Rapid range expansion of an invasive flatworm, *Kontikia andersoni*, on sub-Antarctic Macquarie Island

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Abstract Spanning the Southern Ocean high latitudes, Sub-Antarctic islands are protected areas with high conservation values. Despite the remoteness of these islands, non-native species threaten native species and ecosystem function. The most ubiquitous and speciose group of non-native species in the region are invertebrates. Due to their cryptic habits and ambiguous establishment history, the impacts of non-native invertebrates on native species and ecosystems in the region remains largely unknown. Understanding how non-native invertebrate species are transported, disperse, establish and colonise new habitats is key to understanding their existing and future impacts. This research is fundamental to improving biosecurity practice and informing future management of Southern Ocean islands. We undertook invertebrate surveys on Macquarie Island to determine the current status of four non-native macro-invertebrates—*Kontikia andersoni* and *Arthurdendyus vegrandis* (Platyhelminthes: Geoplanidae), *Styloniscus otakensis* (Isopoda: Styloniscidae) and *Puhuruhuru patersoni* (Amphipoda: Talitridae). *Arthurdendyus vegrandis* was not intercepted in our surveys, while we found *S. otakensis* and *P. patersoni* had not expanded their range. In contrast, *K. andersoni* has more than doubled its previously mapped area and expanded at a rate of ~500 m-yr since 2004. We discuss the possible underlying mechanisms for the dramatic range expansion of *K. andersoni* and consider the implications for the future management of Macquarie Island.

Keywords Platyhelminthes · Geoplanidae · Terrestrial crustacea · Biosecurity · Invasion · Land planarian

Introduction

Invasive species have devastating impacts on global biodiversity, particularly on islands (Mack et al. 2000; McCreless et al. 2016). These impacts may occur directly through predation (Courchamp et al. 2003; Angel et al. 2009; Wanless et al. 2012; Dilley et al. 2018; Lebouvier et al. 2020), or indirectly, for example via habitat transformation (Croll et al. 2005;
Fukami et al. 2006; Mulder et al. 2009), hyper-predation (Couchamp et al. 2000; Travers et al. 2021), changes in soil fertility and decomposition processes (Fukami et al. 2006; Wardle et al. 2009; Towns et al. 2009), mutualisms between non-native species (Convey et al. 2010; Leinass et al. 2015) and in many other complex ways. In any case, the flow-on effects in island ecosystems can be profound. This is especially so for sub-Antarctic ecosystems which are characteristically simple and lack representatives of many functional groups (Vernon et al. 1998; Chown and Convey 2016; Houghton 2020). Consequently, in sub-Antarctic ecosystems not only do invasive mammalian predators have particularly devastating consequences (Couchamp et al. 2003; Frenot et al. 2005; Angel et al. 2009), but so can invasive invertebrate predators, pollinators, herbivores, and macro-detritivores (Jones et al. 2003; Smith 2007; Chown et al. 2008; Greenslade et al. 2007, 2008; Convey et al. 2010; Lebouvier et al. 2020), although more research into the extent of such impacts is required (Houghton et al. 2019a).

Sub-Antarctic Macquarie Island (54°30’ S, 158°57’ E) is a ~129 km² World Heritage Area, located in the Southern Ocean approximately 1500 km southeast of Tasmania, Australia (Fig. 1). Macquarie Island’s invertebrate fauna is made up of over 350 species, with 44 endemics and at least 40 species of established non-native invertebrates (Greenslade 2006; Houghton 2020). Although most established non-native invertebrates on Macquarie Island are small detritivores (Houghton 2020), several large-bodied, non-native macro-detritivores have established, including the slug *Derocerus reticulatum* Müller 1774 (Agriolimnacidae), earthworms (Lumbricidae), two terrestrial Crustacea including *Puhuruhuru patersoni* Stephens 1938 (Amphipoda: Talitridae) and *Styloniscus otakensis* Chilton 1911 (Isopoda: Styloniscidae), and two predatory flatworm species (Platyhelminthes: Geoplanidae, *Kontikia andersoni* Jones 1981, and *Arthurdendyus vegrandis* Dendy 1896). The slug and earthworms are pervasive on the island whereas the flatworms and terrestrial Crustacea are more restricted (Greenslade et al. 2006; Greenslade et al. 2007, 2008).

Invasive isopod and amphipod (crustacea)

The terrestrial Crustacea *Puhuruhuru patersoni* (amphipod) and *Styloniscus otakensis* (isopod) (Fig. 2), were discovered on the island around the research station in the 1990s. Prior to its establishment in 1948, the research station was the site of commercial seal harvesting by New Zealand-based operators (Cumpston 1968), thus both terrestrial Crustacea are thought to have been, by association, introduced from their native range in New Zealand between early 1800s and early 1900s (van Klinken and Green 1992; Richardson and Jackson 1995). A comprehensive island-wide survey in 1994 conducted by Davies and Melbourne (1999) across 67 sites did not detect either *P. patersoni* or *S. otakensis*, nor did an island-wide survey in 2004 at 693 sites by Greenslade et al. (2007) (see also Greenslade et al. 2008). More fine-scale surveying in 2004 confirmed that neither the amphipod nor isopod had markedly increased their range, although the isopod had marginally changed its limits within the boundaries of research station (Greenslade et al. 2008). Given that amphipods are highly desirable rodent food (Taylor 1986; Russell et al. 2020), their population is expected to increase following the recent eradication of rodents on Macquarie Island between 2010–2014 (Macquarie Island Pest Eradication Project, ‘MIPEP’) (Houghton 2020).

As macro-detritivores, non-native isopods can have considerable impacts on Southern Ocean Island ecosystems (Jones et al. 2003). Neither native nor non-native isopod species are preferred rodent food according to several rodent diet studies on Southern Ocean Islands where they are present (Houghton et al. 2019a). However, they are potentially sensitive to habitat changes, such as vegetation recovery following the cessation of grazing and burrowing since the removal of rabbits during MIPEP (Shaw et al. 2011; Whinam et al. 2014; Fitzgerald 2020). On Macquarie Island, *S. otakensis* is present in humid habitats with good plant cover, healthy leaf litter and possibly a soil moisture content threshold above 30% (Greenslade et al. 2008). Interestingly, isopod abundance declined at sites monitored for invertebrates between 2015–2018, despite recovering vegetation (post- MIPEP) (Houghton 2020). This may be due to changing soil properties and vegetation communities following invasive mammal removal (Houghton 2020).
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Invasive flatworms (platyhelminthes)

Flatworms were first discovered at two topographically restricted creek-side sites near Lusitania Bay (for island place names, see Fig. 3) on the southeastern coast of Macquarie Island in 1997 by R. Blakemore whilst conducting earthworm surveys (Greenslade et al. 2007). Commercial sealing and...
penguin harvesting by New Zealand-based operators occurred in the Lusitania Bay area until 1919 (Cumpston 1968), thus flatworms were likely introduced from New Zealand to Macquarie Island more than 100 years ago in association (Greenslade et al. 2007). The flatworms collected in 1997 were later identified as *Kontikia andersoni* and *Arthurdendyus vegrandis* (Winsor and Stevens 2005) (Fig. 2).

