Biological Conservation xxx (2010) xxx–xxx

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Turning back the tide of American mink invasion at an unprecedented scale through community participation and adaptive management

Rosalind Bryce, Matthew K. Oliver, Llinos Davies, Helen Gray, Jamie Urquhart, Xavier Lambin *

School of Biological Sciences, Aberdeen University, Zoology Building, Tillydrone Avenue, Aberdeen AB24 2TZ, Scotland, UK

ARTICLE INFO

Article history:
Received 24 July 2010
Received in revised form 20 October 2010
Accepted 25 October 2010
Available online xxxx

Keywords:
American mink
Invasive alien species
Eradication
Volunteer participation
Adaptive management
Community conservation

ABSTRACT

Successful eradications of harmful invasive species have been mostly confined to islands while control programs in mainland areas remain small, uncoordinated and vulnerable to recolonisation. To allow the recovery of threatened native species, innovative management strategies are required to remove invasives from large areas. We took an adaptive approach to achieve large scale eradication of invasive American mink in North East Scotland. The project was centred on the Cairngorms National Park (Scotland), with the primary aim of protecting endangered water vole populations. The project was initiated by scientists and supported and implemented through a partnership comprising a government agency, national park authority and local fisheries boards. Capitalising on the convergent interests of a diverse range of local stakeholders, we created a coordinated coalition of trained volunteers to detect and trap mink. Starting in montane headwaters, we systematically moved down river catchments, deploying mink rafts, an effective detection and trapping platform. Volunteers took increasing responsibility for raft monitoring and mink trapping as the project progressed. Within 3 years, the project removed 376 mink from 10570 km^2 with the involvement of 186 volunteers. Capture rate within sub-catchments increased with greater connectivity to mink in other sub-catchments and with proximity to the coast where there is more productive habitat. The main factor underpinning the success of this project was functional volunteer participation. The project is a reason for optimism that the tide of invasion can be rolled back on a large scale where the convergent interest of local communities can be harnessed.

1. Introduction

The spread of invasive non-native species has a devastating impact on native biodiversity. Many alien opportunistic predator species have caused fundamental changes in ecosystems via their impacts on native species (Simberloff, 2001). There is a growing realisation of the need for active management to minimise such impacts. Eradication of vertebrate aliens has been successful in a few instances, when control actions were taken early (e.g. coypu in Britain (Gosling and Baker, 1989)), and is increasingly achieved on oceanic islands through the use of toxins that can be spread aerially (Parkes et al., 2006; Saffer and Calver, 2001). Poisoning is also used in sparsely populated areas of mainland Australia and New Zealand to suppress introduced carnivore (Cromarty et al., 2002; Parkes et al., 2006). However, owing to its higher human population density, diversity of land use and smaller size of protected areas, poison-based eradication programs of carnivores would not be possible in Europe (Bertolino and Genovesi, 2003). Management of vertebrate aliens in Europe must therefore be undertaken with the support, and possibly active involvement, of local communities using techniques such as live trapping.

Until recently, the scale of the task led to the widespread view that eradication of aliens was prohibitively expensive, and carried too high a risk of failure (Bomford and Obrien, 1995). This has been challenged by recent successes in removing rats from islands of increasing size, soon matched by further successes with goats, cats, mongoose and foxes (Bester et al., 2002; Ebbert and Byrd, 2002; Lorvelec and Pascal, 2005). Eradicating carnivores however, especially mustelids, remains particularly challenging because of often low and heterogeneous trappability, difficulties in detecting low numbers and high mobility (Craik, 2008; Harrington et al., 2008; King et al., 2009).

Despite an improving success rate and greater boldness with eradications of invasive vertebrates from islands, most mainland areas remain badly affected. Whilst there is a consensus that reversing continental scale invasions remains unfeasible, there is little consensus on the feasibility and cost-effectiveness of region-wide eradications (Bomford and Obrien, 1995). While New Zealand's fenced "mainland islands" preserve intact populations or communities of focal native species by excluding all invasive species, these are capital intensive and only protect small

* Corresponding author. Tel.: +44 1224 273 259.
E-mail address: X.lambin@abdn.ac.uk (X. Lambin).

0006-3207/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.biocon.2010.10.013

areas (Saunders and Norton, 2001). In the absence of barriers to immigration such as in mainland Australia, sustained trapping or iterated baiting campaigns aimed at suppressing, rather than eradicating invasive red fox and feral cats are undertaken as part of native marsupial conservation efforts (Saunders et al., 2010). Where management interventions fall short of eradication, they must be sustained in perpetuity, with potentially ongoing expenditure owing to recolonisation from uncontrolled areas.

