Large scale eradication of non-native invasive American mink (*Neovison vison*) from the Outer Hebrides of Scotland

I.A. Macleod, D. Maclennan, R. Raynor, D.B.A. Thompson and S. Whitaker

Scottish Natural Heritage, Great Glen House, Leachkin Road, Inverness, IV3 8NW, UK. <iain.macleod@nature.scot>.

Abstract The Hebridean Mink Project was tasked with eradicating American mink (*Neovison vison*) from the Outer Hebrides, an extensive, complex island archipelago, amounting to 3,050 km^2. Hundreds of islands contribute to a coastline of approximately 2,500 km, 15% of Scotland's total. The geographical complexity continues inland with over 7,500 freshwater lochs, ~24% of Scotland's total, which enables invasive American mink, in suitable habitats, to reach densities seldom encountered elsewhere. With major funding from the EU LIFE programme, removal from the Uists began in 2001. By 2006 eradication was declared there, as no captures had occurred for 16 months. In 2007 the project extended into Harris and Lewis, adopting a systematic network of live capture traps (7,039 spaced at 450–500 m intervals utilising prominent features of the riparian network and coastline). The traps were checked in rotation until at least a 95% reduction in population had been achieved. An incremental, strategic change from systematic trapping to detection; by means of footprint monitoring, cameras and dog searching, followed by responsive trapping then occurred from 2011 onwards. By 2013 a lethal monitoring system utilising 'kill traps' was employed alongside remote alert systems which allowed the project to remove the remaining population of mink from Lewis and Harris, with a reduced staff resource, and increase the trap night total to in excess of 500,000. To date, 2,198 mink have been caught, but only two non-breeding females and associated males have been caught in Lewis and Harris in the last 18 months (no juveniles captured). The challenges of geographical scale, terrain, climatic conditions and a continuously reducing staff complement have required an adaptive management approach to achieve the project goal of a mink-free Outer Hebrides that benefits ground nesting birds and migratory fisheries. This is viewed as a highly effective eradication project, and lessons learnt can be put into place for other ambitious control programmes.

Keywords: adaptive management, anal gland lure, dog searching, monitoring techniques, remote alert systems, trapping

INTRODUCTION

The Outer Hebrides of Scotland support some of the most important breeding populations of waders in Europe. Species include redshank (*Tringa totanus*), snipe (*Gallinago gallinago*), lapwing (*Vanellus vanellus*) and oystercatcher (*Haematopus ostralegus*); with dunlin (*Calidris alpina*) and ringed plover (*Charadrius hiaticula*) nesting at the highest densities recorded anywhere in the world (Stroud, et al., 2001). In recognition of this, many of the nesting areas have been notified as Sites of Special Scientific Interest (SSSI) under the Nature Conservation (Scotland) Act 2004, and classified as Special Protection Areas (SPA) under the EC Birds Directive, covering an area of about 37,596 ha and 87,158 ha respectively.

At the international level, there are many more species of birds that are represented by important populations on these sites. Species include red-throated diver (*Gavia stellata*), black-throated diver (*Gavia arctica*), great northern diver (*Gavia immer*), hen harrier (*Circus cyaneus*), merlin (*Falco columbarius*), short-eared owl (*Asio flammeus*), greylag goose (*Anser anser*), mallard (*Anas platyrhynchos*), teal (*Anas crecca*), wigeon (*Anas penelope*), gadwall (*Anas strepera*), shoveler (*Anas clypeata*), tufted duck (*Aythya fuligula*), eider (*Somateria mollissima*), shelduck (*Tadorna tadorna*), red-breasted merganser (*Mergus serrator*), golden plover (*Pluvialis apricaria*), common sandpiper (*Actitis hypoleucos*), curlew (*Numenius arquata*), corncrake (*Crex crex*), common tern (*Sterna hirundo*). Ground nesting seabirds such as little tern (*Sternula albifrons*), arctic tern (*Sterna paradisaea*) (Clode & Macdonald, 2002) and arctic skua (*Stercorarius parasiticus*) also occur in significant numbers.

