Identifying marine invasion threats and management priorities through introduction pathway analysis in a remote sub-Antarctic ecosystem

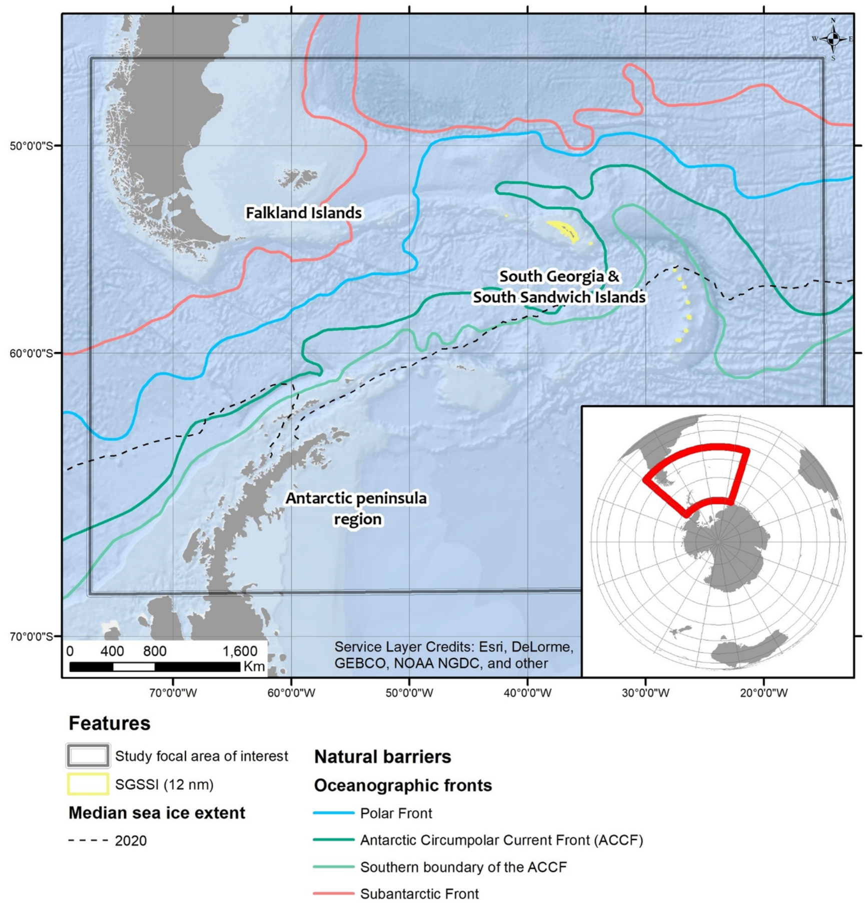
Dan Bayley[1], Paul Brewin[2], Ross James[3], Arlie McCarthy[4], and Paul Brickle[2]

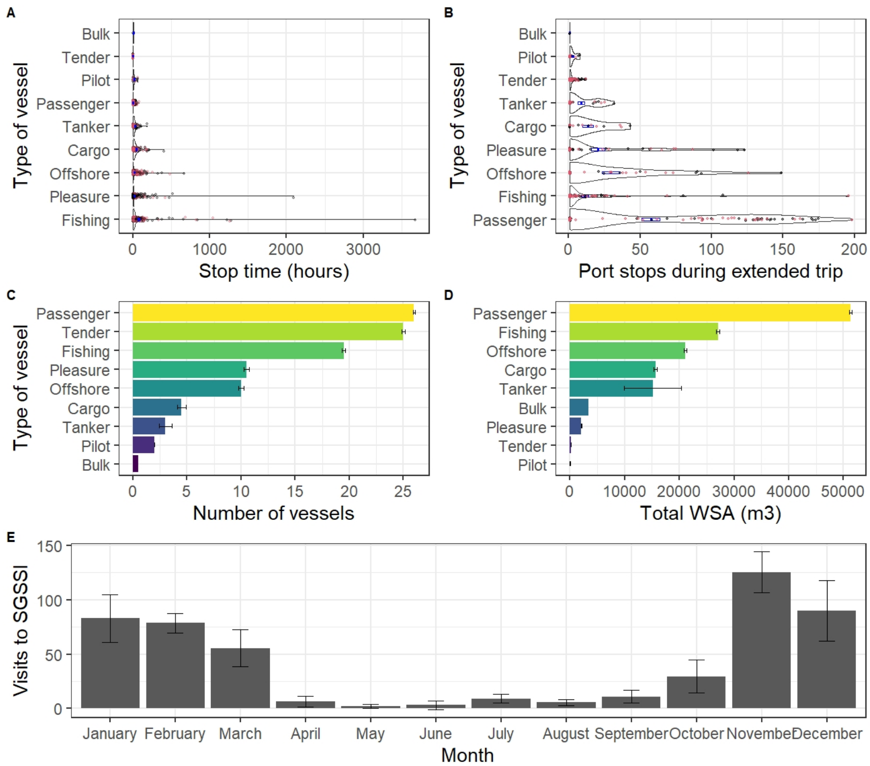
[1]University College London
[2]South Atlantic Environmental Research Institute
[3]Government of South Georgia & the South Sandwich Islands
[4]Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research

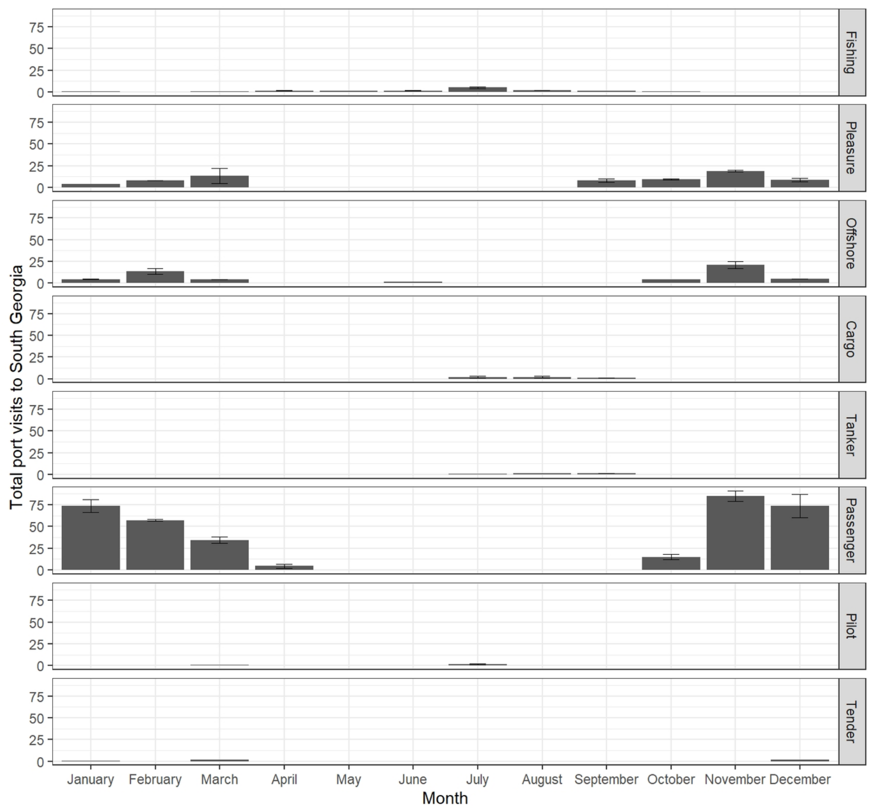
April 20, 2024

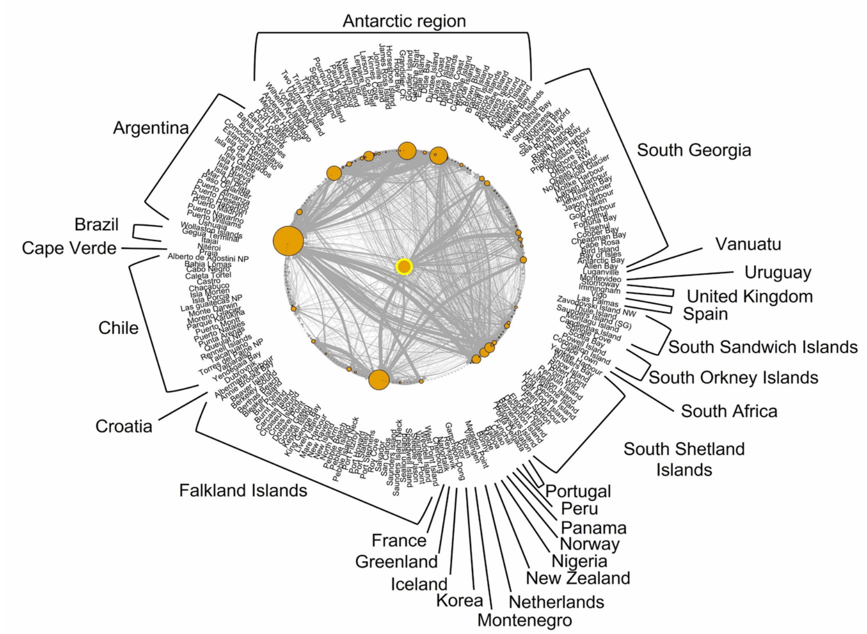
Abstract

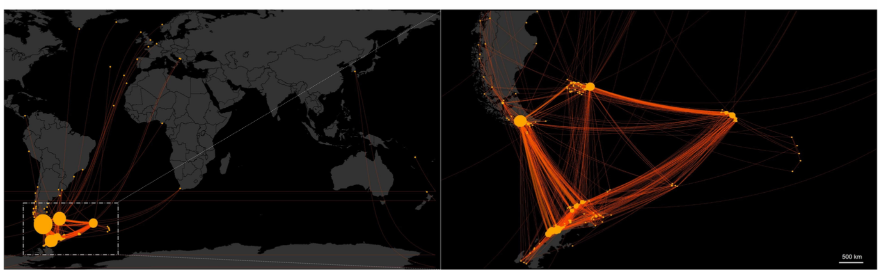
The threat from novel marine species introductions is a global issue. When Non-native marine species are introduced to novel environments and become invasive, they can affect biodiversity, industry, ecosystem function, and both human and wildlife health. Isolated areas with sensitive or highly specialised endemic species can be particularly impacted. The global increase in the scope of tourism activities together with a rapidly changing climate, now put these remote ecosystems under threat. In this context, we analyse invasion pathways into South Georgia & the South Sandwich Islands (SGSSI) for marine non-native species via vessel biofouling. The SGSSI archipelago has high biodiversity and endemism, and has historically been highly isolated from the South American mainland. The islands sit just below the Polar Front temperature boundary, affording some protection against introductions. However, the region is now warming and SGSSI increasingly acts as a gateway port for vessel traffic into the wider Antarctic, amplifying invasion likelihood. We use remote AIS vessel-tracking data over a two-year period to map vessel movement and behaviour around South Georgia, and across the 'Scotia Sea', 'Magellanic', and northern 'Continental High Antarctic' ecoregions. We find multiple vessel types from locations across the globe frequently now enter shallow inshore waters and stop for prolonged periods (weeks/months) at anchor. Vessels are active throughout the year and stop at multiple port hubs, frequently crossing international waters and ecoregions. Management recommendations to reduce marine invasion likelihood within SGSSI include initiating benthic and hull monitoring at the identified activity/dispersion hubs of King Edward Point, Bay of Isles, Gold Harbour, St Andrews Bay and Stromness Bay. More broadly, regional collaboration and coordination is necessary at neighbouring international ports. Here vessels need increased pre- and post-arrival biosecurity assessment following set protocols, and improved monitoring of hulls for biofouling to pre-emptively mitigate this threat.

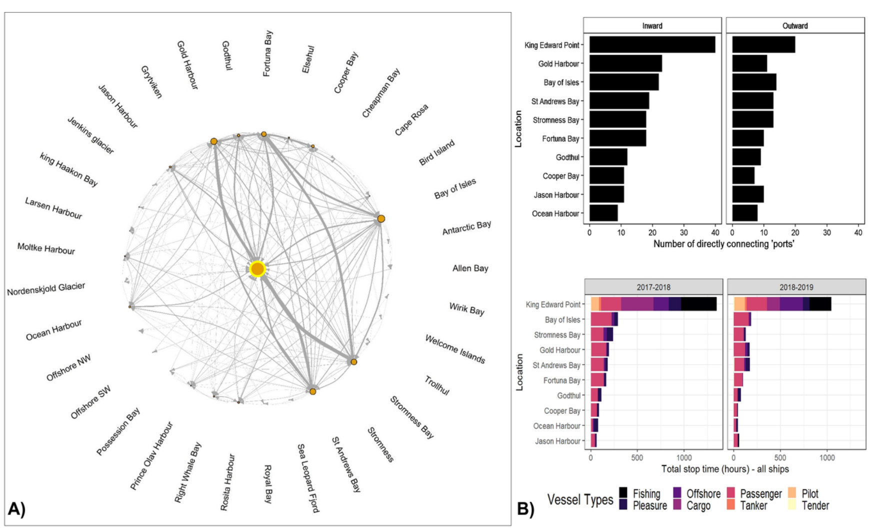

Falkland Islands
South Georgia &
South Sandwich Islands
Antarctic peninsula
region
50°0'0"S
60°0'0"S
70°0'0"S
70°0'0"W
60°0'0"W
50°0'0"W
40°0'0"W
30°0'0"W
20°0'0"W
0 400 800 1,600
Km
Service Layer Credits: Esri, DeLorme, GEBCO, NOAA NGDC, and other
Features
Study focal area of interest
SGSSI (12 nm)
Median sea ice extent
2020
Natural barriers
Oceanographic fronts
Polar Front
Antarctic Circumpolar Current Front (ACCF)
Southern boundary of the ACCF
Subantarctic Front


A
Type of vessel
Bulk
Tender
Pilot
Passenger
Tanker
Cargo
Offshore
Pleasure
Fishing
0
1000
2000
3000
Stop time (hours)
B
Type of vessel
Bulk
Pilot
Tender
Tanker
Cargo
Pleasure
Offshore
Fishing
Passenger
0
50
100
150
200
Port stops during extended trip
C
Type of vessel
Passenger
Tender
Fishing
Pleasure
Offshore
Cargo
Tanker
Pilot
Bulk
0
5
10
15
20
25
Number of vessels
D
Passenger
Fishing
Offshore
Cargo
Tanker
Bulk
Pleasure
Tender
Pilot
0
10000
20000
30000
40000
50000
Total WSA (m3)
E
Visits to SGSSI
150
100
50
0
January
February
March
April
May
June
July
August
September
October
Novembe
December
Month


Fishing
Pleasure
Offshore
Cargo
Tanker
Passenger
Pilot
Tender
75
50
25
0
Total port visits to South Georgia
January
February
March
April
May
June
July
August
September
October
November
December
Month


Antarctic region
Argentina
Brazil
Cape Verde
Chile
Croatia
Falkland Islands
France
Greenland
Iceland
Korea
Montenegro
Netherlands
New Zealand
Nigeria
Norway
Panama
Peru
Portugal
South Shetland Islands
South Africa
South Orkney Islands
South Sandwich Islands
Spain
United Kingdom
Uruguay
Vanuatu
South Georgia


