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Review

# Human-mediated dispersal of terrestrial species between Antarctic biogeographic regions: A preliminary risk assessment

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ABSTRACT

The distribution of terrestrial biodiversity within Antarctica is complex, with 16 distinct biogeographic regions (Antarctic Conservation Biogeographic Regions) currently recognised within the Antarctic continent, Peninsula and Scotia Arc archipelagos of the Antarctic Treaty area. Much of this diversity is endemic not only to Antarctica as a whole, but to specific regions within it. Further complexity is added by inclusion of the biodiversity found on the islands located in the Southern Ocean north of the Treaty area. Within Antarctica, scientific, logistic and tourism activities may inadvertently move organisms over potentially long distances, far beyond natural dispersal ranges. Such translocation can disrupt natural species distribution patterns and biogeography through: (1) movement of spatially restricted indigenous species to other areas of Antarctica; (2) movement of distinct populations of more generally distributed species from one area of Antarctica to another, leading to genetic homogenisation and loss of assumed local patterns of adaptation; and (3) further dispersal of introduced non-native species from one area of Antarctica to another. Species can be moved between regions in association with people and cargo, by ship, aircraft and overland travel. Movement of cargo and personnel by ship between stations located in different biogeographic regions is likely to present one of the greatest risks, particularly as coastal stations may experience similar climatic conditions, making establishment more likely. Recognising that reducing the risk of inter-regional transfer of species is a priority issue for the Antarctic Treaty Consultative Meeting, we make practical recommendations aimed at reducing this risk, including the implementation of appropriate biosecurity procedures.

## 1. Introduction

Since the benchmark review of non-native species presence in Antarctica and the sub-Antarctic islands of Frenot et al. (2005), increasing numbers of non-native species of, predominantly, terrestrial invertebrates and plants, are being recorded within Antarctica, particularly in the region of the northern Antarctic Peninsula and South Shetland Islands (Molina-Montenegro et al., 2012, 2015; Greenslade et al., 2012; Volonterio et al., 2013; Hughes et al., 2015a; Potocka and Krzeminska, 2018). However, little research has been undertaken regarding the transfer of indigenous species either between different biogeographic zones within Antarctica (Lee and Chown, 2011) or between isolated populations within a single biogeographic region, including the possibility of biological or genetic homogenisation (Convey et al., 2000; Chown and Convey, 2007; Hughes and Convey, 2010). Currently, the main elements of human presence and activity in Antarctica are the scientific programmes run by national governmental operators, and the largely but not completely ship-based tourism industry, which together are increasing the footprint and intensity of human activity within Antarctica (Tin et al., 2009; Hughes et al., 2011a; Pertierra et al., 2017a). Human activity may therefore increase the risks of species transfer more widely within Antarctica and within its distinct eco-regions (Hughes and Convey, 2010).

In this work we first outline briefly the governance system applying to Antarctica and recent advances of understanding of existing Antarctic biogeographic patterns, then consider the capacity of species to establish once translocated, identify high risk mechanisms for anthropogenic movement of species into and around the continent, and make recommendations for practical measures to reduce potential threats.

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## 2. Antarctic governance and international agreements

International governance of the Antarctic Treaty area (i.e. the area south of latitude 60°S) is achieved through the Antarctic Treaty Consultative Meeting, which currently comprises the 29 Consultative (decision making) Parties of the 53 nations that are signatories to the Antarctic Treaty. International agreements with relevance to non-native species within the Treaty area are contained within the Protocol on Environmental Protection to the Antarctic Treaty (henceforth referred to as 'the Protocol'; agreed 1991, entered into force 1998) and are amongst the strictest in existence globally (Hughes and Convey, 2010, 2014; Hughes and Pertierra, 2016). Annex II Conservation of Fauna and Flora prohibits the deliberate introduction of non-native species into Antarctica without a permit and states that importation of non-sterile soil is to be avoided due to the risk of introducing associated non-native microorganisms (but see Bergstrom et al., 2017). Regarding the movement of native species between different regions of the continent, the Protocol states that activities in the Antarctic Treaty area '*shall be planned and conducted so as to avoid detrimental changes in the distribution, abundance or productivity of species or populations of species of fauna and flora*' (Article 3(2b)) and that permitted activities shall be limited to ensure '*the diversity of species, as well as the habitats essential to their existence, and the balance of the ecological systems existing within the Antarctic Treaty area are maintained*' (Article 3(3c)). Furthermore, the signatory nations to the Protocol (the Parties) are obliged to take issues relating to species dispersal into consideration when planning and carrying out activities in Antarctica. In response, the Committee for Environmental Protection, which was established by the Protocol to provide advice on environmental matters to the Antarctic Treaty Consultative Meeting (ATCM), has made non-native species issues, including the inter-regional movement of indigenous species, the highest priority agenda item in its five-year work plan and in its Climate Change Response Work Programme (CCRWP) (see: http://www.ats.aq/e/cep.htm).

In contrast, the various sub- and peri-Antarctic islands and island groups are governed under the jurisdiction of individual sovereign states, where national legislation is applied. Most of the islands have an apparently high level of protection and management in the form of nature reserves and associated management plans implemented under national jurisdiction. Some islands have additional status under international agreements such as the UNESCO World Heritage Convention (1972) or have been recognised as Wetlands of International Importance (Ramsar) (Grant et al., 2012). In response, the relevant national governments have drafted strict legislation to prevent non-native species introductions (e.g. Parks and Wildlife Service, 2006; Department of Environmental Affairs Directorate: Antarctica and Islands, 2010).

## 3. Antarctic biogeography

Within the scope of this research, we focus predominantly upon distinct biogeographic regions within the Antarctic Treaty area, but also refer to the sub-Antarctic islands, which are recognised as associated and dependant ecosystems by the Antarctic Treaty System (i.e. Article 2 of the Protocol). Antarctic macroscopic terrestrial and freshwater biodiversity is low compared to many other areas of the globe. Food webs are typically simple and dominated by a limited diversity of vascular plants, cryptogams and invertebrates (Convey, 2017), but also host potentially much more diverse microbial communities (Cowan and Ah Tow, 2004; Lopez-Bueno et al., 2009; Tytgat et al., 2014). Nevertheless, Antarctic biodiversity varies considerably over a range of spatial scales. The species distribution patterns present today are the result of predominantly natural distribution and successful colonisation events that have occurred over a range of timescales (Chown and Convey, 2012). Terrestrial species depend upon the presence of ice-free ground for establishment and colonisation, but Antarctica is predominantly covered in permanent ice with only c. 0.18% of its area ice-free, and much of this it too steep or exposed to support substantial biological communities (Kennedy, 1993; Burton-Johnson et al., 2016). This has led to great variability in species diversity and abundance at different locations. Antarctic terrestrial habitats can be considered as isolated 'islands', of varying size, separated by ice or ocean on scales of metres to hundreds of kilometres (Bergstrom and Chown, 1999; Chown and Convey, 2007). Ice extent has not been constant with cycles of glaciations and deglaciation changing dramatically the availability of ice-free ground on the timescale of hundreds to thousands of years (Convey et al., 2008, 2009; DeConto and Pollard, 2016). This natural variation continues today, but is now additionally affected by anthropogenically-induced climate change (along with other environmental impacts), which is predicted to further reduce ice cover, over the Antarctic Peninsula in particular, at a rapid rate (Lee et al., 2017). Consequences of ice loss are likely to include greater connectivity of existing biological communities, possible local extinctions of less competitive species, and the increased distribution of non-native species (Lee et al., 2017). During earlier cycles of glacial advance, which are widely thought to have largely overwhelmed most ice-free areas, in some regions geothermally-heated areas may have remained ice-free and acted as refugia for species that were subsequently able to recolonise once the ice receded (Convey and Smith, 2006; Fraser et al., 2014).

Several natural dispersal mechanisms may be used by different terrestrial biological groups, including wind (Marshall, 1996; van Zanten, 1983), birds (Schlichting et al., 1978; Bailey and James, 1979), marine mammals (Pugh, 1997; Barnes et al., 2004), water (Rounsevell and Horne, 1986; Stevens and Hogg, 2006) and marine debris (Barnes and Fraser, 2003; Barnes et al., 2004, 2006; Marshall and Convey, 2004). However, it is also now appreciated that high levels of endemism characterise most of the main terrestrial biological groups within Antarctica (Maslen and Convey, 2006; Pugh and Convey, 2008; Iakovenko et al., 2015; Kociolek et al., 2017), suggesting that successful colonisation events are rare. This suggestion is supported by recent molecular phylogeographic analyses of mosses that infer individual colonisation events occurring on multi-million year timescales (Hill et al., 2011; Biersma et al., 2017). Therefore, the processes leading to the current structure of Antarctic biogeography are likely to have been complex, with biotic, abiotic and stochastic factors each playing a part (Convey et al., 2008, 2009).

### 3.1. Identification of distinct Antarctic biogeographic regions

Substantial and ancient regional differences in Antarctic terrestrial diversity were first highlighted between the Antarctic Peninsula and the rest of continent with the identification of the Gressitt Line (Chown and Convey, 2007), an analogue of the more widely known Wallace Line of south-east Asia. More recently, 16 biologically distinct ice-free areas of Antarctica, named Antarctic Conservation Biogeographic Regions (ACBRs), have been identified (Terauds et al., 2012; Terauds and Lee, 2016) (see Fig. 1a and Table S1 in the supplementary material), and their use for conservation planning endorsed by the Antarctic Treaty Consultative Meeting (Resolution 3, (2017)). ACBRs were derived from available spatially explicit and taxonomically robust biodiversity data, which for many locations and biological groups remains imperfect, leading to a 'best estimate' of biogeographic patterns. As more data become available, particularly from molecular biological studies, these boundaries may be refined further (see Fig. 2 of James Ross Island showing how the boundary between ACBRs 1 and 3 has led to a distribution of 'islands' that are in close proximity) as well as further distinct areas recognised. ACBRs are a first high-level evidence-based attempt at classifying Antarctica into biogeographic zones, but in reality unique species and communities exist at smaller spatial scales, with distinct biodiversity features existing at specific locations that make them atypical of their parent ACBR. For instance, the terrestrial invertebrate community of Marion Nunataks, Charcot Island, appears to