*Arthurdendyus vegrandis* was described as a new species by Winsor and Stevens (2005), however it is likely to be con-specific with species from the South Island of New Zealand (Greenslade et al. 2007) where many *Arthurdendyus* species are undescribed (Yeates et al. 1997). Greenslade et al. (2007) conducted a baseline survey for flatworms in 2004, which included 182 sites in the south-east ‘target area’, and an additional 511 sites across Macquarie Island. No surveys were conducted in restricted access areas, such as the south-eastern coast of the island south of Lusitania Bay. The 2004 survey confirmed that both flatworm species had spread from their likely region of introduction. The location of the 511 additional island-wide sites reporting negative results for both flatworms were not available to us. The island-wide invertebrate survey in 1994 which included timed search counts at 67 sites also did not detect either *A. vegrandis* or *K. andersoni* (Davies and Melbourne 1999). Greenslade et al. (2007) reports that these 67 sites were outside the ‘target area’ for flatworm searches. The precise locations of these sites were also not available to us.

Globally, flatworms have been, and continue to be, inadvertently but readily introduced to new regions alongside human activity (Sluys 2016). Once introduced, they often remain undetected for a time, spread easily, and become invasive (Sluys 2016). Their success is attributed to their cryptic nature, generalist predation, unpalatability to predators, ability to regenerate when cut in two and asexually reproduce via fission (fragmentation) (Winsor et al. 2004; Sluys 2016). Being voracious generalist predators of native soil invertebrates, including earthworms, snails, slugs, insect larvae, isopods, springtails and more, their invasion can have serious consequences for local ecosystems, affecting nutrient cycling regimes, threatening native species, and altering plant communities (Sluys 2016). *Arthurdendyus* species are all native to New Zealand and prey heavily on earthworms (Yeates et al. 1997). Two species of *Arthurdendyus* are invasive pests in the United Kingdom (UK)—A.
triangulatus in particular is a major pest causing a reduction or temporary elimination of native earthworms with serious implications for soil functioning (Boag et al. 1997; Boag and Yeates 2001; Cannon et al. 1999; Murchie and Gordon 2013), and drastic declines in other animals that rely on earthworms as prey (Alford et al. 1996; Boag 2000). Kontikia andersoni is also a pest in the UK. Its feeding habits are not well known (Winsor et al. 2004), except that it specialises in predation of Collembola (springtails), and consumes slugs and lumbricid worms (Flatworms of Cornwall 2021). The impacts of Kontikia and Arthurdendyus species in the UK are considered so great that it is an offence under the UK’s Wildlife and Countryside Act to knowingly distribute them (Eversham 2013; Sluys 2016).

We used historical data on the distribution of the two flatworm species (Greenslade et al. 2007) and the two terrestrial Crustacea (Greenslade et al. 2008) on Macquarie Island together with contemporary surveys of each species to assess their current distribution and status. The data sources were (1) an island-wide invertebrate trapping program (2015–2018), (2) focused searching in areas where these species had been previously detected (i.e. by Greenslade et al. 2007, 2008), and (3) a dedicated island-wide survey for flatworms. We discuss mechanisms by which these species may spread, make recommendations for
reducing the risk of further intra-island transfer, and highlight the biosecurity implications for Australia.

Methods

Island-wide invertebrate monitoring

Comprehensive invertebrate surveys were carried out at 24 sites across Macquarie Island over three consecutive austral summers (2015–2018). At each site, a variety of trapping techniques were used—pit-falls, sweeping, 20-min counts and litter sampling. Vegetation beating was added in the second season (2016–2017), yellow pans in the third season (2018). Replicates of each trap type were used within sites (five pitfalls, three yellow pans, three beatings, three sweeps, two counts, three litter samples), and trapping events at each site for pitfalls, beatings, sweeps, and counts were repeated multiple times during each season—2015/2016, 2016/2017 three events, 2018 three events, except for pitfalls with two events (see Houghton et al. 2019b and Houghton 2020 for detailed trapping and surveillance methodology). The 24 sites were selected to represent five key vegetation communities on the island (‘Herbfield’, ‘Stilbocarpa’, ‘Short grassland’, ‘Tall grassland’ and ‘Feldmark’, as per Selkirk et al. 1990), and were defined by 10 × 10 m vegetation surveys (Houghton 2020) (Survey data available via the Australian Antarctic Division Data Centre, doi:10.26179/k24z-nx57).

As the distributions of the four target non-native invertebrate species began to emerge from the island-wide monitoring, it became clear that (1) focused searching would be sufficient for the terrestrial crustacea, (2) A. vergrandis was not readily found, and (3) K. andersoni appeared more widespread. These latter revelations prompted a dedicated island-wide survey for flatworms.

Terrestrial crustacea survey

Based on the 2004 baseline distribution of P. patersoni and S. otakensis (Greenslade et al. 2008), focused searching was conducted for P. patersoni around the isthmus south of the research station (the northern tip of the island) and for S. otakensis to the south and west of Halfway Hill (north-east corner of the island) (Greenslade et al. 2008). Areas that were searched by Greenslade et al. (2008) were revisited. Both P. patersoni and S. otakensis are relatively large (up to 5.5 and 11 mm respectively—Greenslade 2006; Richardson and Jackson 1995), thus dedicated searches in suitable habitat were sufficient to indicate presence or absence.

Island-wide flatworm survey

A comprehensive survey was designed to map the distribution of flatworms on the island in more detail. Permits were acquired for all restricted coastal areas except for the sensitive areas at the far south-western corner of the island. Sites were selected around each 1 km centroid in coastal areas, from which the closest suitable habitat (i.e. vegetated and damp) within 100 m was identified to conduct a timed hand search. Additional to the coastal sites, four cross-island transects following major drainage areas were also surveyed, with sites spaced every 500 m. A GPS coordinate was taken to mark the centre point of each survey site. Wetness of the ground surface was determined by assessment in the field (MH), utilising sight and touch. A five-point scale was used with the ground surface defined as being dry to touch (1), being damp to touch (2), being wet to touch (3), being very wet with water visible (4) and being saturated and severely waterlogged (5). Dominant vegetation at each site was noted, as were other significant features including drainage, aspect, nearby water sources, bare surface, and animal activity. A total of 59 sites were surveyed from the eastern half of the island, and 44 from the western half (includes coastal and inland areas).