Historically, the introduction of mink in Scotland has been directly connected to the fur farming industry which was established in the 1950s (Dunstone, 1993; Bonesi & Palazon, 2007). In the Outer Hebrides this was mirrored when two fur farms on the Isle of Lewis went out of business in the 1960s resulting in a feral mink population becoming established (Angus, 1993). Small scale control operations carried out by sporting estates and an attempt by SNH to prevent the mink population spreading south had little effect. By 1999, breeding populations of mink were established on North Uist and Benbecula (Harrington, et al., 1999).

Invasive non-native species are one of the main causes of biodiversity loss worldwide (Genovesi, 2009) and predatory species, such as mink, can have a devastating impact on native species (Macdonald, et al., 2007). The need to manage non-native species is increasingly recognised as a necessity to minimise these impacts (Bryce, et al., 2011). In particular the impact of mink predation on ground nesting colonial seabirds can have a significant effect, on not only the breeding success of the species concerned but also the long term viability of the population (Craik, 1997; Craik, 1998). It is documented that mink at relatively low densities can also seriously affect salmonids (Areal & Roy 2006). Atlantic salmon (*Salmo salar*) is a species in decline, for which two Special Areas of Conservation have been established in the Outer Hebrides. The removal of mink can have significant beneficial consequences to a range of species, especially in island ecosystems (Nordström, et al., 2003).

In the Outer Hebrides the impacts of invasive mink over decades had become a significant concern and the most immediate effects were on the colonial nesting species such as tern which were being severely impacted both in terms of their productivity and also the loss of significant numbers of adult birds.

MATERIALS AND METHODS

The Outer Hebrides of Scotland are a highly complex archipelago of hundreds of islands which also includes the third biggest island in the UK, Lewis and Harris. It is characterised by vast expanses of moorland dissected

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by numerous convoluted freshwater lochs that amount to approximately 24% of the freshwater linear edge of Scotland's total. Due to the remoteness of some areas, and the general coastal nature of the American mink's behaviour, much of the work required the use of rigid hull inflatable sea-going boats that were used extensively, as well as Canadian open canoes in the complex freshwater habitats.

The project design was first established during the application process for LIFE funding but from its earliest conception it was regarded as an innovative trial of eradication techniques and an experimental project that required continuous critical appraisal of the progress being made.

Phase I of the Hebridean Mink Project was to remove all mink from the southern isles of the Outer Hebrides; South Uist, Benbecula and North Uist. The plan was also to reduce the mink density on South Harris to create a buffer zone between North Harris and Lewis (Helyar, 2005), minimising re-immigration, see Fig. 1.

Live capture traps were chosen as the core removal method due to the perception that kill traps were too much of a risk in terms of by-catch. Later in the project it was recognised that with experience, training and robust protocols these risks could be reduced to extremely low levels. Traps were made using 3 mm gauge wire mesh 18 × 15 × 60 cm and had galvanised steel doors. Caught mink were despatched using a .22 calibre air pistol.

From November 2001, for a period of three months, a total of 2,545 traps were dug into the ground and dressed in order that they became part of the landscape, although no more than 10% were open at any time. This provided a large number of pre-located traps, which could be used in rotation. The most efficient spacing of traps was established to be approximately 500 m apart, but with a higher trap density at individual den sites. Traps were initially baited with horse mackerel (*Trachurus trachurus*), that was later replaced or accompanied with anal gland lure which was more efficient (Roy, et al., 2006).