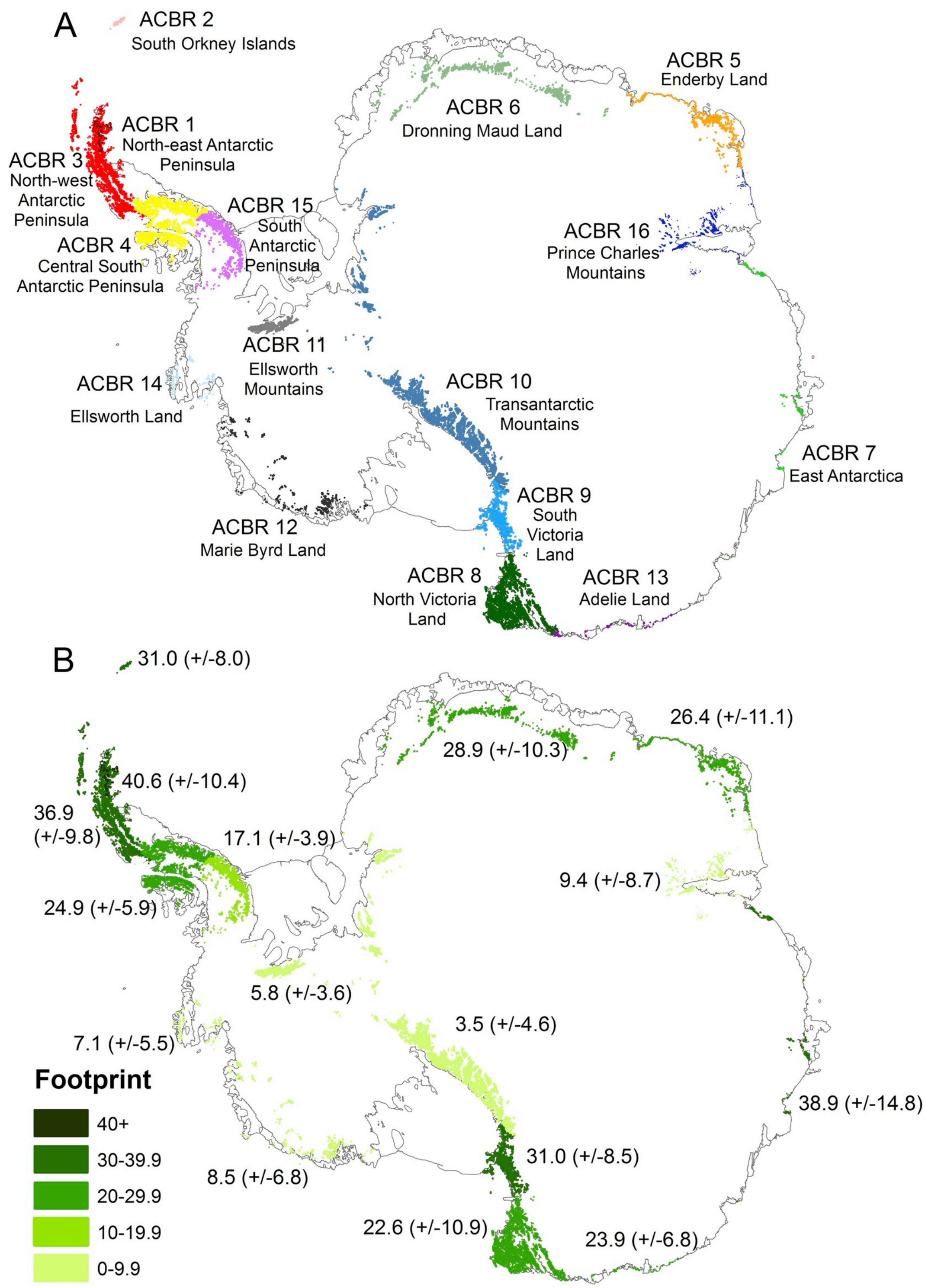


**Fig. 1.** Antarctic Conservation Biogeographic Regions (ACBRs). (A) Map showing the 16 currently recognised ACBRs (Terauds et al., 2012; Terauds and Lee, 2016). (B) Mean footprint values ( ± SD) for each ACBR (Pertierra et al., 2017a).

lack the springtails that are otherwise ubiquitous and abundant throughout the Antarctic Peninsula and, in particular, ACBR 4 in which it is located (Convey et al., 2000). While the ACBRs describe broad eco-regions of similar biodiversity on scales of tens or hundreds of kilometres, the limitations of natural dispersal mechanisms may mean that biological communities within different isolated nunataks, geothermal areas, or lakes within a single ACBR may differ markedly. Consequently, the risk of species transfer also exists at much smaller spatial scales (Convey and Smith, 2006; Chown and Convey, 2007; Pertierra et al., 2017b).

## 4. Species transfer within Antarctica

Patterns and mechanisms facilitating human activity within and between the numerous ice-free areas of Antarctica are complex and the potential for species transfer is substantial. During any Antarctic visit, humans may move between distinct ice-free areas within a single Antarctic biogeographic region, or at a larger scale, move between

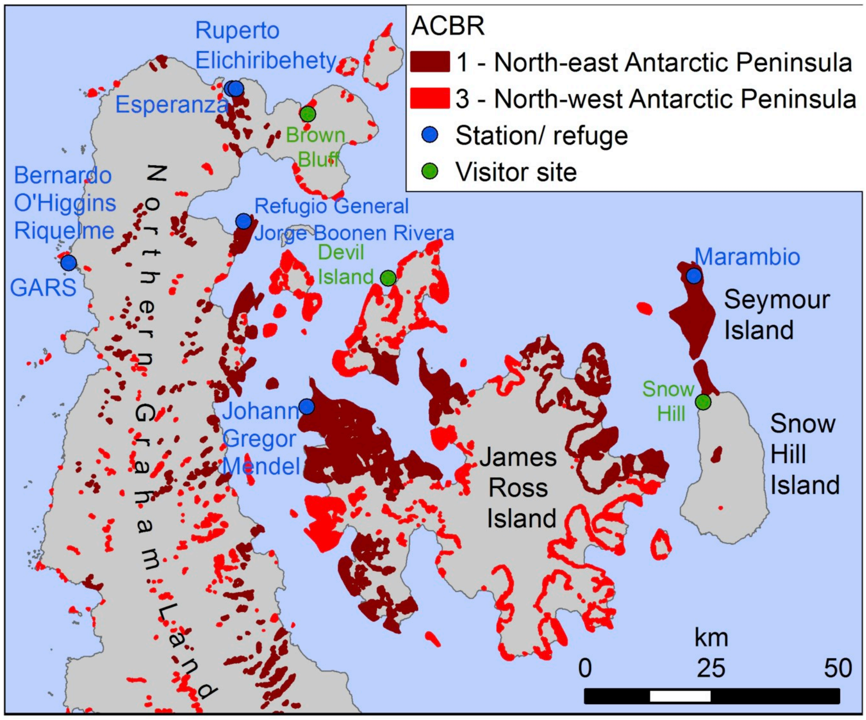


**Fig. 2.** Map of the northern Antarctic Peninsula, showing the distribution of 'islands' of ice-free ground assigned as either Antarctic Conservation Biogeographic Region 1 North-east Antarctic Peninsula or ACBR 3 North-west Antarctic Peninsula.

biogeographic regions (see Fig. S1 in the Supplementary Material, which shows examples of scenarios where movement of personnel and cargo/equipment may transfer species between) or within (e.g. Example 2) different biogeographic regions within Antarctica and the sub-Antarctic islands. Several of the sub-Antarctic islands and/or different Antarctic locations are visited, often sequentially, at a variety of frequencies as part of standard shipping and air itineraries, with national Antarctic programmes adopting these practices including those of Argentina, Australia, Chile, France, New Zealand, Norway, South Africa, Spain, the United Kingdom and the USA.

### 4.1. *Movement of spatially restricted indigenous species within the Antarctic and sub-Antarctic*

Notwithstanding substantial recent advances, the biogeography of Antarctica is poorly understood in comparison with other continents. As a result, both distributions and diversity are likely to be underestimated due to inadequate sampling, while conserved morphology in many of the typically cryptic and/or microbial groups will result in further underestimation. However, even with these limitations, some species do currently appear to be restricted to single biogeographic regions (Adams et al., 2006; Pugh and Convey, 2008; Velasco-Castrillón et al., 2014) or even too much smaller parts of single regions (Coetzee, 1997; De Smet and Gibson, 2008; Guidetti et al., 2014).

As yet there are no published reports of the establishment of Antarctic indigenous species that have been transferred between ACBRs, but transfers have occurred between the sub-Antarctic islands and Antarctica. For example, Hughes et al. (2010a) reported the transfer of many live individuals of multiple species in soil transferred from sub-Antarctic South Georgia to Adelaide Island, Antarctic Peninsula. The lack of reports of transfers between ACBRs may reflect a lack of systematic monitoring or research priority given to this area and in understanding of existing biodiversity. One of the few studies to quantify transfer of species between sub-Antarctic and Antarctic eco-regions examined the propagule load on scientists and logistic personnel travelling from the South African research station on Marion Island to SANAE IV Station in Dronning Maud Land (ACBR 6) (Lee and Chown, 2011). Propagules of several species were transported, including some that are invasive in the sub-Antarctic islands. One sub-Antarctic invasive species, *Poa annua*, has already been introduced on several occasions to the northern Antarctic Peninsula and has the capacity to expand its distribution (Molina-Montenegro et al., 2012; Galera et al., 2017).

Microbial species have almost certainly been moved between regions in association with soil inadvertently entrained with cargo, camping equipment and personal clothing and effects. Circumstantial evidence for such transfer is provided by studies (e.g. Miwa, 1976; Toyoda et al., 1985; Abyzov et al., 1986; Kerry, 1990) that found certain microbial taxa in the immediate vicinity of research stations, but not in similar less- or non-impacted ground further from those stations (Convey, 2008). At a different spatial scale, research has shown distinct microbial populations to exist within individual valleys of the Dry Valleys, Southern Victoria Land (ACBR 9) (Lee et al., 2012), and although no quantitative estimates currently exist, the potential for species transfer by human activities within this area may be substantial (Cowan et al., 2011; Hughes et al., 2015b).

A further issue is the potential movement of microbial disease organisms of plants or animals from one area to another. Pathogens may originate from within or beyond Antarctica and may cause high levels of mortality in their host organisms. Inadvertent transfer of pathogens has the potential to spread disease rapidly (Curry et al., 2002; Kerry and Riddle, 2009). It is clear that the synergy of climate change and increasing human activity will affect pathogens and vectors and may result in emergence of a wider variety of diseases across a broader spatial scale (Kerry and Riddle, 2009; Grimaldi et al., 2015).

### 4.2. *Genetic homogenisation*

A second risk is the movement of genetically distinct populations of more widely distributed indigenous species from one area of Antarctica to another, leading to mixing and exchange of genetic material between populations (genetic homogenisation) (Chown and Convey, 2007).