As pointed out by Donlan et al. (2003), there are few articles in international journals dealing with research on eradication techniques, and a large knowledge gap on how to optimise the cost-effectiveness and sustainability of control attempts of invasives in mainland areas. A systematic review report failed to assess the effectiveness of trapping on mink populations in the UK due to a sparcity of data and lack of replication within studies (Tyler et al., 2005). Common sense dictates that eliminating an invasive from a large scale area is likely to reduce recolonisation, but the relationship between the size of an area cleared of an invasive and the rate of recolonisation is not known for any system. While stakeholders and community involvement is deemed valuable to achieve large spatial coverage in professionally-led campaigns (Davis, 2009; Epanchin-Niell et al., 2010; Stokes et al., 2006), as well as to deliver a range of economic and social benefits (Bell, 2003), we are aware of no study measuring the success of harnessing volunteer manpower to achieve specific conservation objectives.

In this paper, we describe the strategy and achievements to date of one of the largest-scale invasive alien species projects worldwide targeting a carnivore species, the American mink, *Neovison vison*, in a mainland area. The project follows an adaptive management approach and capitalises on the motivations and interests of local communities by facilitating their roles as conservation volunteers within a coordinated partnership. This functional approach to participation made it possible to continually increase the size of the controlled area, whilst maintaining a constant high level of vigilance and a rapid response upon detection of the pest species, thereby reducing immigration and providing greater benefits to affected native species.

2. Materials and methods

2.1. The invasive alien species

The American mink is established as an alien in much of Europe, Iceland, South America and Japan (Macdonald and Harrington, 2003). Territories are linked to water and extend for up to 2 or 3 km along the bank of a waterway (Dunstone, 1993). Mink produce a litter of 6–10 young in April–May who can fend for themselves by late August (Bonesi et al., 2006). Mink are generalist predators, feeding on fish, mammals, amphibians and invertebrate prey. Mink are responsible for a conservation crisis with numerous native species badly affected (Aars et al., 2001; Craik, 1997; Moore et al., 2003; Nordstrom et al., 2003; Woodroffe et al., 1990). The mink is classified as a damaging non-native species in the British Wildlife and Countryside Act 1981 and as a priority species for control by the Scottish Natural Heritage Species Management Framework (Anonymous, 2007).

2.2. The focal native species

The water vole is a large rodent especially vulnerable to predation by mink. British water voles have experienced an accelerating decline of no less than 96% since 1950, largely attributable to mink predation (Strachan et al., 2000; Strachan and Jefferies, 1993). In Britain, voles exclusively inhabit water margins and as a consequence mink encounter and prey on a large proportion of the population, with extinction of colonies inevitably ensuing within a few weeks (Aars et al., 2001; Barreto and MacDonald, 2000). The species is now protected under the Wildlife and Countryside Act 1981 and is a priority species under the UK Biodiversity Action Plan, and the subject of conservation efforts (e.g. (Harrington et al., 2009). Whilst water voles have disappeared from the majority of lowland waterways, widespread but small water vole colonies still persist in upland moorland areas (Aars et al., 2001; Lambin et al., 1998).

2.3. The project area

The project area is centred on the Cairngorms National Park (CNP ~57°0′N 3°3′W), established in 2003 and covering 3800 km^2. The park encompasses an area of montane and semi-natural moorland habitat. Thirty-nine percent of its surface is designated as important for nature heritage and 25% is of European importance (http://www.cairngorms.co.uk/thepark/keyfacts/). The moorland areas are privately owned, typically by large estates, and generally managed for grouse shooting and deer stalking. Livestock farming and forestry are the main land uses in the lowland areas. Five major rivers flow out of the area and are managed for recreational Atlantic salmon fishing. The initial target area also encompassed an additional 1700 km^2 buffering the CNP to make up the 5500 km^2 Cairngorms Local Biodiversity Action Plan (CLBAP) area. However, the project expanded beyond this zone in its second year.

The headwaters of river catchments in the Cairngorms were known to be a stronghold for water voles, possibly because upland moorland represent a partial low productivity refuge from mink predation even though mink do occur due to the presence of rabbit colonies (Capreolus Wildlife Consultancy, 2005; Lambin et al., 1998; Oliver et al., 2009; WildCRU, 2004). Upland water vole populations had not experienced the catastrophic collapse seen in lowland areas, but there was nevertheless evidence of an 80% decline from 2000 to 2006 in the Eastern part of the CNP (Aars et al., 2001; Capreolus Wildlife Consultancy, 2005). These were likely caused by repeated short-lived forays by mink into upland sub-catchments resulting in the simultaneous extinction of local water vole colonies.

A smaller scale lowland project initially centred on the River Ythan flowing through primarily agricultural lowland had begun prior to the Cairngorms project in 2004, and subsequently informed initial activities in the larger scale effort. Its original focus was restricted to a 58 km^2 sub-catchment where remnant water vole populations had survived.