500 km


Gold Harbour
Godthul
Fortuna Bay
Elsehul
Cooper Bay
Cheapman Bay
Cape Rosa
Bird Island
Bay of Isles
Antarctic Bay
Allen Bay
Wirik Bay
Welcome Islands
Trollhul
Stromness Bay
Stromness
St Andrews Bay
Sea Leopard Fjord
Royal Bay
Rosita Harbour
Right Whale Bay
Prince Olav Harbour
Possession Bay
Offshore SW
Offshore NW
Ocean Harbour
Nordenskjold Glacier
Moltke Harbour
Larsen Harbour
king Haakon Bay
Jenkins glacier
Jason Harbour
Grytviken
A)
Inward
Outward
Location
King Edward Point
Gold Harbour
Bay of Isles
St Andrews Bay
Stromness Bay
Fortuna Bay
Godthul
Cooper Bay
Jason Harbour
Ocean Harbour
Number of directly connecting 'ports'
2017-2018
2018-2019
Total stop time (hours) - all ships
B)
Vessel Types
Fishing
Pleasure
Offshore
Cargo
Passenger
Tanker
Pilot
Tender

Locations	**Higher values infer:**
Total number of visits	↑ Likelihood of initial introductions
Overall WSA within port	↑ hull substrate area for biofouling & transport
Period of time stoppped at anchor	↑ likelihood of settlement, establishment and dispersal
Number of identified links to port	↑ likelihood of introduction and dispersal
Number of identified links from port	↑ likelihood of dispersal
Number of vessel types using port	↑ likelihood of introduction
Vessels	**Higher values infer:**
Total vessel number present	↑ Likelihood of initial introductions
Total WSA (m^2)	↑ hull substrate for biofouling & transport
Maximum number of extended 'journeys'	↑ likelihood of biofouling & dispersal. ↓likelihood of hull cleaning
Maximum number of stops during extended 'journey	↑ likelihood of introduction and dispersal
Total months of activity	↑ likelihood of biofouling, dispersal, & survival over more months ↓likelihood of hull cleaning
Average stop time at port (hours) - within study area	↑ likelihood of settlement, establishment and dispersal
Total number of 'countries of origin'	↑ likelihood of novel introduction and dispersal
Maximum number of trans-national trips	↑ likelihood of novel introduction and dispersal

	Bulk		Cargo		Fishing		Offshore		Passenger		Pilot		Pleasure (Yachts)		Tanker		Tender	
Annual values by vessel type	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Vessel number	0.5	(0-1)	4.5	(4.1-4.9)	19.5	(19.3-19.7)	10	(9.8-10.2)	26	(25.9-26.1)	2	(2-2)	10.5	(10.2-10.8)	3	(2.4-3.6)	25	(24.8-25.2)
Cumulative WSA (m^2)	3429	(0-6858)	15678	(15392-15964)	27084	(26767-27401)	21152	(20908-21397)	51259	(50997-51522)	47	(28-65)	2126	(2045-2208)	15174	(9968-20379)	248	(248-248)
Number of extended 'journeys'	2	(0-4)	1.8	(1.3-2.2)	2.3	(2-2.7)	1.9	(1.6-2.2)	2	(1.9-2)	2.5	(0.8-4.2)	2.3	(2-2.7)	3.3	(1.6-5)	2	(1.8-2.1)
Number of stops during extended 'journey'	1	(1-1)	13.6	(6.2-20.9)	11.4	(6-16.8)	29.4	(16.8-42)	57.5	(44.8-70.2)	2.8	(1-4.6)	20.6	(10.9-30.2)	8.6	(3.9-13.3)	2.5	(2-3)
Stop time at port (hours) - within study area	6.5	(1.5-11.5)	45.1	(31.8-58.5)	71.4	(45-97.7)	19.4	(15.5-23.2)	4	(3.9-4.2)	15.3	(3.3-27.2)	19.7	(12.7-26.8)	24.6	(17.3-32)	1.4	(1.3-1.5)
Total number of 'countries of origin'	1	(1-1)	7	(6-8)	12	(9-15)	12	(10-14)	11	(4-18)	5	(5-5)	11	(8-14)	8	(7-9)	14	(10-18)
Number of trans-national trips	0	(0-0)	5.7	(0.3-11)	3.2	(2.1-4.2)	10.5	(6-15)	35	(32.1-37.9)	0.8	(-0.8-2.3)	7.9	(5.6-10.2)	2.7	(0.2-5.1)	1.5	(0.9-2)

Species (ranked)	Common name	Priority threat †		Depth range (m) / Max known depth	Feeding method	Substrate (Soft / Hard / Biological)	Non-larval mobility type	Life Span (years)	Maximum planktonic phase (days)	Temp range (˚C)	Salinity range (PSU)	Reproduction	Larval pelagic development	Potenital Routes
		SGSSI	FI											
*Mytilus chilensis**	Chilean mussel	○	○	< 20	Filter / suspension	S / H / B	sessile / Crawler	Up to 24 (typically <3)	180	-1.8 to 29	10 to 35	Sexual (ext)	Planktotrophic	Hull
Mytilus edulis	Blue mussel	○	○	< 20	Filter / suspension	S / H / B	sessile / Crawler	Up to 24 (typically <3)	180	-1.8 to 29	10 to 35	Sexual (ext)	Planktotrophic	Hull
Undaria pinnatifida	Asian kelp		○	5 to 25	Photosynthetic	H / B	Sessile	1	14	0 to 27	20 to 37	Sexual (ext) / sporogenesis / veeetative	Gametophytic plankton	Hull
Botryllus schlosseri	Colonial ascidian	○	○	< 200	Active suspension feeder	H / B	Sessile	<1	2	-1 to 30	14 to 44	Sexual (ext)	Lecithotrophic	Hull
Carcinus maenas	European shore crab	○	○	< 60	Predator / Scavenger	S / H / B	Crawler / Walker	3 to 5	90	-1 to 35	1.4 to 54	Sexual (int)	Planktotrophic	Hull / Ballast
Mytilus galloprovincialis	Mediterranean mussel	○	○	< 20	Filter / suspension	S / H / B	sessile / Crawler	<2	40	3 to 25	10 to 38	Sexual (ext)	Planktotrophic	Hull
Ascidiella aspersa	European sea squirt	○	○	< 20	Filter / suspension	H / B	Sessile	<2	< 2	3 to 26	12 to 40	Asexul / Sexual (ext)	Lecithotrophic	Hull
Amphibalanus amphitrite	Striped barnacle		○	< 20	Filter / suspension	H / B	Sessile	1 to 5	17	1.5 to 40	10 to 52	Sex brooding	Planktotrophic	Hull
Balanus glandula	Barnacle		○	< 20	Filter / suspension	H	Sessile	7 to 10	28	-2 to 35	14 to 70+	Sexual (int) / broadcast spawner	Planktotrophic	Hull
Codium fragile subsp. Fragile	Green sea fingers - algae	○	○	< 20	Photosynthetic	H / B	Sessile	1	-	-2 to 30	12 to 42	Sexual (ext) / sporogenesis / vegetative	Gametophytic plankton	Hull
Ciona intestinalis	Yellow sea squirt	○		< 1000	Filter / suspension	H / B	Sessile	2 to 5	7	0 to 27	12 to 40	Sexual (ext)	Lecithotrophic	Hull
Halicarcinus planatus	Decapod	○		< 270	Deposit feeder	S / H / B	Crawler / Walker	<2	80	2 to 17	5 to 60	Sex brooding	Planktotrophic	Other / Ballast / Hull
Bugula neritina	Ruby bryozoan	○		< 320	Filter / suspension	H / B	Sessile	<2	<1	4 to 30	18 to 40	Asexual / Sex brooding	Lecithotrophic	Hull
Austrominius modestus	Darwin's barnacle	○		< 20	Filter / suspension	H / B	Sessile	<2	40	4 to 21	14 to 47	Sexual (int)	Planktotrophic	Hull / Other

Identifying marine invasion threats and management priorities through introduction pathway analysis in a remote sub-Antarctic ecosystem

Authors: Daniel T.I. Bayley[1,2*], Paul. E. Brewin[1,3], Ross James[4], Arlie H. McCarthy[5,6], and Paul Brickle[1,3,7]

Correspondence author email: Daniel.bayley.14@ucl.ac.uk

Affiliations:

1. South Atlantic Environment Research Institute, Stanley, Falkland Islands
2. Centre for Biodiversity and Environment Research, University College London, Bloomsbury, London, UK
3. Shallow Marine Surveys Group, Stanley, Falkland Islands
4. Government of South Georgia & the South Sandwich Islands, Stanley, Falkland Islands
5. Helmholtz Institute for Functional Marine Biodiversity at the University of Oldenburg (HIFMB), 26129 Oldenburg, Germany
6. Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar- und Meeresforschung, 27570 Bremerhaven, Germany
7. School of Biological Sciences (Zoology), University of Aberdeen, Aberdeen, UK.

Keywords: Non-native species, Polar ecosystems, Biosecurity, Marine management, Network Analysis

ABSTRACT

The threat from novel marine species introductions is a global issue. When Non-native marine species are introduced to novel environments and become invasive, they can affect biodiversity, industry, ecosystem function, and both human and wildlife health. Isolated areas with sensitive or highly specialised endemic species can be particularly impacted. The global increase in the scope of tourism activities together with a rapidly changing climate, now put these remote ecosystems under threat. In this context, we analyse invasion pathways into South Georgia & the South Sandwich Islands (SGSSI) for marine non-native species via vessel biofouling. The SGSSI archipelago has high biodiversity and endemism, and has historically been highly isolated from the South American mainland. The islands sit just below the Polar Front temperature boundary, affording some protection against introductions. However, the region is now warming and SGSSI increasingly acts as a gateway port for vessel traffic into the wider Antarctic, amplifying invasion likelihood.

We use remote AIS vessel-tracking data over a two-year period to map vessel movement and behaviour around South Georgia, and across the ‘Scotia Sea’, ‘Magellanic’, and northern ‘Continental High Antarctic’ ecoregions. We find multiple vessel types from locations across the globe frequently now enter shallow inshore waters and stop for prolonged periods (weeks/months) at anchor. Vessels are active throughout the year and stop at multiple port hubs, frequently crossing international waters and ecoregions. Management recommendations to reduce marine invasion likelihood within SGSSI include initiating benthic and hull monitoring at the identified activity/dispersion hubs of King Edward Point, Bay of Isles, Gold Harbour, St Andrews Bay and Stromness Bay. More broadly, regional collaboration and coordination is necessary at neighbouring international ports. Here vessels need increased pre- and post-arrival biosecurity assessment following set protocols, and improved monitoring of hulls for biofouling to pre-emptively mitigate this threat.

INTRODUCTION

Marine invasive species can threaten biodiversity, industry, and both human and wildlife health (Bax et al., 2003). Invasive species can also cause significant damage to ecosystems. Biological invasions can typically cause habitat disturbance, competition, predation, induced toxicity, and genetic introgressive hybridization. In extreme cases, loss of ecosystem function, extinctions, or structural change of whole landscapes can occur (Jeschke et al., 2014; Ricciardi and Cohen, 2007; Simberloff et al., 2011). The process leading to these impacts on the existing environment begin with the introduction and establishment of species in an area beyond their native ranges (Blackburn et al., 2011; Jeschke et al., 2014). Once a species has established, control and remediation measures can be very difficult and costly to both ecosystems and infrastructure (Marbuah et al., 2014). The threat from marine invasive species is a global issue, where < 16% of marine ecoregions have no reported invasions (Molnar et al., 2008), and new global primary detections of ‘aquatic non-indigenous species’ have occurred at a rate of roughly one new detection every 8.4 days for 50 years (Bailey et al., 2020). Moreover, there is often no data available to establish baselines and monitor for coastal introductions, particularly in remote locations (Varnham, 2006), meaning real introduction numbers may be higher still.

Species that arrive in new locations by anthropogenic means are considered non-native, regardless of their level of impact (Lockwood et al., 2013), yet each new introduction has the potential to become invasive. Precautionary management includes pathway-focused practices that prevent or minimise the introduction of any non-native species. Non-native species can be introduced to new marine environments through a range of pathways, with major dispersal vectors including ballast water release, biofouling of hulls and internal seawater systems, and equipment contamination (Bax et al., 2003; Molnar et al., 2008; Bailey et al., 2020; Davidson et al., 2021). The Antarctic and sub-Antarctic regions are some of the most remote and inaccessible locations on Earth, and were once thought to be essentially impenetrable to marine non-native species due to the remoteness and extreme environments, but this region’s climate and accessibility is now rapidly changing (Chown et al., 2012; Clarke et al., 2005; Hughes et al., 2020; McCarthy et al., 2022, 2019). The risk from future introductions and successful establishments is considered greatest for northerly areas that are warmer and closer to a mainland, such as the archipelago of South Georgia (Chown et al., 2012; Hughes et al., 2020).

The threat of non-native species introduction and dispersal through ballast water exchange (Lewis et al., 2003; McCarthy et al., 2019; Dulière et al 2022) is globally regulated (though not strictly implemented) through the IMO Ballast Water Management Convention (IMO, 2004), and recommendations specifically for the polar regions are outlined in the Antarctic Ballast Water Guidelines (IMO, 2007). These guidelines require exchange or release of ballast waters offshore (north of either the Polar Frontal Zone or 60°S, and at least 200 nautical miles from the nearest land). Regular maintenance is also required, alongside log-keeping, and internal mitigation treatment. However, the other major introduction pathways, biofouling on hulls and within internal seawater systems, are still largely unmitigated aside from broad guidance such as the IMO Biofouling Guidelines (IMO, 2011). This represents a significant unmanaged potential threat to marine biodiversity in this region (Bailey, 2015; Bax et al., 2001).

The Scotia Sea ecoregion (Spalding et al., 2007) is made up of South Georgia & the South Sandwich Islands (SGSSI), the Antarctic Peninsula, South Orkney, and the South Shetland Islands. This ecoregion has few historical recordings of non-native species within their territorial areas, and these are almost entirely terrestrial non-native species (Frenot et al., 2005). However, there have now been multiple observations of non-native marine algae and invertebrates within the nearby Antarctic peninsula region (Cárdenas et al., 2020; McCarthy et al., 2019), and the first record of an established marine non-native within South Georgia waters was recently recorded (Mrwowicki and Brodie, 2023). A number of studies indicate that low-level passive dispersal of marine non-native species occurs (Brasier et al., 2021; Avila et al. 2020), with increasingly frequent transport of species to the archipelago through rafting on kelp or plastic (Convey and Peck 2019; Fraser et al., 2018; Griffiths and

Waller, 2016). However, the majority of current introductions to this region are likely facilitated through active transport between locations via vessels through biofouling or through poorly maintained, emergency, or illegal vessel ballast release (McCarthy et al., 2022). Despite this, little is currently known about the exact routes, frequency, and composition of vessel traffic into this ecoregion, or which vessels' movement behaviours are more likely to introduce non-native species.

SGSSI's location just south of the Polar Frontal Zone and north of the Antarctic Circumpolar Current Front (ACCF), means it acts as both a Northern and Southern range limit for many species (Griffiths et al., 2009; Hogg et al., 2011). This biogeographic isolation and the increasing number of international vessels frequently crossing the natural barrier of the fronts, makes this area at growing risk of invasion (Hughes et al., 2020; Kennicutt et al., 2019; McCarthy et al., 2019). A recent global analysis by McCarthy et al. (2022) of ship traffic travelling into the neighbouring Antarctic further found the Scotia region to have the greatest and most diverse volume of traffic passing through their port hubs, making SGSSI a key 'gateway port' location.