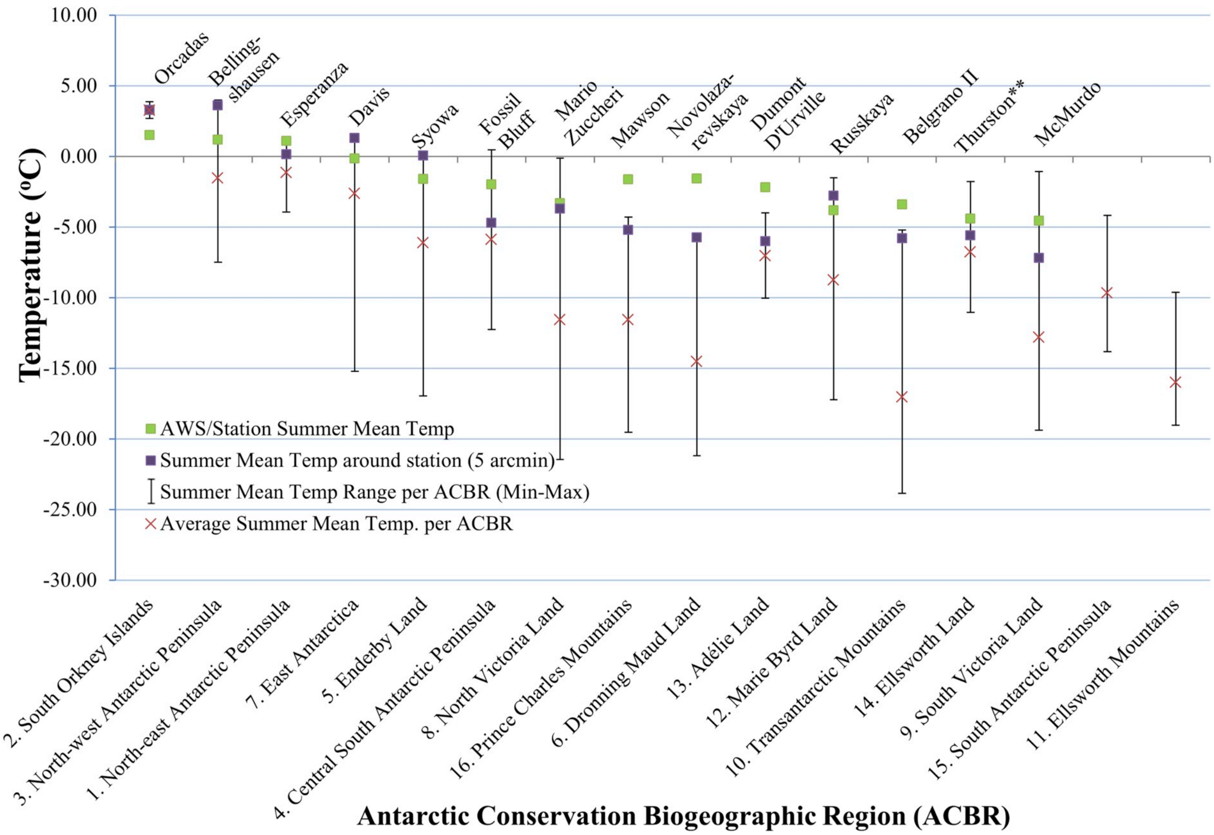


**Fig. 3.** Mean summer temperature found at ice-free areas within each Antarctic Conservation Biogeographic Region (ACBR) during 2000–2010 decade; results are displayed as the interval bar between minima and maxima for the period per region. In addition, individual squares are incorporated to either represent the mean summer temperature obtained at a scientific station with meteorological data monitoring in each ACBR (green squares) and the MERRAclim value obtained for the cell of ice-free area where the station is located (purple squares) (Vega et al., 2017).

Many terrestrial populations are isolated from one another by large expanses of ocean or areas of permanent ice, and have been so possibly on timescales of up to millions of years (Stevens and Hogg, 2003, 2006; McGaughran et al., 2010; Beet et al., 2016). For example, divergences found in four endemic Antarctic springtail species (*Cryptopygus* species and related genera) indicate that their lineages have not shared a common evolutionary history and have been isolated from one another for between 5 and 23 million years, resulting in a distinct genetic make-up (Stevens et al., 2006). Anthropogenic inter-regional species movements may therefore compromise future research programmes examining biogeographical patterns using genetic methodologies, through generating misleading patterns of genetic relationships (Chown and Convey, 2007, 2012).

### *4.3. Further dispersal of already established non-native species to other areas within Antarctica*

A major concern, closely linked to the issue of redistribution of indigenous Antarctic species to other Antarctic biogeographic regions, is the anthropogenic dispersal of existing non-indigenous species from sites of initial introduction to other locations within the continent. Some highly visited sites in the Antarctic Peninsula, as well as on sub-Antarctic islands such as South Georgia, have already been invaded by one or more non-native species. Therefore, potential exists for further stepwise transfer at local and regional scales, with establishment enhanced by predicted climate change (Frenot et al., 2005; Hughes et al., 2015a; Duffy et al., 2017; Pertierra et al., 2017d). Currently, most established non-native species are located in ACBR 3 North-west Antarctic Peninsula (Hughes et al., 2015a) (Table S2 Supplementary Material). However, other ACBRs also host non-native species with, for instance, the commonly invasive collembolan *Hypogastrura viatica* found in ACBR 1 Northeast Antarctic Peninsula on Devil Island, and the flightless chironomid midge *Eretmoptera murphyi* and enchytraeid worm *Christensenidrilus blocki* established in ACBR 2 South Orkney Islands near the UK research station on Signy Island (Hughes and Worland, 2010).

## 5. Species establishment

Following anthropogenic transfer of a species to a new location, the likelihood of establishment depends upon both the physical characteristics of the new location and how these match the environmental features within the natural range of the species in question, and upon the biological characteristics of the translocated species (Crooks and Rilov, 2009). Very few studies have directly attempted to quantify the impact of invading species on native communities and diversity within the Antarctic Treaty area (but see Molina-Montenegro et al., 2012), although many clear examples are available from the sub-Antarctic islands (Frenot et al., 2005; Convey and Lebouvier, 2009). However, given the unique and isolated nature of Antarctic terrestrial communities, and their often long history of evolutionary isolation and divergence, the introduction of any new species can be considered to be an important impact in itself, as well as a challenge to the future conservation of Antarctic biodiversity.

### *5.1. The physical environment*

Physical factors affecting species establishment in Antarctica are generally complex and vary greatly over even small spatial scales (Peck et al., 2006; Convey et al., 2014). These may include, for instance, precipitation, air temperature, solar radiation, nutrient supply (geologically or biologically sourced), proximity to the ocean, presence of bird colonies or marine mammal haul-out sites and disturbance of ground due to human impacts. However, a dominant factor, closely linked with surface air temperature, is the availability of liquid water, which has been recognised as the primary driver for biodiversity in the Antarctic (Convey et al., 2014). Many of Antarctica's indigenous terrestrial species show substantial physiological and biochemical flexibility, due to the large and rapid temperature variability common in many terrestrial Antarctic habitats (Davey et al., 1992; Peck et al., 2006; Convey et al., 2018). Therefore, species capable of surviving and reproducing under the conditions found in one region of Antarctica, may also be well suited to surviving in other regions where the temperature regimes are similar, or also warmer or cooler. In essence the main factors affecting successful establishment in a new Antarctic location/region are the presence of suitable habitat, and possession of appropriate tolerance features enabling survival of the physical/abiotic environmental stresses experienced.

To investigate the potential for contemporary indigenous species survival if they were to be transported from their native region to different ACBRs, we examined (1) the mean austral summer temperature within each of the ACBRs, (2) the mean summer temperatures recorded at a typical research station within each ACBR, if any were present, and (3) the temperatures in the 5 arcmin grid square immediately surrounding them (see Supplementary Material A and Fig. 3). Gridded meteorological data were obtained from the MERRAclim BIO10 dataset (Vega et al., 2017) and research station weather monitoring data were retrieved from BAS MetReader (https://legacy.bas.ac.uk/met/READER/data.html). For the purpose of this study, the average interannual mean temperatures of the warmest quarter of the year (December–February) were examined for the decade 2000–2010. In the case of Ellsworth Land no scientific station is present in the region, so data from the Thurston Automatic Weather Station (AWS) was used. In addition, two ACBRs (ACBR 15 South Antarctic Peninsula and ACBR 11 Ellsworth Mountains) do not have any land-based scientific station or AWS, so no data for specific locations within the ACBR were provided, and temperatures shown for these ACBRs only come from MERRA remotely sensed data (Fig. 3). The temperatures reported for each ACBR represented the maximum and minimum summer mean temperature values present across the entire extent of each bioregion (including both generally milder coastal and colder inland locations). It is important to note that the macroclimatic mean temperatures may not give a good representation of microhabitat temperatures, and are likely to give an impression of areas being more climatically extreme than they are in reality at relevant biological scales (Davey et al., 1992; Convey, 1996; Convey et al., 2018).

There was substantial variation in temperatures of the ACBRs overall. ACBRs 10 Transantarctic Mountains and 11 Ellsworth Mountains had, respectively, the lowest minima and mean values due to their predominantly inland locations at generally high latitudes and altitudes. The warmest ACBRs were ACBRs 1, 2 and 3, which are located on the Antarctic Peninsula or Scotia Arc, and all three example stations had mean summer temperatures greater than 0 °C. This result fits with the earlier classification that defines the area encompassed by ACBRs 1, 2 and 3 as the Maritime Antarctic region, as compared to the rest of the Antarctic ice-free areas, which are referred to as the Continental Antarctic region (Smith, 1984). In turn, continental ACBRs generally experienced lower mean temperatures than ACBRs 1, 2, and 3 (Fig. 3). Despite the variability in continental ACBR mean summer temperatures, there was considerably less variability in the mean summer temperatures at the research stations across the different continental ACBRs (i.e. between 0 and -5 °C). The mean temperatures reported for the stations were generally higher than the values reported for the ACBR overall, as stations are often located in coastal locations to facilitate resupply by ship, and less climatically extreme sites are selected to make human habitation less challenging.

As ACBRs 1, 2 and 3 contain over 50% of Antarctica's stations and facilities and experience the great majority of tourist activity, the likelihood of potential translocation of species between regions and their subsequent survival is particularly high. More generally, given that ice-free ground in the vicinity of research stations may be most vulnerable to colonisation by species transported there by human activity, the similarity in temperatures between Antarctic stations means the probability of colonisation and establishment may be disproportionately high. Similar air temperature regimes at stations in different and often adjacent ACBRs, is also a cause for concern, particularly if these stations are regularly resupplied by the same vessels or other transport routes have been established. For example, Davis Station (ACBR 7) has climatically similar conditions to Mawson Station (ACBR 16) and both stations may be resupplied sequentially by the same vessels. Furthermore, Davis Station and Syowa Station (ACBR 5) also experience similar temperatures to those stations examined on the Antarctic Peninsula and South Orkney Islands, making colonisation of transferred species between Maritime and Continental Antarctica plausible. It should also be noted that several other stations present within the Maritime Antarctic are located in more climatically extreme areas (e.g., Rothera Research Station and San Martin (ACBR 3)), which are closer analogues to the climatic conditions found at stations in the Continental Antarctic region and thus may sustain biota that present a higher risk of establishment following transfer to this region.