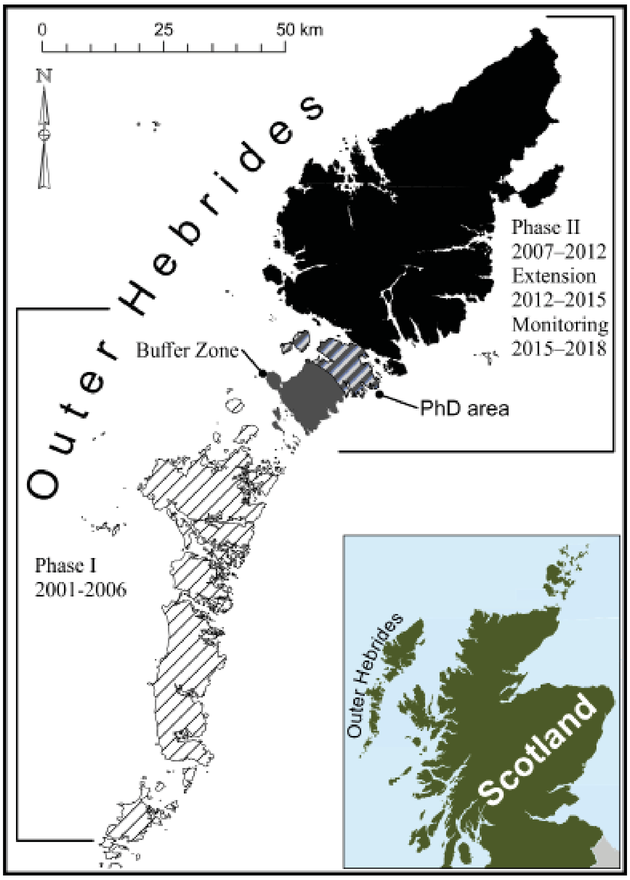

Fig. 1 The Outer Hebrides of Scotland showing the Hebridean Mink Project areas completed with timeframes.

The team was comprised of a project co-ordinator, two trapper supervisors (one each on Harris and Uist), six permanent trappers, and seasonal/casual workers who assisted when required. The trappers worked a defined 37 hours per week, setting traps on a given route on a Monday and closing them on a Friday. This gave a weekly total of four trap nights per trap opened on any individual route. Traps were most efficient in the first few days of opening, see Fig. 2, and were left open for two weeks initially, reducing to one week in subsequent years.

During 2004 and 2005 the trapping was punctuated with high intensity trapping regimes. This involved co-ordinating a group of up to 25 individuals to trap simultaneously for a period of two to three weeks. The extra support was drawn from external organisational staff from DEFRA and the State Veterinary Service. The aim was to increase the likelihood of capturing any remaining, highly mobile mink.

Throughout Phase I, the most difficult areas to trap were the offshore islands. Two Rigid-Hulled Inflatable Boats (RHIB) were purchased and the associated training was given to trapping staff to enable them to reach all areas.

Dog searches were introduced as a technique during the summer denning period, when trapping is less efficient.

The final mink caught during Phase I was on 23rd March 2005 (see Fig. 2). This was followed by a further 5,567 trap nights and a 'summer' of dog searches with no further mink sighted or caught, bringing Phase I to an end in June 2006. In the interim between Phase I and II, two trappers were employed to keep the mink population low across the South Harris buffer zone.

Phase II of the project aimed to remove all mink from Harris and Lewis, to complete a full eradication from the entire Outer Hebrides. This project commenced in February 2007 and was initially due to end in March 2014, but at present is still ongoing.

Trap locations were pre-determined through the use of a GIS system. Trap positions were chosen by placing them at obvious intersections of linear riparian or coastal features, with 500 m buffer zones to ensure there were no geographical gaps. When in the field, staff were given a leeway of 50 m from the pre-positioned point to allow the

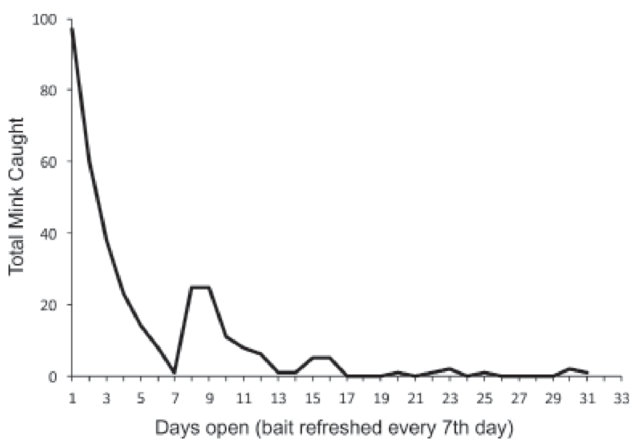

Fig. 2 The number of mink caught per length of time an individual trap remains open (SNH, 2006).

best position to be chosen in relation to the habitat. Once traps were installed, they were mapped on the GIS system to confirm absolute coverage of an area.