2.4. The partnership

The project capitalised upon the convergent interests of a diverse range of organisations, both national funding bodies and organisations active in the project area and relying in different ways upon the biodiversity resource in the CNP. Initial action was funded through the CLBAP to the University of Aberdeen. The large scale of the project that followed was made possible by a subsequent formal partnership developed to provide the project with funds and in-kind contributions from national and local organisations with an interest in mink control. A grant from the Tubney Charitable Trust was supplemented by financial and in-kind support from Scottish Natural Heritage (SNH), CNP Authority and three Salmon District Fisheries boards (rivers Dee, Spey, and Bogie Isla Deveron). The fisheries boards are statutory bodies empowered to protect, enhance and conserve Atlantic salmon and sea trout fisheries. They work closely with fisheries trusts, which are charitable bodies working to enhance ecological knowledge and improve river management. These funds were matched by a "partnership" grant awarded by UK's Natural Environment Research Council to support collaborative research activities between academic researchers and public or private sector partners. All grants were applied for by XL and managed by the University of Aberdeen.

The project heavily relied upon participation by volunteers from local communities who fell into five categories. We use the term 'volunteer' to describe individuals who agree to follow the procedures proposed by the project to provide us with scientific data and mink carcasses. While many volunteers already carried out some mink control, we believe their willingness to use novel methods and perform additional duties for the project justifies the term. 1. *Gamekeepers* employed by private estates to manage game through habitat management including predator control. 2. *Fisheries staff* river bailiffs and river biologists, employed by fisheries trusts and boards, and fishing ghillies employed by private estates whose duties include control of invasive species. 3. *Wildlife conservation professionals* included individuals working for governmental (e.g. local councils) or non-governmental organizations (e.g. National Trust for Scotland) with a conservation focus. This group included wildlife rangers; some of whom were employed by private estates. 4. *Land managers* included people with a responsibility for the management of the land they occupy or own such as farmers. 5. *Local residents* were people living in the project area who participated out of their own interest rather than as part of their occupation. No financial reward was offered for participation in the project because we wished to empower local communities to fulfil the shared objective of pushing back the mink invasion as opposed to fulfilling an objective held by an external body.

2.5. The project strategy

The strategy of the project consisted of coordinating and optimising the efforts of an existing, local and skilled workforce with convergent interests to deliver coordinated, systematic sub-catchment by sub-catchment eradication and monitoring of American mink, so as to achieve maximum conservation benefit on a scale not previously attempted anywhere worldwide. Our approach to participation was thus functional (Pretty, 1995) as volunteers were recruited for achieving pre-determined project objectives and for providing the man power required to cover our large target geographical area.

A key component of the strategy was to promote the systematic use of Game Conservancy Trust Mink rafts (Reynolds et al., 2004). Mink rafts are floating platforms with a footprint-recording plate made of moist clay and sand under a wooden tunnel. Mink rafts are designed to act both as a monitoring device and as a trapping site for American mink. Traps are placed in the tunnel of the raft subsequent to mink footprints being recorded during fortnightly checks. Rafts thus provide a targeted, highly effective method of mink trapping. Raft monitoring also provides feedback on the impact of trapping, which helps to motivate project partners.

The strategy of the project was to expand mink control spatially and establish a "rolling carpet", deploying rafts and recruiting volunteers to operate them in each sub-catchment, moving downstream from the headwaters of the five main river catchments that flow from CNP but retaining the network of rafts behind the expanding control front to ensure detection and removal of immigrants. Sub-catchments were defined as major tributaries to main catchments (median size: 55 km^2, max: 697 km^2). Rafts were deployed through the project area at a target approximate spacing of 2 km along all waterways, ensuring coverage of small waterways known to be predominantly used by female mink (Zuberogoitia et al., 2006). Sections of waterways deemed unsuitable to mink or where water flow was too fast for rafts were left uncovered. Loss of damage of rafts was a hazard in spate-prone montane streams but we found they could be used successfully in most locations by encouraging volunteers to increase check frequency in spate conditions to ensure rafts were well positioned and to temporarily remove them during floods. Modifying fixtures and anchor attachments also increased stability. Our long-term management goal was to achieve sustainable catchment-wide removal of mink, hence creating suitable conditions for the recovery of the focal native species on a large scale by promoting ownership of biodiversity resources by local communities. We hypothesised that increasing contiguous coverage in a downstream direction would suppress re-invasion of covered areas from source populations of mink in the productive lowland areas of catchments and reduce recolonisation rate of sub-catchments; increasing the size of mink free areas and allowing us to further expand coverage. While the primary objective of the project was to protect water vole populations within the restricted area of CNP, no outer limit for the extent of control effort was set at the outset of the project. Instead, we contemplated catchment-wide eradication as a long-term management goal and we hypothesised it would be possible to increasingly recruit fisheries staff as the project expanded away from the moorland area where gamekeepers operate and took on lower reaches of rivers where salmon fishing replaces game-bird shooting as the main economic activity involving wildlife resources. We planned to hand over an increasing fraction of rafts to members of the community behind the project expansion front so as to allow project staff to extend mink removal to lower reaches of river catchments.