### *5.2. Life history characteristics*

#### *5.2.1. Antarctic and sub-Antarctic species*

The life history strategies of Antarctic terrestrial species are generally ‘adversity-selected’, meaning that they show considerable investment in various stress tolerance strategies. Competitive abilities are generally poorly developed and low in adversity-selected organisms (Convey, 1996), and biotic interactions such as inter-species competition are regarded as of low or insignificant importance (Hogg et al., 2006; but see also Caruso et al., 2013). In contrast many invading species, including some of those already established in the sub- and maritime Antarctic, are typically stronger competitors (Frenot et al., 2005). Thus their establishment in Antarctic ecosystems inevitably has negative impacts on native community members. However, isolated Antarctic terrestrial communities, particularly those in more extreme parts of the continent, may be at greater risk from the introduction and establishment of other Antarctic species translocated from a different biogeographic region of the continent or sub-Antarctic than from non-native species introduced from lower latitudes beyond Antarctica and therefore less well adapted to the extreme conditions.

At present, most recorded examples of non-native species within the Antarctic Treaty area relate to terrestrial invertebrates. However, 1960s plant transplant experiments (Edwards, 1980) confirmed that several South Georgia native plant species could survive for a number of years on Signy Island (60°S, South Orkney Islands; ACBR 2). The sub-Antarctic endemic chironomid midge *E. murphyi* was likely introduced to Signy Island from South Georgia during these transplants in the 1960s (Block et al., 1984). Its distribution range on Signy has subsequently expanded, but its maritime Antarctic distribution is still confined to the island (Hughes and Worland, 2010). However, growth rate and microclimatic modelling of *E. murphyi* showed that temperature constraints on larval development in the vicinity of Rothera Research Station (68°S; ACBR 3) were theoretically similar to those on Signy Island, even though it is 750 km further south (Everatt et al., 2012; Hughes et al., 2013). Establishment of this non-native midge within a climatic envelope encompassing the entire western Antarctic Peninsula is therefore plausible, given the widespread existence along the Antarctic Peninsula of the moss-dominated and fellfield habitats that typify its colonised area on Signy Island. A further life history feature compounding the risk of establishment of *E. murphyi* at new locations is that the species is parthenogenetic (Convey, 1992), therefore theoretically

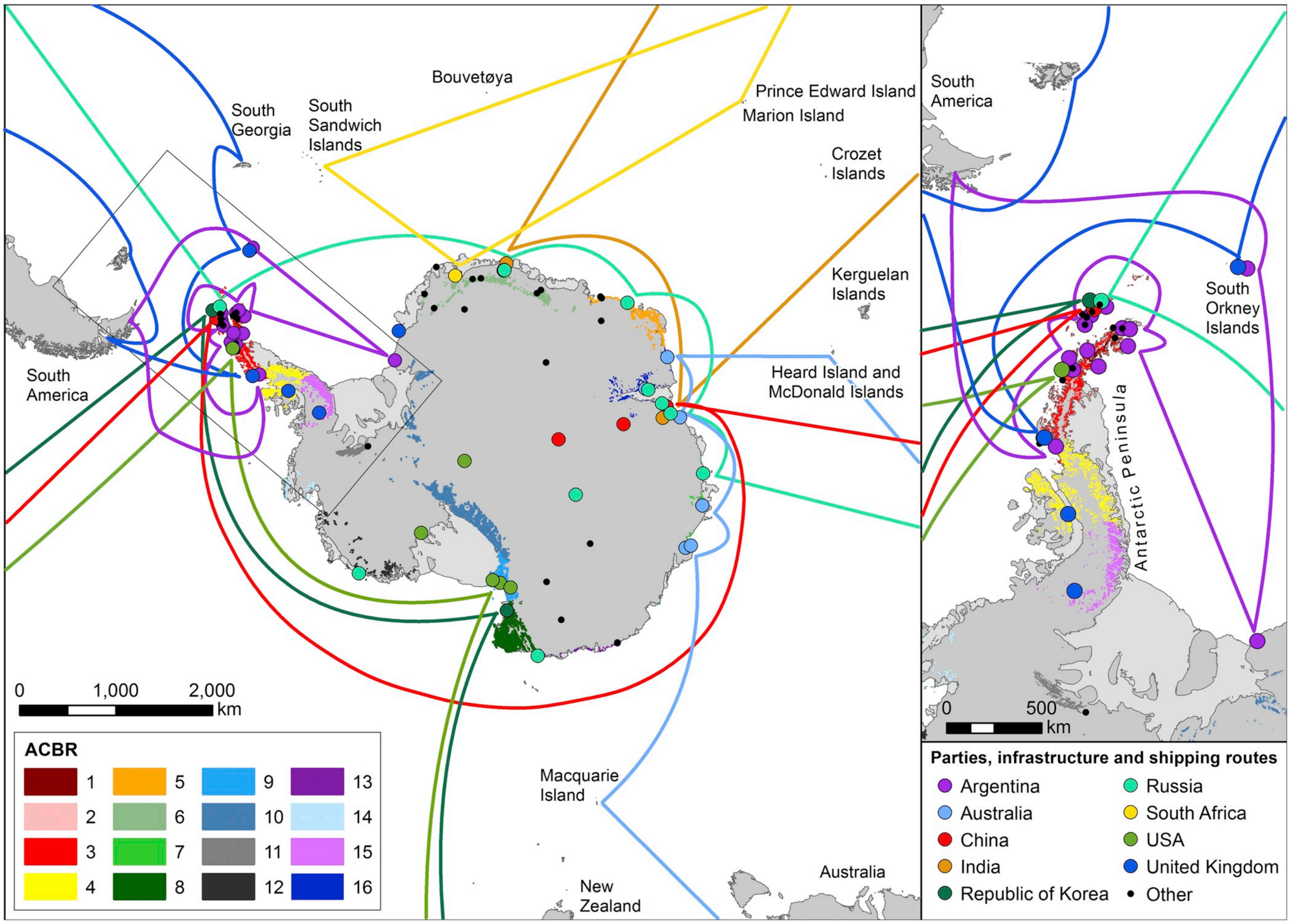


**Fig. 4.** Map showing possible resupply routes used by Parties with more than one station on ice-free ground in Antarctica. Ship movements for other reasons, including the support of scientific projects, are not shown but are likely to be extensive for some Parties. In both the main map and the insert, the rock outcrops are colour-coded to represent the different Antarctic Conservation Biogeographic Regions, while the supply route and research stations (shown by lines and circles, respectively) are colour-coded to represent the activities and infrastructure of different Antarctic Treaty Parties.

requiring introduction of only a single individual. Parthenogenicity is a feature of many of the micro-invertebrates constituting the Antarctic terrestrial fauna. Therefore, it was a matter of concern when, in 2005/06, over 132 kg of soil from South Georgia was inadvertently imported to Rothera Research Station (ACBR 3) associated with construction vehicles, and living *E. murphyi* larvae were found within the soil (Hughes et al., 2010a). The soil was removed and disposed of, and no subsequent evidence of colonisation of *E. murphyi* has been detected, but this incident does emphasise the risks associated with failure of existing biosecurity procedures allowing inter-regional transfer of contaminated cargo.

A further feature of Antarctic terrestrial fauna, flora and microbes that may affect successful intra-continental transfer and establishment, in addition to the well-developed cryptobiotic adaptations, is the possession of very flexible life cycles (Convey, 1996). In such life cycles, development can be opportunistic depending on the often infrequent availability of suitable conditions; for instance, some continental Antarctic springtails (Sømme, 1986) and nematodes (Adams et al., 2014) may be active for only a few days in total each year, and not at all in some years. As a result, overall life cycle duration can be extremely variable, with overwintering occurring in multiple if not all juvenile instars, sometimes repeatedly (e.g. Convey, 1994), although in this respect *E. murphyi* provides an exception as a species that is thought to undergo a true diapause in its final larval instar.

### *5.2.2. Introduced non-Antarctic species*

For some non-native species introduced to the Antarctic, their possession (or otherwise) of appropriate dispersal mechanisms may be the dominant factor influencing subsequent distribution expansion by natural or anthropogenic mechanisms, rather than Antarctic environmental conditions limiting growth and reproduction *per se*. For instance, the invading grass *Poa annua* is capable of setting seed on King George Island, leading to rapid expansion in its occupied distribution in the vicinity of its introduction location at Arctowski Station (Chwedorzewska et al., 2015). In contrast, the persistent introduced species *P. pratensis* at Cierva Point, Danco Coast, Antarctic Peninsula, was unable to set seed at this location and was restricted to small-scale vegetative spread ($< 2\,m^2$) before its removal in 2014 (Pertierra et al., 2013, 2017c). However, both of these European species are able to set seed on several sub-Antarctic islands, where they are widely distributed, highlighting their potential impacts once environmental limits to life histories have been passed, which is also an important element of predicting the consequences of regional environmental change. Recent studies have suggested that the potential niche of these and other globally invasive species is far less restrictive in the Antarctic than anticipated, and it is reasonable to assume that other cold-tolerant species present in Arctic or Alpine environments would also be able to establish in the Antarctic following anthropogenic translocation (Pertierra et al., 2017d; Duffy et al., 2017). For example, *Puccinellia svalbardensis* appears to have been transferred from an Arctic location

