South Africa works towards eradicating introduced house mice from sub-Antarctic Marion Island: the largest island yet attempted for mice

G.R. Preston[1], B.J. Dilley[2], J. Cooper[3], J. Beaumont[1], L.F. Chauke[1], S. L. Chown[4], N. Devanunthan[1], M. Dopolo[1], L. Fikizolo[1], J. Heine[5], S. Henderson[6], C.A. Jacobs[1], F. Johnson[6], J. Kelly[7], A.B. Makhado[1], C. Marais[1], J. Maroga[6], M. Mayekiso[1], G. McClelland[2], J. Mphepya[1], D. Muir[1], N. Ngcaba[1], N. Ngcobo[1], J.P. Parkes[8], F. Paulsen[10], S. Schoombie[2], K. Springer[7], C. Stringer[7], H. Valentine[1], R.M. Wanless[2,10] and P.G. Ryan[2]

[1]Department of Environmental Affairs, Private Bag X4390, Cape Town 8000, South Africa. <GPreston@environment.gov.za>. [2]FitzPatrick Institute of African Ornithology, DST-NRF Centre of Excellence, University of Cape Town, Rondebosch 7701, South Africa. [3]Department of Botany and Zoology, Stellenbosch University, Pvt Bag X1, Matieland 7602, South Africa. [4]School of Biological Sciences, Monash University, Melbourne, Victoria 3800, Australia. [5]Johan Heine, Kishugu, 1 Club Street, Old Nelspruit Airport, Nelspruit 1200, South Africa. [6]Department of Public Works, 266 Pretorius Street, Centre Walk Building, Pretoria 0001, South Africa. [7]Royal Society for the Protection of Birds, Sandy, Bedfordshire, UK. [8]Kurahaupo Consulting, 2 Ashdale Lane, Strowan, Christchurch 8052, New Zealand. [9]Mamont Foundation, St Julian's Court, St Julian's Avenue, St Peter Port, GY1 6AX, Guernsey. [10]Seabird Conservation Programme, Birdlife South Africa, PO Box 7119, Cape Town 8012, South Africa.

Abstract House mice (*Mus musculus*) were introduced to South Africa's sub-Antarctic Marion Island, the larger of the two Prince Edward Islands, by sealers in the early 19th century. Over the last two centuries they have greatly reduced the abundance of native invertebrates. Domestic cats (*Felis catus*) taken to the island in 1948 to control mice at the South African weather station soon turned feral, killing large numbers of breeding seabirds. An eradication programme finally removed cats from the island by 1991, in what is still the largest island area cleared of cats at 290 km^2. Removal of the cats, coupled with the warmer and drier climate on the island over the last half century, has seen increasing densities of mice accumulating each summer. As resources run out in late summer, the mice seek alternative food sources. Marion is home to globally important seabird populations and since the early 2000s mice have resorted to attacking seabird chicks. Since 2015 c. 5% of summer-breeding albatross fledglings have been killed each year, as well as some winter-breeding petrel and albatross chicks. As a Special Nature Reserve, the Prince Edward Islands are afforded the highest degree of protection under South African environmental legislation. A recent feasibility plan suggests that mice can be eradicated using aerial baiting. The South African Department of Environmental Affairs is planning to mount an eradication attempt in the winter of 2021, following a partnership with the Royal Society for the Protection of Birds to eradicate mice on Gough Island in the winter of 2020. The eradication programme on Marion Island will be spearheaded by the South African Working for Water programme – Africa's biggest conservation programme focusing on the control of invasive species –which is already driving eradication projects against nine other invasive species on Marion Island.

Keywords: albatross, climate change, eradication, *Felis catus*, invasive species, *Mus musculus*, petrel, predation

INTRODUCTION

In the late 18th and early 19th century humans travelled far and wide in the southern oceans to exploit marine wildlife (Trathan & Reid, 2009). An unfortunate consequence of this travel was the deliberate or incidental introduction of alien animal and plant species to distant environments, causing extensive changes in biological communities (Mooney & Cleland, 2001). The effects of invasive species on biodiversity have been described as "immense, insidious and usually irreversible" (IUCN, 2000). Island ecosystems are highly susceptible to change and introduced species are the main cause of species extinctions on islands (Manne, et al., 1999; Chapin, et al., 2000).

