doubt on the assumption of an increase in a nation's Antarctic scientific output resulting from the construction of a new research station, particularly if the station is not the first to be constructed in Antarctica by that nation. Furthermore, Chignell et al. (2021) studied the relationship between field camp placement and scientific productivity in the McMurdo Dry Valleys, finding that scientific output did not necessarily correspond to the number of field camps, and that constructing a field camp does not always lead to an increase in published research from the local area.

4.8. Wider considerations

Under the Antarctic Treaty, Parties may designate observers to carry out inspections, including all stations, installations and equipment within those areas, and all ships and aircraft at points of discharge or embarkation of cargo or personnel in Antarctica (see Article VII). Inspection reports (available via the Antarctic Treaty Secretariat website at: https://www.ats.aq/devAS/Ats/InspectionsDatabase?lang=e) have reported, in some cases repeatedly, poor environmental practices at some little-used, and potentially effectively abandoned, stations. Here, inadequate maintenance of buildings and storage of waste may result in release and/or dispersal of hazardous and non-hazardous materials into the environment. As highlighted by Tamm (2018), the inspection regime has promoted compliance and transparency amongst Parties, but '*it does not appear that the legal structure is fully prepared for an event where values of goodwill and cooperation stumble*'. Inevitably, Antarctic environmental values will continue to be degraded so long as Parties with poorly maintained infrastructure have little or no incentive to comply with the requirements of the Protocol.

As mentioned previously, Article 8 (3) of Annex III to the Protocol

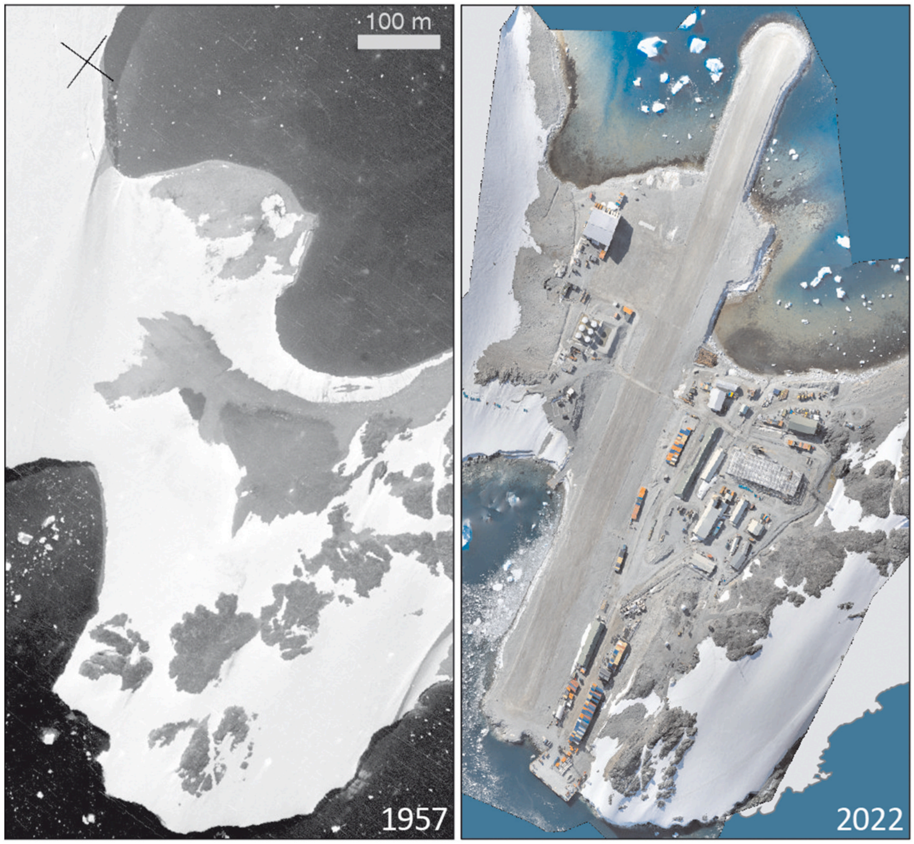

Fig. 5. Images of Rothera Point, Marguerite Bay, Antarctic Peninsula taken in 1957 (BAS image ref.: FIDASE; 26/FID/66; id X26FID0660159) and 2022 (drone image). Construction and upgrading of the UK Rothera Research Station on Rothera Point over several decades has resulted in substantial alteration of the landscape and impacts upon marine and terrestrial environments.

states that each Treaty Party shall prepare an inventory of locations of past activities before the information is lost, so that such locations can be taken into account in the planning of future scientific programmes. The recording of the locations of lost equipment should be a component of this exercise, but it is unclear to what extent and level of detail, if at all, this has been carried out by the different national Antarctic programmes.