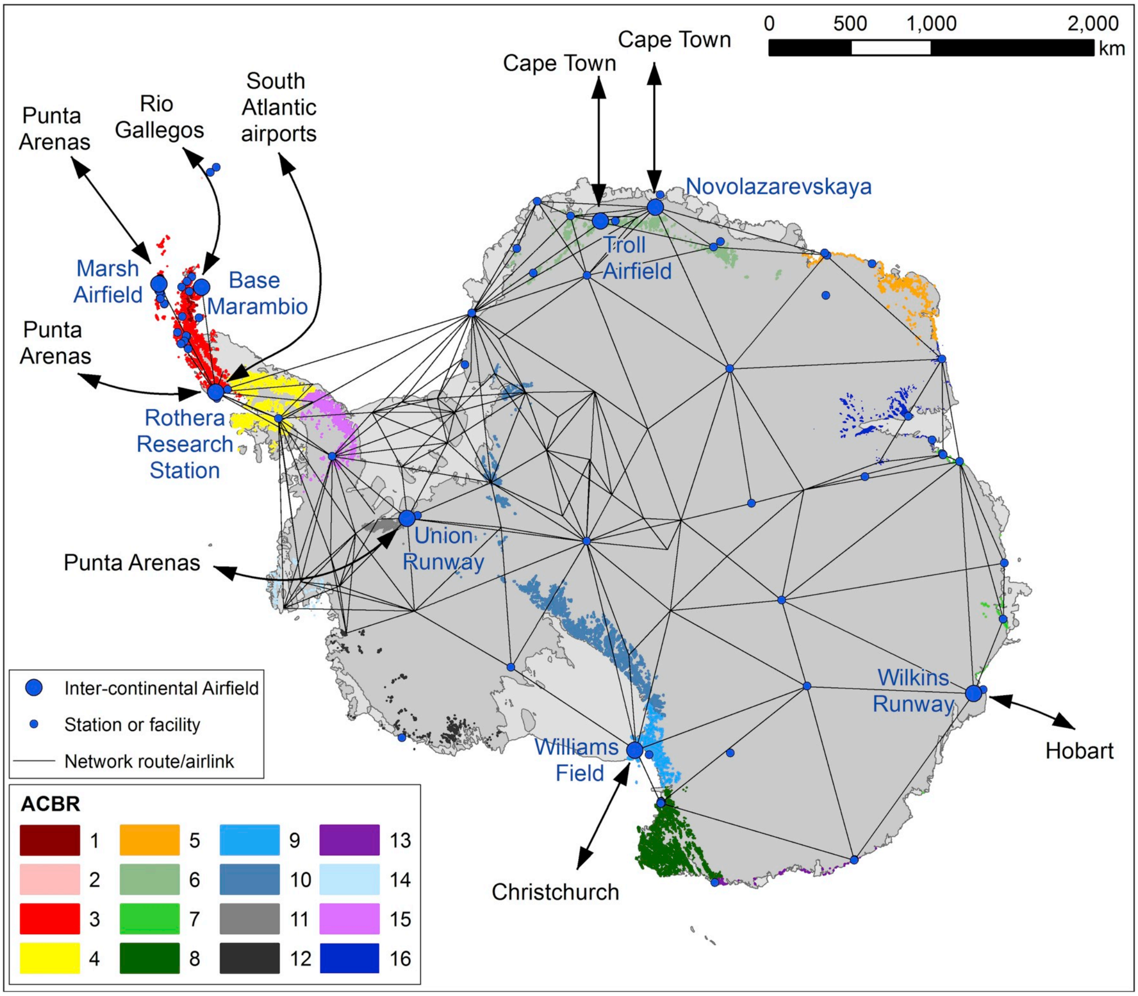


**Fig. 5.** Map showing the location of runways for intercontinental aircraft and other landing sites constructed predominantly on permanent snow and ice. Active runways constructed on ice-free ground are located at Marambio Base (Seymour Island), Teniente Rodolfo Marsh Martin Airfield (Fildes Peninsula) and Rothera Research Station (Adelaide Island), which are all within the Antarctic Peninsula. In addition, ski-equipped aircraft land and operate from both prepared and undefined snow or ice runways in support of field parties and operations across the continent. Aircraft journeys around the edge and across the centre of Antarctica are undertaken routinely each year.

by Japanese researchers working in both regions, and managed to survive for over a decade on the continent before removal (Tsujimoto et al., 2010). In a further example, the dipteran *Trichocera maculipennis* has become established in several sewage treatment plants within stations on King George Island (Volonterio et al., 2013; Potocka and Krzeminska, 2018). This species may not only survive synanthropically on King George Island, and it is thought it may also survive and disperse within the Antarctic environment (Volonterio et al., 2013); its existing natural range encompasses much of the Holarctic and Arctic, including Greenland where it may also have been introduced (Dahl and Krzeminska, 2015).

## 6. Identification of risks

### 6.1. Identification of high risk routes for species translocation

Species may be moved between regions within Antarctica by a variety of anthropogenic mechanisms, including ships, aircraft and overland vehicles (see Figs. 4 and 5 and Supplementary Material B). A body of recent scientific work has focussed on the quantification of non-native species propagule loads being transferred into Antarctica associated with different human-associated pathways, such as cargo (Lee and Chown, 2009a,b; Osyczka et al., 2012; Tsujimoto and Imura, 2012; Houghton et al., 2014; Newman et al., 2018), vehicles (Hughes et al., 2010a), fresh food (Hughes et al., 2011b), ships (Lewis et al., 2003; Lee and Chown, 2007; Hughes and Ashton, 2017) and through human clothing and personal equipment (Chown et al., 2012; Litynska-Zajac et al., 2012; Huiskes et al., 2014). However, with the exception of the study by Lee and Chown (2011), who looked at propagule load on personnel travelling from sub-Antarctic Marion Island to SANAE IV station (ACBR 6), propagule loads are yet to be quantified for personnel moving between biogeographic regions, and detailed information on the number of people and quantities of cargo moving across the boundaries separating biogeographic regions is not readily available. Nevertheless, it seems reasonable to assume that propagule loads transferred into the Antarctic may be similar to soil and propagule loads on personnel, vehicles and cargo moving around Antarctica, albeit that further research is needed.

Acknowledging that data that would enable a comprehensive risk assessment of movement of species between biogeographic regions is currently lacking, we attempted to produce a preliminary assessment of the relative risks of intra-continental species transfer by different Antarctic transport mechanisms (Table 1 and Supplementary Material B). For each of the main methods of human movement around and within Antarctica, we allocated a score of 1–5 for each of four factors: (i) relative propagule load of a typical vector including associated personnel and cargo, (ii) relative number active in Antarctica, (iii) proportion moving between ACBRs, and (iv) relative likelihood of

**Table 1**
Risk assessment for transport of propagules between ACBRs by different anthropogenic transportation mechanisms (see Supplementary Material B for information supporting the allocated scores). Scores are given in the range 1–5. Overall risk is calculated as the product of the scores shown in columns 2 to 5. The colours correspond to allocated scores, i.e. green = 1, yellow = 2, light orange = 3, dark orange = 4, red = 5.

| | Relative propagule load of a typical vector including associated personnel and cargo[1] | Relative number active within Antarctica | Proportion moving between ACBRs | Relative likelihood of propagule entrainment and release in different ACBRs | Overall risk score |
|---|---|---|---|---|---|
| National Operator vessels[2] | 5 | 5 | 3 | 5 | 375 |
| Ship-borne tourism[3] | 2 | 5 | 3 | 2 | 60 |
| Helicopters on ice-free ground | 2 | 3 | 2 | 2 | 24 |
| Yachts | 2 | 3 | 2 | 2 | 24 |
| Fishing vessels | 3 | 5 | 1 | 1 | 15 |
| Fixed wing aircraft landing on rock airstrips[4] | 3 | 2 | 1 | 2 | 12 |
| Travelling field parties predominantly on ice-free ground | 3 | 1 | 1 | 3 | 9 |
| Fixed wing aircraft landing on ice | 2 | 4 | 1 | 1 | 8 |
| Tractor trains | 4 | 2 | 1 | 1 | 8 |
| Aircraft-borne tourism | 2 | 2 | 1 | 2 | 8 |
| Autonomous and remotely piloted aircraft systems | 1 | 3 | 1 | 1 | 3 |
| Travelling field parties predominantly on ice | 1 | 1 | 1 | 1 | 1 |

[1] Estimate largely based upon physical size of potential vector and nature of the activities undertaken within Antarctica
[2] See Table 3 for an estimate of the risk of ship-borne propagule translocation associated with different National Operators
[3] Takes into consideration the biosecurity methods commonly employed by the Antarctic tourism industry
[4] This estimate does not take into consideration the risk of transportation of non-native species into Antarctic from elsewhere

propagule entrainment and release in different ACBRs. The scores for each factor were multiplied together to produce an overall risk score. We suggest that the highest risks of inter-regional species transfers are associated with cargo and personnel movement by national operator vessels and in particular those operated by Parties with research stations in more than one ACBR. Movement of tourist vessels between ACBRs presented a lesser risk overall, due to general lack of cargo movement and the well-established simple biosecurity procedures in place on most cruise ships; however, the large volume of tourism movement between ACBRs 1 and 3 may be a cause for concern, particularly when considering the large numbers of tourist landings that occur in these two regions (see Fig. 2). Yachts and helicopters landing on ice-free ground had lower scores, predominantly due to their lower potential propagule loading relative to larger ships and a lower likelihood of movement between ACBRs. Fishing vessels were rated as presenting a minimal risk, mainly because they only rarely land personnel at Antarctic ice-free locations and opportunities for species transfer are therefore limited. Similarly, the number of locations where aircraft land on ice-free ground in Antarctic is limited. Therefore, aircraft travel between rock airstrips is uncommon and largely limited to the northern Antarctic Peninsula (i.e. airstrips at Rothera Research Station, Marambio Station and Frei Station). Travelling field parties that move long distances between ACBRs are now increasingly rare so propagule transfer by this mechanism may also be low. Activities that are largely undertaken on permanent ice, which include travelling field parties, fixed wing aircraft landing on ice and tractor trains, were assessed as presenting the lowest risks as opportunities for propagule entrainment and release were few or non-existent. Further details of current mechanisms and associated risks of propagule transfer within Antarctica are given in Supplementary Material B.

*6.1.1. National programme operational footprint*

To estimate the likelihood of national programmes moving people and cargo between ACBRs, we examined the number of ACBRs across which each national operator's major research facilities (including stations occupied year-round as well as only during the summer season) were distributed (see COMNAP, 2017). Argentina, Australia, China, Germany, India, Japan, Republic of Korea, Russian Federation, United Kingdom, United States and Uruguay all operate research stations in more than one ACBR (Tables 2 and 3) and the operational footprints of Brazil, Chile, France, Italy and New Zealand routinely extend across more than one ACBR. However, not all of these operators use the same ships, tractor trains and/or aircraft to resupply all their different stations, which means in some cases there may be little risk of species transfer by anthropogenic mechanisms between ACBRs. Of particular significance, Australia, France, New Zealand, South Africa and the United Kingdom routinely include activities in the sub-Antarctic, where research stations have been established. As well as hosting their own native and often endemic biota, many of these islands have already been colonised by invasive species from other parts of the world, and therefore may act as a source of potentially invasive species within the broader Antarctic region (Frenot et al., 2005; Convey and Lebouvier, 2009).