Many seabirds nest on isolated islands that lack land mammals and consequently one of the major threats to oceanic seabird species is the introduction of mammalian predators such as rats (*Rattus* spp.), domestic cats (*Felis catus*) and house mice (*Mus musculus*) onto their breeding islands (Croxall, et al., 2012). The devastating impact of rats on seabird populations breeding on oceanic islands has been well documented (Atkinson, 1985; Jones, et al., 2008). However, mice have been introduced to even more oceanic islands than have rats and, although their impacts on sub-Antarctic island biota are legion (Angel, et al., 2009), until recently they were considered to have little impact on seabird populations (Wanless, et al., 2007; Jones, et al., 2008).

Sub-Antarctic Marion Island (290 km^2, 46°54′S, 37°45′E) is the larger of the two South African Prince Edward Islands which lie c.2,300 km south-east of Cape Town in the south-western Indian Ocean (Fig. 1). As a Special Nature Reserve, established in 1995, the Prince Edward Islands are afforded the highest degree of protection under South African environmental legislation (de Villiers & Cooper, 2008). They also have been a Wetland of International Importance in terms of the Ramsar Convention since 2007 (de Villiers, et al., 2011) and are surrounded by a large (180,000 km²) Marine Protected Area, declared in 2013, that reaches in places to the edges of South Africa's Exclusive Economic Zone (Lombard, et al., 2007; Nel & Omardien, 2008).A revised management plan adopted in 2014 guides and controls activities at the island group, including biosecurity protocols to avoid alien introductions (DST-NRF Centre of Excellence for Invasion Biology, 2014).

The Prince Edward Islands currently support breeding populations of 29 species of birds, all but two of which probably breed on Marion Island (Ryan & Bester, 2008; Peter Ryan, FitzPatrick Institute unpubl. data; Table 1). Eight bird species of the order Procellariiformes that breed on Marion are listed by the International Agreement on the Conservation of Albatrosses and Petrels, to which South Africa is a founding signatory (Cooper, et al., 2006).These four albatross and four petrel (*Macronectes* and *Procellaria*)

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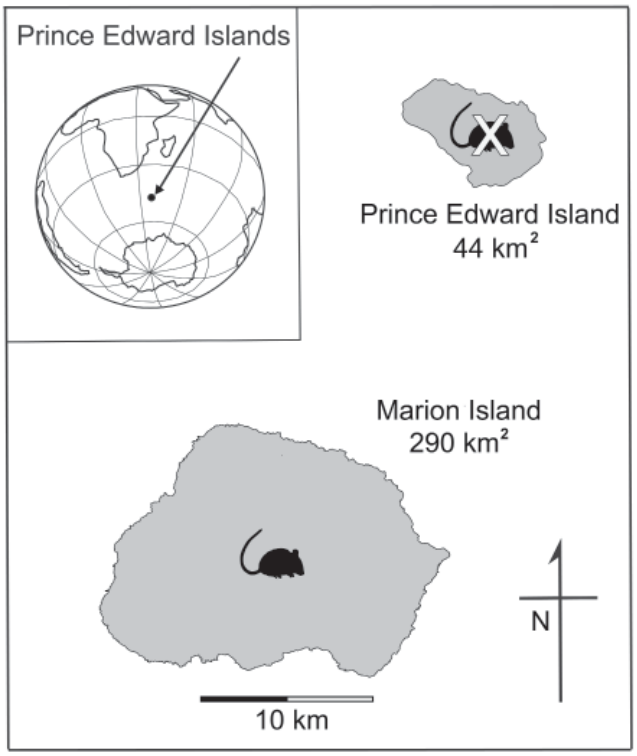

Fig. 1 South Africa's Prince Edward Islands (46°54´S, 37°45´E) lie 2,300 km south-east of Cape Town in the south-western Indian Ocean. Marion Island has introduced house mice, but Prince Edward Island, 22 km to the north-east, remains free of introduced mammals.