Here we analyse potential for marine non-native species to be introduced via ships to the currently unimpacted SGSSI through analysis of AIS (Automatic Identification System) vessel tracking. We conduct a regional-scale network analysis and spatial assessment of vessel movement across the South American sub-Antarctic (across an area of ~8.5 million km^2) to assess these potential marine introduction routes. To inform invasion mitigation and planning for this remote archipelago, we highlight major factors associated with vessel movement and behaviour that increase the potential for introductions. Finally, we set out potential biosecurity controls for inshore vessel management, and list priority sites for monitoring. These management actions aim to help protect the unique biodiversity of SGSSI's marine and coastal ecosystems. Pre-emptive management here and in neighbouring major ports to reduce invasion likelihood will be essential for safeguarding the wider Antarctic and sub-Antarctic 'wilderness'.

MATERIALS AND METHODS

Our study focuses on vessel traffic in and out of the UK Overseas Territory (UKOT) of SGSSI. To capture the connecting stops before and after arrival in SGSSI, we used vessel traffic data in an Area of Interest (AOI) that included SGSSI's ecoregion of the 'Scotia Sea', and the surrounding ecoregions of 'Magellanic' and the northern 'Continental High Antarctic'. South Georgia and the neighbouring South Sandwich Islands are relatively isolated geographically, and a large (1.24 million km^2) IUCN category VI Marine Protected Area (MPA) has also protected SGSSI administratively since 2012 (UNEP-WCMC, 2021). There is no permanent population on South Georgia or the smaller islands, and there is an average annual presence of ~40 people. Small settlements are located in Grytviken and King Edward Point (on South Georgia), and on neighbouring Bird Island.

Our work focuses on the analysis of vessel movement patterns using Automatic Identification System (AIS) tracking data. AIS data were assessed over a 2-year period (running 1st July 2017 to 30th June 2019), from austral winter to austral winter, at an hourly resolution. Hourly resolution was chosen to limit the number of position reports, while maintaining critical movement and behavioural information. The data therefore details the path that was travelled by each vessel when underway (speed > 0.2 knots) and any stop locations (≤ 0.2 knots or moving < 400 m over 1 hour), following standard 'transit simplification' data cleaning recommendations from MMO (2013).

A two-year period was chosen to ensure any anomalies associated with any particular year were accounted for. Results are therefore mean averages over the two years. Data were analysed for all vessels with AIS transmissions, within a defined Area of Interest (AOI), ranging from 68.5° S to 45° S latitude, and 77° W to 15° W longitude (Figure 1). International Maritime Organization (IMO) regulations requires AIS to be fitted onboard: 1) all ships of 300 gross tonnage and upwards engaged on international voyages; 2) cargo ships of 500 gross tonnage and upwards not engaged on international voyages; and 3) all passenger ships irrespective of size (IMO, 2021).

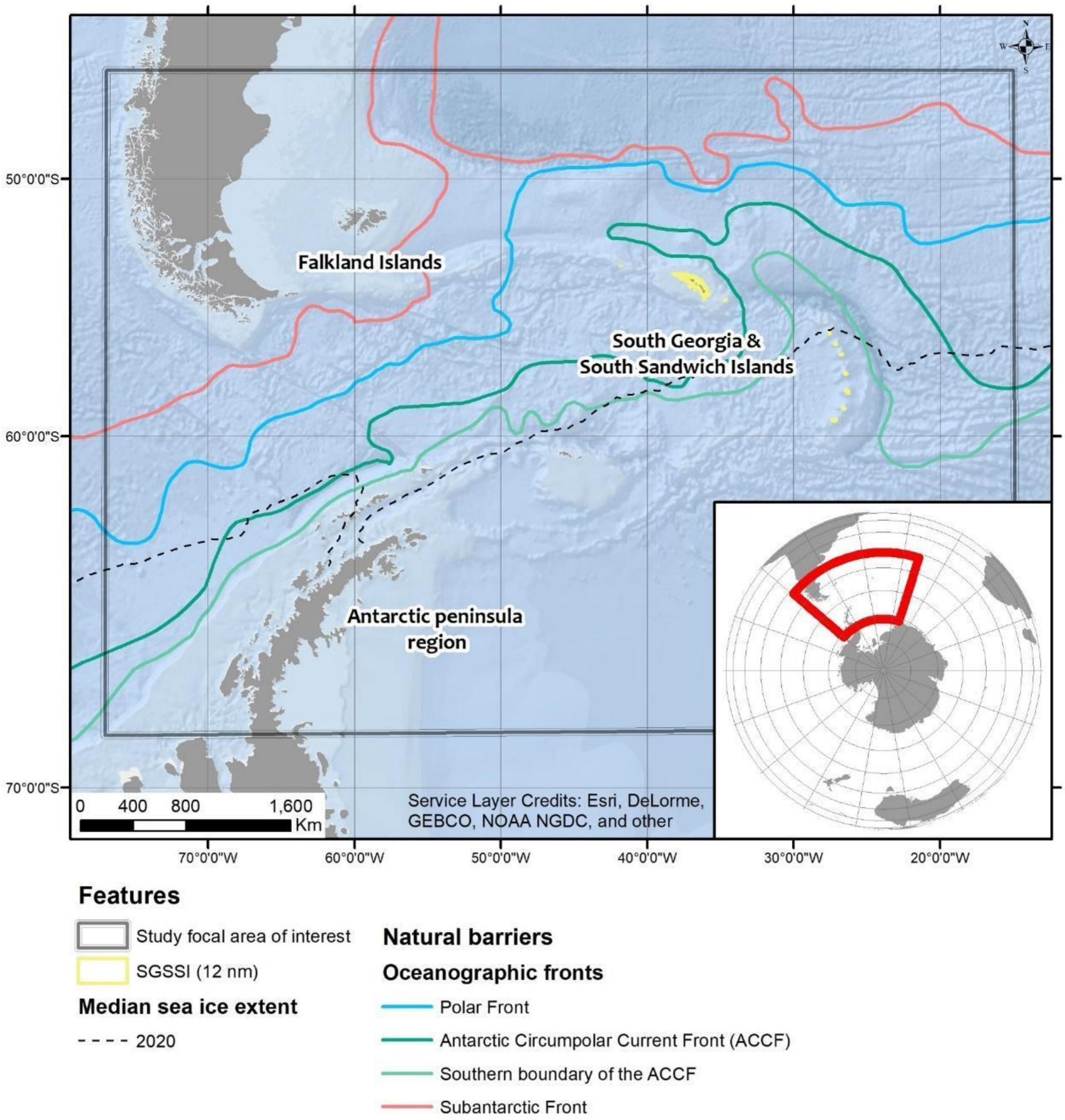


Figure 1. Map detailing study area of interest for analysis of vessel movement in and out of South Georgia and the South Sandwich Islands' waters. Key features: Study focal area i.e. Automated Identification System (AIS) data extent for period July 2017-2019), winter sea-ice extent (2020), and major regional oceanographic current fronts.

Data attributes used in the analysis included vessel Maritime Mobile Service Identity (MMSI) number, IMO number, and vessel name. Movement details included: Time stamp (UTC date and time); Latitude & Longitude (WGS84, DGPS, Loran-C); Course (degrees); Status (e.g. moored, underway); Speed in knots; and (vessel-specified) major port of origin. Vessel dimension data included: 'Length overall' (L_{OA}) in m; 'Breadth overall' (B_{OA}) in m; Volume / 'Gross Tonnage' (V); Dead Weight Tonnage (DWT);

Draft (T) in m, and Vessel type (Bulk, Cargo, Fishing, Offshore, Passenger, Pilot, Pleasure, Tanker, and Tender). Data was supplied by 'BigOceanData' (https://www.bigoceandata.com).

Data cleaning and node definition

Data were initially cleaned and filtered to remove any points associated with vessels (classed by unique MMSI codes) which never enter within the SGSSI Maritime Zone (200 nm limit). 'Nodes' (spatial clustering of vessel activity signifying ports or temporary anchorages) were created following Letschert et al., (2021), whereby we use the 'Geosphere' package (Haversine function) in R (version 4.1.1 / RStudio v1.4.1717) to calculate the sequential AIS point-to-point distances for each vessel within the AOI, from the raw hourly AIS signal data over time. Using these individual-vessel sequentially occurring point-to-point distances, the data was then filtered to only include stationary vessels (i.e. anchored / moored / at port etc. which are therefore likely to present higher propagule release in that location). Stationary vessels were defined as those moving < 400 m over 1 hour (equivalent to a speed of ~0.2 knots, as per MMO, (2013) guidance), and with an AIS 'Speed' classification of < 1 knot. The combination of these two variables ensured that the analysis only included vessels at anchor or stationary holding position, and accounted for any potential signal errors in either one of the location or speed attributes.

We created network nodes for all clusters of stationary vessels within 12 nm of land. All buffers were created using a World Azimuthal Equidistant projection. We created network nodes using a 5 km buffer, based on clustering of stationary vessels, and linked these locations to closest major ports, known anchorage, or geographic features. Buffers were spatially joined to vessel stop points to link location to event. Unique vessel 'events' (extended stationary periods in time for a vessel > 1 hour) were calculated based on cumulative time stopped at a location for each vessel (over a unique continuous period of time). We limited the analysis to prolonged stationary periods rather than all passing traffic as longer periods at port are known to increase the opportunities for organisms to both attach to hull surfaces and for them to spread into the new environment (Sylvester et al., 2011). In addition to nodes created inside the AOI, if vessel-specified 'port of origin' data was different to the known origin node identified through AIS point analysis (i.e. outside the AOI), we used this data to identify broader global port links. This amalgamation of data types gives a clearer picture of pathways into the region. It is however important to note there may have been intermediate stops in between the stated origin port and the time the vessel enters our AOI. All locations in the study were also assigned to a recognised country or territory in order to group regional activity.

Network analysis & route (edge) definition

Networks were created using the 'igraph' package in R (Csardi and Nepusz, 2006) to visualise vessel route linkages (edges) between all vessel anchorages (nodes) and compute the frequency of journeys to and between them by vessels. Network node size was based on the total number of visits during the study period. Edge connection routes and 'weight' were calculated based on the frequency of unique vessel trips along each port-to-port route. The factors included here (Table 1), such as number of ports / regions visited, and period of time in transit (i.e. without hull cleaning) are known key factors increasing colonization pressure i.e. invasion potential from accumulated new species (McCarthy et al., 2019; Davidson et al., 2016; Sylvester et al., 2011). It is important to note however that hull condition (i.e. frequency of cleaning and therefore level of biofouling) is not known for any vessel in this analysis, based on this dataset. While factors including hull condition, biofouling species composition, and environment characteristics of start and end port etc are also important considerations affecting colonization pressure we had to limit this analysis to factors based on vessel design and movement behaviour. Length of time travelling without prolonged periods at rest in port is therefore used as an indicative proxy of this unknown biofouling extent element.

Table 1. Study factors known to increase the likelihood of non-native species introduction, spread, settlement and establishment. Factors split between location (i.e. applied to certain ports / anchorages) and vessels (i.e. applied to all vessels, split by type). Values calculated for annual periods and applied solely to the study 'area of interest'. Refer McCarthy et al., 2019 & Davidson et al., 2016 for more details on types and mechanisms of known high-risk factors.

Locations	**Higher values infer:**
Total number of visits	↑ Likelihood of initial introductions
Overall WSA within port	↑ hull substrate area for biofouling & transport
Period of time stoppped at anchor	↑ likelihood of settlement, establishment and dispersal
Number of identified links to port	↑ likelihood of introduction and dispersal
Number of identified links from port	↑ likelihood of dispersal
Number of vessel types using port	↑ likelihood of introduction
Vessels	**Higher values infer:**
Total vessel number present	↑ Likelihood of initial introductions
Total WSA (m^2)	↑ hull substrate for biofouling & transport
Maximum number of extended 'journeys'	↑ likelihood of biofouling & dispersal. ↓likelihood of hull cleaning
Maximum number of stops during extended 'journey	↑ likelihood of introduction and dispersal
Total months of activity	↑ likelihood of biofouling, dispersal, & survival over more months ↓likelihood of hull cleaning
Average stop time at port (hours) - within study area	↑ likelihood of settlement, establishment and dispersal
Total number of 'countries of origin'	↑ likelihood of novel introduction and dispersal
Maximum number of trans-national trips	↑ likelihood of novel introduction and dispersal

Wetted Surface Area analysis

Wetted Surface Area (WSA) is a key metric which represents the potential of a boat's hull to transport marine species which settle over time (Moser et al., 2016). Wetted Surface Area (WSA) was calculated for each unique vessel (unique MMSI) following the method by Moser et al. (2016), using the Denny-Mumford WSA regression formula, and grouping vessels using the nine standard classes (Bulk, Cargo, Fishing, Offshore, Passenger, Pilot, Pleasure (Yachts), Tanker, and Tender). The 'Pleasure' vessel category incorporates both yachts and small motorised crafts (ranging from 14-69 m in overall length in our study). As Moser et al. (2016) did not include small yachts / pleasure crafts, WSA calculations for pleasure vessels < 26 m L_{OA} followed Bakker & van Vlaardingen, (2017) also using the Denny-Mumford formula (WSA = 1.7 · LOA · T + V / T). Larger pleasure vessels used values from the 'fishing vessel' category from Moser et al. (2016). 'Service' vessels were split into 'Pilot' or 'Tender' vessel types. 'Offshore' vessels were entirely composed of research vessels and followed the 'Other' category from Moser et al. (2016).

WSA calculations used the equation $WSA = a\ DWT^{b}$, with 'a' = regression coefficient, 'b' = regression exponent, and 'DWT' = Dead Weight Tonnage (Moser et al., 2016). If DWT values were unavailable for 'Fishing vessels', 'Tugs and supply', and 'Passenger ships', vessel 'Breadth Overall' (B_{OA}) was used (with corresponding regression values). For 'Other ships', vessel 'Length Overall' (L_{OA}) was used (with corresponding regression values). All individual tenders were classed as having 9.9 m^2 WSA, based on Bakker & van Vlaardingen, (2017) values for vessels 4-6 m in length.

Relative threat from different vessel types

This analysis assumes equal levels of hull maintenance and condition for all vessels, as monitoring and assessment is not currently underway. The work in this sense is based on a scenario for this region in which all vessel hulls have some (uniform) degree of biofouling, and therefore each vessel has the potential to spread non-native species propagules based on the size of that vessel and its behaviour alone. All vessels are assumed to comply with ballast water exchange regulation (outside of South Georgia waters), and this potential release of propagules from ballast water is therefore not a focus of the assessment. Further, by including WSA, this aspect of analysis explicitly differentiates biofouling on different vessel classes only in relation to hull fouling. While larger vessels typically have more extensive internal seawater systems, the wetted area within such systems has not explicitly been calculated or included in this study.