Transfer of people and cargo between biogeographic regions is likely to be greatest where national operators have established research stations within adjacent (or nearby) biogeographic regions and exchange of cargo and personnel between those stations is a common occurrence (Fig. 4). Table 3 shows which national operators with research stations and/or field activities in neighbouring ACBRs may be at greatest risk of inter-ACBR species transfer. In each example, the sum of the footprint values for the two ACBRs give some indication of the potential for human activity across the two ACBRs, with higher values indicating higher potential risk of species transfer. Generally, the

**Table 2**
Distribution of national operator footprint and Antarctic stations located on or close to ice-free ground within Antarctica and the sub-Antarctic Islands (X: facilities; ●: no station present, but operational footprint extends into region).

| | Antarctic bioregion | | | | | | | | | | | | | | | | | | | | | | | | | | Total[b] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Antarctic Conservation Biogeographic Region (ACBR) No. | | | | | | | | | | | | | | | | Sub-Antarctic island or island group[a] | | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | SG | SSI | Bou | Mar | PEI | Cr | Ker | HI | MDI | Mcq | |
| Argentina | X | X | X | ● | | | | | | X | | | | | | | | | | | | | | | | | 5(4) |
| Australia[a] | | | | | ● | | X[c] | | | ● | | | | | | X | | | | | | | | ● | ● | X | 7(3) |
| Belarus[d] | | | | | X | | | | | | | | | | | | | | | | | | | | | | 1(1) |
| Belgium | | | | | | X | | | | | | | | | | | | | | | | | | | | | 1(1) |
| Brazil | ● | | X | | | | | | | | ● | | | | | | | | | | | | | | | | 3(1) |
| Bulgaria | | | X | | | | | | | | | | | | | | | | | | | | | | | | 1(1) |
| Chile | ● | | X | ● | | | | | | | X | | | | ● | | | | | | | | | | | | 5(2) |
| China | | | X | | | | X | | ● | | | | | | | ● | | | | | | | | | | | 4(2) |
| Czech Republic | X | | ● | | | | | | | | | | | | | | | | | | | | | | | | 2(1) |
| Ecuador | | | X | | | | | | | | | | | | | | | | | | | | | | | | 1(1) |
| Finland | | | | | | X | | | | | | | | | | | | | | | | | | | | | 1(1) |
| France[a] | | | | | | | | ● | | | | | X | | | | | | | | | X | X | | | | 4(3) |
| Germany | | | X[e] | | | ● | | X | | | | | | | | | | | | | | | | | | | 3(2) |
| India | | | | | | X | X | | | | | | | | | | | | | | | | | | | | 2(2) |
| Italy | | | | | | | | X | ● | | | | ● | | | | | | | | | | | | | | 3(1) |
| Japan | | | | | X | ● | | | | | | | | | | | | | | | | | | | | | 2(1) |
| Korea (ROK) | | | X | | | | | X | ● | | | | | | | | | | | | | | | | | | 3(2) |
| Netherlands | | | X[f] | | | | | | | | | | | | | | | | | | | | | | | | 1(1) |
| New Zealand | | | | | | | | ● | X | ● | | | | | | | | | | | | | | | | | 3(1) |
| Norway[a] | | | | | | X | | | | | | | | | | | | | ● | | | | | | | | 2(1) |
| Peru | | | X | | | | | | | | | | | | | | | | | | | | | | | | 1(1) |
| Poland | | | X | | | | | | | | | | | | | | | | | | | | | | | | 1(1) |
| Romania[d] | | | | | | | X[c] | | | | | | | | | | | | | | | | | | | | 1(1) |
| Russian Federation | | | X | | X | X | X | X | | | | X | | | | X | | | | | | | | | | | 7(7) |
| South Africa[a] | | | | | | X | | | | | | | | | | | | ● | | X | ● | | | | | | 3(2) |
| Spain | ● | | X | | | | | | | | | | | | | | | | | | | | | | | | 2(1) |
| Sweden | | | | | | X | | | | | | | | | | | | | | | | | | | | | 1(1) |
| Ukraine | | | X | | | | | | | | | | | | | | | | | | | | | | | | 1(1) |
| United Kingdom[a] | ● | X | X | X | | ● | | | | ● | ● | | | ● | X | | X | ● | | | | | | | | | 10(5) |
| United States | ● | ● | X | ● | | | | ● | X | ● | | ● | | ● | | | | | | | | | | | | | 9(2) |
| Uruguay | X | | X | | | | | | | | | | | | | | | | | | | | | | | | 2(2) |

[a] Australia, France, South Africa and the United Kingdom have research stations on sub-Antarctic islands that are often visited as part of their Antarctic station resupply programme, which may present a further opportunity for species transfer between distinct biogeographic regions (see Frenot et al., 2005). SG: South Georgia, SSI: South Sandwich Islands, Bou: Bouvet Island, Mar: Marion Island, PEI: Prince Edward Island, Cr: Crozet Islands, Ker: Kerguelen Islands, HI: Heard Island, MI: McDonald Island, Mcq: Macquarie Island.
[b] Total number of biogeographic regions in which the Party normally operates, with total number of biogeographic regions in which the Party has permanent facilities in brackets.
[c] The Law - Racovita – Negoita Station is operated jointly by Australia and Romania.
[d] Non-Consultative Parties to the Antarctic Treaty.
[e] The German Dallman lab is located within Carlini Station, which is operated by Argentina, while the German Antarctic Receiving Station (GARS) is located close to O'Higgins Station, which is operated by Chile.
[f] The Dirck Gerritsz Laboratory within the UK's Rothera Research Station is funded by the Netherlands.

**Table 3**
Risk of transfer of species between Parties' research stations and facilities within different Antarctic Conservation Biogeographic Regions (ACBRs).

| | ACBRs commonly linked by overland, sea or air routes and/or in close proximity[a] | Parties with research station/facilities situated on or near ice-free ground within adjacent or nearby ACBRs | | Parties whose operation footprint extends across both ACBRs | |
|---|---|---|---|---|---|
| | | Party (no. of stations in each ACBR) | Distance between the nearest stations operated by that Party within the two ACBRs | Sum of footprint value for each ACBR | National operators generally active in both regions |
| 1 | ACBR 1 Northeast Antarctic Peninsula ↔ ACBR 3 Northwest Antarctic Peninsula[b] | Uruguay (ACBR 1: 1; ACBR 3: 1) | 220 km (Ruperto Elichiribehety ↔ Artigas) | 80.9 | Argentina, Brazil, Chile, Czech Republic, Spain, United Kingdom, United States, Uruguay |
| | | Argentina (ACBR 1: 2; ACBR 3: 8) | 40 km (Esperanza ↔ Petrel) | | |
| 2 | ACBR 1 Northeast Antarctic Peninsula ↔ ACBR 2 South Orkney Islands | Argentina (ACBR 1: 2; ACBR 2: 1) | 705 km (Esperanza ↔ Orcadas) | 74.8 | Argentina, United Kingdom, United States |
| 3 | ACBR 2 South Orkney Islands ↔ ACBR 3 Northwest Antarctic Peninsula | United Kingdom (ACBR 1: 1; ACBR 3: 1) | 1320 km (Signy Research Station ↔ Rothera Research Station) | 71.7 | Argentina, United Kingdom, United States |
| | | Argentina (ACBR 2: 1; ACBR 3: 8) | 675 km (Orcadas ↔ Petrel) | | |
| 4 | ACBR 5 Enderby Land ↔ ACBR 7 East Antarctica | Russian Federation (ACBR 5: 2; ACBR 7: 3) | 2000 km (Molodezhnaya Station ↔ Mirny Station) | 64.5 | Australia, Russian Federation |
| 5 | ACBR 3 Northwest Antarctic Peninsula ↔ ACBR 4 Central South Antarctic Peninsula | United Kingdom (ACBR 3: 1; ACBR 4: 1) | 420 km (Rothera Research Station ↔ Fossil Bluff) | 64.2 | Argentina, Chile, United Kingdom, United States |
| 6 | ACBR 3 Northwest Antarctic Peninsula ↔ ACBR 15 South Antarctic Peninsula | United Kingdom (ACBR 3: 1; ACBR 15: 1) | 820 km (Rothera Research Station ↔ Sky Blu) | 56.0 | Chile, United Kingdom |
| 7 | ACBR 5 Enderby Land ↔ ACBR 6 Dronning Maud Land) | Russian Federation (ACBR 5: 2; ACBR 6: 1) | 1380 km (Molodezhnaya Station ↔ Novolazarevskaya Station) | 54.5 | Japan, Russian Federation |
| | | Japan (ACBR 5: 1; ACBR 6: 1) | 645 km (Syowa Station ↔ Asuka Station)[c] | | |
| 8 | ACBR 8 North Victoria Land ↔ ACBR 9 South Victoria Land[d] | - | - | 54.6 | Italy, Korea, New Zealand, United States |
| 9 | ACBR 7 East Antarctica ↔ ACBR 16 Prince Charles Mountains | Australia (ACBR 7: 5; ACBR 16: 1) | 590 km (Law-Racovita-Negoita ↔ Mawson) | 47.6 | Australia, China, Russian Federation |
| | | Russian Federation (ACBR 7: 3; ACBR 16: 2) | 110 km (Progress 3 Station ↔ Druzhnaya 4 Station) | | |
| 10 | ACBR 4 Central South Antarctic Peninsula ↔ ACBR 15 South Antarctic Peninsula | United Kingdom (ACBR 4: 1; ACBR 15: 1) | 400 km (Fossil Bluff ↔ Sky Blu) | 42.4 | Chile, United Kingdom |
| 11 | ACBR 5 Enderby Land ↔ ACBR 16 Prince Charles Mountains | Russian Federation (ACBR 5: 2; ACBR 16: 2) | 960 km (Molodezhnaya Station ↔ Soyuz Station) | 35.7 | Australia, Russian Federation |
| 12 | ACBR 9 South Victoria Land ↔ ACBR 10 Transantarctic Mountains | United States (ACBR 9: 4; ACBR 10: 1) | 800 km (McMurdo ↔ Shackleton Glacier Camp) | 35.0 | New Zealand, United States |

[a] France and Italy jointly operate the Concondia Station at Dome C, which is resupplied by aircraft and tractor train from Mario Zucchelli Station (ACBR 8 Northern Victoria Land) and Dumont D'Urville Station (ACBR 13 Adélie Land). Transfer of soil and propagules between these regions via Dome C is unlikely to be high.
[b] Approximately 40 cruise vessels operate in the northern Antarctic Peninsula area, generally making multiple visits during the austral summer season, with tourist visitation of locations within ACBRs 1 and 3 a common occurrence.
[c] Asuka Station (Japan) is now used infrequently.
[d] A small number of cruise vessels (< 10) transfer tourists between ACBRs 8 and 9 with annual tourist visitation to this area in the region of c. 500 passengers.

closest stations within different ACBRs are likely to face a higher risk of species and propagules being transferred in a viable state, although some propagules have been shown to retain viability following sea or air journeys of long duration (Hughes et al., 2010b). The national Antarctic operations of Argentina, Australia, the Russian Federation, Uruguay and the United Kingdom therefore present a greater risk of inter-regional transfer of species, compared with most other national programmes whose major infrastructure is located within a single ACBR. For example, the closest stations in two different ACBRs operated by the same nation (Argentina) are Esperanza and Petrel in ACBRs 1 and 3, respectively, which are located only 40 km apart. However, Brazil, Chile, Czech Republic, Spain, United Kingdom, United States and Uruguay all regularly operate in both ACBRs 1 and 3, alongside tourist vessels, indicating that the likely risk of species transfer between these ACBRs is high. Some operators' logistic programmes (such as the Republic of Korea and China), while making only a single shipping transfer between continental coastline stations and the Antarctic Peninsula/South Shetland Islands in a typical season, also present an opportunity for species transfer between ACBRs.