From 2007 there were 12 full-time trappers working 37 hours per week, reduced to six full-time trappers in 2012, and three in 2015. By 2008, 7,500 live capture traps had been permanently placed approximately 350–500 m apart, across Lewis and Harris. Traps within an area of approximately 100 km^2 were open at one time, for a period of four days. From 2008 to 2014, systematic trapping continued from the south-to-north, twice yearly. An exception was made in 2012 when the direction of trapping was altered to a north-to-south direction to ensure that specific areas were not always being trapped at the same time of year.

The mink population had been reduced to much lower densities by 2013 An assessment was carried out to ascertain whether the number of trap nights per 2.5 km^2 area was comparable, ensuring effort was distributed evenly across the entire project site. An extensive monitoring programme was set up in areas where there had previously been the highest mink densities, with 17 monitoring devices placed within 10 km^2 areas of interest. Monitoring devices included the use of footprint monitoring tunnels (clay and carbon plate), footprint monitoring rafts, camera traps and dog searches. These monitoring techniques were replaced with more efficient technology in the form of remote monitoring alarms (RMAs) which are activated when a trap is triggered. The monitoring devices are attached to a magnet which is pulled off when a trap is triggered, sending an SMS or email message to chosen team members. The devices were placed on traps situated in areas of good mobile phone coverage.

In 2014 the team reduced to three trappers. In order to maintain good monitoring coverage the live capture traps which had historically caught were replaced with 140 × 140 mm '116 Magnum bodygrip' spring traps contained in a bespoke designed wire mesh cage to exclude all non-target species. Over a period of two years almost 450 bodygrip traps were installed and 120 live capture traps were fitted with remote monitoring alarms.

Meanwhile on the Uist's, a few individual mink re-emerged in North Uist, which were immediately captured. In December 2014 another two mink were sighted in the northern end of North Uist, initiating another trapping project on the Uists. Staff from the Uist Wader project installed kill traps in a small area to detect any further mink. As more traps were installed, more mink were caught, and the trapping area was widened. From 2014 to the present there has been an increase in both trap nights and the number of mink caught on the Uists, with the trapping area now extending from North Uist down to Locheynort and due to be expanded to cover the entire Uists.

RESULTS

Phase I

A total of 532 mink from approximately 200,000 trap nights were caught during Phase I, see Table 1. Approximately half of those caught were on the Uists, compared with a similar number being caught in just the south of Harris (Fig. 3). This demonstrated that the mink population in the Uists had not yet reached carrying capacity, as south Harris has very similar terrain, and large areas of available habitat on South Uist had few captures. Between November 2004 and March 2005, only females were caught. This is likely a result of the trap density and the wider ranging behaviour of male mink. No mink were caught while trapping on the Uists between March 2005 and March 2006.

During the initial stages of Phase I it was quickly determined that the traps were most effective at catching during the first four days of being open. When opened for a further four days during the second week, the trap still caught mink but in far fewer numbers (Fig. 2).

In South Harris, due to a much higher trapper resource for the area available to trap, this number of trapping cycles per year was much higher, up to five times per year compared to just twice a year, and resulted in a very quick collapse in the territorial mink population. Thereafter, trapped animals were generally those immigrating, from the north, into the area, as indicated by a higher proportion of males caught during this period.

An important difference in the capture locations between the Uist's and South Harris became evident in the first few months of the project with the Uist's showing a significantly higher proportion of captures inland compared to coastal habitats. The difference was largely due to the

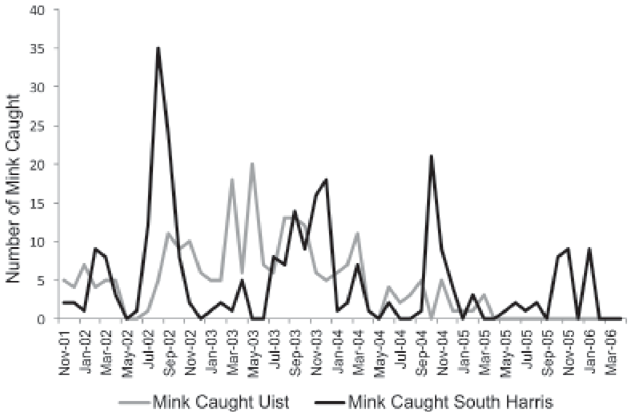

Fig. 3 Number of mink captured per month and year on both South Harris and the Uists during Phase I (SNH, 2006).

