Rapid range expansion of an invasive flatworm, *Kontikia andersoni*, on subantarctic Macquarie Island

Melissa Jane Houghton (✉ melissa.houghton@nre.tas.gov.au)

Department of Natural Resources and Environment, Tasmania <https://orcid.org/0000-0001-7256-5711>

Aleks Terauds

Australian Antarctic Division

Justine D Shaw

Queensland University of Technology

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Abstract

Spanning the Southern Ocean high latitudes, subantarctic islands are protected areas with high conservation values. Despite the remoteness of these islands, invasive species threaten their native species and ecosystem function. The most ubiquitous and speciose group of invasive species are invertebrates. Due to their cryptic habits and ambiguous establishment history, the impacts of invasive invertebrates on native species and ecosystems in the region remains largely unknown. Understanding how invasive invertebrate species are transported, disperse, establish and colonise new habitats is key to understanding their existing and future impacts. This knowledge is also fundamental to improving biosecurity practise 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). We found *A. vegrandis*, *S. otakensis* and *P. patersoni* had not markedly expanded their range. In contrast, *K. andersoni* has more than doubled its previously mapped area and expanded at a rate of $\sim 500\text{m}^{-1}\text{yr}$ 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.

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), or indirectly, for example via habitat transformation (Croll et al. 2005; Fukami et al. 2006; Mulder et al. 2009), hyper-predation (Courchamp et al. 2000; Travers et al. 2021), changes to 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 subantarctic ecosystems which are characteristically simple and lack representatives of many functional groups (Vernon et al. 1998; Chown and Convey 2016; Houghton 2020). Consequently, in subantarctic ecosystems not only do invasive mammalian predators have particularly devastating consequences (Courchamp 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), although more research into the extent of such impacts is required (Houghton et al. 2019a).

Subantarctic Macquarie Island (54°30' S, 158°57' E) is a $\sim 129\text{ km}^2$ World Heritage Area, located in the Southern Ocean approximately 1500 km southeast of Tasmania, Australia. 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 and flightless detritivores (Houghton 2020), several

large-bodied, non-native macro-detritivores have established, including the slug *Derocerus reticulatum* (Limnaciidae), earthworms (Lumbricidae), two terrestrial Crustacea including *Puhuruhuru patersoni* (Amphipoda: Taltridae) and *Styloniscus otakensis* (Isopoda: Styloniscidae), and two predatory flatworm species (Platyhelminthes: Geoplanidae, *Kontikia andersoni*, and *Arthurdendyus vegrandis*). The slug and earthworms are pervasive on the island whereas the flatworms and terrestrial Crustacea are more restricted (Greenslade 2006; Greenslade et al. 2007; Greenslade et al. 2008).

Invasive isopod and amphipod (Crustacea)

The terrestrial Crustacea *Puhuruhuru patersoni* (amphipod) and *Styloniscus otakensis* (isopod), were discovered on the island around the research station in the 1990s (for island place names, see Online Resource 1). 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) (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 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 and the cessation of grazing and burrowing following 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 likely 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).

Invasive flatworms (Platyhelminthes)

Flatworms were first discovered at two topographically restricted creek-side sites near Lusitania Bay (for island place names, see Online Resource 1) on the south-eastern 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). *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, e.g. 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. An island-wide invertebrate survey in 1994 which included timed search counts at 67 sites 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 has 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 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 i) an island-wide invertebrate trapping program (2015-2018), ii) focused searching in areas where these species had been previously detected (i.e. by Greenslade et al. 2007; 2008), and iii) 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 during three consecutive sampling seasons (2015-2018; see Houghton et al. 2019b and Houghton 2020 for detailed trapping and surveillance methodology). At each site, a variety of trapping techniques were used. Replicates were used within sites and both sites and techniques were repeated multiple times during each season. The 24 sites were selected to represent five distinct and previously recognised vegetation communities on the island ('Herbfield', 'Stilbocarpa', 'Short grassland', 'Tall grassland' and 'Feldmark' as per Selkirk et al. 1990), and were prescribed for this work through 10 x 10 m vegetation surveys (Houghton 2020) (Survey data available via the Australian Antarctic Divisions Data Centre, doi:10.26179/k24z-nx57).

As the distributions of the four target species began to emerge from the island-wide monitoring, it became clear that i) focused searching would be sufficient for the terrestrial crustacea, ii) *A. vergrandis* was not common, and iii) *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 southwestern 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 metres 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 (on a scale of 1-5) and dominant vegetation at the site were 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 minutes (sites F1 – F36, excepting F6), but it became clear that flatworms, if present, were detectable in under 20 minutes. Thereafter, search time was reduced to 20 or 21 minutes at each site, depending on the number of people conducting the survey, 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 minutes each totalled 20 minutes; three people searching 7 minutes each, totalled 21 minutes). 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 1km grid to quantify occupancy by *K. andersoni* at these time periods. We then quantified the change in the number of occupied 1km x 1km cells and the proportion of the island occupied by *K. andersoni* over time.