The project was initiated with only partial knowledge of upland mink populations. Specifically, we did not know how large an increase in mink trapping effort beyond the baseline level was required so as to bring about a sustained decline in the local mink population. Gamekeepers interviewed prior to the project indicated that 60–70 mink within the CNP were caught yearly, but we had no way of knowing how this figure related to the production of the local mink population or to the size of the influx of immigrants from the lower reaches of catchments. We thus chose to use an adaptive management approach, with information gained in the early stages used to optimise the project's conservation benefit, sustainability and cost-effectiveness. It was thus essential to systematically collect data from all aspects and participants of the projects to inform management. This included the location of rafts, frequency and outcome of raft checks, success of trapping attempts, and sex, age and genotype of all mink caught.

During raft deployment, officers selected approximate raft locations using maps and then sought permission from landowners. Volunteers were recruited to take over raft monitoring wherever possible. On sporting estates and nature reserves, land management employees were identified and contacted by telephone. In other areas, requests for volunteers were advertised by poster displays, leaflet distribution, articles in local media and as part of community talks given about the project. Residents in the vicinity of rafts were also asked if they would be willing to participate. Volunteers were trained in the use of rafts. Project staff monitored mink rafts where volunteers were unavailable. Volunteers were instructed to set cage live-traps on rafts whenever mink footprints or sightings were recorded and/or contact a project officer or named volunteer to carry out trapping and dispatch of mink. Those willing were trained to dispatch mink humanely using air rifles or pistols of sufficient power (minimum muzzle energy of 3.1 ft lbs) and suitable hardened pellets (Prometheus™ .22 lead free pellets). Project staff met and communicated with volunteers regularly to provide advice, information and supplies. Project results were disseminated via 6 monthly newsletters and a website (http://www.watervole-scotland.org/).

2.6. Statistical analyses

We assessed the effects of the spatial scale of the project on the number of mink captured within each river sub-catchment as more sub-catchments were sequentially added to the control effort. Raft check and trapping data was analysed on a 6 monthly basis (January to June: period of mate searching and breeding; and July to December: juvenile dispersal) from January 2006 to December 2009. Data from three catchments fully covered by rafts were included in these analyses to investigate mink capture rate over time from coverage of a small number of sub-catchments to complete catchment coverage. To understand how the number of mink caught in a 6 month period in a focal sub-catchment was influenced by the proximity and extent of controlled and uncontrolled areas within the catchment, we used the connectivity measure S^R (Hanski, 1994):

$$S_i = \sum \exp(-d_{ij}/d')A_j \tag{1}$$

where S_i^R is the connectivity of sub-catchment i to all other sub-catchments within a catchment, d_{ij} is the distance (m) between sub-catchment i and sub-catchment j, and A_j is the number of mink in sub-catchment j. A_j was taken as the maximum number of mink trapped in sub-catchment j prior to the 6 month period when mink rafts were fully deployed, and as the number of mink trapped per time period in sub-catchment j thereafter. Here we are estimating the effect of the distance to, and number of, assumed (when a sub-catchment is not covered), or captured, mink in surrounding sub-catchments within a catchment. With this function, S^R increases linearly with the number of mink present in the catchment, weighted by a negative exponential function of the distance. The shape of the negative exponential is tuned by the unknown parameter d', which reflects the propensity of mink to disperse between sub-catchments, with higher values of d' indicating higher mink mobility and effectively increasing connectivity between sub-catchments. We estimated d' from the data using profile likelihood for a range of values from 10 to 25,000 m. The most likely value of d' was taken as that which yielded the model with the highest log-likelihood. As a time-lag may be expected in the influence of the surrounding area on mink numbers in a focal sub-catchment, profiling of d' and statistical analyses were conducted for connectivity in the previous 6 months (S_{t-6}) and 12 months (S_{t-12}) in addition to the present time frame (S_{t0}). In order to test the hypothesis that the lower reaches of a catchment acts as a source of mink that disperse upstream, we also included the distance of a sub-catchment to the coast as a standardised covariate and its interaction with connectivity.

To account for the study design, a generalized linear mixed modelling (glmm) approach was used, implemented in the lme4 package (Bates and Maechler, 2010) in R, with sub-catchment nested within catchment assigned as a random effect and all other covariates including season as fixed effects. Since the data were counts, models were fitted using Poisson errors. Although it would have been desirable to directly include the effect of time of raft coverage on mink capture rate, this variable was collinear with connectivity. Remodelling the data with and without either effect revealed that the inclusion of one variable strongly influenced the interpretation of the effect of the other. In both cases