The absence of stations operated by a single nation in neighbouring ACBRs may remove the opportunity for the interchange of personnel and supplies between stations. However, the operational footprint (mostly in terms of accessibility) of one or more nations may extend across several ACBRs. For example, no Parties operate stations in both ACBR 8 (North Victoria Land) and ACBR 9 (South Victoria Land) but the two ACBRs are within the operation footprint of the United States, New Zealand, Italy and Korea, resulting in opportunities for species and propagule transfer in association with clothing, footwear and field and scientific equipment (Table 2). Similarly, no stations have been established in the 'unclaimed sector' of Antarctica (encompassing most of ACBRs 12 Marie Byrd Land and 14 Ellsworth Land), yet these regions receive national operator visitation from both the Antarctic Peninsula and Victoria Land directions.

As noted, data quantifying levels of human movement between ACBRs are not readily available; however, human footprint values determined from reported national operator and tourism industry activity within the areas encompassed by each of the 16 ACBRs (Pertierra et al., 2017a), may give a proxy for the level of activity within adjacent ACBRs (see Fig. 1a and b and Table S1 in the Supplementary Material). In the study by Pertierra et al. (2017a), human footprint was considered to be the spatial pressure on Antarctic ice-free ground, caused either by the existing (i.e. currently operating facilities) or potential presence (in terms of accessibility) of any human activity within the continent and off-shore islands located south of latitude 60°S. Five spatial features relating to different human capabilities were aggregated in the development of an Antarctic footprint model. The five features incorporated into the footprint calculations were: (1) land use/occupancy type (i.e. large/small station, visitor site, camp, protected area, none); (2) facility/land density (i.e. respectively, the number of station beds, number of visitors and levels of permitted access); (3) distance to the nearest coast (maritime accessibility); (4) distance to nearest aerodrome (aerial accessibility); and (5) distance to the nearest continent (connectivity).

. To obtain the aggregated human footprint score for each ice-free site, the values from the five features analysed within the Antarctic continent were added. Data were then re-scaled to the range 1–100. On this basis, the mean human footprint values calculated within the ACBRs differed, with ACBRs encompassing the northern Antarctic Peninsula and offshore islands (ACBRs 1 and 3), southern Victoria Land (ACBR 8) and East Antarctica (ACBR 7) subject to substantial human activity and footprint, albeit distributed heterogeneously within each region (Fig. 1a and b; Table 2). Due to the high levels of human activity in ACBRs 1, 2 and 3, exchange of people and cargo between these regions may also be high relative to other less populated and visited ACBRs (e.g. between ACBR 9 South Victoria Land and ACBR 10 Transantarctic Mountains).

#### *6.1.2. Further dispersal of established non-native species from Antarctic logistic hubs*

The risk of further dispersal of established non-native species within Antarctica is likely to be high where their introduction sites are located near logistic hubs. This mirrors the situation at many of the entry ports used to support Antarctic logistics where, for instance, there is a high risk of entraining propagules of ruderal weedy plant species and invertebrates (e.g. Lee and Chown, 2009a, b; Tsujimoto and Imura, 2012; Houghton et al., 2014). Antarctic stations with regular inter-continental links (e.g. with airstrips or port facilities connecting with these gateway ports) are therefore at higher risk of non-native species introductions, meaning that onwards dispersal from these stations to other Antarctic regions should be a substantial concern. In this context, a particularly high risk location is provided by Fildes Peninsula, King George Island, which contains five research stations (Great Wall (China), Bellingshausen (Russian Federation), Artigas (Uruguay), Professor Julio Escudero (Chilean Antarctic Institute), Eduardo Frei Montalva (Chilean Air Force), as well as various refuge huts, and with King Sejong (South Korea) also located adjacent) that are largely resupplied by ship. Very close to all of these, the Teniente R. Marsh Martin Airfield provides an inter-continental link with South America, as well acting as a logistics hub for onwards travel within the Antarctic. The airfield also serves the tourism industry by enabling visitors to fly into King George Island, either for onward transfer directly to waiting cruise ships, or for day or overnight trips using a tented tourist camp set up close by before return directly to Punta Arenas in Chile (Bender et al., 2016). Importation of large numbers of personnel and volumes of cargo from South America, Europe and elsewhere over more than five decades has resulted in the introduction of non-native plants and invertebrates, such as the grass *Poa annua* (Peter et al., 2008, 2013) the non-native dipteran *Trichocera maculipennis* (Volonterio et al., 2013), and the Acari *Coccotydaeolus* cf. *krantzii*, *Speleorchestes* sp. and *Terpnacarus gibbosus* (Russell et al., 2013; Hughes et al., 2015a) as well as colloquial reports of other invertebrates. In addition, non-native seeds (including species belonging to Poaceae, Juncaceae and Asteraceae families that are known to be invasive on some sub-Antarctic islands) have been found in the topsoil in the vicinity of the airfield and station buildings (Fuentes-Lillo et al., 2017). It is clear that the existing situation at Fildes Peninsula may present a substantial risk of further dispersal of existing non-native species and propagules, as well as a continued risk of importation of new non-native species. Elsewhere on King George Island, seeds of *Juncus bufonius* have been found (Cuba-Diaz et al., 2012), although it is not explicitly clear that these are the result of human introduction. In Admiralty Bay, the introduction and invasion of *P. annua* followed by now substantial efforts for its ongoing eradication (see Chwedorzewska and Bednarek, 2012; Galera et al., 2017) provide further evidence of the importance of applying appropriate biosecurity measures when transiting on to other locations so that further non-native species dispersal is avoided.

## 7. Management actions to strengthen biosecurity

### *7.1. Existing guidelines for biosecurity*

Guidelines to reduce the risk of non-native species transfer into Antarctica from other areas of the Earth have been developed in recent years, and many of the recommendations contained therein may be usefully applied to reduce risk of species transfer between ACBRs. For example, the CEP combined available information and expertise together into the Non-native Species Manual (Revison 2017; available from the Antarctic Treaty Secretariat website: http://www.ats.aq/e/ep_faflo.htm), and, to support Parties in identifying simple cost-effective biosecurity measures to reduce propagule transfer, the Council of Managers of National Antarctic Programs (COMNAP), in association with the Scientific Committee on Antarctic Research (SCAR), produced the 'Checklist for supply chain managers of national Antarctic programs to reduce the risk of transfer of non-native species' (available at: https://www.comnap.aq/Publications/Comnap%20Publications/COMNAP_SCAR_Checklists_for_Supply_Chain_Managers.pdf). In recent years SCAR has also been involved in the production or review of several guidance documents to help Parties reduce the likelihood of species movement between biogeographic regions, albeit this information is often incorporated into other general guidance on reducing the risk of non-native species introductions from beyond the Treaty area. For example, SCAR's 'Environmental code of conduct for terrestrial scientific field research in Antarctica', released in 2009 and revised in 2018, sets out the risks associated with movement of indigenous species around Antarctica, particularly relating to the modification of the genetic structure of populations should species be translocated (see: https://www.scar.org/policy/scar-codes-of-conduct/). It goes on to recommend that, between sampling events at different terrestrial or freshwater environment locations, equipment be thoroughly cleaned or a separate set of equipment used. Two years later in 2011, SCAR's 'Code of conduct for the exploration and research of subglacial aquatic environments' was produced, which recognised that '*sub-glacial aquatic environments contain living organisms, and precautions should be adopted to prevent any permanent alteration of the biology (including introduction of alien species) or habitat properties of these environments*' (para. 27). Most recently, in 2016, the SCAR 'Code of conduct for activity within terrestrial geothermal environments in Antarctica' was endorsed by the Antarctic Treaty Consultative Meeting (Resolution 3 (2016)). These guidelines included recommendations on ways to prevent introduction of species to these spatially limited and unique habitats, and also to prevent cross-transfer of species between geothermal sites or sub-sites (para. 56).

The extent to which researchers and other operator staff are aware of the existence or content of these guidelines and the level of compliance is not known. Neither is it known how existing guidelines are integrated by national authorities into the environmental impact assessment process that is required under the Antarctic Treaty System to mitigating the risks of proposed activities. With great variability apparent in the profile of non-native species and biosecurity issues within different national operators concerning the more easily grasped concept of non-native species transfer to Antarctica from other continents, the more subtle – but potentially more serious – concept of inter-regional transfer may be more difficult to communicate and attract the necessary resources to facilitate appropriate precautions (COMNAP, 2008). Specific guidelines on the prevention of transfer of indigenous species between locations have not been formally agreed by the Antarctic Treaty Parties, although the identification of the need for such guidelines for inclusion in the CEP Non-native Species Manual are included in the CEP's Climate Change Response Work Programme (Hughes and Pertierra, 2016).

The Antarctic tourism industry, through the International Association of Antarctica Tour Operators (IAATO), has been proactive in the development and application of biosecurity procedures for use by passengers and staff leaving gateway ports and while in transit between Antarctic locations (see: https://iaato.org/dont-pack-a-pest and https://iaato.org/documents/10157/14310/Boot_Washing07.pdf) (IAATO, 2017a). Therefore, as long as these procedures are actively used and enforced, the risk presented by tourism is likely to be reduced. However, the overall risk of species transfer may increase if the number of visitors at a site increases, or multiple sites within different ACBRs are visited during a single cruise without adequate biosecurity practices being employed. Furthermore, the range of activities offered by the tourism industry continues to expand (e.g. sea kayaking, scuba diving, marathon running and mountaineering) and, if adequate cleaning practices are not employed, potential exists to transfer propagules between regions on activity-specific equipment.

The Antarctic Treaty Consultative Meeting has generated Site Guidelines for Visitors (see https://www.ats.aq/devAS/ats_other_siteguidelines.aspx?lang=e) for 39 of the most popular visitor locations (mostly located in ACBR 3, but also ACBRs 1, 2, 8 and 9), some of which may receive up to c. 17,000 tourist visitors, in addition to national operator personnel, in a single austral summer season (IAATO, 2018). The Site Guidelines provide information for visitors, including tourism operators, regarding how to manage visits to each location. When visitor sites were surveyed for the presence of non-native soil invertebrates, 80% were colonised by one or more non-native species (i.e. eight of ten sites examined) (Greenslade et al., 2012; Russell et al., 2013). Whether other visitor sites have similar levels of invasion is unknown. Furthermore, it is not known if neighbouring non-visitor sites are invaded, which would also be a pertinent piece of knowledge with regard to species dispersal characteristics and rates.