species are at risk at sea to bycatch by commercial fisheries, especially longlining, and are considered threatened or near threatened at regional (Taylor, et al., 2015) and global (BirdLife International, 2017) levels. Marion Island supports about 25% of the world's breeding population of wandering albatrosses *Diomedea exulans* (globally and regionally Vulnerable), 12% of sooty (*Phoebetria fusca*) and 7% of grey-headed (*Thalassarche chrysostoma*) albatrosses (both globally and regionally Endangered) and smaller percentages of light-mantled albatrosses (*P. palpebrata*) (globally and regionally Near Threatened) and grey petrels (*Procellaria cinerea*) (globally Near Threatened and regionally Vulnerable).

We show that these five ACAP-listed species, along with the regionally Near Threatened great-winged petrel (*Pterodroma macroptera*), are at serious risk to predation from introduced mice on Marion Island. Mice were accidentally introduced to Marion Island during the sealing era sometime before 1818 and were the sole introduced mammal until 1948 when five domestic cats were introduced to control mice at the newly-established weather station (Watkins & Cooper, 1986). However, even in the 1950s, little was known about the potential harmful effects of invasive species on islands. Rand (1954) was the biologist on the Eighth South African Expedition to Marion Island over 1951/52 and noted how "a few domestic cats have gone feral and prey on the smaller petrels or mice that are widespread over the coastal plain" (p. 178) and "mice often burrow into the [albatross] nest cone but do no appreciable damage" (p. 189). Unfortunately, the cats preferred to eat the island's native birds, especially the burrow-nesting petrels, and by the 1970s more than 2,000 cats were killing some 450,000 birds each year (van Aarde, 1980). As a result, at least one species, the common diving petrel (*Pelecanoides urinatrix*), disappeared from the island and all the other burrowing petrels became far less common than at nearby predator-free Prince Edward Island. A sustained eradication programme that commenced in the mid-1970s had finally eradicated cats from the island by 1991 (Bester, et al., 2002), in what until recently was the largest island area cleared of cats.

We give an overview of the adverse impacts of mice on Marion Island's biota and ecosystem and discuss the mouse eradication attempt planned for the austral winter of 2020.

A syndrome of adverse factors

House mice have been present on Marion Island for nearly 200 years (Berry, et al., 1978), significantly disrupting terrestrial ecosystem functioning (Chown & Smith, 1993). The mice may be seen as part of a syndrome of interacting factors (Parkes, 2016) having adverse impacts on native invertebrates, plants and seabirds (e.g. Phiri, et al., 2009; Angel & Cooper, 2011). The mice have changed the state of Marion Island's ecosystems compared with the near-pristine condition of neighbouring Prince Edward Island (45 km^2, see Fig. 1).

For more than 30 years the burrowing petrel populations on Marion Island were impacted by cats (top predators) and mice (mesopredators). Whereas mice target eggs and chicks (Fugler, et al., 1987; Dilley, et al., 2015; Dilley, et al., 2018), reducing reproductive success, cat predation was far more detrimental because they killed chicks and adults, affecting both reproduction and adult survival (Le Corre, 2008). Removal of the top predator on Marion Island has benefited adult survival but may have triggered a 'mesopredator release' effect (Zavaleta, et al., 2001; Le Corre, 2008), whereby mouse numbers expanded, increasing their impact on petrel populations (Rayner, et al., 2007). The dramatic decrease in burrowing petrel populations at Marion Island caused by the cats is again presumed to have adversely affected key ecological processes driven by burrowing petrels such as soil turn-over and marine nutrient imports (Caut, et al., 2012).

Mouse numbers cycle seasonally on Marion Island, linked partly to changes in the abundance of invertebrates and seeds. Mouse densities are highest in autumn, when breeding ceases, and are lowest in early summer, before breeding resumes. Invertebrate biomass also changes seasonally, but not to the same extent, so that the *per capita* food supply (from macro invertebrates as the primary food of the mice) was estimated to be 3.4 kg/ha and 3.6 kg/ha in early summer but only 0.4 kg/ha and 0.2 kg/ha in early winter in the Biotic and Mire habitats favoured by mice, respectively (Avenant & Smith, 2003).