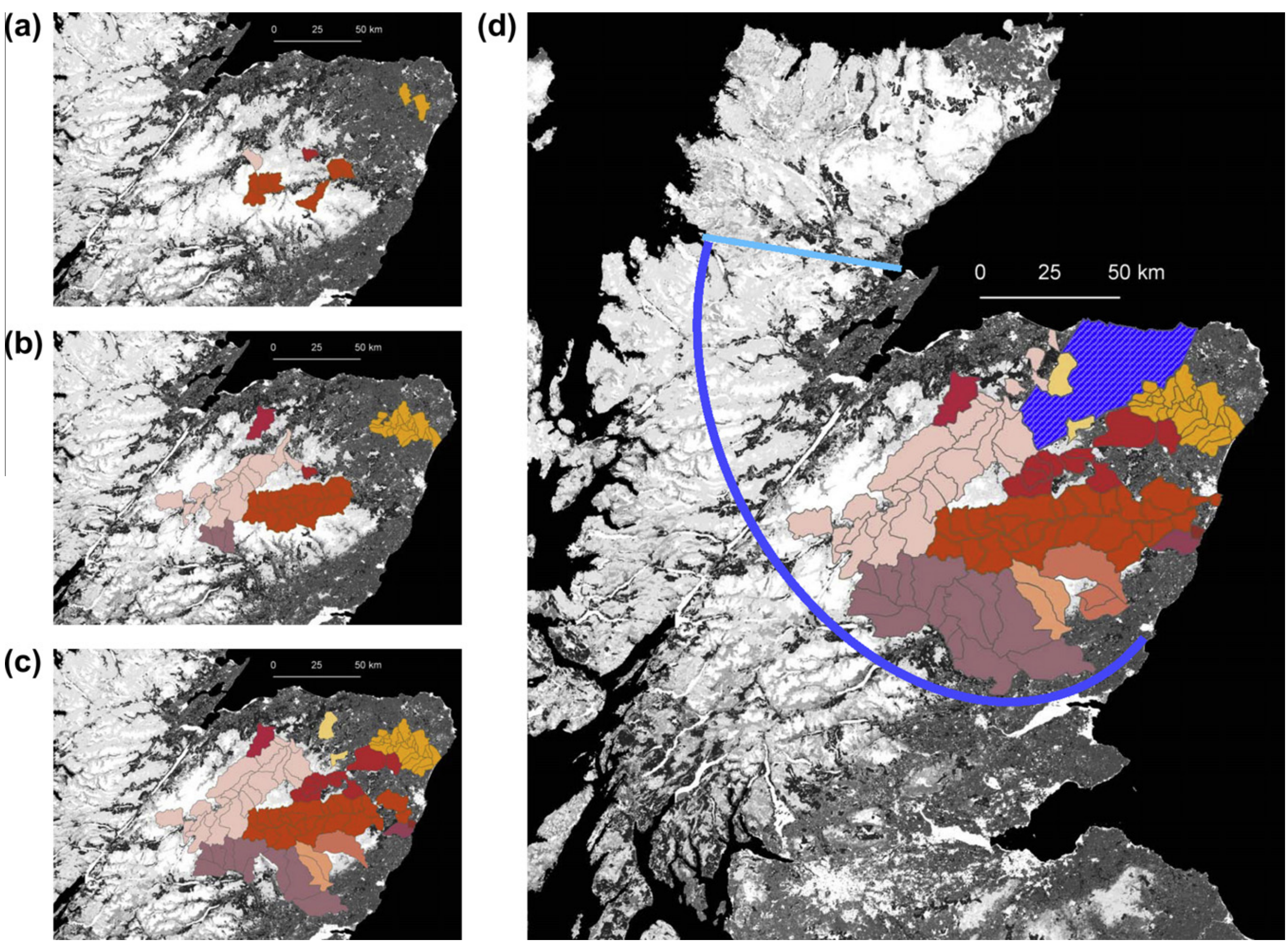

Fig. 1. Catchment coverage expansion. Maps (a–d) illustrate the annual expansion (January to December) of project coverage over the entire project area over a 3 year period (a: 2006; b: 2007; c: 2008; d: 2009). River catchments are represented by different colours and are shown subdivided into sub-catchments. The area within the blue arc on the larger map of Scotland (d) is the current spatial focus for a new partnership coordinated by RAFTS in association with two sister projects; the Deveron, Bogie and Isla Rivers Trust project (shown by striped blue area) and the NW mink project (north of coloured areas). No breeding mink are believed to be present to the north of the light blue line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