Surveys (timed searches by 1, 2, or 3 people) were conducted in daylight hours between the 22nd February and 16th March 2018. Due to their relatively large size (up to 2 cm), flatworms are easily detected by the naked eye. Search time was initially 40 min (sites F1 – F36, excepting F6), but it became clear that flatworms, if present, were detectable in under 20 min. Thereafter, depending on the number of people conducting the survey, search time was reduced to 20 or 21 min at each site, allowing more sites to be surveyed. When more than one person attended the survey, each searched separately from the site centre, and the total search time was divided by the number of people (i.e. two people searching 10 min each totalled 20 min; three people searching 7 min each, totalled
21 min). Searching involved overturning stones and rocks, teasing apart wet leaves and litter, looking at the base of plants. The search carried on until a flatworm was detected (upon which the search time was recorded), or until the total search time had elapsed. If no flatworms were found within this time limit, a negative result was recorded. In total, 103 sites were surveyed across Macquarie Island of which 48 were searched by a single person (MH), 17 by a team of two people, and 38 by a team of three people (doi:10.26179/k24z-nx57).

Mapping

To calculate the change in distribution of *K. andersoni* over time, we first divided the island into 1 km grid squares using Manifold GIS Systems (Version 8). Both the 2004 and the 2015–2018 survey data were overlaid onto the 1 km grid to quantify occupancy by *K. andersoni* at these time periods. We then quantified the change in the number of occupied 1 km x 1 km cells and the proportion of the island occupied by *K. andersoni* over time.

Results

Isopod and amphipod

Focused low intensity searching in 2018 for *S. otakensis* and *P. patersoni*, combined with results from the 24 island-wide invertebrate monitoring sites (2015–2018), revealed that these species had not markedly expanded their range since they were last surveyed in 2004. Neither of these species were incidentally detected during the island-wide flatworm surveys which covered suitable habitat.

Flatworms

*A. vergrandis* was not detected at any of the 24 island-wide invertebrate monitoring sites, nor during the island-wide flatworm survey, despite additional focussed searches in its last recorded range in 2004 (doi:10.26179/k24z-nx57).

*K. andersoni* was found at six of the 24 island-wide invertebrate monitoring sites, of which four were outside its previously known distribution (doi:10.26179/k24z-nx57). Two of the new sites were on the west coast, at which only a single *K. andersoni* was detected during the three years of monitoring. At the other two new sites (one on the east coast, one on the southern coast), *K. andersoni* was abundant across years.

During the island-wide flatworm survey, *K. andersoni* was found at 29 of the 103 sites (Fig. 1, doi:10.26179/k24z-nx57), with 24 outside its previous mapped distribution in 2004. Our survey found *K. andersoni* occupying most south-eastern coastal areas of Macquarie Island, as well as inland areas in the central region of the island around Green Gorge tarn and the eastern slopes of Mt Law. *K. andersoni* was detected at 24 eastern sites, the northernmost being ~500 m north of Brothers Point in the northeast of the island (Fig. 1, see Fig. 3 for island place names). Eighteen of these were from coastal areas (below the escarpment edge), while six were found at inland sites. *K. andersoni* was also found at five west coast sites, the northernmost being at Sellick Bay.

*K. andersoni* animals were found both on the ground surface over decaying plant material and within wet leaves and litter up to 1–2 cm deep. They were more often associated with wet, rather than damp or dry sites, meaning the soil at these sites was never dry or pliable, the soil always moist and at times waterlogged (three and four on the wetness scale). At coastal sites, *K. andersoni* typically occurred in the wet litter of tussock grass (*Poa foliosa*) and Macquarie Island cabbage (*Stilbocarpa polaris*). In areas where these species do not occur (e.g. away from the coast, on inland tracks, and in the region of Green Gorge tarn and Mt Law), *K. andersoni* was typically found in wet moss beds and amongst small *Epilobium* spp. herbs. All 24 detections of *K. andersoni* on the east coast were at sites with a wetness index of three or four (i.e. wet, or very wet). On the west coast, the five detections coincided with a wetness index of three.

*Kontikia andersoni* expansion

*Kontikia andersoni* has more than doubled its occupancy (at the 1 km scale) since 2004. In 2004, *K. andersoni* occupied 14 of 193 1 km grid cells (or 7.2% of the island). In 2018 *K. andersoni* occupied 32 grid cells (or 16.6% of the island) (Fig. 3).

The detection of *K. andersoni* at Hurd Point, the southernmost point of the island, indicates that
between 2004 and 2018 the flatworm spread south 6.4 km over 14 years – a mean rate of ~460 m/yr. It also spread 7.2 km north from its 2004 limit, representing a mean rate of ~515 m/yr. It has also expanded inland to an area of ~170 m in altitude around Mt Law. Furthermore, for the first time we found *K. andersoni* on the west coast of the island, 3.9 km from its previous western extent in 2004. While it was detected over a span of 11.4 km on the west coast, its density was much less than the east coast distribution.

**Discussion**

Over a 14-year period, the small, flightless and slow-moving invasive flatworm *Kontikia andersoni*, has greatly expanded its range on Macquarie Island, while the distributions of *A. vergrandis*, *S. otakensis* and *P. patersoni* have not markedly changed. Since Greenslade et al. (2007) calculated invasive flatworms had spread from their presumed introduction site at Lusitania Bay at a rate of ~10 m/yr, the invasion of *K. andersoni* has accelerated south, west and north at around 500 m/yr, and more than doubled its range. It is possible that *K. andersoni* was present south of Lusitania Bay but was undetected in 2004 as this area was not surveyed due to access restrictions (Greenslade et al. 2007). However, despite this uncertainty, our finding that *K. andersoni* has rapidly expanded its range since 2004 is supported by flatworm absences previously reported by Davies and Melbourne (1999) and Greenslade et al. (2007) across 578 sites island-wide. Such a lag in the invasion rate for a non-native invertebrate has been detected in the region, notably for the flightless, predatory carabid beetle (*Merizodus soledadinus*) on sub-Antarctic Kerguelen Island. Introduced more than 100 years ago, in the past few decades the beetle has drastically expanded its range with devastating consequences for endemic invertebrate fauna (Lebouvier et al. 2020). Such lag phases in invasion processes are common, including for invertebrates (see Lebouvier et al. 2020, and references within for discussion), but not regularly documented.