Peak mouse densities occur in April–May, and have increased between 1990 and 2008, driven in part by a warmer, drier climate (Ferreira, et al., 2006; le Roux & McGeoch, 2008; McClelland, et al., 2018). By comparison, invertebrate biomass has decreased >80% since the late 1970s (McClelland, et al., 2018). Since 2015, there has been a marked increase in the frequency of mice attacking surface-breeding seabird chicks (Dilley, et al., 2016a) and if invertebrate biomass continues to decline, the impact of mouse predation on Marion's seabird chicks is likely to become even more serious.

Overview of mice attacking seabirds at Marion Island

The first signs of mouse attacks on seabirds at Marion Island were recorded in 2003, when wandering albatross chicks were observed with rump wounds typical of those inflicted by mice on Tristan albatross (*D. dabbenena*) chicks on Gough Island (Jones & Ryan, 2010; Table 2). The first attacks on summer-breeding albatross chicks were

Table 1 Estimated risk of local extirpation of bird species currently known or thought to breed on Marion Island if the mice are not eradicated.

Species	Estimated numbers of breeding pairs	Known or considered vulnerable to predation	Estimated years to local extirpation
Grey-backed storm petrel *Garrodia nereis**	?[1]	yes	possibly locally extirpated
Black-bellied storm petrel *Fregetta tropica**	?[1]	yes	possibly locally extirpated
Grey petrel *Procellaria cinerea*	800[2]	yes	30
Cape petrel *Daption capense*	<5[2]	yes	30
Kerguelen petrel *Lugensa brevirostris*	5,000[2]	yes	50
South Georgian diving petrel *Pelecanoides georgicus*	1,000[1]	yes	50
Common diving petrel *Pelecanoides urinatrix*	50–100[2]	yes	50
Great-winged petrel *Pterodroma macroptera*	14,000[2]	yes	50–100
Light-mantled albatross *Phoebetria palpebrata*	300[3]	yes	50–100
Sooty albatross *Phoebetria fusca*	1,465[3]	yes	50–100
Grey-headed albatross *Thalassarche chrysostoma*	7,900[1]	yes	50–100
Wandering albatross *Diomedea exulans*	1,800[1]	yes	50–100
Fairy prion *Pachyptila turtur*	1,000[1]	yes	50–100
Salvin's prion *Pachyptila salvini*	150,000[2]	yes	50–100
Blue petrel *Halobaena caerulea*	145,000[4]	yes	50–100
Soft-plumaged petrel *Pterodroma mollis*	5,000[1]	yes	50–100
White-chinned petrel *Procellaria aequinoctialis*	24,000[5]	yes	50–100
Antarctic tern *Sterna vittata*	25[1]	yes	50–100
Kerguelen tern *Sterna virgata*	50[1]	yes	50–100
Southern giant petrel *Macronectes giganteus*	1,750[1]	uncertain	
Northern giant petrel *Macronectes halli*	400[1]	uncertain	
Crozet shag *Leucocarbo melanogenis*	270[1]	uncertain	
Brown skua *Catharacta antarctica*	300[6]	uncertain	
Kelp gull *Larus dominicanus*	100[1]	uncertain	
Lesser sheathbill *Chionis minor*	700[1]	uncertain	
King penguin *Aptenodytes patagonicus*	220,000[1]	no	
Gentoo penguin *Pygoscelis papua*	900[1]	no	
Macaroni penguin *Eudyptes chrysolophus*	370,000[1]	no	
Southern rockhopper penguin *Eudyptes chrysocome*	67,000[1]	no	