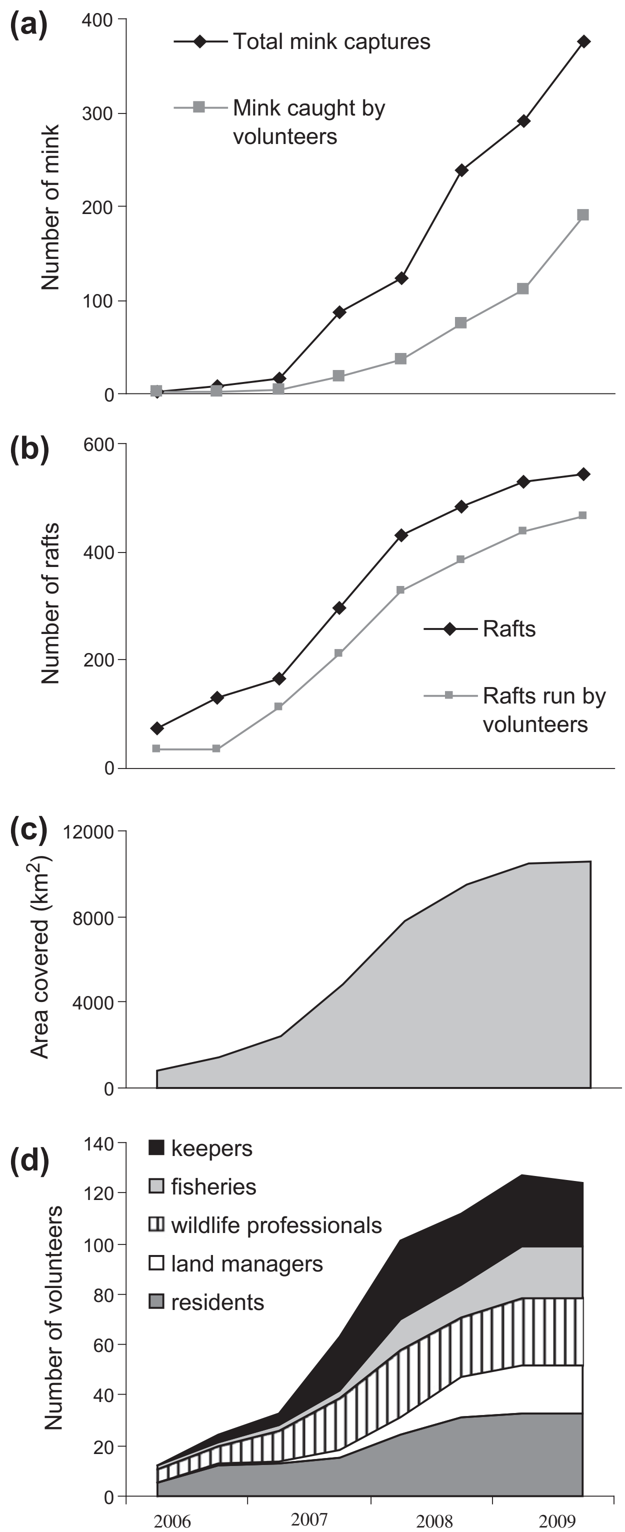

Fig. 2. (a) Cumulative mink captures over the entire project area accompanied by a curve showing an increasing number of captures by volunteers. (b) The cumulative total number of rafts deployed over the course of the project accompanied by the number of the total monitored by volunteers. (c) The cumulative project area covered over the course of the project. (d) The total number of active volunteers throughout the project shown by category.

coefficients were stronger (though directionality was maintained) in the absence of the other variable. However, connectivity was a much more powerful predictor of mink capture rate than time of raft coverage, whether either, or both, variables were fitted in a particular model. Connectivity was therefore used as the variable to examine the effect of the mink control strategy. However, a small proportion of variance in mink capture rate accounted for by connectivity may be attributable to the effect of duration of raft coverage within a focal sub-catchment.

We analysed volunteer retention as a binary variable (analogous to survival) using multinomial regression according to time since the inception of the project, the timing of their recruitment relative to the start of the project, the length of their involvement and the group they belonged to. Analyses were carried out using program MARK (White and Burnham, 1999). Probability of knowing volunteer status (analogous to trappability) was fixed as one and model selection was based on AICc.

3. Results

The project achieved multi-catchment scale mink removal, with the catchment area covered with 543 rafts reaching 10570 km^2 within 3 years of its inception in 2006 (Fig. 2b and c). Of this area, approximately 10000 km^2 appears free of breeding mink as of December 2009. The project began with a single project officer working in eight sub-catchments in the headwaters of the rivers Dee and the Spey (Fig. 1a). From May 2007, with two further project officers, the project expanded rapidly around the Cairngorms, with another officer expanding the Ythan lowland project. The target area of 5500 km^2 was reached ahead of schedule by the end of 2007 (Fig. 1b). A decision was then taken to expand mink control to lowland agricultural areas, the putative source of mink invading moorland and montane areas, rather than holding a control line at the boundary of the CLBAP area. We surpassed our goal by achieving multi-catchment-wide coverage.

No mink were captured in 2006 when rafts were mostly deployed in catchment headwaters in close proximity to water vole colonies. Capture rate increased rapidly as raft deployment progressed downstream (Figs. 2a and 3). By December 2009, 376 mink had been caught (Fig. 2a), of which 46.6% were females. Ninety-six percent of mink captures in the Cairngorms area were made below 300 m, a fraction well in excess of expectation if mink were distributed irrespective of altitude ($X^2 = 33$, df = 1, $p < 0.0001$, Fig. 3).