The dispersal mechanism for *K. andersoni* on Macquarie Island is unknown. Its predominantly coastal distribution is not surprising given the large tracts of unsuitable habitat in-between the east and west coasts. Specifically, the island’s interior is colder, drier, higher in altitude, often comprised of fieldmark and gravel, and with low vegetation cover. Yet *K. andersoni* has overcome this barrier, dispersing kilometres from its east coast introduction site to colonise the west coast of the island. Humans are important vectors of non-native plant and invertebrate propagules to Antarctica and sub-Antarctic islands (Frenot et al. 2005; Chown et al. 2012; Houghton et al. 2016; Duffy and Lee 2019). Human activities also drive intra-regional transfer of propagules within Antarctic sites and sub-Antarctic islands (Lee and Chown 2011; Hughes et al. 2019; Bartlett et al. 2020; Lebouvier et al. 2020). On Marion Island, cargo movements by helicopters are implicated as likely vectors of introduced slugs (*Derocerus panormitanum*), which are now widespread and abundant on the island (Smith 1992; Chown et al. 2002). Helicopter transport of people and cargo is frequent during Macquarie Island resupply operations, but these movements rarely occur between field huts, or between the east and west coasts. However, there was a significant increase in helicopter activity between 2011–2014 during the large-scale MIPEP program (Springer 2016). Following the aerial baiting phase of the pest eradication program, a three-year active hunting phase commenced. During this time, high quantities of cargo were moved between field huts, the research station and the ship (Houghton, pers. obs.). Despite this increase in cargo movement, *K. andersoni* has not been detected at the research station where suitable habitat is present.

The spread of flatworms between and within regions around the world is closely linked to the movement of horticultural material such as soil, pots, plants and garden supplies (Boag et al. 2010; Sluys 2016). While soil and plants are not actively transported around Macquarie Island, human foot traffic around the island is common, by which wet plant and soil material is transported on boots and equipment. Flatworms have been found moving along Macquarie Island walking tracks (Greenslade et al. 2007), and footpads have been identified as dispersal corridors for invasive invertebrate movement elsewhere in the region (Bartlett et al. 2020). Similar observations have been made for invasive plants in the sub-Antarctic (Scott and Kirkpatrick 1994; Le Roux et al. 2013; Sindel et al. 2017). Given the flatworm’s ability to fragment and regenerate (Winsor et al. 2004;
Sluys 2016), human-mediated transport of *K. andersoni* via foot is highly probable. There was intensive foot traffic on the island during MIPEP (Springer 2016). First mitigation teams were deployed on foot to bury carcasses, followed by 2.5 years of hunting teams industriously traversing the island by foot in search of remaining rodents and rabbits. Five temporary huts were placed in locations distant from the established network of walking tracks to enable field workers working access to more of the island. Annual hunting field teams comprised 12–14 people and up to eleven detection dogs, each walking over all accessible ground on the island (including between coasts) on a daily basis. The flatworm’s presence at Mt Law and the southern flank of Green Gorge tarn is close to routes regularly used by hunters and park rangers to travel between the east and west coasts.

Birds may also contribute to the dispersal of *K. andersoni* on Macquarie Island. Seabirds inadvertently transport non-native biological material between and within landmasses in the lower latitudes, as well as the Antarctic and sub-Antarctic region, including soil microarthropods up to 1.5 mm in size (Krivolutsky et al. 2004), plant seeds (Vidal et al. 2003; Turner et al. 2006; Sindel et al. 2017), bacterial pathogens (Cerdà-Cuéllar et al. 2019) and viruses (Springer and Carmichael 2012). Their activity is a possible dispersal mechanism for non-native invertebrates on Signy Island (Hughes and Worland 2010) and the Kerguelen archipelago (Lebouvier et al. 2020). Birds could transport flatworms or their fragments on their feathers or feet, in mud or guano, as they move between flatworm-suitable coastal habitats around penguin colonies and waterways. Furthermore, frequent seabird travellers along and between the west and east coasts include kelp gulls (*Larus dominicanus* Lichtenstein, 1823), skuas (*Stercorarius antarcticus* Lesson, 1831) and giant petrels (*Macronectes giganteus* Gmelin, 1789, *Macronectes halli* Mathews, 1912) (Travers 2021). However, bird-mediated dispersal does not explain the northern limits of the flatworm’s range, nor its rapid and recent range expansion. Likewise, its distribution cannot be explained by considering ocean currents as a potential dispersal pathway via marine debris or marine animals. Salinity stress experiments on the larvae of the Ephemeroptera *murphyi*, a fly introduced to Signy Island, found they could survive up to two weeks in sea water (e.g. caught in terrestrial vegetation washed into the sea, or trapped in seal fur), and suggested that this might permit local movement and colonisation on a scale of tens of kilometres (Bartlett et al. 2021). Similar studies into the salinity tolerance of *K. andersoni* would help to clarify its potential to disperse in this way.

*Kontikia andersoni* has an intermittent occurrence on the west coast of Macquarie Island over a range of ~11.04 km and was only detected as singletons at our western fixed invertebrate monitoring sites. These observations point to less abundant populations on the west coast of the island, where we generally observed sites with a lower wetness index than eastern sites (doi: 10.26179/k24z-nx57). Future research is needed to clarify the role of aspect, climate and microclimate on habitat availability and suitability for *K. andersoni*.

Climate is changing across the region. There have been recent decadal changes in summer water availability, increased wind speed and sunshine hours on Macquarie Island (Bergstrom et al. 2015). It is not yet known how climatic change will influence *K. andersoni*. Observations and predictive models from other sub-Antarctic islands suggest there may be changes to available habitat and changes in species-species interactions (e.g. Davies et al. 2011). A recent study on Iles Kerguelen found climate change was a key factor in the recent rapid range expansion of an invasive beetle due to increases in suitable habitat (Lebouvier et al. 2020). Multiple studies for the region predict warming climate will influence biodiversity of soil invertebrates (e.g. Bokhorst et al. 2008; Janion et al. 2010; Nielsen and Wall 2013; Andriuzzi et al. 2018). Furthermore, warming climate is predicted to drive expansion of existing non-native species and see the arrival and expansion of new non-native species; plants (Pertierra et al. 2017; Molina-Montenegro et al. 2019; March-Salas and Pertierra 2020) and invertebrates (Lebouvier et al. 2011; Bartlett et al. 2020; Pertierra et al. 2020), or both (Frenot et al. 2005; Duffy et al. 2017; Lee et al. 2017; Duffy and Lee 2019).