*Current breeding not proven but suspected
Data sources: [1]Ryan & Bester (2008); [2]FitzPatrick unpubl. data; [3]Schoombie et al., (2016); [4]Dilley et al., (2017); [5]Ryan et al., (2012); [6]Ryan et al., (2009)

recorded in April 2009 when sooty albatross fledglings at two colonies were found 'scalped' with raw, bleeding crowns and necks (Jones & Ryan, 2010; Fig. 2). Mice were suspected of being responsible for these wounds (Jones & Ryan, 2010), even though summer-breeding albatross chicks are seldom attacked by mice on Gough Island (Cuthbert, et al., 2013). Another sooty albatross fledgling was attacked in 2010 at one of the colonies where scalpings occurred in 2009 (Ben Dilley, FitzPatrick Institute unpubl. data), but no further attacks were recorded until 2015, when mice attacked large chicks of all three albatross species that fledge in autumn: grey-headed (Fig. 3), sooty and light-mantled albatrosses (Dilley, et al., 2016a, Table 2). Filming at night confirmed that mice were responsible for these wounds, with most affected chicks dying within a few days of being attacked (Dilley, et al., 2016a). Attacks started independently in small pockets all around the island's 70 km coastline, separated by distances hundreds of times greater than mouse home ranges (Wanless, et al., 2008; Dilley, et al., 2016a; Fig. 2). In 2015, three of the six mouse-injured wandering albatross chicks had head wounds ('scalpings', see Fig. 4). In 2016, 2017 and 2018 mouse attacks continued on summer-breeding albatross fledglings, indicating that the sudden increase in 2015 was not a one-off event.

With cats having been eradicated from Marion Island by 1991, we expected burrowing petrel populations to

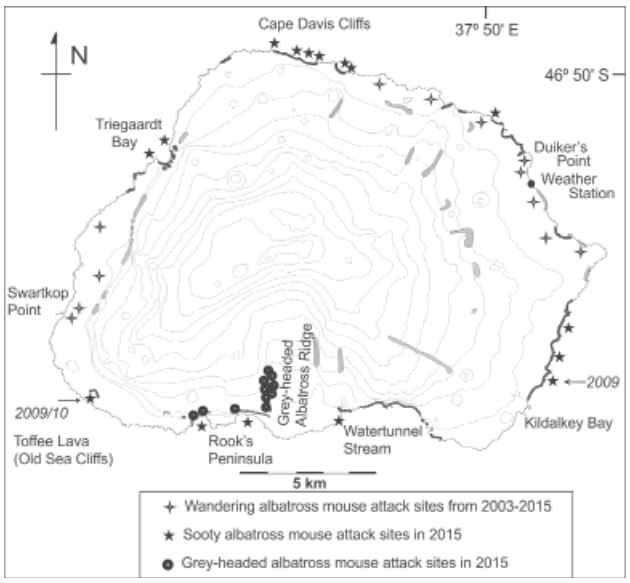

Fig. 2 Marion Island showing the locations of albatross breeding colonies (sooty albatross = dark grey shade; light-mantled albatross = light grey shade; all grey-headed albatross colonies are along Grey-headed Albatross Ridge and Rook's Peninsula) and mouse-attack sites from 2009–2015 (adapted from Dilley, et al., 2016a). Contour lines indicate 100 m.

Fig. 3 Grey-headed albatross chicks showing distinctive 'scalping' wounds inflicted by mice on Marion Island in 2015 (photo Ben Dilley).

have recovered by two decades later. Initial indications were positive; following the removal of cats there were marked increases in the breeding success of burrowing petrels, especially great-winged petrels that breed in winter when cat predation pressure was most severe (Cooper & Fourie, 1991; Cooper, et al., 1995). However, the post-cat recovery of burrowing petrel numbers on Marion has been much slower than anticipated, especially for smaller species (Dilley, et al., 2016b). Of the nine species of burrowing petrels breeding on Marion Island, the two smallest species (black-bellied (*Fregetta tropica*) and grey-backed storm petrels (*Garrodia nereis*)) are now very uncommon and are likely locally extirpated on the island due to mice (Dilley, et al., 2016b). Recent evidence from a repeat survey of burrow densities (Dilley, et al., 2016b) and from analyses of brown skua *Catharacta antarctica* prey remains (Cerfonteyn & Ryan, 2016) both suggest there has been little or no recovery of burrowing petrel populations at Marion since cats were eradicated.