Results

Isopod and Amphipod

Focussed 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 significantly 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 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, where only a single *K. andersoni* was detected at each 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 (Figure 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 (Online Resource 1). Eighteen of these were from coastal areas (below the escarpment edge), while six were at inland sites. It was also found at five west coast sites, the northern-most 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 (3 and 4 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* herbs. All twenty-four detections of *K. andersoni* on the east coast were at sites with a wetness index of three or four. 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 (or 16.6% of the island) (Online Resource 1).

The detection of *K. andersoni* at Hurd Point, the southernmost point of the island, indicates that between 2004 and 2018 it spread south 6.4 km over 14 years – a mean rate of ~460m⁻¹yr. It also spread 7.2 km north from its 2004 limit, representing a mean rate of ~515 m⁻¹yr. It has also expanded inland to an area of ~170 m 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 $\sim 10\text{m}^{-1}\text{yr}$, the invasion of *K. andersoni* has accelerated south, west and north at around $500\text{m}^{-1}\text{yr}$, 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 across 760 sites island-wide (Davies and Melbourne 1999; Greenslade et al. 2007).

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 altitude, often comprised of feldmark and gravel, with low vegetation cover.

Humans are important vectors of non-native plant and invertebrate propagules to Antarctica and subantarctic islands (Lee and Chown 2009; Chown et al. 2012; Chwedorzewska et al. 2013; Hughes et al. 2010; 2011; Houghton et al. 2016). Human activities also drive intra-regional transfer of propagules within Antarctic sites and subantarctic islands (Lee and Chown 2011; Potocka and Krzemińska 2018; Hughes et al. 2019; Bartlett 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 during a recent large scale pest eradication program between 2011-2014 (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. 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 by people, 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 subantarctic (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, the recent eradication program (Springer 2016). First mitigation teams were deployed on foot to bury carcasses, followed by 2.5 years of hunting teams industriously walking the island in search of remaining rodents and rabbits. Five

new 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 to 14 people and up to eleven detection dogs, each traversing 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 subantarctic 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). They are also thought to contribute to dispersal of non-native invertebrates on Signy Island (Hughes and Worland 2010). Birds could transport flatworms or their fragments on their feathers or feet, in mud or guano, as birds move between flatworm-suitable coastal habitats around penguin colonies and waterways. There are numerous kelp gulls (*Larus dominicanus*), skuas (*Stercorarius antarcticus*) and giant petrels (*Macronectes* sp.) frequently travelling along the coast and between the west and east coasts (Travers 2021). However, bird-mediated dispersal does not explain the northern limits of the flatworm's range, or its rapid and recent range expansion.

K. andersoni has an intermittent occurrence on the west coast of Macquarie Island over a range of ~11 .4 km and was only detected as singletons at our fixed invertebrate monitoring sites (doi:10.26179/k24z-nx57). On Macquarie Island there have been recent decadal changes in summer water availability, increased wind speed and sunshine hours, (Bergstrom et al. 2015). Future studies should explore the role of aspect, climate and microclimate on habitat availability and suitability. This information would aid in identifying areas at risk of future invasion. A similar study was undertaken for an invasive midge on Signy Island (Bartlett et al. 2020).

Arthurdendylus 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 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 previous recorded distribution (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* were more widespread and at least three times more abundant than *A. vergrandis*.

Styloniscus otakensis and *Puhuruhuru patersoni* have not expanded their ranges. They remain restricted to the north of the island. The removal of invasive rodents from the island, known on subantarctic islands

to preferentially prey on Amphipods (Houghton et al. 2019), has not influenced Amphipod numbers on Macquarie Island. 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). Factors limiting their spread remain unclear. 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-mediated or wind-swept vagrants. The high winds experienced on Macquarie Island are renowned for dispersing flightless 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 communities.

As 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.

K. andersoni and *Arthurdendyus* flatworms 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.

Australia's Biosecurity Act 2015 and its associated regulations aim to control the movement of plants and animals, but land flatworms are not specifically included as targets. The detection of a novel species to Australia triggers an alert to members of the Consultative Committee on Emergency Plant Pests (CCEPP),

who decide on a course of action depending on its economic and environmental impact. Except for *P. patersoni*, all four species discussed here are already registered as introduced species to Australia, as residents of Macquarie Island which is officially part of Tasmania (ABRS 2021). However, their presence 1500 km distant from mainland Tasmania, has perhaps kept them of serious attention. Biosecurity protocols for transport from Macquarie Island to Tasmania should be considered to minimise the risk of inadvertently moving invasive flatworms in this direction. Our work demonstrates how quickly these invaders can spread, even on a remote world heritage island.

Declarations

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Competing interests

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

Author contributions

All authors contributed to the study conception and survey design. Field data collection and species identifications were undertaken by Melissa Houghton. Analysis was performed by Aleks Terauds, Melissa Houghton and Justine Shaw. All figures are by Aleks Terauds. All authors contributed to drafting of the manuscript. All authors read and approved the final manuscript.

Data availability

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

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Figures

Figure 1

Macquarie Island flatworm survey sites indicating positive and negative results for *K. andersoni* - a) in 2004 by Greenslade et al. (2007), and b) this work, which included a combination of twenty four island-wide invertebrate monitoring sites (2015-2018) and a dedicated flatworm survey in 2018. Note that Greenslade et al. (2007) surveyed a further 511 sites island-wide with negative results for *K. andersoni* but spatially explicit data for these were not recorded

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