Species distribution models and ecological niche models of both native and non-native species under different climate change scenarios point to both range contractions and expansions. For example, the native Antarctic chironomid midge *Parochlus steinerrti* Gerke, 1889 is predicted to expand its distribution on the Antarctic Peninsula as the climate warms (Contador et al. 2020), while ensemble forecasting of
four species of non-native Collembola in Antarctica identifies several areas in which environmental conditions will be suitable for their invasion under future warming scenarios (Vega et al. 2021). Such research informs pre-emptive biosecurity, targeted surveillance at high-risk sites, the identification of pathways of introduction, and development of rapid responses in the early stages of invasion, all of which are increasingly required (Wilson et al. 2009; Foxcroft et al. 2011; Duffy et al. 2017). However, to inform the management of established invasive species, information on native species and community functioning is critical (Molina-Montenegro et al. 2019). Monitoring native invertebrate populations on Macquarie Island is essential to determine how *K. andersoni* is impacting the island ecosystem. Invertebrate monitoring will also broaden our understanding of the role of climate change is impacting the island ecosystem.

*Arthurdendyus vergrandis* was not detected during the island-wide invertebrate monitoring program between 2015–2018, despite one of these sites overlapping an area where *A. vergrandis* was found in 2004 (Greenslade et al. 2007). Our monitoring program involved multiple trap methods in replicates each season, including timed searches. *A. vergrandis* was also not found during the dedicated island-wide flatworm survey, despite searches in both areas of its previous recorded distribution (in 2004). Rocks, stones and debris were regularly upturned and examined during our survey, a technique which had previously detected *A. vergrandis* (Greenslade et al. 2007). It seems unlikely that having established, *A. vergrandis* is now absent from Macquarie Island. We assume that it remains at least within the limited areas described by Greenslade et al (2007), but at a much lower abundance than *K. andersoni*. This finding is consistent with Greenslade et al. (2007), that *K. andersoni* are more widespread and at least three times more abundant than *A. vergrandis*.

Invasion across the sub-Antarctic region is relatively recent with most of the islands discovered only 200 or so years ago (see Frenot et al. 2005). Invasion studies from the sub-Antarctic and Antarctic (Hughes and Worland 2010; Frenot et al. 2005; McGeoch et al. 2015), and more broadly (Williamson and Fitter 1996; Kolar and Lodge 2001; Sol et al. 2012; Walther et al. 2009), show only a minority of non-native species introduced become invasive, while many other non-native species establish and are ‘persistent’ neither expanding or contracting their range over decades. Our survey found *Arthurdendyus vergrandis* had very low or localised populations, and we found no evidence that *Styloniscus otakensis* and *Puhuruhuru patersoni* have expanded their ranges, remaining restricted to the north of the island. Despite all three of these species residing on the island for more than 100 years, to date they have persisted in a narrow range. Suitable habitat for both *S. otakensis* and *P. patersoni* is available outside and adjacent to their existing range (van Klinken and Greenslade 1992; Richardson and Jackson 1995) and there are no identifiable barriers to their dispersal. Factors limiting their spread therefore remain unclear. Furthermore, the removal of invasive rodents from the island, which are known on sub-Antarctic islands to preferentially prey on amphipods (Houghton et al. 2019a), has not influenced amphipod numbers. Although in 2018 we detected singletons of *S. otakensis* at sites outside their 2004 range, given the animal’s tendency to mass in high numbers where present (Houghton, pers. obs.), up to 4000–6000 animals per square metre (Greenslade et al. 2008), and as multiple years of monitoring did not reveal further individuals at these sites, we suspect these detections were bird-assisted or wind-swept vagrants. The high winds experienced on Macquarie Island are renowned for dispersing invertebrates (Hawes et al. 2013). Similarly, a single *S. otakensis* detected in 2004, 2 km south of its mapped distribution (Greenslade et al. 2008), may also have been a vagrant, as we found no individuals in this region during our survey. It is possible that some populations of *S. otakensis* remain undetected by past surveys and our work, as despite high densities where it is found, its distribution is patchy (Greenslade et al. 2008).

**Management implications**

The impact of a rapidly expanding *K. andersoni* population on the Macquarie Island ecosystem is unknown. Flatworms are generalist predators and on Macquarie Island they have no known predators and little competition from other invertebrates. *K. andersoni* could reduce the abundance and diversity of invertebrates on the island, as invasive flatworms do elsewhere (Boag and Yeates 2001; Cannon et al. 1999; Murchie and Gordon 2013; Sluys 2016), altering soil nutrient cycling and impacting vegetation.

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communities. This study highlights the need to establish an appropriate monitoring program of native invertebrates on Macquarie Island in order to identify and quantify impacts of invasive species.

Given there is similar habitat outside of *K. andersoni*’s current range on the island, further expansion is feasible. Proactive development of hygiene measures would help to prevent the inadvertent transport of *K. andersoni*. Rigorous washing of boots, shoes, walking poles and other equipment that have been in contact with the soil when leaving invaded areas is recommended. This could be done in many of the numerous fresh running streams or accessible water on the coast. The use of suitable biocides should be investigated.

*Kontikia andersoni* and flatworms of the genus *Arthurdendyus* are not known to be present in other parts of Australia (Greenslade et al. 2007). Both flatworms present potential environmental and agricultural risks to mainland Australia based on their invasive impacts elsewhere. Of real concern, is that *K. andersoni* will continue to advance north to the island’s research station, where during resupply operations propagules attached to outdoor stored cargo could be transferred via the resupply ship back to Tasmania. In this context there is pressing need to identify appropriate biosecurity measures. Currently, no washing or biocides are used on cargo and equipment returning to Australia.

All four species discussed here are registered as introduced species to Australia (ABRS 2021) as they occur on Macquarie Island, which falls under Tasmanian jurisdiction. However, their presence 1500 km away from mainland Tasmania may have influenced the amount of attention they have received. Biosecurity protocols for transport from Macquarie Island to mainland Australia may have influenced the amount of attention they have received. Biosecurity protocols for transport from Macquarie Island to mainland Tasmania, and Australia. Our work demonstrates how quickly these invaders can spread, even on a remote world heritage island.

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**Data availability** All data generated or analysed during this study are included in this published article and its supplementary information files.