Predation by mice is the most likely explanation for the limited recovery of Marion's petrel populations (Dilley, et al., 2016b). Recent evidence from breeding success studies shows that mice are suppressing the recovery of burrowing petrel populations, especially those that breed in winter, through predation on eggs and chicks (Dilley, et al., 2018). Winter breeders had lower breeding success than did summer breeders, with most fatalities being of small chicks <14 days old. Mice were filmed attacking and killing chicks of two winter-breeding species: grey petrel (three of 18 nests filmed; <https://youtu.be/Og1d6a2cmXQ>) and great-winged petrel (one of 19; <https://youtu.be/D9vPoFsjvgs>, Dilley, et al., 2018). Grey petrel chicks, which had the highest mortality rate, hatch in early winter when mouse densities are still fairly high, but food availability is low, resulting in the lowest seasonal *per capita* food availability for mice (Dilley, et al., 2018). Most grey petrel mortalities occurred when chicks were <7 days old, and were likely due to mouse predation (Dilley, et al.,2018).

We conclude that mice are currently suppressing the recovery of burrowing petrel populations on Marion Island, especially those that breed in winter, through predation on eggs and chicks. The widespread increase in mouse predation on albatross chicks at Marion in 2015 is also a cause for concern. Left uncontrolled, it is feared that 18 of the 28 species breeding on Marion Island may be vulnerable to local extirpation (see Table 1), should the mice not be eradicated.

PLAN OF ACTION

The Prince Edward Islands are recognised as a Special Nature Reserve, which affords the highest degree of protection under South African environmental legislation, and the islands' management plan aims to eradicate alien plants and animals as far as possible (DST-NRF Centre of Excellence for Invasion Biology, 2014). As summarised above, the structure of Marion Island's terrestrial ecosystem has been radically transformed by introduced mice, which are now threatening the island's globally important seabird

Table 2 Summary of mouse attacks on surface-nesting seabirds breeding on Marion Island (from Dilley, et al., 2016a and FitzPatrick Institute unpubl. data).

Species	Year of first attack	Maximum number attacked	% of annual production
Wandering albatross	2003	6	0.8%
Sooty albatross	2009	45	4.3%
Light-mantled albatross	2015	1	4.0%
Grey-headed albatross	2015	102	4.6%

Fig. 4 A Wandering albatross chick being scalped by a mouse on Marion Island in the winter of 2015 (photo Stefan Schoombie).

populations. Given the island's importance as a breeding site for threatened albatrosses and other seabird species that are being killed by mice, there is an urgent need to eradicate mice from the island. A detailed feasibility plan (Parkes, 2016) suggests that mice can be eradicated using aerial baiting. This follows the now well-established approach of using helicopters fitted with GPS guidance systems and under slung bait-distribution buckets to spread brodifacoum-laced pellets across the entire island over a relatively short period, to ensure that all rodents have access to the poison bait. Such operations, pioneered on New Zealand's offshore islands, have a good track record in recent years with 21 of 22 operations around the world targeting mice being successful in the last decade (DIISE, 2015). However, the operation on Marion Island will be an order of magnitude larger than any previous island eradication targeting mice only (cf. Springer, 2016; Martin & Richardson, 2017). This will require the deployment of poison bait with a high level of accuracy given the small home ranges of mice relative to rats (Parkes, 2016).

The South African Department of Environmental Affairs is planning to mount an eradication attempt on Marion Island in the austral winter of 2021. This is timed to follow a planned eradication of mice on Gough Island led by the United Kingdom's Royal Society for the Protection of Birds in the winter of 2020. Gough Island, part of the UK Overseas Territory of St Helena, Ascension and Tristan da Cunha, is one of the world's most important seabird breeding islands. It is the site where mice were first appreciated to pose a significant risk to breeding seabirds (Cuthbert & Hilton 2004; Wanless, et al., 2007), and experiences very high levels of chick mortality in several species, including the Tristan albatross (globally Critically Endangered), Atlantic petrel (*Pterodroma incerta*) (Endangered) and Macgillivray's prion (*Pachyptila macgillivrayi*) (Endangered) (Davies, et al., 2015; Dilley, et al., 2015). Despite these impacts, the island still supports some 12 million breeding seabirds of 22 species and is regarded as a top-priority island for rodent eradication world-wide (Hilton & Cuthbert, 2010).