Year beginning	Trap nights		Mink captured by trapping		Mink captured per 1000 trap nights		Mink captured by dog searches (dependent young in brackets)	
	Uist	Harris	Uist	Harris	Uist	Harris	Uist	Harris
Sep-2001	22,155	15,350	42	73	1.85	4.76	0	6
Sep-2002	26,357	13,213	80	54	2.97	4.08	12 (18)	1 (2)
Sep-2003	30,064	10,325	56	64	1.86	6.20	4 (2)	(3)
Sep-2004	20,037	2755	13	38	0.65	13.79	1	3 (1)
Sep-2005	1,114	76	0	1	0	13.15	0	0
Total	100,824	41,674	191	230	1.89	5.15	37	18

Table 1 The numbers of trap nights, mink captures and trap successes in the Uists and South Harris during Phase I (Roy, et al., 2015).

greater availability of food resources inland in the Uist's, including a large number of duck and wader species closely associated with the freshwater edge but, importantly, the presence of field voles in the moorland habitat that were absent from Lewis and Harris.

Phase II

Trapping took place over large areas, only moving on when a low mink density had been achieved. This resulted in a significant drop to the overall mink population, with 51% of the final captures so far, being caught in the first two years. The final total of mink captures by March 2012 was 91% of the current figure. From April 2012 a further 116 mink were caught over the next three years, equating to a further 6% of the current final total.

Initially there was a two week live trapping cycle carried out but this was reduced to a one week cycle to increase the efficiency of the knock down phase. Whilst initially unpopular with the trapping staff, as they felt they were leaving animals behind, the speed with which the project reduced the mink population over a wide area soon became apparent and the staff bought into the techniques employed.

From 2007 to the present a total of 1,666 mink have been caught from 527,431 trap nights, across Lewis and Harris.

The major result of moving from live traps to a kill trapping regime was an increase in the total trapping effort, despite being reduced to a trapping team of just three. This can be seen in Table 2, where up to 14,000 trap nights per month were being achieved compared to approximately 2,000–2,500 per month when 12 trappers were employed for live capture trapping.

The captures per unit effort have declined over time but reflect the seasonality related to the trapability of more mobile mink during the rut and the naivety of young animals during the dispersal period (Fig. 4). The striking issue, however, is the extremely long tail to the graph which describes the extreme difficulty in catching the final animals over such a large geographical area with a declining staff resource (see Fig. 5). Two modelling exercises were completed, (Shirley, et al., 2012) and the modelling exercise carried out by Aberdeen University (Lambin, et al., 2014) did predict that this would be the case: 80% of iterations predicting eradication by 2017, using the data up to 2011 and a trapping regime based on live capture and a trapping regime of 12 trappers see Table 2.

Table 2 Actual trap nights and captures for all years of the project from 2007 onwards.

Year	Total trap nights	Total captures	Male	Female
2007	14,914	280	146	134
2008	24,755	527	266	261
2009	38,749	367	171	196
2010	40,894	212	98	114
2011	33,446	137	53	84
2012	26,665	56	31	25
2013	21,695	31	19	12
2014	41,954	26	16	10
2015	126,088	23	14	9
2016	158,271	7	5	2
2017*	87,000	4	3	1

*2017 figures to the end of June.