Connectivity to other mink within river catchments explained significant variance in mink capture rate within sub-catchments (ΔAIC = 70; Table 1), with mink capture rate increasing with connectivity to mink in other sub-catchments as predicted (Fig. 4). Measuring the connectivity to mink in surrounding sub-catchments 12 months previously explained more variation in mink captures within a sub-catchment than using connectivity 6 months previ-

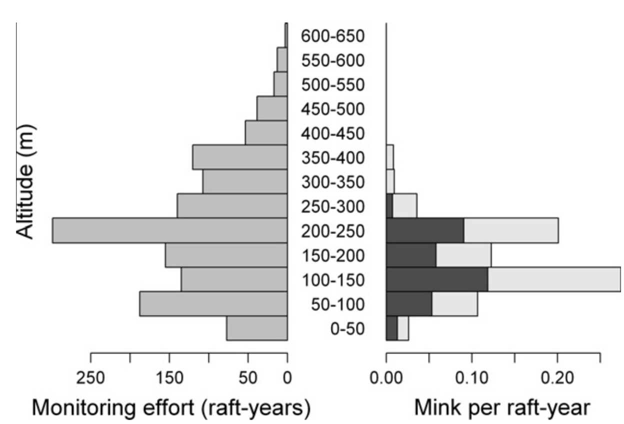

Fig. 3. (a) Monitoring effort measured as raft years at a range of altitudes in the Cairngorms. (b) Mink caught per raft year by altitude in the Cairngorms. Female mink are shown in dark grey and males in light grey.

Please cite this article in press as: Bryce, R., et al. Turning back the tide of American mink invasion at an unprecedented scale through community participation and adaptive management. Biol. Conserv. (2010), doi:10.1016/j.biocon.2010.10.013

Table 1
Parameter estimates with associated standard errors, *Z* and *P* values for variables included in the model of mink captures per sub-catchment per 6 months. ΔAIC is the change in AIC following removal of each parameter from the model.:

Parameters	Estimate (β)	se	*Z*	*P*	ΔAIC
Intercept	−2.96	0.46	−6.45	$1.15e^{-10}$	
Connectivity	0.19	0.03	7.48	$7.21e^{-14}$	70
Distance to coast	−2.67	0.71	−3.74	0.0002	11.7
Connectivity:					
Distance to coast	0.15	0.05	2.78	0.0054	6.1
Time period					
January–June vs. July–December	−0.79	0.16	−4.85	$1.21e^{-06}$	24.5

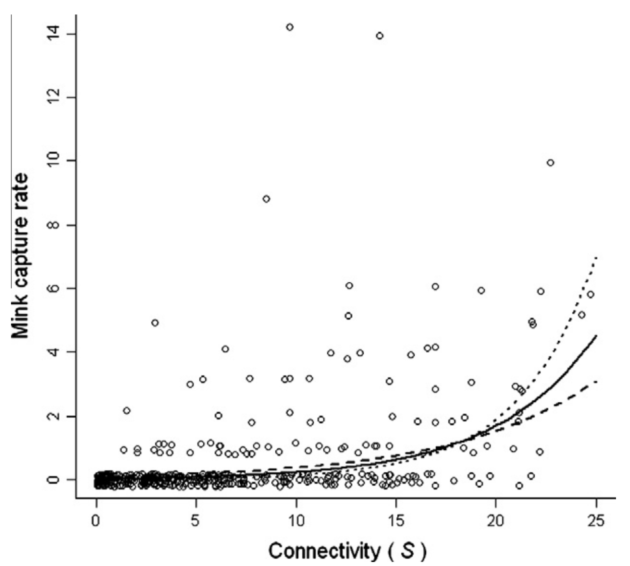

Fig. 4. Predicted relationship between the number of mink captured per sub-catchment in a 6 month period and connectivity to mink in surrounding sub-catchments, with connectivity measured 12 months previously, calculated as $S_i = \Sigma \exp(-d_{ij}/10{,}500)\, N(\text{mink})_j$. The data points are raw values, and do not account for other covariates in the model, or random effects. A small degree of jitter has been added to clarify the density of data points. The lines illustrate the interaction between connectivity and distance to the coast: the dashed, solid and dotted lines represent the predicted effect of connectivity on mink capture rate for the 1st quartile, median and 3rd quartile distances of sub-catchments to the coast respectively.

ously, or in the current 6 month time period: S_{t-12} dev = 360.3, AIC = 374.3; S_{t-6} dev = 362.2, AIC = 376.2; S_{t0} dev = 376.4, AIC = 390. The maximum likelihood value of d' was S_{t-12} d' = 10500 m. The rate of mink capture decreased significantly with distance to the coast, although this effect was relatively weak. However, interaction terms showed that the positive effect of connectivity on mink capture rate increased with distance from the coast (Fig. 4). Mink capture rate was higher between July and December than between January and June.