At 65 km^2, Gough will be the largest island where an eradication has been attempted targeting mice alone (mice were eradicated from 129 km^2 Macquarie Island (Australia), but they occurred at lower densities than on Marion due to the presence of black rats (*R. rattus*) on the island (Springer 2016; <http://www.parks.tas.gov.au/?base=13013>). Planning for the Gough Island eradication has involved more than a decade of research to ensure the highest probability of success (e.g. Angel & Cooper, 2006; Brown, 2007; Parkes, 2008; Wanless, et al., 2009; Cuthbert, et al., 2011a; Cuthbert, et al., 2011b; Cuthbert, et al., 2014; Cuthbert, et al., 2016). At 290 km^2, Marion Island is almost five times larger than Gough Island, but the terrain is less rugged, and the presence of a largely un-vegetated interior above 800 m with few, if any, mice in winter makes an eradication attempt at Marion less challenging in some regards (Parkes, 2016). The intention is to commence the operation during early winter, when mouse numbers are falling due to lack of food and cold conditions, increasing the likelihood of all animals consuming bait (see Parkes, 2019, for further details on the crucial decision of 'when to bait' on Marion). Mice also cease breeding on Marion from late May to August, reducing the chances of semi-independent young in the den failing to encounter bait (Parkes, 2016). Winter also coincides with the period of lowest numbers of brown skuas and giant petrels (*Macronectes* spp.) present on the island, which might be killed accidentally by either primary or secondary poisoning.

Mitigation plans will be needed to reduce the impacts on resident scavenging species (Wanless, et al., 2010). At this stage, the intention is to keep approximately 100 lesser sheathbills (*Chionis minor*) in captivity during the eradication attempt, given the moderate level of mortality of snowy sheathbills (*C. albus*) during the rodent eradication at South Georgia (Martin & Richardson, 2017). The Prince Edward Islands are home to an endemic subspecies of sheathbill *C. m. marionensis*, but nearby Prince Edward Island houses a substantial population of this subspecies and could be used to re-establish birds on Marion Island. Kelp gulls (*Larus dominicanus*) also are resident scavengers at Marion Island, but they may be less susceptible to non-target poisoning (Martin & Richardson, 2017). Given the small population size (Table 1) and difficulty of catching and maintaining captive birds, there is currently no plan to mitigate impacts on this species. Gulls are thought to move freely between Marion and Prince Edward Island, so immigration should aid the recovery of the Marion population after the eradication.

The eradication on Marion Island was stimulated by the donation of US$100,000 and the three helicopters used in the South Georgia rodent eradication by the Mamont Foundation to the South African Department of Environmental Affairs in early 2017. South Africa has a weather station on Gough Island, and will assist this eradication effort through the provision of accommodation (including possible refurbishments on the island), the hosting of the eradication team from its Cape Town harbour, and assistance with transportation. In return, the equipment used and expertise developed during the Gough eradication will be transferred to South Africa for use in the planned Marion eradication. The programme on Marion Island will be spearheaded by the Department of Environmental Affairs' Working for Water programme – Africa's biggest conservation programme focusing on the control of invasive species. Working for Water is already managing eradication projects against eight invasive vascular plant species on Marion Island, and the possible eradication of one introduced invertebrate, the rough woodlouse (*Porcellio scaber*), is being assessed (D. Muir). The South African Government is budgeting for this programme (with an initial budget of about US$2.2 million). It will seek to raise co-funding, including through a crowd-funding initiative being led by BirdLife South Africa, a non-governmental organisation.

Eradicating rodents from islands is an effective, long-term conservation management action, provided robust biosecurity measures are put in place to minimise the likelihood of any reintroductions. The South African National Antarctic Programme has imposed stringent quarantine measures on all vessels and materials going to the Prince Edward Islands (and Gough Island) since the

early 1990s. These include fumigation of the resupply vessel prior to each voyage, use of rat guards on all hawsers when in harbour, placement of rodenticide baits at strategic points throughout the ship, and inspection of all cargo before being opened ashore (DST-NRF Centre of Excellence for Invasion Biology, 2014).

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