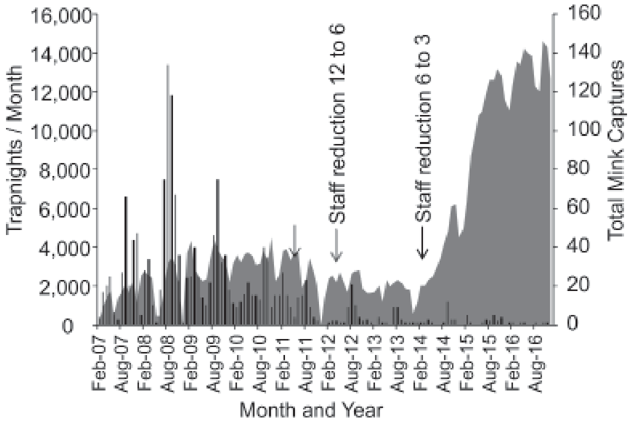

Fig. 4 Trap captures from Feb 2007–Nov 2016. Black bars are mink caught; grey area is the trapping effort.

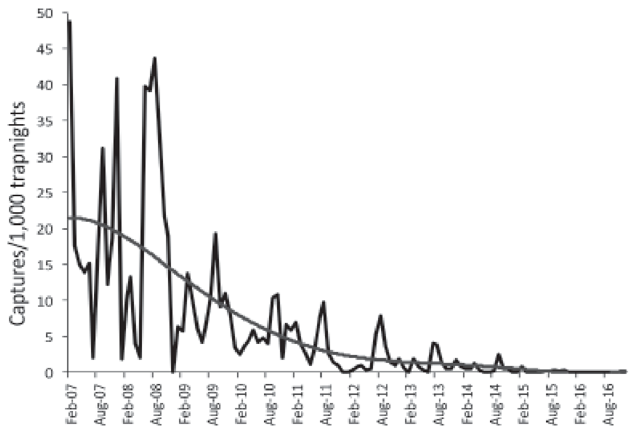

Fig. 5 Number of mink captures per 1,000 trap nights between February 2007 and December 2016.

During the final monitoring phase of the project in Lewis and Harris, the final 1.5% of the mink population was caught and functionally the population was eradicated with only isolated individuals, unable to find a mate and breed, left to track down. No juveniles have been caught in Lewis and Harris since August 2015

Through an increase in trapping effort and larger areas being monitored, there has been an increase in the number of mink being caught on the Uists since 2014 (Table 3). These animals are finally reducing in number as the same kill trapping regime used in Lewis and Harris takes effect.

Table 3 Number of trap nights and mink caught from the re-emerged population in the Uists between 2014 and present.

Year beginning	Trap nights	Total captures	Male	Female	Unk
Jan 2014	36	5	5	0	0
Jan 2015	507	22	12	5	5
Jan 2016	3,776	63	38	21	4
Jan 2017*	4,799	41	23	14	3
Total	9,118	131	78	40	12

*2017 figures to the end of June.

DISCUSSION

In 2001 when this project was initiated, there were few, if any, successful eradications that used trapping as the main technique for the removal of an invasive non-native mammal; the only UK example being the coypu eradication in Norfolk, (Gosling & Baker, 1989). In addition, there was a limited range of literature available providing examples of wildlife management project design and best practice to follow (IUCN, 2000). The EU LIFE fund recognised that the project would need to adapt as it progressed and agreed to provide funding based on the understanding that it was innovative in its concept, scale and design.

During Phase I, one of the main lessons learnt was the necessity to ensure trap distribution was coordinated by the supervisor. Initially trappers were relied upon to distribute traps in the field according to their own judgement, with only a specific distance between traps to guide them. This meant that traps were situated in ideal locations for catching mink, but trappers on the ground were unable to ensure that there were no gaps in the overall trap coverage, leading to irregular densities. Over time, the emergence of better GPS technology enabled trappers to be more efficient in the field and able to provide more accurate trap locations. Establishing the most effective trapping schedule was important as it was not possible to trap the entire area at once with the staff available. A twice yearly minimum trapping cycle of the entire trap network was vital to ensure that all areas maintained sufficient trap nights, while removing animals in a timely manner to avoid successful breeding.

Despite the ongoing learning process during the first phase, the project managed to achieve the removal of the majority of the mink from the project area in just under three and a half years, followed by a summer of monitoring. It was thought at this point that it was very unlikely that any mink remained in the Uists and Benbecula and that eradication from these islands had been achieved.