RESULTS

Vessel Analysis

A total of 143 unique vessels entered the SGSSI maritime zone over the study period. Of these vessels, 123 (86%) stopped within 12 nm of land (noting that the total falls to 78 vessels when excluding vessel tenders). An average total of 100 separate vessels were present within any one year. Passenger and fishing vessels, (and associated small tenders), were the most common vessel types entering within SGSSI Maritime Zone, with more passenger vessels than bulk, tanker, pilot, and cargo vessels combined (Figure 2). Similarly, cumulative wetted surface area was largest for the passenger vessels. These vessels were followed by the mid-sized vessels used for 'fishing' and 'offshore' research surveys. Despite their low frequency of occurrence, cargo and tanker vessels had a relatively high WSA due to their considerable size.

Vessels typically made a small number of extended journeys (i.e. consecutive multi-stop journeys with no prolonged intervening stop period) during each year within the AOI. Each of these journeys was followed by long periods (> 1 month) stopped at port. Tankers had the highest average number of extended journeys within a year (mean = 3.3, n = 6, range = 2-6), and cargo vessels the lowest (mean = 1.8, n = 9, range = 1-3), further data summaries shown in Appendix 1. Extended periods of inactivity were dominated by fishing and pleasure vessels (Figure 2), with some individuals of these vessel types inactive for > 4 months. Offshore survey vessels and cargo freighters likewise stayed stationary for multiple weeks. Mean stationary time at port ranged from 71.4 hours (n = 354, range = 1-3675 hours) for fishing boats, to 1.36 hours (n = 215, range = 1-4 hours) for tenders. Total port stops during extended journeys were highest for the passenger vessels (Figure 2), which had a mean average of 57.5 stops (n = 102, range = 1-198), and lowest for the bulk carrier with a mean average of 1 stop (n =2).

Vessels were present throughout the year. However, vessels start arriving inshore in abundance from October (Figure 2), corresponding to the tourist season and changes in animal activity (e.g. the arrival of penguins), reduced ice cover, and increased daylight. November was the peak period with a mean average of 126 unique visits over the two years, and mean visits each month afterwards ranged from 90 to 56 per month until April. Low activity season ranges from April to September and was at a minimum in May/June with 2-3 unique visits per month.

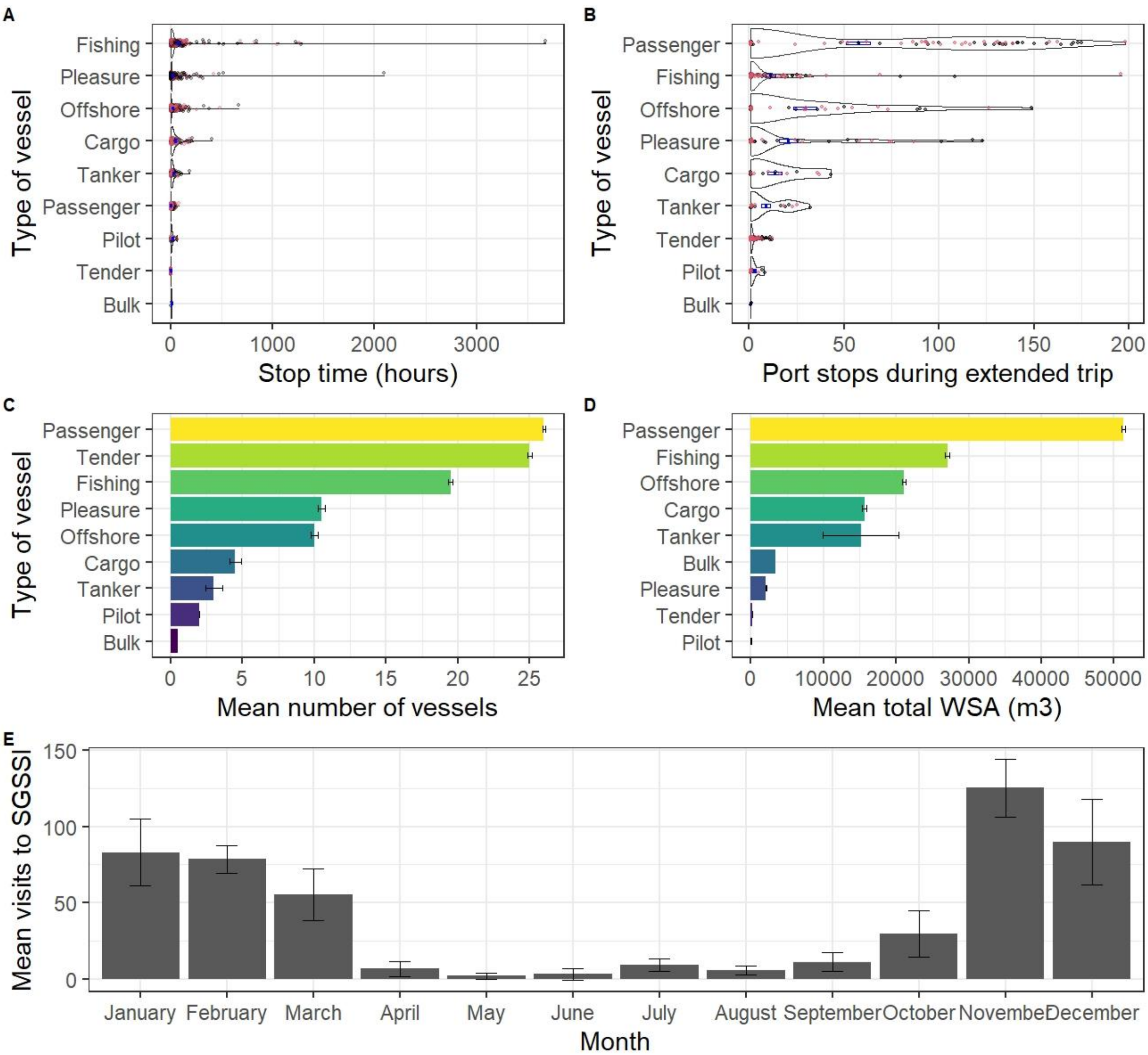


Figure 2. Figure shows violin plots of (A) the total stop time, and (B) number of separate locations stopped in during a continuous extended trip (before a rest of period of >1 month) for all vessel types. Overlaid (grey/red) points show data for 2017-2018 or 2018-2019, blue boxes detail mean ± SE. C & D show bar plots of the total number of vessels active around SGSSI and their total Wetted Surface Area (WSA) for all vessel types. (E) shows frequency of all vessel activity over the course of the year. All panels averaged across 2 years 2017-2019, for all vessels within the area of interest, centred around the Scotia Sea ecoregion. Error bars detail mean ± SE.

Breaking this activity down into vessel type, passenger vessels were most abundant (followed by pleasure yachts), and generally occurred October to March during the warmer Summer / Autumn months. Fishing vessels, while less numerous, occurred throughout the year (except summer). Similarly, research vessels occurred in all months except Spring. Tankers and cargo vessels were highly seasonal, occurring only in Spring during the analysis period (Figure 3).

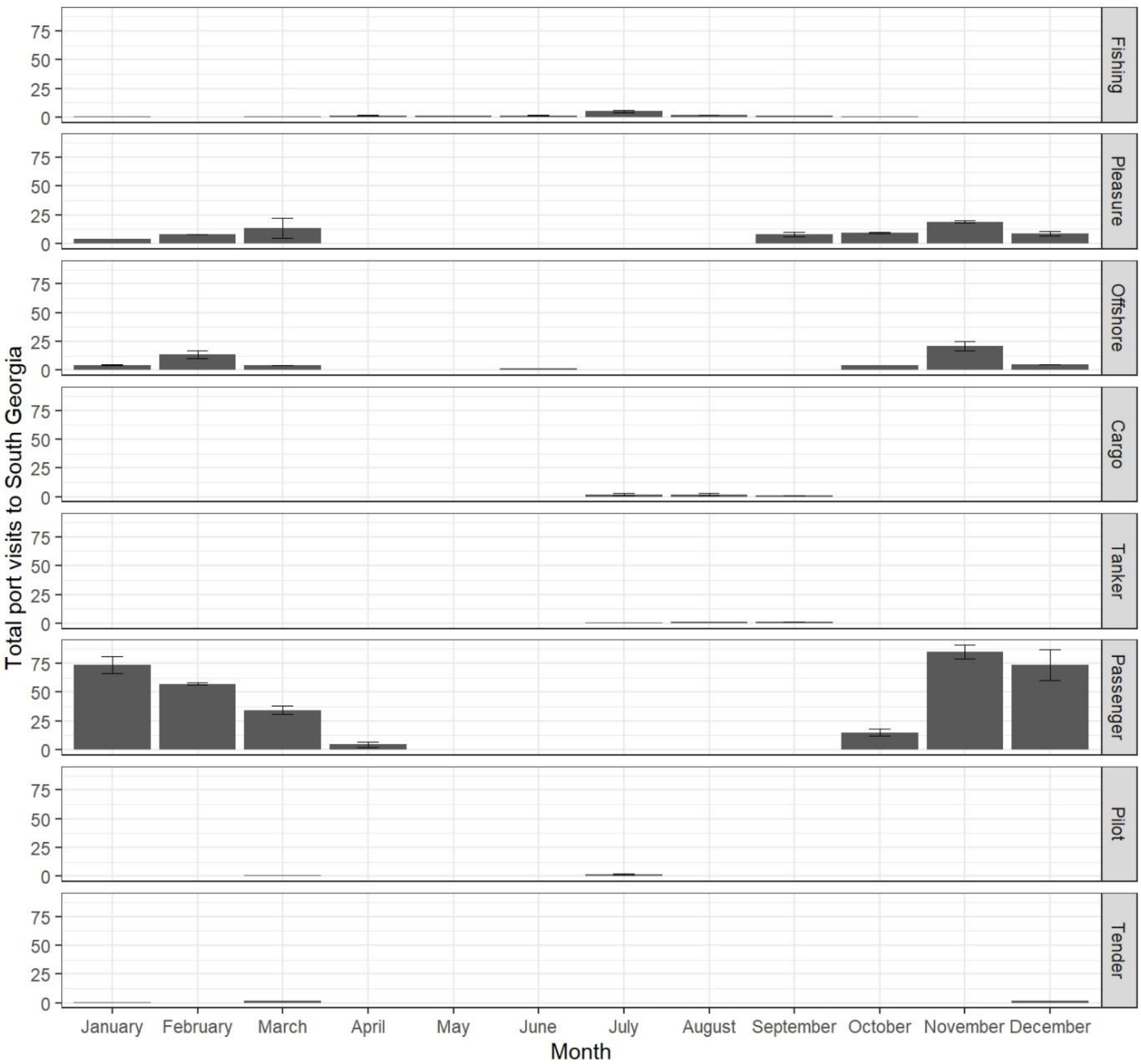


Figure 3. Figure details mean abundance of all vessel types present within SGSSI throughout the year. Data averaged for all vessels across 2 years (2017-2019). Error bars detail mean ± SE

Locations

Vessels ranged in their origin from across 29 countries / territories, with South Georgia counted separately from the South Sandwich Islands (Figure 4). The majority of journeys into South Georgia started in the Falkland Islands and the Antarctic Peninsula. For the majority of vessels, the first observation in our data (i.e. their initial known port or anchorage in their unique journey according to AIS transmission or records) was in South Georgia itself. It is important to note here however that all these vessels (aside from the pilot vessels) do typically leave South Georgia waters and return to the region at least once annually. All vessels do therefore pose a threat of introducing new species to the region and dispersing them locally or regionally. Other vessels (ranging from individual vessels to > 60 from a single country), came from a range of locations across Europe, Africa, the Pacific, Asia, central and South America, and the Arctic, primarily from South America. Most vessels entering directly into South Georgia (i.e. based on location of the last port of call before South Georgia) were from the Falkland Islands. This was followed by boats moving around from location to location within South Georgia, as well as vessels from within the local Scotia Arc region, Patagonia and the Antarctic.

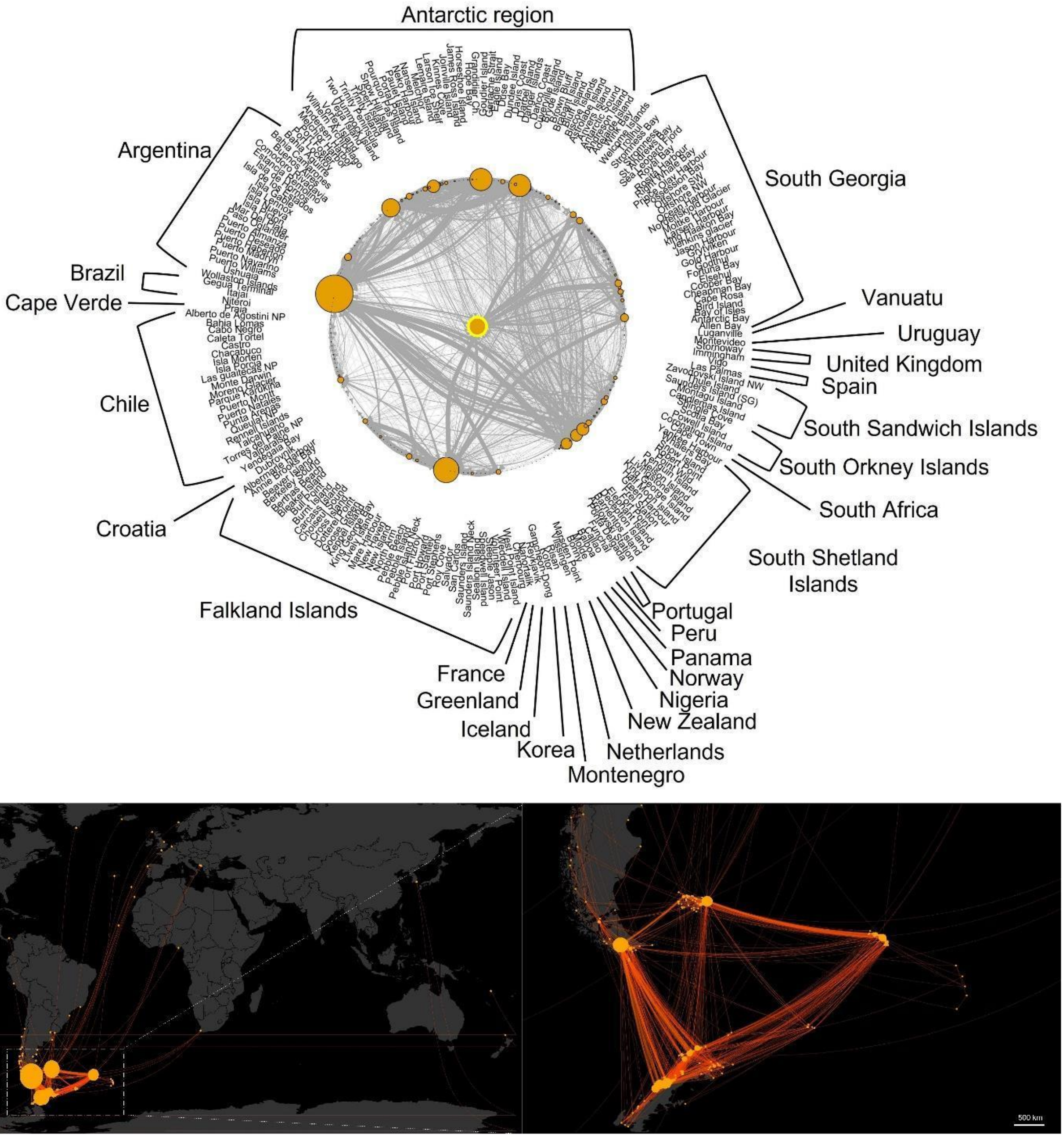


Figure 4. Countries of origin and number of vessels entering the South Georgia and South Sandwich Islands during the period 2017-2019. Within all panels, larger node (orange circles) size and edge (grey/orange lines) thickness indicates higher vessel frequency, based on known movements, averaged over 2 years. Analysis includes a total of 28 countries of origin (inclusive of the shared Antarctic Peninsula region). Top panel centre node (highlighted with a yellow ring) is King Edward Point, South Georgia. Bottom panels show idealised direct routes from port to port for each vessel within the analysis.