**Declarations**

**Conflict of interests** The authors have no relevant financial or non-financial interests to disclose.

**References**

Alford DV, Lole MJ, & Emmett BJ (1996) Alien terrestrial planarians in England & wales, and implications for horticultural trade. Brighton crop protection conference: Pests & Diseases 1996: Volume 3: Proceedings of an International Conference, Brighton, UK, 18–21 November 1996 1083–1088

Andriuzzi W, Adams B, Barrett J, Virginia R, Wall D (2018) Observed trends of soil fauna in theantarctic dry valleys: early signs of shifts predicted under climate change. Ecology 99(2):312–321

Angel A, Wanless RM, Cooper J (2009) Review of impacts of the introduced house mouse on islands in the Southern Ocean: are mice equivalent to rats? Biol Invasions 11(7):1743–1754. https://doi.org/10.1007/s10530-008-9401-4

Bartlett JC, Convey P, Perttierra LR, Hayward SA (2020) An insect invasion of Antarctica: the past, present and future distribution of eretmoptera murphyi (*Diptera, Chironomidae*) on SIGNY Island. Insect Conserv Divers 13(1):77–90

Bartlett JC, Convey P, Hughes K, Thorpe S, Hayward S (2021) Ocean currents as a potential dispersal pathway for Antarctica’s most persistent non-native terrestrial insect. Polar Biol 44(1):209–216

Bergstrom DM, Bricher PK, Raymond B, Terauds A, Doley D, McGeoch MA, Whinam J, Glen M, Yuan Z, Kiefer K (2015) Rapid collapse of a sub-antarctic alpine ecosystem: the role of climate and pathogens. J Appl Ecol 52(3):774–783
Boag B (2000) The impact of the New Zealand flatworm on earthworms and moles in agricultural land in western Scotland. Asp Appl Biol 62:79–84

Boag B, Yeates GW (2001) The potential impact of the New Zealand flatworm, a predator of earthworms, in western Europe. Ecol Appl 11(5):1276–1286

Boag B, Palmer LF, Neilson R, Legg R (1997) Distribution, prevalence and intensity of earthworm populations in arable land and grassland in Scotland. Ann Appl Biol 130(1):153–165. https://doi.org/10.1111/j.1744-7348.1997.tb05791.x

Boag B, Mackenzie K, McNicol JW, Neilson R (2010) Sampling for the New Zealand flatworm. Proc Crop Prot North Br 2010:45–50

Bokhorst S, Huiskes A, Convey P, Van Bodegom PM, Aerts R (2008) Climate change effects on soil arthropod communities from the Falkland Islands and the maritime Antarctic. Soil Biol Biochem 40(7):1547–1556

Cannon RJC, Baker RHA, Taylor MC, Moore JP (1999) A review of the status of the New Zealand flatworm in the UK. Ann Appl Biol 135(3):597–614

Cerdà-Cuéllar M, Moré E, Ayats T, Aguilera M, Muñoz-González S, Antilles N, Ryan PG, González-Solís J (2019) Do humans spread zoonotic enteric bacteria in Antarctica? Sci Total Environ 654:190–196

Chilton C (1911) The crustacean of the Kermadec Islands. Trans NZ Inst 43:544–573

Chown SL, Convey P (2016) Antarctic entomology. Annu Rev Entomol 61:119–137

Chown SL, McGeoch MA, Marshall DJ (2002) Diversity and conservation of invertebrates on the sub-Antarctic Prince Edward Islands. Afr Entomol 10(1):67–82

Chown SL, Lee JE, Shaw JD (2008) Conservation of Southern Ocean Islands: Invertebrates as exemplars. J Insect Conserv 12(3):277–291. https://doi.org/10.1007/s10841-008-9151-8

Chown SL, Huiskes AHL, Greenslade P, Melbourne BA, Stevens MI (2008) The status of exotic terrestrial flatworms to sub-Antarctic Macquarie Island. Polar Biol 31(11):1195–1204

Chown SL, Convey P (2016) Antarctic entomology. Annu Rev Entomol 61:119–137

Croll DA, Marion JA, Estes EM, Danner EM, Byrd GV (2005) Introduced Predators Transform Subarctic Islands from Grassland to Tundra. Science 307:1959–1961. https://doi.org/10.1126/science.1108485

Cumpston JS (1968) Macquarie Island. Australia department of external affairs, Antarctic Division

Davies GF, Melbourne BA (1999) Statistical models of invertebrate distribution on Macquarie Island: a tool to assess climate change and local human impacts. Polar Biol 21:240–250

Davies GF, Melbourne BA, McClenahan JL, Tuff T (2011) Statistical models for monitoring and predicting effects of climate change and invasion on the free-living insects and a spider from sub-Antarctic Heard Island. Polar Biol 34:119–125

Dendy A (1986) Notes of the New Zealand land Planarians. Part II. Trans New Zealand Inst 28:210–214

Dilley BJ, Schoombie S, Stevens K, Davies D, Perold V, Osborne A, Schoombie J, Brink CW, Carpenter-Kling T, Ryan PG (2018) Mouse predation affects breeding success of burrow-nesting petrels at sub-Antarctic Marion Island. Antarct Sci 30(2):93–104

Duffy GA, Lee JR (2019) Ice-free area expansion compounds the non-native species threat to Antarctic terrestrial biodiversity. Biol Cons 232:253–257

Duffy GA, Coetzee BW, Latombe G, Akerman AH, McGeoch MA, Chown SL (2017) Barriers to globally invasive species are weakening across the Antarctic. Divers Distrib 23(9):982–996

Eversham B, (2013) A land flatworm new to Britain from Cambridgeshire (No. 55; Nature in Cambridgeshire, pp. 46–49)

Fitzgerald NB (2020) Vegetation change on sub-Antarctic Macquarie Island. University of Tasmania

Flatworms of Cornwall (2021) The Student Non-Native Working Group, Cornwall College. https://flatwormsofcornwall.wordpress.com/2014/07/03/kontikia-andersoni/

Foxcroft LC, Jarosik V, Pyssek P, Richardson DM, Rouget M (2011) Protected-area boundaries as filters of plant invasions. Conserv Biol 25(2):400–405

Frentz Y, Chown SL, Whinam J, Selkirk P, Convey P, Skotnicki M, Bergstrom DM (2005) Biological invasions in the Antarctic: extent, impacts and implications. Biol Rev 80(01):45–72

Fukami T, Wardle DA, Bellingham PJ, Mulder CPH, Towns DR, Yeates GW, Bonner KI, Durrett MS, Grant-Hoffman MN, Williamson W (2006) Above and below ground impacts of introduced predators in seabird-dominated island ecosystems. Ecol Lett 9:1299–1307. https://doi.org/10.1111/j.1461-0248.2006.00983.x

Gerke G (1889) Vorläufige Nachricht über die Fliegen Süd-Georgiens, nach der Ausbeute der Deutschen Station. Anstalt 6:153–154

Greenslade P (2006) The invertebrates of Macquarie Island. Australian Antarctic Division

Greenslade P, Melbourne BA, Stevens MI (2007) The status of two exotic terrestrial flatworms to sub-Antarctic Macquarie Island. Polar Biol 30:961–967

Greenslade P, Melbourne BA, Stevens MI (2008) The status of two exotic terrestrial crustacean of sub-Antarctic Macquarie Island. Polar Rec 44:15–23
Rapid range expansion of an invasive flatworm, Kontikia andersoni, on sub-Antarctic Macquarie Island.