The second phase of the project was an absolute requirement if the gains of the first phase were to be secured over an even larger geographical area and the investment in the previous five years was to be protected. Scottish Natural Heritage demonstrated significant commitment in proceeding with Phase II, helped with funding from the Esmeè Fairbairn Foundation, but from the outset the budgetary constraints on the project were clear. The modelling work undertaken by the Central Science Laboratory (now Animal and Plant Health Agency) indicated that 16 trappers would be ideal (Moore, et al., 2003) but due to budgetary constraints, the project proceeded with just 12. Restricted resources continued into the project extension and the monitoring phases and required significant adaptive changes to strategy and efficiency in order to give the project the greatest chance of success. It is undoubtedly true that the project has taken longer due to these budgetary constraints and that, if fully funded for the entire requirement of 10 years plus two extra years to ensure eradication, significant savings could have accrued over this period. This type of consecutive long-term funding is simply not available in the UK, (Lambin, et al., 2014), as it does not fit with the funder's requirement to demonstrate success, generally within five years, and exceeds the acceptable commitment levels between political administrations.

Throughout the project, different methods were employed at various stages to overcome the challenges of limited resources. The addition of the bodygrip traps instead of solely live traps enabled a high level of trapping effort to be maintained with limited staff. Bodygrip traps meant that trappers did not have to respond to triggered traps immediately as the mink would be dead upon capture. The initial concern of accidental by-catch was reduced to an acceptable level through very strict protocol in the practical setting of the trap, including the bespoke tunnels which excluded all non-target species, and camouflage technique.

Monitoring such a huge geographical area with only six trappers was challenging and several monitoring devices and techniques were trialled. Footprint rafts were not able to withstand the extreme weather of winter months either through wind or high water spate events, the cameras had slow triggers and reset times which led to missed targets, while the clay/carbon footprint monitoring required careful set-up and protection from the elements to provide useful data. In addition, the time between detecting the mink and being able to initiate the trapping was too long to catch a highly mobile individual. The acquisition of trap RMAs were particularly useful for the monitoring period, giving a precise time stamp for when a trap caught and enabling further traps to be installed in the area immediately. This was immediately effective as the mink population had begun to cluster in their distribution, not only during the rutting period which would be expected, but animals would also set up territories next to existing ones rather than be isolated and alone. This helped greatly once an individual was trapped, as a localised trapping campaign could be mobilised to catch a few additional animals.

The Hebridean Mink Project is now into its 16th year, and has cost a total of £5.26M. The learning process has been difficult and expensive and these lessons should be passed on to others. There is a requirement for simple tools to be developed that will allow projects to recognise the key stages of eradication from the data they collect. These comprise: population crash completion (knock down), identification of groups of target species (cluster effect) and difficult to trap areas to allow targeted action (trap everywhere at the same intensity), detection of individuals and their rapid removal (find the right monitoring technique), effective and efficient long-term monitoring and biosecurity (ensure the last individuals are not left behind or re-introduced).

Clearly there are vast amounts of data associated with this project that could provide a lifetime of analysis opportunities of which only a tiny fraction has been used here. Some of the intuitive assumptions made within this paper need to be statistically analysed to provide definitive proof of behaviours such as clustering, which appear so obvious from mapping the capture data geographically over time.

CONCLUSIONS

Phase II of the Hebridean Mink Project commenced with a wealth of knowledge, practical scientific information, techniques and trapping scheme models, not to mention a core of well-trained staff. This no doubt contributed to the success in greatly reducing the population of American mink to near eradication. With the re-emergence of mink in the Uists, the main lesson that can be learnt from Phase I, is the importance of ensuring a sufficiently long monitoring period with a sustained level of effort is implemented once the last mink is thought to have been captured. Maintaining sufficient resources to continue monitoring during the final years following eradication is crucial to ensuring the project's success (Rout, et al., 2009). Any lapse in funding before eradication is declared could result in the mink being able to breed successfully and repopulate, leading to financial losses that are both immediate and exponential.

If eradication can be achieved in the Outer Hebrides this would represent the largest mammalian eradication initiative worldwide using just trapping techniques.

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