An additional network analysis was used to identify the top ten locations for vessel activity within SGSSI over the study period (Figure 5). King Edward Point (KEP) / King Edward Cove was busiest and had the greatest links, followed by Bay of Isles, Gold Harbour, St Andrews Bay, and Stromness Bay. The site with the greatest number of links to it was, as expected, KEP with 40 linked mooring sites / ports, followed by Gold Harbour with 23. KEP has a large number of separate visits throughout the year, by all ship types, and with these vessels averaging 10 hours stationary (up to a maximum of 159 hrs within the study period). It therefore has a high WSA of hulls from diverse origins in the water over a relatively prolonged period.

The site with most outward links was again KEP with 20 linked sites, followed by Bay of Isles with 14. The sites with the greatest number of *initial* entry / first port-of-call stops into South Georgia from other countries across the region were primarily KEP, Gold Harbour, St Andrews Bay, Cooper Bay, Bay of Isles, and Stromness Bay.

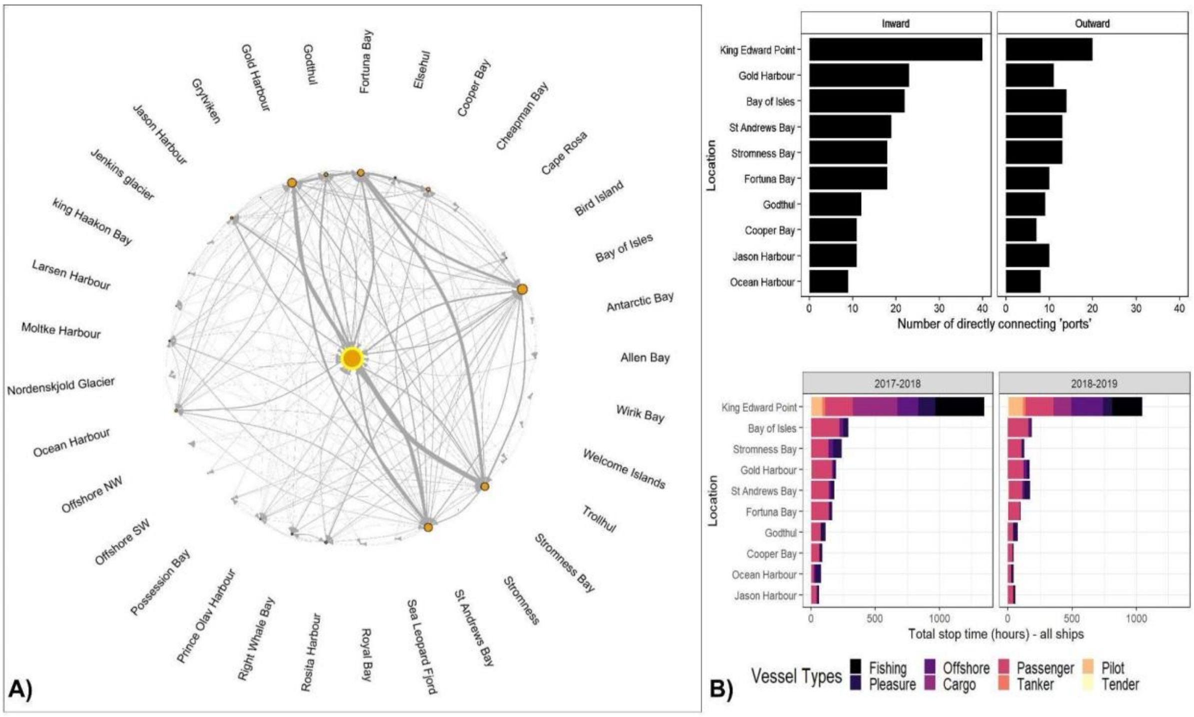


Figure 5. Figure shows: (A) Network analysis of local vessel routes, route frequency (edges) in grey and abundance of vessels (nodes) in orange at each local anchoring location within South Georgia (central orange node with yellow ring indicates King Edward Point). Data averaged across 2 years from 2017-2019; (B) Number of immediately connected port locations in and out of the 10 busiest South Georgia locations, and vessel activity at each of these 10 locations. within South Georgia.

Vessel behaviour and specification factors

Passenger vessels were highlighted as having the highest overall threat level of the vessel types entering South Georgia (Table 2, Appendix 1). This was due to having the largest average number (26, CI = 25.9-26.1) of vessels annually entering SSGGI waters, all with relatively high WSA, resulting in the largest cumulative WSA annually (51259 m^2, CI = 50997-51522) by a large margin. Passenger vessels also had the highest average number of stops in different locations during their voyages (57.5, CI = 44.8-70.2), were typically active 7 months of the year and crossed international waters an average of 35 (CI = 32.1-37.9) times between 12 different countries or territories. Passenger vessels were followed by fishing vessels, offshore survey vessels, and yachts. These were all again characterised by large vessel numbers of intermediate size, crossing between multiple countries or territories on extended journeys throughout most of the year. Tankers, pilot, and cargo vessels were of medium threat (Tankers and cargo vessels being very large, crossing multiple countries, and stopping for extended periods). Bulk carriers were low threat due to their low occurrence within SGSSI waters. Tenders were also a medium threat, but these are strongly linked to a variety of 'mother ship' vessel types. King Edward Point was the port around South Georgia with the highest likelihood of introductions across all factors. Ports with a medium likelihood of introductions were Bay of isles, Gold Harbour, St Andrews Bay and Stromness Bay (each with broadly equal likelihood across the six factors evaluated).

Table 2. Heat range map (red = highest, white = lowest) of annual mean vessel movement, and design characteristics associated with introduction of non-native species within South Georgia. Analysis is split by vessel type. All values are based on AIS data assessed over the period 2017-2019.

	Bulk		Cargo		Fishing		Offshore		Passenger		Pilot		Pleasure (Yachts)		Tanker		Tender	
Annual values by vessel type	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**
Vessel number	**0.5**	(0-1)	**4.5**	(4.1-4.9)	**19.5**	(19.3-19.7)	**10**	(9.8-10.2)	**26**	(25.9-26.1)	**2**	(2-2)	**10.5**	(10.2-10.8)	**3**	(2.4-3.6)	**25**	(24.8-25.2)
Cumulative WSA (m^2)	**3429**	(0-6858)	**15678**	(15392-15964)	**27084**	(26767-27401)	**21152**	(20908-21397)	**51259**	(50997-51522)	**47**	(28-65)	**2126**	(2045-2208)	**15174**	(9968-20379)	**248**	(248-248)
Number of extended 'journeys'	**2**	(0-4)	**1.8**	(1.3-2.2)	**2.3**	(2-2.7)	**1.9**	(1.6-2.2)	**2**	(1.9-2)	**2.5**	(0.8-4.2)	**2.3**	(2-2.7)	**3.3**	(1.6-5)	**2**	(1.8-2.1)
Number of stops during extended 'journey'	**1**	(1-1)	**13.6**	(6.2-20.9)	**11.4**	(6-16.8)	**29.4**	(16.8-42)	**57.5**	(44.8-70.2)	**2.8**	(1-4.6)	**20.6**	(10.9-30.2)	**8.6**	(3.9-13.3)	**2.5**	(2-3)
Stop time at port (hours) - within study area	**6.5**	(1.5-11.5)	**45.1**	(31.8-58.5)	**71.4**	(45-97.7)	**19.4**	(15.5-23.2)	**4**	(3.9-4.2)	**15.3**	(3.3-27.2)	**19.7**	(12.7-26.8)	**24.6**	(17.3-32)	**1.4**	(1.3-1.5)
Total number of 'countries of origin'	**1**	(1-1)	**7**	(6-8)	**12**	(9-15)	**12**	(10-14)	**11**	(4-18)	**5**	(5-5)	**11**	(8-14)	**8**	(7-9)	**14**	(10-18)
Number of trans-national trips	**0**	(0-0)	**5.7**	(0.3-11)	**3.2**	(2.1-4.2)	**10.5**	(6-15)	**35**	(32.1-37.9)	**0.8**	(-0.8-2.3)	**7.9**	(5.6-10.2)	**2.7**	(0.2-5.1)	**1.5**	(0.9-2)

Species of concern

There are currently 12 identified likely invasive species of concern for South Georgia, and 11 for the neighbouring Falkland Islands, based on a Horizon Scanning' workshop conducted in 2018 with regional experts (Roy et al. 2019), incorporated within Table 3. The marine species identified are primarily composed of fully marine invertebrate filter-feeders / omnivores, along with two types of algae and one saltmarsh grass (*Spartina* spp. excluded from this study as not spread via hull biofouling). Species' native ranges (original point of origin) are from across both the North and South Atlantic, Mediterranean, West Pacific, and sub-Antarctic regions (Roy et al. 2019; Hughes et al. 2020). All species are primarily epibenthic when adult, and are typically annual breeders with an extended larval phase, and high fecundity, originating from high Boreal/Austral or temperate marine environments. Many also demonstrate a tolerance to surviving a broad range of temperature and salinity levels (although less is known of their sustained reproductive capacity across these conditions). It is important to note that none of these species have yet been recorded in SGSSI and so there is a large amount of uncertainty regarding their real-world survival and reproduction potential, and pivotally, whether other species, not considered here, will arrive first (e.g. Mrwowicki and Brodie, 2023).

Table 3. Invasive Non-Native Species with high likelihood of arrival, establishment and impacts within the Falkland Islands and South Georgia & South Sandwich Islands. Temperatures and salinity levels based on recorded or projected species survival, rather than upper and lower reproductive / developmental thresholds (as data is limited). † Details including most likely potential pathways of arrival and the list is ranked by potential to arrive, establish, and pose a threat through biodiversity and/or economic impacts, based on (Roy *et al* 2019). Primary routes of transport also shown. * *Mytilus chilensis* based on close relative *Mytilus edulis* due to limited species-specific knowledge. Traits amalgamated from Degen & Faulwetter (2019), https://invasions.si.edu/nemesis, https://www.marlin.ac.uk/, and https://www.sealifebase.se/.

Species (ranked)	**Common name**	**Priority threat †**		**Depth range (m) / Max known depth**	**Feeding method**	**Substrate (Soft / Hard / Biological)**	**Non-larval mobility type**	**Life Span (years)**	**Maximum planktonic phase (days)**	**Temp range (˚C)**	**Salinity range (PSU)**	**Reproduction**	**Larval pelagic development**	**Potenital Routes**
		SGSSI	**FI**											
*Mytilus chilensis**	Chilean mussel	○	○	< 20	Filter / suspension	S / H / B	sessile / Crawler	Up to 24 (typically <3)	180	-1.8 to 29	10 to 35	Sexual (ext)	Planktotrophic	Hull
Mytilus edulis	Blue mussel	○	○	< 20	Filter / suspension	S / H / B	sessile / Crawler	Up to 24 (typically <3)	180	-1.8 to 29	10 to 35	Sexual (ext)	Planktotrophic	Hull
Undaria pinnatifida	Asian kelp		○	5 to 25	Photosynthetic	H / B	Sessile	1	14	0 to 27	20 to 37	Sexual (ext) / sporogenesis / vegetative	Gametophytic plankton	Hull
Botryllus schlosseri	Colonial ascidian	○	○	< 200	Active suspension feeder	H / B	Sessile	<1	2	-1 to 30	14 to 44	Sexual (ext)	Lecithotrophic	Hull
Carcinus maenas	European shore crab	○	○	< 60	Predator / Scavenger	S / H / B	Crawler / Walker	3 to 5	90	-1 to 35	1.4 to 54	Sexual (int)	Planktotrophic	Hull / Ballast
Mytilus galloprovincialis	Mediterranean mussel	○	○	< 20	Filter / suspension	S / H / B	sessile / Crawler	<2	40	3 to 25	10 to 38	Sexual (ext)	Planktotrophic	Hull
Ascidiella aspersa	European sea squirt	○	○	< 20	Filter / suspension	H / B	Sessile	<2	< 2	3 to 26	12 to 40	Asexul / Sexual (ext)	Lecithotrophic	Hull
Amphibalanus amphitrite	Striped barnacle		○	< 20	Filter / suspension	H / B	Sessile	1 to 5	17	1.5 to 40	10 to 52	Sex brooding	Planktotrophic	Hull
Balanus glandula	Barnacle		○	< 20	Filter / suspension	H	Sessile	7 to 10	28	-2 to 35	14 to 70+	Sexual (int) / broadcast spawner	Planktotrophic	Hull
Codium fragile subsp. Fragile	Green sea fingers - algae	○	○	< 20	Photosynthetic	H / B	Sessile	1	-	-2 to 30	12 to 42	Sexual (ext) / sporogenesis / vegetative	Gametophytic plankton	Hull
Ciona intestinalis	Yellow sea squirt	○		< 1000	Filter / suspension	H / B	Sessile	2 to 5	7	0 to 27	12 to 40	Sexual (ext)	Lecithotrophic	Hull
Halicarcinus planatus	Decapod	○		< 270	Deposit feeder	S / H / B	Crawler / Walker	<2	80	2 to 17	5 to 60	Sex brooding	Planktotrophic	Other / Ballast / Hull
Bugula neritina	Ruby bryozoan	○		< 320	Filter / suspension	H / B	Sessile	<2	<1	4 to 30	18 to 40	Asexual / Sex brooding	Lecithotrophic	Hull
Austrominінus modestus	Darwin's barnacle	○		< 20	Filter / suspension	H / B	Sessile	<2	40	4 to 21	14 to 47	Sexual (int)	Planktotrophic	Hull / Other

DISCUSSION

Hull biofouling is a major issue for both the maritime industry and environmental managers, as it increases ship drag and corrosion while also acting as a direct vector for dispersal of non-native marine species (Davidson et al., 2016). Dispersal of non-native species via this vector is known to be relatively high as organisms can last long periods attached to hulls and often have time to develop in warmer waters before the journey South (Hughes and Ashton, 2017; Lewis et al., 2003). While modern anti-fouling coatings can reduce the likelihood of attachment considerably, a number of species are still potentially able to persist, particularly in protected niche areas such as shafts and sea chests, on any uncoated surfaces, and on vessels that are not regularly maintained (Davidson et al., 2016; Frey et al., 2014; Lee & Chown, 2007). A range of other factors can influence survivorship of attached communities, including vessel movement behaviour and environmental conditions, as well as hull surface scour from turbulence of fast-moving vessels (Coutts et al., 2010; Lewis et al., 2003) and scour from ice (Hughes and Ashton, 2017; Lee & Chown, 2009; Lewis et al., 2003). Historically these factors such as sea temperature and ice cover have likely shielded SGSSI. However, there have been recordings of species surviving despite such scour, primarily where they are positioned on hard-to-reach niche areas that are protected from such effects, or if ice cover and/or thickness has receded, as it has around the Antarctic and sub-Antarctic region (Chown et al., 2012; Coutts et al., 2010; Hughes and Ashton, 2017; Stammerjohn et al., 2012).