### 7.2. Additional recommendations

Human presence, activity and movement around the Antarctic continent and between ACBRs and sub-Antarctic eco-regions continue to increase, and with them the risk of intra- and inter-regional transfer of indigenous and non-indigenous species within Antarctica. If practical steps are to be taken collectively by the Parties active in Antarctica, a first challenge will be to determine the spatial scale of discrete areas that can be effectively biosecured. The analyses leading to the definition of the existing ACBRs used spatially explicit biodiversity information to identify biologically distinct areas. Therefore, having been endorsed by the ATCM as a tool for conservation planning, ACBRs present a good foundation for the development and implementation of biosecurity precautions by national operators and the tourism industry when travelling within Antarctica. Other management tools may be available under the Antarctic Treaty System to guide or mandate implementation of more stringent biosecurity measures, including the designation of Antarctic Specially Managed Areas (ASMAs) and Antarctic Specially Protected Areas (ASPAs) (Hughes and Convey, 2010; Hughes and Grant, 2017; Coetzee et al., 2017). ASPAs and ASMAs may be particularly suitable for areas at scales much smaller than ACBRs where distinct populations of some species are found that may merit stringent biosecurity standards being applied at a 'sub-ACBR' scale to prevent propagule transfer and subsequently species or population homogenisation (Pertierra et al., 2017b).

We have described the anthropogenic mechanisms that exist for potential transfer of species within Antarctica, and shown that there are similarities in environmental characteristics between ACBRs. When these factors are considered alongside the well-documented flexibility in life history and ecophysiological characteristics typical of many Antarctic terrestrial biota, it is apparent that intra-regional species transfer and establishment is possible and likely, particularly in concert with predicted climate change impacts (Lee et al., 2017). To reduce the risk of species movement between biogeographic regions, simple recommendations may include those detailed in Table 4. We recognize that it is impossible to completely eliminate the risk of anthropogenic of species within Antarctica. However, as has been well-established for the issue of non-native species transfer into Antarctica, the consistent application of relatively simple and inexpensive biosecurity measures by national operators and the tourism industry will reduce this risk inter-regional transfer.

In addition to practical recommendations, further research is required to determine the biogeographic patterns of different biological groups (including microbiota) across Antarctica and at finer spatial scale than is currently available, so that existing and new management tools and practices can be employed appropriately to safeguard Antarctica's biodiversity and ecosystems, and their intrinsic and scientific values. More generally, research is needed to further define the extents of the existing ACBRs (see Fig. 2, and also Lee et al., 2017), which will require more effort being devoted to obtaining baseline biodiversity information, and also to ascertain the spatial scale over which biosecurity measures can be applied in a pragmatic but still effective way. Data are also needed to inform a detailed risk assessment

**Table 4**
Recommendations to reduce the risk of inter-regional transfer of species within Antarctica.

| No. | Recommendations |
|---|---|
| *General* | |
| 1 | The risks of inter-regional species transfer must be adequately considered within the mandatory Environmental Impact Assessments that are required for all Antarctic projects (see Annex I to the Protocol on Environmental Protection to the Antarctic Treaty). Once the risks have been identified, mitigation measures should be put in place and effective biosecurity practices adopted to remove soil and propagules from people and cargo moving between Antarctic biogeographic regions, including between ACBRs and sub-Antarctic islands. |
| 2 | Provide appropriate training and education on the risk of inter-regional transfer to: (1) those with operational responsibilities within Antarctica, and (2) environmental managers with responsibilities for assessing Environmental Impact Assessments of Antarctic field work. |
| 3 | Some research station act as logistic hubs for field parties that are moved into the field by aircraft, vessel or overland vehicle. If used field equipment is returned to a research station for redeployment with subsequent field parties, ensure adequate provision of cleaning equipment on the research stations. Ensure that removed soil and propagules can be disposed of without risk of dispersal into the local environment (e.g. by incineration). |
| 4 | At ACBR boundary areas, where ice-free areas that are allocated to different ACBRs are interdispersed (e.g. ACBR 1 and 3; see Fig. 2), ensure field personnel are aware of where the boundaries are located so that biosecurity measures can be implemented as necessary. |
| *Field activities* | |
| 5 | Prior to the commencement of the field activity, undertake effective cleaning of activity-specific scientific (e.g. soil corers) or field equipment (e.g. climbing harnesses that can trap seeds in Velcro®), particularly if it was used previously in other cold or high altitude environments. |
| 6 | To the maximum degree possible, avoid unnecessary visits to ice-free ground. If such activities are necessary for essential research or logistic reasons, minimise the amount of time and travel within these areas to reduce the likelihood of propagule entrainment. |
| 7 | Where feasible, plan field activities so that each trip away from the supporting ship or research station is limited to work undertaken within a single ACBR. Field equipment, footwear and clothing should be cleaned to remove soil and propagules between subsequent deployments. |
| 8 | Tents and camping equipment can trap soil and propagules. Therefore, avoid camping on ice-free ground, particularly if moving to further ice-free areas. |
| 9 | Undertake regular cleaning of the interior and exterior of aircraft (especially helicopters that land routinely on ice-free ground). |
| 10 | Where possible, restrict vehicle use to areas of permanent ice and snow to prevent entrainment of propagules and soil that may be subsequently moved to other biogeographic regions. If vehicles are used on ice-free ground, ensure they are adequately cleaned and free of soil and propagules before transfer to ice-free areas in other ACBRs or sub-Antarctic islands. |
| 11 | Consider dedicating specific field equipment for use only within specific ACBRs or sub-Antarctic eco-regions. |
| 12 | In accordance with recent recommendations (see the SCAR codes of conduct: https://www.scar.org/policy/scar-codes-of-conduct/), consider the use of stricter biosecurity measures, such as use of sterile protective overclothing, at high altitude geothermal sites and in other little visited or little impacted habitats vulnerable to species transfer. |
| *Monitoring* | |
| 13 | Undertake baseline studies and on-going monitoring at high risk sites, such as rock airstrips and regularly used helicopter landing sites in ice-free ground, as well as major national operator and tourism landing sites (such as Deception Island, Fildes Peninsula) as these may act as hubs for the further dispersal of any translocated species. |
| 14 | Implement a systematic programme of monitoring for emerging disease at wildlife colonies that may facilitate the tracking of infectious diseases, and provide early warning so that sites of infection can be quarantined and agreed biosecurity practices implemented. |
| *Policy* | |
| 15 | Agree effective biosecurity measures and practices to reduce the risk of inter-regional transfer that can be applied by national operators and the tourism and fishing industries, as appropriate (e.g. for inclusion within the Non-native Species Manual, developed by the Committee for Environmental Protection). |
| 16 | At locations where Site Guidelines for Visitors have been developed, include within them information on existing non-native species and any biosecurity measures appropriate for the site. |
| 17 | Given the early stages of the development of autonomous aerial, marine and terrestrial vehicle technology, develop basic levels of biosecurity in their use so that appropriate measures can become standard operating procedures. |
| 18 | Ensure adequate consideration and planning is given to controlling and recording current and future human movement within Antarctica (i.e. human footprint), in light of predicted expansion of ice-free areas as a result of climate change. |

for species transfer between ACBRs, particularly as the level of risk is likely to vary for different biological groups and in different regions (see Table 3).

### 7.3. Future risks and developments

On-going developments in the intensity and distribution of human activity mean that the risks of intra- and inter-regional species transfer within Antarctica are likely to increase. The number of tourist visits is increasing, particularly within the Antarctic Peninsula, with numbers of visitors reaching over 43,000 in the 2017/18 season compared with fewer than 20,000 in 2003/4 (IAATO, 2018). In response, IAATO is planning the use of sophisticated conservation planning methodologies to determine how to maximise tourist visits while minimising impact upon the environment (SCAR and IAATO, 2017). Parties that have shown little previous interest in Antarctic research are increasing their science and logistical activity and/or developing stations in Antarctica (e.g. Colombia, Austria, Thailand and Turkey all became members of SCAR in 2016). Some Parties with existing stations are developing new stations, often in different regions of Antarctica. In future, the footprint of national programmes will continue to increase, and seldom visited and currently uninhabited areas of Antarctica (e.g. ACBRs 10, 11, 12, 14) may receive more attention, support more field camps and, eventually, the establishment of research stations. Changes in sea-ice conditions may alter the accessibility of ice-free areas (in recent years increasingly accessible in the western Antarctic Peninsula, while decreasing in parts of East Antarctica). Technological developments, resulting in improved and expanded links between ice-free areas by ship and aircraft, will increase the opportunities for species transfer between regions. To increase efficiency and reduce operational cost, national programmes may share logistics resulting in ships more frequently resupplying multiple stations operated by different Parties in different ACBRs. Furthermore, increasingly science projects are being undertaken at a larger scale, involving scientific and logistic input from multiple Parties. Consequently, participating scientists may arrive at a given location from stations and other starting points within different ACBRs, further increasing the risk of inter-regional species distribution. However, and more positively, given the small number of Antarctic 'gateway' ports, and limited number of transportation routes between currently recognised ACBRs, implementing appropriate biosecurity precautions should be achievable using trivial amounts of resource relative to the cost of operating Antarctic infrastructure. The challenge for the Antarctic Treaty Consultative Meeting will be timely action in addressing biosecurity and developing effective policy and pragmatic mechanisms for its implementation.

## 8. Conclusions

With the endorsement of the Antarctic Conservation Biogeographic Regions by the ATCM in 2012, environmental managers and policy makes had their first continent-wide framework through which to consider (1) the distinct biodiversity within different Antarctic regions and (2) the risk of movement of species across the wider region, including the remote sub-Antarctic islands. Concurrent studies have also shown that human activities, such as ship or aircraft movement of cargo and personnel, could unintentionally transport organisms rapidly between Antarctica's bioregions, and beyond natural dispersal ranges, resulting in disruptions of natural species distribution patterns and biogeography. Our preliminary risk assessment showed that ship transfer of cargo and/or personnel may constitute the most substantial risk to indigenous biological communities. Furthermore, the risks may be exacerbated by the milder climatic conditions found at coastal locations, compared to locations found more inland, which may increase the likelihood of species establishment. We have provided simple and cost-effective recommendation to reduce the threat of species transfer between bioregions. More research effort to quantify propagule pressure between Antarctic regions and predict likelihood of species establishment will increase our understanding of the risks. However, unless the risks of inter-regional species transfer are adequately considered within the mandatory Environmental Impact Assessment required for all Antarctic projects, and effective biosecurity measures are put in place, the intrinsic environmental and scientific values of the region may be compromised forever.

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## Appendix A. Supplementary data

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