Experiences in Antarctica may have lessons for those undertaking exploration and research activities in other analogous environments, including remote deserts, rainforests, hydrothermal vents and other areas of seabed, as well as those on extraterrestrial bodies such as the Moon, Mars and other planets and their associated moons. Many actors, including China, India, the European Union, the Russian Federation and the Unites States, are undertaking increasingly sophisticated exploratory missions on extra-terrestrial bodies, including the use of rovers and RPAS. In many respects, the increased interest in human exploration of extra-terrestrial bodies reflects the position Antarctica was in c. 80 years ago when substantial human activity commenced in the region. However, in the intervening time, a great deal of information regarding the location of past Antarctic activities and installation of infrastructure has been lost. As a result, we do not fully understand the level of environmental impact to which the region has been subjected or which areas can be considered reliably free from local human impacts. Therefore, we encourage recording of sites of activity and lost equipment in other pristine areas subject to new research activities, including remote Earth environments and more distant extra-terrestrial bodies (Kramer, 2014).

5. Conclusions and recommendations

Antarctica is commonly considered to be amongst the most pristine environments on Earth; however, there is increasing evidence that Antarctica is no longer a pristine wilderness (Tin et al., 2009, 2014; Horton and Barnes, 2020). Historical practices and losses, as well as modern incidents of lost equipment, continue to contribute to environmental degradation. Carefully managing human activities in the region, as well as employing evolving technology to reduce our impact, may represent the best chance we have to slow the ongoing degradation of this once pristine wilderness. In light of the findings of this research, national operators and policy makers may wish to consider the following recommendations.

- To help understand cumulative scientific impacts upon the Antarctic environment, national Antarctic programmes should ensure details of any lost equipment are recorded and made available, potentially as part of their organisational environmental management system (EMS). Actions should then be taken to prevent the reoccurrence of events that led to equipment losses (e.g., improved management systems, better securing of equipment under windy conditions, etc.).
- National Antarctic programmes should raise awareness within their personnel of the need to report incidents of lost equipment, e.g., through their pre-deployment training and through their post-season review of Antarctic projects whereby irretrievable unintentional deployments not recorded in the original EIA can be captured retrospectively and inform planning of future projects.
- Each year, Antarctic Treaty Parties should make appropriate efforts to submit to the Antarctic Treaty Secretariat's Electronic Information Exchange System (EIES) details of equipment lost to the environment, including location information (see: https://www.ats.aq/e/exchange-requirements.html).
- Environmental managers and researchers should be further encouraged to work together to minimise the level and range of impacts

associated with specific research projects (including the quantity of equipment intentionally lost to the Antarctic environment).

- During the publication of research findings from Antarctica fieldwork in peer-reviewed journals, researchers should be encouraged to provide details of equipment losses and substantial environmental impacts resulting from their field activities (as demonstrated by many of the researchers whose studies are quoted in this paper).
- EIAs should be undertaken either before, or as soon as possible after, a science project is approved for funding to ensure the levels of environmental impact are minimised at an early stage of planning. If need be, consideration should be given by the national competent authority to withholding the permit for the proposed project if the likely impact is deemed to be too great.
- The Antarctic Treaty Parties, possibly with input from SCAR, should consider developing guidelines to help national competent authorities ensure that the likely impacts resulting from planned research are commensurate with the anticipated scientific benefits.
- Given that substantially greater environmental impacts commonly result from the construction of research stations and other operational facilities (runways, wharfs, etc.), compared with the loss of equipment resulting from field research activities, Parties should be encouraged to operate their research out of existing stations, where possible, in an effort to reduce the development of new infrastructure and thereby minimise Antarctic habitat loss and environmental damage.

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Kevin A. Hughes: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Visualization, Writing – review & editing. **Claire P. Boyle:** Investigation, Data curation, Visualization. **Kate Morley-Hurst:** Investigation. **Laura Gerrish:** Visualization. **Steve R. Colwell:** Investigation. **Peter Convey:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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