Our analysis highlighted passenger vessels, fishing vessels, offshore survey vessels, and pleasure yachts as highest priority threats for the potential introduction of marine non-native species, relative to other vessel types in this analysis (Table 2). These vessels are all relatively numerous, of a mid to large size (high WSA), were active throughout most of the year, and all stop at multiple ports whilst frequently crossing international waters. Vessels also typically originate from a range of international ports, predominantly within the Scotia Sea and Magellanic ecoregions (namely within areas holding species acclimatised to similar environmental conditions).

Length of time sitting stationary in port before extended voyages is a key factor governing biofouling accumulation and establishment. The scour, cavitation, and turbulence from frequent fast movement will reduce the likelihood of both initial hull settlement and survival once settled (Coutts et al. 2010). Vessels which have prolonged stationary periods followed by multiple occasional journeys to a number of locations, such as yachts and fishing vessels are therefore more likely to introduce biofouling species (McCarthy et al., 2019; Williams et al., 2013).

In this context, the likelihood of introductions from hull biofouling is broadly equal across commercial and recreational vessels (Williams et al., 2013). However, some individual vessels will have greater funds available to conduct maintenance on a periodic schedule, or will be incentivised through improved aesthetic appearance for customers and efficiency of travel (Davidson et al., 2016). The trade-off between the streamlining benefits to the hull through regular maintenance and the cost of such maintenance to owners, will likely be the primary decision governing current levels of biofouling on each vessel in the absence of specific regulation. Furthermore, niche areas (i.e. inaccessible parts of a vessel's underwater surface more susceptible to biofouling, such as sea chests, propellers etc.) on all vessels tend to accumulate and protect species, and are often missed in basic cleaning (Davidson et al. 2016). Internal seawater systems (here considered distinct from, though connected to, sea chests) can also house high densities of marine non-native species but can be difficult and expensive to monitor and clean and are therefore often neglected (Davidson et. al. 2021). This makes them another under-researched potential route for spread of species.

The majority of vessels in this analysis came to South Georgia via intermediate stops in nearby regional locations such as South America. The likelihood of introductions from areas such as Europe or Asia is therefore considered lower. This is also due to extended travel time and varying environmental conditions from these farther away locations. However, they cannot be discounted entirely as some indirect routes may play an important role in spreading marine non-native species (Saebi et al., 2020). Furthermore, some vessels identified in the Area of Interest showed their last ports of call at locations across the globe. These vessels visited SGSSI frequently or annually and typically stayed anchored for long periods at ports and inshore areas so may still be important vectors.

Within South Georgia itself, the location with the highest likelihood of introductions was King Edward Point (KEP). KEP is the territory's administrative centre, and port at which vessels are required to call to complete Customs clearance for SGSSI waters). However, stationary vessels were clustered in seven distinct locations around the wider Cumberland Bay area adjoining KEP, primarily at Grytviken, east of King Edward Point, and north of the Greene Peninsula. KEP was also identified as an important dispersion hub to other ports for any potential non-native species as all vessels visiting South Georgia, or fishing within its waters *must* call at KEP at some point in their visit. Mandatory customs visit compliance here is currently considered to be 100%. However, vessels transiting through SGSSI waters don't need to report to KEP, but must stay outside the territory's 12 nm limit, and therefore present lower threat.

The busy anchorages of the Bay of Isles, Gold Harbour, St Andrews Bay and Stromness Bay, which have a number of route connections to other ports, will be important locations to monitor over time to assess whether introductions have occurred, and to alert management authorities to stop further spread. Importantly, the *initial* inshore anchorage within South Georgia made by new vessels is not always at the mandatory stop of KEP, particularly for Pleasure yachts and passenger cruise ships. Other locations around the island are also being frequently used as initial entry stops prior to arrival at KEP. Initial introduction to any of these identified priority locations is likely to lead to rapid spread to other locations due to their being hubs of vessel movement around the island.

Existing regional knowledge and legislation

The initial non-native species management prioritisation work completed by Roy et al. (2019) adapted in

Table 3, highlighted the likeliest novel (terrestrial and marine) species arrivals into SGSSI using the existing limited knowledge for the territory. These species are considered through expert opinion to be most likely to arrive, establish and impact the territory. Following the work, the Government of SGSSI implemented a new 'Biosecurity Audit' system over the 2018/19 season to check biosecurity procedures of visiting vessels, aiming to help facilitate effective biosecurity checks before arrival to SGSSI. Subsequently the Non-Native Species Secretariat also identified remaining gaps here and in the wider UKOTs (Key and Moore, 2019), and made recommendations for strengthening the biosecurity systems of each territory (Government of South Georgia & the South Sandwich Islands, 2019; Key, 2018). However, while terrestrial invasive species mitigation and ballast exchange protocols are in place, there is no similar current mitigation for reducing the risk of marine introductions from the hulls or internal seawater systems of visiting vessels. This should therefore be a management priority.

As discussed, the likelihood of introduction (propagule pressure) and dispersal potential of the prioritised species likeliest to arrive, and other non-native species associated with vessel biofouling, are governed by a range of factors such as condition and frequency of maintenance of the vessel, and direction of travel (Lewis et al., 2003; Sylvester et al., 2011). In response to the risks posed by vessel biofouling, the International Maritime Organisation (IMO) have created broad internationally-relevant guidelines for the control and management of ship biofouling to minimise invasive species introductions and spread (International Maritime Organisation, 2011). These guidelines are further supported at the regional level by the IMO Polar code (International Maritime Organisation, 2017). However, this guidance does not currently require mandatory cleaning before entry to the Antarctic region (including SGSSI). The guidelines currently only recommend creation of a biofouling management plan, keeping a record book, and installation and maintenance of anti-fouling systems. Along with regular in-water inspection, cleaning, and maintenance of ship hulls and submerged surfaces / systems (International Maritime Organisation, 2011). There are also separate guidelines for smaller recreational vessels < 24 m in length (International Maritime Organisation, 2012). This leaves broad scope for improvement of these regulations.

Management recommendations & future research

This analysis looks purely at the movement, behaviour and hull specifications of vessels normally entering SGSSI waters. Threat assessments from this data are therefore based on a scenario where hull condition and maintenance are considered poor enough to facilitate the introduction of non-native species. It is however likely that some individual or general vessel types are typically in better or worse condition than others. This factor will therefore strongly weigh the threat towards those vessels which have poor maintenance, even if their behaviour is considered relatively less likely to introduce non-native species. Similarly, coastal locations which receive more of these poorly maintained vessels will be under greater threat than those receiving vessels with regular cleaning or re-antifouling schedules. Assessment of actual levels of compliance, maintenance and condition for each vessel type known to enter the region is therefore essential.

Relatively little is known about the full diversity of existing native species found around the SGSSI archipelago and their natural extent (Barnes et al., 2006; Brewin and Brickle, 2010; Convey and Peck, 2019; Glon et al., 2020; Hogg et al., 2011). This baseline data is essential to highlight new non-native species and predict their effect on the native systems. A key next step will therefore be to better characterise the native baseline fauna and flora, allowing detection and monitoring of emergent non-native species. This baseline knowledge regarding species and typical vessel conditions is key to creating an effective comprehensive risk assessment, and to progressing efficient and successful management. Williams et al. (2013) shows that reducing the risk from biofouling and ballast release requires managing both large and small crafts, and from both commercial and recreational settings as they broadly carry the same typical biofouling accumulation loads and percent of non-native species. Assuming that smaller vessels are negligible risk, or that commercially managed boats are better maintained would allow these unquantified pathways to remain hazardous (Williams et al., 2013; Zabin et al., 2014). Instead, the majority of known established non-native species are associated with multiple vectors (Williams et al., 2013), therefore the key to reducing future rates of non-native species introductions is to assess all vectors and risks simultaneously, creating a prioritisation framework based on these multiple factors (Castro et al., 2021; Davidson et al., 2017; Williams et al., 2013).

Prioritisation of management and conservation actions (Giakoumi et al., 2019; Hiscock et al., 2013), as well as focussed attention on routes and sites most likely to be facilitating or receiving non-native species introductions (McGeoch et al., 2016), will be an essential management step due to the limited resources available and increasing activity across the region. This process will likely require decision-analysis to play-off multiple options, costs, practicality etc. until more data is known for vessel conditions and species presence (Esmail & Geneletti, 2018; Booy et al., 2017). For instance, vessels travelling from local – intermediate distances tend to have the highest likelihood of introduction success (Seebens et al., 2013), and vessels from similar environments are more likely to carry organisms that survive transit and establish once arrived (Holland et al., 2021; Keller et al., 2011). Within this analysis' context, 'local' areas (i.e. ~2-4000 km distance), would include Argentina, Chile, Uruguay, Brazil, South Africa. 'Intermediate' areas (i.e. ~8-10000 km distance), which are most likely to be source locations for non-native species, would be temperate African, Mediterranean and Caribbean regions. The identified high-threat vessels in our analysis such as passenger vessels, travelling from these local similar locations such as Patagonian South America and the Falkland Islands, are a management and monitoring priority. International and cross-territory collaboration will therefore be a key component of making such management decisions effective.

Little is currently known on any potential non-native's species-specific physiological tolerances to environmental changes (or ability to reproduce) either during transit to, or within the environmental extremes found within SGSSI and the sub-Antarctic, e.g. (Convey and Peck, 2019; Davenport and Macalister, 1996; Holland et al., 2021; Peck et al., 2014, 2004). These data will be a key next step in order to identify riskiest ports of origin, based on species known or predicted to come from certain locations. And also to ascertain which species are able to survive both the journey and new environment, and the consequences of their introduction to SGSSI biodiversity.

A recent study by Holland et al. (2021) suggests that likelihood of hull fouling species surviving in the environmentally-similar shallow benthic habitats near Australia's East Antarctica locations, are currently very low, but plausible. Four species (*Asterias amurensis*, *Geukensia demissa*, *Hypnea musciformis*, and *Undaria pinnatifida*) of the 33 analysed, were identified as potential current threats, and five species (adding *Charybdis japonica*) were identified as threats under future modelled climate change (Holland et al. 2021). Holland et al. (2021) further noted that other invasive species, such as *Carcinus maenas* (also identified as likely threats to SGSSI), have the ability to adapt to cold conditions well below those experienced in its native range, and therefore future modelling predictions such as theirs are likely to underestimate threat from highly plastic species. More broadly, improved knowledge of species' life-history characteristics (e.g. reproductive thermal tolerance, life span, dispersal potential), is critical to our ability to better manage, predict, and mitigate their threat (Costello et al. 2015).

Looking to the future within a rapidly changing environment, we also need to be able to project future environmental conditions in the territories over the short to mid-term, to assess which new species are likely to *become* threats from vessel introductions. This future research would need to include the fundamental niches and potential distribution of both: 1) known regional species extending their range to SGSSI; and 2) non-native species (i.e. within the Scotia Arc, Antarctica, South America, and South Africa), in order to determine likelihood of natural introductions as conditions change.

Biosecurity monitoring

Beyond predictions, the ability to rapidly detect and identify any new arrivals is essential for appropriate threat mitigation. Key monitoring locations identified in this vessel movement analysis can help to flag such new species arriving, which have not currently been identified as risks. In practice, this may initially take the form of species settlement plates at these sites to identify non-native species. Similarly, characterising which vessels are arriving from global connected ports with similar environmental envelopes to SGSSI will highlight likely origins of future introduction and management priorities (Keller et al., 2011). Establishing monitoring protocols in these nearby higher-traffic ports such as Port Stanley (Falkland Islands) and Ushuaia (Argentina) will act as a buffer to future threats. Inspection of under-researched 'niche areas', internal seawater systems, ballast water, and logbook history to identify typical levels of maintenance for this region is also important. This will allow managers to assess general compliance, effectiveness of procedures, and level of overall introduction likelihood from each vessel type, as well as check for any new species.

Overall, monitoring at the identified connected ports with highest level of threat would likely come in the form of focussed vessel inspection based on identified threat characteristics, assessment of biofouling & ballast water management documentation, and diver-based / Remotely Operated Vehicle (ROV) surveys of hulls and niche areas (Zabin et al., 2018). Such monitoring and pre-emptive actions have been used to good effect in countries such as New Zealand and Hawaii etc. where risks from marine introductions are broadly similar (Zabin et al., 2018; Georgiades et al., 2020). However, it should be noted that in SGSSI itself, this kind of monitoring outside of KEP would be complex and logistically difficult to achieve.

Study limitations

The factors used in this analysis were chosen based on existing knowledge of vessel activity behaviour and ship design that is considered to increase the likelihood of introducing non-native marine species to an environment. However, a range of additional factors exist, such as the environmental conditions at the origin and destination ports and individual species' physiological tolerances etc. These additional factors were outside this analysis but will of course affect the overall likelihood of non-native species initial arrival and establishment now and as environmental conditions change (Davidson et al., 2017; Hughes et al., 2020).

Smaller-sized yachts (pleasure vessels) active within our study region are not required to transmit AIS, and are therefore missed from the overall assessment. The threat associated with yachts (pleasure vessels) will therefore likely be higher. Similarly, AIS signals can be deliberately switched on and off, or put into ‘receive mode’, e.g. by patrol vessels, tenders, port pilot vessels, or illegal operators, or can be unintentionally lost through adverse conditions interfering with the GPS etc. These intermittent or lost signals, while rare, can cause analysis gaps or confusing analysis outputs. Some smaller yachts do not use AIS at all, causing gaps in our knowledge of their full movement and behaviour, which can only be supplemented by (more simplified) port records. Vessel AIS attributes also have the potential to change through time (i.e. vessel name and vessel type designations), or be incorrectly entered into the AIS database, meaning that these data must be treated with caution, and a degree of scepticism.

Finally, the vessels in this analysis are assumed to comply with international ballast water exchange regulations, however there is scope for emergency release, or non-compliance from some vessels.

Summary and recommendations

Initial management actions to mitigate the threat of non-native species could include introducing marine biosecurity measures as conditions of entry on fishing licences and visit permits for vessels entering SGSSI. Options applied would depend on feasibility locally, however measures might include a pre-arrival inspection at a gateway port, or a requirement for the first port-of-call on entering the SGSSI Maritime Zone to be KEP, if vessels are stopping inshore. This would allow vessel hull, internal seawater systems, and ballast-system state to be assessed. This would further limit any potential spread to one location (KEP), and would allow quarantine if needed (Hewitt and Campbell, 2007). Additional standards could be introduced to lower the likelihood of established biofouling communities arriving (Davidson et al., 2016). This might require hull cleaning to have been conducted within a set time-period, or random inspections on high-threat vessels before entry to inshore waters. This will be for the government of SGSSI to decide on details, however they may wish to follow similar voluntary or mandatory best-practice guidelines from other nearby or similar countries such as Chile, New Zealand and Australia (see GEF-UNDP-IMO, 2022 for a summary of guidelines). Australia for instance has relatively strict rules requiring vessels to have been cleaned of all biofouling within 30 days of arriving (DAWE, 2022). This also includes an active biofouling management plan and record book, and regular antifouling renewal schedule. Hull cleaning could more broadly be specified to a set international standard, protocol, or certification (when developed), and evidenced in logbooks as per current IMO ballast rules.