Hawes TC, Greenslade P (2013) The aerial invertebrate fauna of sub-Antarctic Macquarie Island. J Biogeogr 40(8):1501–1511

Houghton M, McQuillan PB, Bergstrom DM, Frost L, van den Hoff J, Shaw J (2016) Pathways of alien invertebrate transfer to the Antarctic region. Polar Biol. https://doi.org/10.1007/s00300-014-1599-2

Houghton M, Terauds A, Shaw J (2019b) Methods for monitoring invertebrate response to vertebrate eradication. Isl Invasives: Scaling Meet Chal 62:381

Houghton M, Terauds A, Merritt D, Driessen M, & Shaw J (2019a) The impacts of non-native species on the invertebrates of Southern Ocean Islands. J Insect Conserv 1–18

Houghton M (2020) Invertebrate monitoring as measure of ecosystem change. University of Queensland

Hughes KA, Worland R (2010) Spatial distribution, habitat preference and colonization status of two alien terrestrial invertebrate species in Antarctica. Antarct Sci 22(3):22–231

Hughes KA, Convey P, Perttierra LR, Vega GC, Aragón P, Olalla-Tárraga MÁ (2019) Human-mediated dispersal of terrestrial species between Antarctic biogeographic regions: a preliminary risk assessment. J Environ Manag 232:73–89

Janion C, Leinaas HP, Terblanche JS, Chown SL (2010) Trait means and reaction norms: the consequences of climate change/invasion interactions at the organism level. Evol Ecol 24:1365–1380. https://doi.org/10.1007/s10682-010-9405-2

Jones HD (1981) A new species of land Planaria from Northern Ireland (Platyhelminthes: Turbellaria.). J Zool London 193:71–79

Jones AG, Chown SL, Ryan PG, Gremmen NJM, Gaston KJ (2003) A review of conservation threats on Gough Island: a case study for terrestrial conservation in the Southern Oceans. Biol Cons 113(1):75–87. https://doi.org/10.1016/S0006-3207(02)00351-8

Kolar CS, Lodge DM (2001) Predicting invaders: response from Kolar and lodge. Trends Ecol Evol 16(10):546

Krivolutsky D, Lebedeva N, Gavrilov M (2004) Soil microarthropods in the feathers of Antarctic birds. Dokl Biol Sci 397(1):342–345

Lee JR, Raymond B, Bracegirdle TJ, Chades I, Fuller RA, Shaw JD, Terauds A (2017) Climate change drives expansion of Antarctic ice-free habitat. Nature 547(7661):49–54

Le Roux PC, Ramaswiela T, Kalwijb JM, Shaw JD, Ryan PG, Treasure AM, McClelland GTW, McGeoch MA, Chown SL (2013) Human activities, propagule pressure and alien plants in the sub-Antarctic: tests of generalities and evidence in support of management. Biol Cons 161:18. https://doi.org/10.1016/j.biocon.2013.02.005

Lebouvier M, Laperie M, Hulle M, Marais A, Cozic Y, Lalouette L, Vernon P, Candresse T, Frenot Y, Renault D (2011) The significance of the sub-Antarctic Kerguelen Islands for the assessment of the vulnerability of native communities to climate change, alien insect invasions and plant virus. Biol Invasions 13:1195–1208

Lebouvier M, Lambret P, Garnier A, Convey P, Frenot Y, Vernon P, Renault D (2020) Spotlight on the invasion of a carabid beetle on an Oceanic Island over a 105-year period. Sci Rep 10(1):1–17

Lee JE, Chown SL (2011) Quantification of intra-regional propagule movements in the Antarctic. Antarct Sci 23(4):337–342

Leinaas HP, Bengtsson J, Janion-Scheepers C, Chown SL (2015) Indirect effects of habitat disturbance on invasion: nutritious litter from a grazing resistant plant favors alien over native Collembo. Ecol Evol 5(16):3462–3471. https://doi.org/10.1002/ece3.1483

Lesson RP (1831) Tableau méthodique des ordres, sous-ordres, familles, tribus, genres, sous-genres et races d’oiseaux

Lichtenstein H (1823) Verzeichniss der Doubletten des Zoologischen Museums der Königl. Universität zu Berlin nebst Beschreibung vieler bisher unbekannter Arten von Säugethieren, Vögeln, Amphibien und Fröschen, pp 1–118. Berlin, Trautwein

Mack RN, Simberloff D, Lonsdale WM, Evans H, Clout M, Bazzaz A, F (2000) Biotic invasions: causes, epidemiology, global consequences, and control. Ecol Appl 10(3):689–710

March-Salas M, Perttierra LR (2020) Warmer and less variable temperatures favour an accelerated plant phenology of two invasive weeds across sub-Antarctic Macquarie Island. Austral Ecol 45(5):572–585

Mathews GM (1912) The birds of Australia, vol 2 Part 1, pp 1–120, pis 68–81; part 2, pp 121–236, pis 82–94. Witherby, London

McCreless EE, Huff DD, Croll DA, Tershy BR, Spatz DR, Holmes ND, Butchart SH, Wilcox C (2016) A Past and estimated future impact of invasive alien mammals on insular threatened vertebrate populations. Nat Commun 7:1–11

McGeoch MA, Shaw JD, Terauds A, Lee JE, Chown SL (2015) Monitoring biological invasion across the broader Antarctic: a baseline and indicator framework. Glob Environ Chang 32:108–125

Molina-Montenegro MA, Bergstrom DM, Chwedorzewska KJ, Convey P, Chown SL (2019) Increasing impacts by Antarctic's most widespread invasive plant species as result of direct competition with native vascular plants. Neo-Biota 51:19–40

Mulder CPH, Grant-Hoffman MN, Towns DR, Bellingham PJ, Wardle DA, Durrett MS, Fukami T, Bonner KI (2009) Direct and indirect effects of rats: does rat eradication restore ecosystem functioning of New Zealand seabird islands? Biol Invasions 11(7):1671–1688. https://doi.org/10.1007/s10530-008-9396-x

Müller OF (1774) Vermium terrestrium et fluviatilum seu non marinorum succincta historia, vol 2, no 1, pp 135. Havniæ & Lipsiae

Murchie AK, Gordon AW (2013) The impact of the ‘New Zealand flatworm’, arthurdendyus triangulatus, on earthworm populations in the field. Biol Invasions 15(3):569–586

Nielsen UN, Wall DH (2013) The future of soil invertebrate communities in polar regions: different climate change responses in the Arctic and Antarctic? Ecol Lett 16(3):409–419

Springer
Pertierra LR, Aragón P, Shaw JD, Bergstrom DM, Terauds A, Olalla-Tárraga MÁ (2017) Global thermal niche models of two European grasses show high invasion risks in Antarctica. Glob Change Biol 23(7):2863–2873