Mandatory customs check questions could be relatively easily expanded to include the records of each boat's history regarding last cleaning, antifouling application, recent activities and detailed trip locations within SGSSI (rather than just the current previous and next port of call requirement). This would further allow pre-border risk assessment to be conducted. Similarly, while the likelihood of introducing non-native species is relatively low for tenders, new rules may request tender hulls to have been cleaned when stowed before initially entering SGSSI inshore waters.

Optimally, these requirements would eventually meet an internationally accepted biosecurity compliance standard, regardless of flag state. These standards may potentially follow existing practice in similar archipelagos such as New Zealand, Hawaii or the Galapagos, adapting where necessary to mitigate local threats (see Georgiades et al., 2020 & GEF-UNDP-IMO, 2022 for further details on national, international, and regional biofouling regulation and management practices). Standards would need to be comprehensive to cover the risks associated with South Georgia and beyond (i.e. a regional collaborative management approach), and be feasible for enforcement before entering inshore waters. One potential option for government enforcement would then be to state mandatory compliance and enhanced procedures such as regular hull cleaning within regional agreements such as the IMO / Polar code biofouling guidelines (IMO, 2017), before entry to SGSSI waters. This would allow pre-emptive risk reduction and improve data for future management or additional tougher interventions.

Longer-term, monitoring and assessment efforts of vessels and benthos in key locations (with a priority for long-term monitoring at KEP), would begin to allow detection of any existing occurrence of identified high-risk species and establish benthic baselines. If funding is available there would also be regular site-prioritised monitoring of identified berths and seabed anchorages in the ports with the next highest likelihood of receiving non-native species. Periodic assessment of the state of the hull from randomly chosen vessels could be beneficial, prioritising high-threat vessels. In addition to hull checks, the current 'port visit reports' could require greater detail on *all* stops taken rather than only the previous and final destinations currently required.

All such management will require cross-territory and regional collaboration to ensure that particularly high-threat vessels are frequently monitored and assessed for biofouling extent before they enter into the region (McCarthy et al., 2022; McDonald et al., 2020). If vessels were therefore required to submit biofouling management plans to authorities in SGSSI as well as key regional ports, e.g. Ushuaia and Port Stanley, high-threat vessels could be identified well in advance of their arrival in SGSSI. Further, stronger biosecurity across nations in South America and the South Atlantic would encourage greater adoption of and compliance regarding biosecurity. In all cases, pre-emptive measures, which are prioritised based on risk and initiated *before* arrival, are the key to limiting the likelihood of spread and establishment of non-native species in this highly sensitive environment (Dawson et al., 2022; Booy et al., 2017; Hogg et al., 2011). These islands' high biodiversity, endemicity, and position as a key transport gateway into the Antarctic wilderness region make it a management priority (McCarthy et al., 2019).

Author's contributions

Conceptualization: DTIB, PEB, PB, RJ. Study design: DTIB, PEB, PB. Analysis & interpretation: DTIB, PEB, PB, AHM. Initial drafting & visualisation: DTIB. Acquisition of data & funding: PB, PEB. All authors reviewed the work and approved submission.

Statement on inclusion: Our study brings together authors from a number of different countries, including scientists based in the territories where the study was carried out.

Conflicts of Interest: There are no known conflicts of interest.

Acknowledgements

The authors would like to thank the Government of South Georgia & the South Sandwich Islands for funding the work. Particular thanks to Mark Belchier and Sue Gregory for their comments and advice with the work.

Data accessibility statement

The data used within this analysis contains confidential information about private vessels and their movements (through AIS transmission) and so cannot be made freely available for public view. GIS data and code available on request via the Falkland Islands Data Portal: http://dataportal.saeri.org/

References

Avila, C., Angulo-Preckler, C., Martín-Martín, R.P., Figuerola, B., Griffiths, H.J., Waller, C.L. (2020) Invasive marine species discovered on non–native kelp rafts in the warmest Antarctic island. Scientific Reports. 10, 1639 . https://doi.org/10.1038/s41598-020-58561-y

Bailey SA, Brown L, Campbell ML, Canning-Clode J, Carlton JT, Castro N, Chainho P, Chan FT, Creed JC, Curd A, Darling J, Fofonoff P, Galil BS, Hewitt CL, Inglis GJ, Keith I, Mandrak NE, Marchini A, Mckenzie CH, Occhipinti-Ambrogi A, Ojaveer H, Pires-teixeira LM, Robinson TB, Ruiz GM, Seaward K, Schwindt E, Son MO, Therriault TW, Zhan A (2020) Trends in the detection of aquatic non-indigenous species across global marine, estuarine and freshwater ecosystems: A 50-year perspective. Diversity and Distributions 26: 1780-1797. https://doi.org/10.1111/ddi.13167

Bakker, J., van Vlaardingen, P.L.A., 2017. Wetted surface area of recreational boats: RIVM Report 2017-0116. Available from: https://www.rivm.nl/bibliotheek/rapporten/2017-0116.pdf

Barnes, D.K.A., Linse, K., Waller, C., Morely, S., Enderlein, P., Fraser, K.P.P., Brown, M., 2006. Shallow benthic fauna communities of South Georgia Island. Polar Biol. 29, 223–228. https://doi.org/10.1007/s00300-005-0042-0

Bax, N., Williamson, A., Aguero, M., Gonzalez, E., Geeves, W., 2003. Marine invasive alien species: A threat to global biodiversity. Mar. Policy 27, 313–323. https://doi.org/10.1016/S0308-597X(03)00041-1

Blackburn, T.M., Pyšek, P., Bacher, S., Carlton, J.T., Duncan, R.P., Jarošík, V., Wilson, J.R.U., Richardson, D.M., 2011. A proposed unified framework for biological invasions. Trends Ecol. Evol. 26, 333–339. https://doi.org/10.1016/j.tree.2011.03.023

Booy, O., Mill, A.C., Roy, H.E., Hiley, A., Moore, N., Robertson, P., Baker, S., Brazier, M., Bue, M., Bullock, R., Campbell, S., Eyre, D., Foster, J., Hatton-Ellis, M., Long, J., Macadam, C., Morrison-Bell, C., Mumford, J., Newman, J., Parrott, D., Payne, R., Renals, T., Rodgers, E., Spencer, M., Stebbing, P., Sutton-Croft, M., Walker, K.J., Ward, A., Whittaker, S., Wyn, G., 2017. Risk management to prioritise the eradication of new and emerging invasive non-native species. Biol. Invasions 19, 2401–2417. https://doi.org/10.1007/s10530-017-1451-z

Brasier, M.J., Barnes, D., Bax, N., Brandt, A., Christianson, A.B., Constable, A.J., Downey, R., Figuerola, B., Griffiths, H., Gutt, J., Lockhart, S., Morley, S.A., Post, A.L., Van de Putte, A., Saeedi, H., Stark, J.S., Sumner, M., Waller, C.L., 2021. Responses of Southern Ocean Seafloor Habitats and Communities to Global and Local Drivers of Change. Front. Mar. Sci. 8, 109. https://doi.org/10.3389/fmars.2021.622721

Brewin, P., Brickle, P., 2010. Invasive species monitoring of South Georgia. Shallow Mar. Surv. Gr. Rep. 1, 1–12.

Cárdenas, L., Leclerc, J.C., Bruning, P., Garrido, I., Détrée, C., Figueroa, A., Astorga, M., Navarro, J.M., Johnson, L.E., Carlton, J.T., Pardo, L., 2020. First mussel settlement observed in Antarctica reveals the potential for future invasions. Sci. Rep. 10, 1–8. https://doi.org/10.1038/s41598-020-62340-0

Castro, K.L., Battini, N., Giachetti, C.B., Trovant, B., Abelando, M., Basso, N.G., Schwindt, E., 2021. Early detection of marine invasive species following the deployment of an artificial reef: Integrating tools to assist the decision-making process. J. Environ. Manage. 297. https://doi.org/10.1016/j.jenvman.2021.113333

Chown, S.L., Huiskes, A.H.L., Gremmen, N.J.M., Lee, J.E., Terauds, A., Crosbie, K., Frenot, Y., Hughes, K.A., Imura, S., Kiefer, K., Lebouvier, M., Raymond, B., Tsujimoto, M., Ware, C., Van De Vijver, B., Bergstrom, D.M., 2012. Continent-wide risk assessment for the establishment of nonindigenous species in Antarctica. Proc. Natl. Acad. Sci. U. S. A. 109, 4938–4943. https://doi.org/10.1073/pnas.1119787109

Clarke, A., Barnes, D.K.A., Hodgson, D.A., 2005. How isolated is Antarctica? Trends Ecol. Evol. 20, 1–3. https://doi.org/10.1016/j.tree.2004.10.004

Convey, P., Peck, L.S., 2019. Antarctic environmental change and biological responses. Sci. Adv. 5. https://doi.org/10.1126/sciadv.aaz0888

Costello, M.J., Claus, S., Dekeyzer, S., Vandepitte, L., Tuama, É., Lear, D., Tyler-Walters, H., 2015.

Biological and ecological traits of marine species. PeerJ 2015, 1–29. https://doi.org/10.7717/peerj.1201

Coutts, A.D.M., Piola, R.F., Taylor, M.D., Hewitt, C.L., Gardner, J.P.A., 2010. The effect of vessel speed on the survivorship of biofouling organisms at different hull locations. Biofouling 26, 539–553. https://doi.org/10.1080/08927014.2010.492469

Csardi, G., Nepusz, T., 2006. The igraph software package for complex network research. InterJournal, Complex Syst. 1695, 1–9.

Davenport, J., Macalister, H., 1996. Environmental conditions and physiological tolerances of intertidal fauna in relation to shore zonation at Husvik, South Georgia. J. Mar. Biol. Assoc. United Kingdom 76, 985–1002. https://doi.org/10.1017/S0025315400040923

Davidson, I., Cahill, P., Hinz, A., Kluza, D., Scianni, C., and Georgiades, E., 2021. A Review of Biofouling of Ships' Internal Seawater Systems. Front. Mar. Sci. 8, 1–16. doi:10.3389/fmars.2021.761531.

Davidson, A., Fusaro, A., Sturtevant, R., Kashian, D., 2017. Development of a risk assessment framework to predict invasive species establishment for multiple taxonomic groups and vectors of introduction. Manag. Biol. Invasions 8, 25–36. https://doi.org/10.3391/mbi.2017.8.1.03

Davidson, I.C., Scianni, C., Hewitt, C., Everett, R., Holm, E., Tamburri, M., Ruiz, G., 2016. Mini-review: Assessing the drivers of ship biofouling management – aligning industry and biosecurity goals. Biofouling 32, 411–428. https://doi.org/10.1080/08927014.2016.1149572

DAWE 2022, *Australian biofouling management requirements (Version 1)*, Department of Agriculture, Water and the Environment, Canberra, Australia. Available from: https://www.agriculture.gov.au/sites/default/files/documents/Australian-biofouling-management-requirements.pdf

Dawson, W., Peyton, J.M., Pescott, O.L., Adriaens, T., Cottier-Cook, E.J., Frohlich, D.S., Key, G., Malumphy, C., Martinou, A.F., Minchin, D., Moore, N., Rabitsch, W., Rorke, S.L., Tricarico, E., Turvey, K.M.A., Winfield, I.J., Barnes, D.K.A., Baum, D., Bensusan, K., Burton, F.J., Carr, P., Convey, P., Copeland, A.I., Fa, D.A., Fowler, L., García-Berthou, E., Gonzalez, A., González-Moreno, P., Gray, A., Griffiths, R.W., Guillem, R., Guzman, A.N., Haakonsson, J., Hughes, K.A., James, R., Linares, L., Maczey, N., Mailer, S., Manco, B.N., Martin, S., Monaco, A., Moverley, D.G., Rose-Smyth, C., Shanklin, J., Stevens, N., Stewart, A.J., Vaux, A.G.C., Warr, S.J., Werenkaut, V., Roy, H.E., 2022. Horizon scanning for potential invasive non-native species across the United Kingdom Overseas Territories. Conserv. Lett. 1–12. https://doi.org/10.1111/conl.12928

Degen R & Faulwetter S (2019) The Arctic Traits Database – a repository of Arctic benthic invertebrate traits, Earth System Science Data 11: 301-322. https://doi.org/10.5194/essd-11-301-2019

Dulière, V., Guillaumot, C., Lacroix, G., Saucède, T., López-Farran, Z., Danis, B., Schön, I., & Baetens, K., 2022. Dispersal models alert on the risk of non-native species introduction by Ballast water in protected areas from the Western Antarctic Peninsula. *Divers. Distrib.* 28, 649–666. https://doi:10.1111/ddi.13464

Fraser, C.I., Morrison, A.K., Hogg, A.M.C., Macaya, E.C., van Sebille, E., Ryan, P.G., Padovan, A., Jack, C., Valdivia, N., Waters, J.M., 2018. Antarctica's ecological isolation will be broken by storm-driven dispersal and warming. Nat. Clim. Chang. 8, 704–708. https://doi.org/10.1038/s41558-018-0209-7

Frenot, Y., Chown, S.L., Whinam, J., Selkirk, P.M., Convey, P., Skotnicki, M., Bergstrom, D.M., 2005. Biological invasions in the Antarctic: extent, impacts and implications. Biol. Rev. 80, 45–72. https://doi.org/10.1017/S1464793104006542

Frey, M.A., Simard, N., Robichaud, D.D., Martin, J.L., Therriault, T.W., 2014. Fouling around: Vessel sea-chests as a vector for the introduction and spread of aquatic invasive species. Manag. Biol. Invasions 5, 21–30. https://doi.org/10.3391/mbi.2014.5.1.02

GEF-UNDP-IMO, 2022. GloFouling Partnerships Project and GIA for Marine Biosafety: Compilation and Comparative Analysis of Existing and Emerging Regulations, Standards and Practices Related to Ships' Biofouling Management. Report available from: https://www.glofouling.imo.org/publications-menu

Georgiades, E., Kluza, D., Bates, T., Lubarsky, K., Brunton, J., Growcott, A., Smith, T., McDonald, S., Gould, B., Parker, N., Bell, A., 2020. Regulating Vessel Biofouling to Support New Zealand's Marine Biosecurity System – A Blue Print for Evidence-Based Decision Making. Front. Mar. Sci. 7, 1–15. https://doi.org/10.3389/fmars.2020.00390

Giakoumi, S., Katsanevakis, S., Albano, P.G., Azzurro, E., Cardoso, A.C., Cebrian, E., Deidun, A., Edelist, D., Francour, P., Jimenez, C., Mačić, V., Occhipinti-Ambrogi, A., Rilov, G., Sghaier, Y.R., 2019. Management priorities for marine invasive species. Sci. Total Environ. 688, 976–982. https://doi.org/10.1016/j.scitotenv.2019.06.282

Glon, H., Costa, M., de Lecea, A.M., Goodwin, C., Cartwright, S., Díaz, A., Brickle, P., Brewin, P.E., 2020. First record of the plumose sea anemone, metridium senile (Linnaeus, 1761), from the Falkland Islands. BioInvasions Rec. 9, 461–470. https://doi.org/10.3391/bir.2020.9.3.02

Government of South Georgia & the South Sandwich Islands, 2019. Biosecurity Handbook 2020-2021. Available from: https://www.gov.gs/docsarchive/Environment/Biosecurity/Biosecurity_Handbook.pdf

Griffiths, H.J., Barnes, D.K.A., Linse, K., 2009. Towards a generalized biogeography of the Southern Ocean benthos. J. Biogeogr. 36, 162–177. https://doi.org/10.1111/j.1365-2699.2008.01979.x

Griffiths, H.J., Waller, C.L., 2016. The first comprehensive description of the biodiversity and biogeography of Antarctic and Sub-Antarctic intertidal communities. J. Biogeogr. 43, 1143–1155. https://doi.org/10.1111/jbi.12708

Hewitt, C.L., Campbell, M.L., 2007. Mechanisms for the prevention of marine bioinvasions for better biosecurity. Mar. Pollut. Bull. 55, 395–401. https://doi.org/10.1016/j.marpolbul.2007.01.005

Hiscock, K., Bayley, D.T.I., Pade, N., Lacey, C., Cox, E., Enever, R., 2013. Prioritizing action for recovery and conservation of marine species: A case study based on species of conservation importance around England. Aquat. Conserv. Mar. Freshw. Ecosyst. 23, 88–110. https://doi.org/10.1002/aqc.2283

Hogg, O.T., Barnes, D.K.A., Griffiths, H.J., 2011. Highly diverse, poorly studied and uniquely threatened by climate change: An assessment of marine biodiversity on South Georgia's continental shelf. PLoS One 6. https://doi.org/10.1371/journal.pone.0019795

Holland, O., Shaw, J., Stark, J.S., Wilson, K.A., 2021. Hull fouling marine invasive species pose a very low, but plausible, risk of introduction to East Antarctica in climate change scenarios. Divers. Distrib. 27, 973–988. https://doi.org/10.1111/ddi.13246

Hughes, K.A., Ashton, G. V., 2017. Breaking the ice: the introduction of biofouling organisms to Antarctica on vessel hulls. Aquat. Conserv. Mar. Freshw. Ecosyst. 27, 158–164. https://doi.org/10.1002/aqc.2625

Hughes, K.A., Pescott, O.L., Peyton, J., Adriaens, T., Cottier-Cook, E.J., Key, G., Rabitsch, W., Tricarico, E., Barnes, D.K.A., Baxter, N., Belchier, M., Blake, D., Convey, P., Dawson, W., Frohlich, D., Gardiner, L.M., González-Moreno, P., James, R., Malumphy, C., Martin, S., Martinou, A.F., Minchin, D., Monaco, A., Moore, N., Morley, S.A., Ross, K., Shanklin, J., Turvey, K., Vaughan, D., Vaux, A.G.C., Werenkraut, V., Winfield, I.J., Roy, H.E., 2020. Invasive non-native species likely to threaten biodiversity and ecosystems in the Antarctic Peninsula region. Glob. Chang. Biol. 26, 2702–2716. https://doi.org/10.1111/gcb.14938

International Maritime Organisation, 2017. International Code for Ships Operating in Polar Waters (Polar Code). Available from:

https://wwwcdn.imo.org/localresources/en/MediaCentre/HotTopics/Documents/POLAR%20CODE%20TEXT%20AS%20ADOPTED.pdf

International Maritime Organisation, 2011. Guidelines for the control and management of ships' biofouling to minimize the transfer of invasive aquatic species. Annex 26 Resolution MEPC.207(62). Available from: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/RESOLUTION%20MEPC.207[62].pdf

International Maritime Organisation, 2007. Guidelines for ballast water exchange in the Antarctic Treaty Area. Annex 4. Available from: https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.163(56).pdf

International Maritime Organisation, 2004. International Convention for the Control and Management of ships' ballast water and sediments. BWM/CONF/36, 36. Available from http://library.arcticportal.org/1913/1/International%20Convention%20for%20the%20Control%20and%20Management%20of%20Ships%27%20Ballast%20Water%20and%20Sediments.pdf

Jeschke, J.M., Bacher, S., Blackburn, T.M., Dick, J.T.A., Essl, F., Evans, T., Gaertner, M., Hulme, P.E., Kühn, I., Mrugała, A., Pergl, J., Pyšek, P., Rabitsch, W., Ricciardi, A., Richardson, D.M., Sendek, A., Vilà, M., Winter, M., Kumschick, S., 2014. Defining the impact of non-native species. Conserv. Biol. 28, 1188–1194. https://doi.org/10.1111/cobi.12299

Keller, R.P., Drake, J.M., Drew, M.B., Lodge, D.M., 2011. Linking environmental conditions and ship movements to estimate invasive species transport across the global shipping network. Divers. Distrib. 17, 93–102. https://doi.org/10.1111/j.1472-4642.2010.00696.x

Kennicutt, M.C., Bromwich, D., Liggett, D., Njåstad, B., Peck, L., Rintoul, S.R., Ritz, C., Siegert, M.J., Aitken, A., Brooks, C.M., Cassano, J., Chaturvedi, S., Chen, D., Dodds, K., Golledge, N.R., Le Bohec, C., Leppe, M., Murray, A., Nath, P.C., Raphael, M.N., Rogan-Finnemore, M., Schroeder, D.M., Talley, L., Travouillon, T., Vaughan, D.G., Wang, L., Weatherwax, A.T., Yang, H., Chown, S.L., 2019. Sustained Antarctic Research: A 21st Century Imperative. One Earth 1, 95–113. https://doi.org/10.1016/j.oneear.2019.08.014

Key, J., 2018. Tackling Invasive Non-Native Species in the UK Overseas Territories: Pathway analyses. Available from: https://www.nonnativespecies.org/assets/Pathway_Analyses_Final_Report_March2018.pdf

Key, J., Moore, N.P., 2019. Tackling invasive non-native species in the UK Overseas Territories. Island invasives: scaling up to meet the challenge, (62), p.637. Available from: https://www.sprep.org/attachments/VirLib/Global/tackling-invasive-non-native-species-uk.pdf

Lee, J. E., and Chown, S. L., 2009. Temporal development of hull-fouling assemblages associated with an Antarctic supply vessel. *Mar. Ecol. Prog. Ser.* 386, 97–105. doi:10.3354/meps08074.

Letschert, J., Wolff, M., Kluger, L.C., Freudinger, C., Ronquillo, J., Keith, I., 2021. Uncovered pathways: Modelling dispersal dynamics of ship-mediated marine introduced species. J. Appl. Ecol. 58, 620–631. https://doi.org/10.1111/1365-2664.13817

Lewis, P.N., Hewitt, C., Riddle, M., McMinn, A., 2003. Marine introductions in the Southern Ocean: an unrecognised hazard to biodiversity. Mar. Pollut. Bull. 46, 213–223. https://doi.org/10.1016/S0025-326X(02)00364-8

Lockwood, J. L., Hoopes, M. F., & Marchetti, M. P., 2013. Invasion Ecology (2nd Edition). John Wiley & Sons.

López-Farrán, Z., Guillaumot, C., Vargas-Chacoff, L., Paschke, K., Dulière, V., Danis, B., Poulin, E., Saucède, T., Waters, J. and Gérard, K., 2021. Is the southern crab Halicarcinus planatus (Fabricius, 1775) the next invader of Antarctica? *Glob. Chang. Biol.* 27, 3487–3504. doi:10.1111/gcb.15674.

Marbuah, G., Gren, I.M., McKie, B., 2014. Economics of Harmful Invasive Species: A Review. Diversity

6, 500–523. https://doi.org/10.3390/d6030500

McCarthy, A.H., Peck, L.S., Aldridge, D.C., 2022. Ship traffic connects Antarctica's fragile coasts to worldwide ecosystems. Proc. Natl. Acad. Sci. 119, e2110303118. https://doi.org/10.1073/pnas.2110303118

McCarthy, A.H., Peck, L.S., Hughes, K.A., Aldridge, D.C., 2019. Antarctica: The final frontier for marine biological invasions. Glob. Chang. Biol. 25, 2221–2241. https://doi.org/10.1111/gcb.14600

McDonald, J.I., Wellington, C.M., Coupland, G.T., Pedersen, D., Kitchen, B., Bridgwood, S.D., Hewitt, M., Duggan, R., Abdo, D.A., 2020. A united front against marine invaders: Developing a cost-effective marine biosecurity surveillance partnership between government and industry. J. Appl. Ecol. 57, 77–84. https://doi.org/10.1111/1365-2664.13557

McGeoch, M.A., Genovesi, P., Bellingham, P.J., Costello, M.J., McGrannachan, C., Sheppard, A., 2016. Prioritizing species, pathways, and sites to achieve conservation targets for biological invasion. Biol. Invasions 18, 299–314. https://doi.org/10.1007/s10530-015-1013-1

Marine Management Organisation, 2013. Spatial Trends in Shipping Activity. A report produced for the Marine Management Organisation (MMO), pp. 46. MMO Project No: 1042. Available from: https://repository.oceanbestpractices.org/handle/11329/1690

Molnar, J.L., Gamboa, R.L., Revenga, C., Spalding, M.D., 2008. Assessing the global threat of invasive species to marine biodiversity. Front. Ecol. Environ. 6, 485–492. https://doi.org/10.1890/070064

Moser, C.S., Wier, T.P., Grant, J.F., First, M.R., Tamburri, M.N., Ruiz, G.M., Miller, A.W., Drake, L.A., 2016. Quantifying the total wetted surface area of the world fleet: a first step in determining the potential extent of ships' biofouling. Biol. Invasions 18, 265–277. https://doi.org/10.1007/s10530-015-1007-z

Mrowicki, R.J., Brodie, J. (2023). The first record of a non-native seaweed from South Georgia and confirmation of its establishment in the Falkland Islands: Ulva fenestrata Postels & Ruprecht. Polar Biol 46, 489–496. https://doi.org/10.1007/s00300-023-03136-6

Peck, L.S., Morley, S.A., Richard, J., Clark, M.S., 2014. Acclimation and thermal tolerance in Antarctic marine ectotherms. J. Exp. Biol. 217, 16–22. https://doi.org/10.1242/jeb.089946

Peck, L.S., Webb, K.E., Bailey, D.M., 2004. Extreme sensitivity of biological function to temperature in Antarctic marine species. Funct. Ecol. 18, 625–630. https://doi.org/10.1111/j.0269-8463.2004.00903.x

Ricciardi, A., Cohen, J., 2007. The invasiveness of an introduced species does not predict its impact. Biol. Invasions 9, 309–315. https://doi.org/10.1007/s10530-006-9034-4

Roy, H.E., Peyton, J.M., Pescott, O.L., Rorke, S.L., Ecology, C., Gifford, C., Adriaens, T., Cottier-cook, E., Dawson, W., Frohlich, D., Malumphy, C., Martinou, A.F., Minchin, D., Rabitsch, W., Rorke, S.L., Tricarico, E., Turvey, K.M.A., Winfield, I., 2019. Prioritising Invasive Non-Native Species through Horizon Scanning on the UK Overseas Territories. https://doi.org/10.13140/RG.2.2.18951.34726

Saebi, M., Xu, J., Grey, E. K., Lodge, D. M., Corbett, J. J., and Chawla, N., 2020. Higher-order patterns of aquatic species spread through the global shipping network. *PLoS One* 15, 1–24. doi:10.1371/journal.pone.0220353.

Seebens, H., Gastner, M.T., Blasius, B., 2013. The risk of marine bioinvasion caused by global shipping. Ecol. Lett. 16, 782–790. https://doi.org/10.1111/ele.12111

Simberloff, D., Alyokhin, A., Lockwood, J., Hoopes, M., Marchetti, M., et.al., 2011. Correspondence: Non-natives: 141 scientists object. Nature 475, 36. https://doi.org/10.1038/475036a

Spalding, M.D., Fox, H.E., Allen, G.R., Davidson, N., Ferdaña, Z. a., Finlayson, M., Halpern, B.S., Jorge, M. a., Lombana, A., Lourie, S. a., Martin, K.D., Mcmanus, E., Molnar, J., Recchia, C. a., Robertson, J., 2007. Marine Ecoregions of the World: A Bioregionalization of Coastal and Shelf Areas. Bioscience 57, 573. https://doi.org/10.1641/B570707

Stammerjohn, S., Massom, R., Rind, D., Martinson, D., 2012. Regions of rapid sea ice change: An inter-hemispheric seasonal comparison. Geophys. Res. Lett. 39, 1–8. https://doi.org/10.1029/2012GL050874

Sylvester, F., Kalaci, O., Leung, B., Lacoursière-Roussel, A., Murray, C.C., Choi, F.M., Bravo, M.A., Therriault, T.W., Macisaac, H.J., 2011. Hull fouling as an invasion vector: Can simple models explain a complex problem? J. Appl. Ecol. 48, 415–423. https://doi.org/10.1111/j.1365-2664.2011.01957.x

UNEP-WCMC, 2021. Protected Area Profile for South Georgia and South Sandwich Islands Marine Protected Area [WWW Document]. World Database Prot. Areas. URL https://www.protectedplanet.net/555547601

Varnham, K., 2006. Non-native species in UK Overseas Territories: a review, JNCC Report No. 372, JNCC, Peterborough. Available from: https://data.jncc.gov.uk/data/bdb47e73-aa8b-4958-8658-b2e7f758e5bb/JNCC-Report-372-FINAL-WEB.pdf

Williams, S.L., Davidson, I.C., Pasari, J.R., Ashton, G. V., Carlton, J.T., Crafton, R.E., Fontana, R.E., Grosholz, E.D., Miller, A.W., Ruiz, G.M., Zabin, C.J., 2013. Managing multiple vectors for marine invasions in an increasingly connected world. Bioscience 63, 952–966. https://doi.org/10.1525/bio.2013.63.12.8

Zabin, C.J., Ashton, G. V., Brown, C.W., Davidson, I.C., Sytsma, M.D., Ruiz, G.M., 2014. Small boats provide connectivity for nonindigenous marine species between a highly invaded international port and nearby coastal harbors. Manag. Biol. Invasions 5, 97–112. https://doi.org/10.3391/mbi.2014.5.2.03

APPENDICES

Appendix 1. Summary of vessel movement and specification characteristics for vessel mean and total values assessed using AIS tracking data over 2 years, July 2017-2019. All data for vessels moving within the inshore waters of South Georgia and the South Sandwich Islands, for the 10 busiest SGSSI ports / anchorages.

Mean annual values by location	KEP	Bay of Isles	Gold Harbour	St Andrews Bay	Stromness Bay	Fortuna Bay	Cooper Bay	Godthul	Ocean Harbour	Jason Harbour
Total number of vessel visits	115	55	48	46	43	37	23	21	15	15
Overall WSA within port (m^2)	178815	82905	71570	67555	62758	53910	32081	26302	14431	20819
Mean stop period at anchor (hours)	10	4	4	4	4	3	3	4	4	3
Number of identified links to port	40	22	23	19	18	18	11	12	9	11
Number of identified links from port	20	14	11	13	13	10	7	9	8	10
Number of vessel types using port	8	4	4	4	3	4	2	2	3	4