Pertierra LR, Bartlett JC, Duffy GA, Vega GC, Hughes KA, Hayward SA, Convey P, Olalla-Tárraga MA, Aragón P (2020) Combining correlative and mechanistic niche models with human activity data to elucidate the invasive potential of a sub-Antarctic insect. J Biogeogr 47(3):658–673

Richardson AM, Jackson JE (1995) The first record of a terrestrial landhopper (crustacea: Amphipoda: Talitridae) from Macquarie Island. Polar Biol 15(6):419–422

Russell JC, Peace JE, Houghton M, & Bodey TW (2020) Systematic prey consumption by introduced mice exhausts the ecosystem on Antipodes Island. Biological Invasions

Scott JJ, Kirkpatrick JB (1994) Effects of human trampling on the sub-Antarctic vegetation of Macquarie Island. Polar Rec 30(174):207–220

Selkirk P, Seppelt R, & Selkirk D (1990) Sub-Antarctic Macquarie Island: Environment and biology. Cambridge University Press

Shaw J, Terauds A, Bergstrom D (2011) Rapid commencement of ecosystem recovery following aerial baiting on sub-Antarctic Macquarie Island. Ecol Manag Restor 12(3):241–244. https://doi.org/10.1111/j.1442-8903.2011.00611.x

Sindel BM, Kristiansen PE, Wilson SC, Shaw JD, Williams LK (2018) Managing invasive plants on sub-Antarctic Macquarie Island. Rangel J 39(6):537–549

Sluys R (2016) Invasion of the flatworms. Am Sci 104(5):288–295

Smith VR (1992) Terrestrial slug recorded from sub-Antarctic Marion Island. J Molluscan Stud 58(1):80–81

Smith VR (2007) Terrestrial ecological processes and problems on sub-Antarctic islands. Pap Proc R Soc Tas 141(11):99–110

Sol D, Maspons J, Vall-Llosera M, Bartomeus I, García-Peña GE, Piñol J, Freckleton RP (2012) Unraveling the life history of successful invaders. Science 337(6094):580–583

Springer K (2016) Methodology and challenges of a complex multi-species eradication in the sub-Antarctic and immediate effects of invasive species removal. N Z J Ecol 40(2):273

Springer K, & Carmichael N (2012) Non-target species management for the Macquarie Island pest eradication project. Proceedings of the Vertebrate Pest Conference, 25(25)

Stephensen K (1938) Zoologische Ergebnisse der Reisen von Dr. Kohl-Larsen nach den subantarktischen Inseln bei Neu-Seeland und nach Siid-Georgien. II. Amphipoda, Tanaidacea und Pycnogonida. Senckenbergiana Biologica 20:236–264

Taylor GA (1986) The ecology of Norway rats on Campbell Island. Ecology Division, Department of Scientific and Industrial Research, New Zealand

Townes DR, Wardle DA, Mulder CPH, Yeates GW, Fitzgerald BM, Richard Parrish G, Bellingham PJ, Bonner KI (2009) Predation of seabirds by invasive rats: multiple indirect consequences for invertebrate communities. Oikos 118(3):420–430. https://doi.org/10.1111/j.1600-0706.2008.17186.x

Travers T, Lea MA, Alderman R, Terauds A, Shaw JD (2021) The unintended consequences for top-order predators when eradicating invasive prey. J Appl Ecol 00:1–11. https://doi.org/10.1111/1365-2664.13828

Travers T (2021) The diet breeding, and ecological role of Brown Skuas Stercorarius antarcticus lönnbergi (Mathews, 1912) on Macquarie Island, following the eradication of invasive prey. University of Tasmania

Turner PA M, Scott JJ, & Rozefelds AC (2006) Probable long distance dispersal of Leptinella plumosa Hook. F. To Heard Island: Habitat, status and discussion of its arrival. Polar Biology, 29(3), 160–168

van Klinken RD, Green AJA (1992) The first record of Oniscidea (Terrestrial Isopoda) from Macquarie Island. Polar Rec 28(166):240–242

Vega GC, Pertierra LR, Benayas J, Olalla-Tárraga MÁ (2021) Ensemble forecasting of invasion risk for four alien springtail (Collembola) species in Antarctica. Polar Biol 44(11):2151–2164

Vernon P, Vannier G, Trehen P (1998) A comparative approach to the entomological diversity of polar regions. Acta Oecol 19(3):303–308. https://doi.org/10.1016/S1146-609X(98)80034-9

Vidal E, Jouventin P, Frenot Y (2003) Contribution of alien and indigenous species to plant-community assemblages near penguin rookeries at Crozet archipelago. Polar Biol 26(7):432–437

Walthier GR, Roques A, Hulme PE, Sykes MT, Pyšek P, Kühn I, Settele J (2009) Alien species in a warmer world: risks and opportunities. Trends Ecol Evol 24(12):686–693

Wanless RM, Ratcliffe N, Angel A, Bowie BC, Cita K, Hilton GM, Kritzinger P, Ryan PG, Slabber M, Redpath S, Schaub M (2012) Predation of Atlantic petrel chicks by house mice on Gough Island. Anim Conserv 15(5):472–479. https://doi.org/10.1111/j.1469-1795.2012.00534.x

Wardle DA, Bellingham PJ, Bonner KI, Mulder CPH (2009) Indirect effects of invasive predators on litter decomposition and nutrient resorption on seabird-dominated islands. Ecology 90(2):452–464

Whinam J, Fitzgerald N, Visoiu M, Copson G (2014) Thirty years of vegetation dynamics in response to a fluctuating rabbit population on sub-Antarctic Macquarie Island. Ecol Manag Restor 15(1):41–51

Williamson M, Fitter A (1996) The varying success of invaders. Ecology 77(6):1661–1666

Wilson JR, Dormontt EE, Prentis PJ, Lowe AJ, Richardson DM (2009) Something in the way you move: dispersal pathways affect invasion success. Trends Ecol Evol 24(3):136–144

Winsor L, Stevens M (2005) Terrestrial flatworms (Platyhelminthes: Tricladiida: Terricola) from sub-antarctic Macquarie Island. Kanunnah 1:17–32

Winsor L, Johns PM, Barker GM (2004) Terrestrial planarians (Platyhelminthes: Tricladiida: Terricola) predaceous on terrestrial gastropods. CAB International, Natural Enemies of Terrestrial Molluscs. Oxfordshire, pp 227–278
Yeates GW, Boag B, Johns PM (1997) Observations on feeding and population structure of five New Zealand terrestrial planarians which prey on lumbricid earthworms. Annals of Applied Biology 131(2):351–358

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