Residual based model validation revealed a degree of heterogeneity in the residuals, although this was not consistent with over-dispersion (dispersion parameter of best model = 0.86). The pattern suggested some cases where the observed capture rate of mink was higher than predicted by the model, which is not surprising given that the high prevalence of low capture rates data and our choice to use a simple model. Refitting the model without the 12 observations with highest associated residual values, increased the strength of the effects of connectivity (β = 0.27; se = 0.04; $P = 6.00e^{-12}$) and distance to the coast (β = −3.52; se = 1.08; P = 0.0011), as well as the interaction between the two (β = 0.26, se = 0.08; P = 0.0007) and the effect of time period (β = −0.91; se = 0.19; $P = 1.46e^{-06}$).

The number of volunteers involved in the project and the number of rafts deployed increased rapidly over the course of the project (Fig. 2d). A total of 186 volunteers assisted the four project officers in the task of removing mink. They included 40 wildlife conservation professionals, 51 local residents, 23 land managers, 50 gamekeepers and 24 fisheries staff. The number of volunteering fishery staff increased over the course of the project while proportional contribution of gamekeepers declined. Local resident and wildlife professionals made a consistently large contribution to the project. The overall probability that a volunteer remained actively involved in the project per 6 month period was 86.8% but according to the most parsimonious models based on AIC_c varied according to volunteer categories. Fisheries staff had the highest retention (94.3%; 95% Confidence Interval 83.8–98.0), whereas gamekeepers had the lowest (78.4%; CI: 70.0–84.9). Whereas the former two groups had constant retention rates, those of wildlife conservation professionals, local residents and land managers pooled varied over time. Time variation could be summarized by season for the first six time intervals in the top ranking models with a higher fraction of volunteers ceased to operate mink rafts from January to June (common estimated retention: 74.7%, CI 65.1–82.4) than from July to December (retention: 92.3%; CI: 86.3–95.8). Estimated retention for this group of volunteers was 100% in the last time interval.

The proportion of rafts monitored by volunteers increased from 26% at the end of the first year of the project (2006) to 86% by the end of 2009 (Fig. 2b). The absolute number of rafts monitored by project officers remained relatively constant throughout the project (Fig. 2b). In addition to raft monitoring, the proportion of volunteers taking responsibility of the whole process from monitoring rafts to catching and dispatching mink also increased. Twenty-five percent of mink were being caught by volunteers by then end of the first year and this increased to 51% in the second half of 2009 when a quarter of the active volunteers caught one or more mink.

4. Discussion

The achievements of this project have been to implement the largest mainland invasive species eradication effort worldwide and, through an adaptive management approach, use the convergent interests of local communities to maximum benefit to secure an invasion-free area at such a scale as to considerably reduce recolonisation. While the project still has to be tested over a long time scale, the effective use of a large pool of volunteers and the very large area protected are key components of its long term sustainability. Despite the potential for recolonisation in such a mainland area, we use the term 'eradication' to describe our efforts as our objective has been to create an expanding area completely free of mink where even a small number of individuals is not tolerated. Monitoring is maintained over the entire project area but trapping is largely carried out on the margins to prevent mink reaching the core area.

Despite a small number of dispersing mink still being caught in some parts of the area, there is no evidence of any breeding mink present in an area of 10000 km^2. The project is substantially larger than the 4590 km^2 Isabela Island goat eradication project, the largest island conservation project to date where rapid decimation has been achieved albeit at high cost due to high-tech methods (Cruz et al., 2009), and the long term Aleutian exotic fox eradication project from an archipelago of 39 islands spanning 5000 km^2 (Ebbert and Byrd, 2002). It is also 3.75 times the size of the ongoing attempt to remove mink from the Outer Hebrides Islands in Scotland to protect ground nesting birds (Moore et al., 2003). The two projects also profoundly differ in their strategy, with the latter relying on 12 full time and 4–6 seasonal paid staff with no reliance on volunteers and less emphasis on guarding against re-invasion or detecting residual mink following trapping campaigns.

The scale of the achievement must however be tempered by the observation that much of the extensive montane and moorland areas of the CNP were mostly devoid of resident mink when the project was initiated in 2006. No mink were caught during the first months of the project when we focussed exclusively on these areas. The 3417 km^2 of covered area where there were no mink captures corresponds loosely to the high ground of CNP (as opposed to the 5381 km^2 of lower ground where mink were later caught). However, securing these upland areas was essential as not only had they been subjected to repeated localised invasions with devastating impacts on water voles (Aars et al., 2001), but historical records also show that breeding mink were present in high elevation areas in the past, possibly facilitated by the presence of rabbits in abandoned hill farms (Oliver et al., 2009). The seemingly fruitless initial focus on the high altitude parts of the CNP was vindicated by the capture of one female mink during the breeding season in moorland above 250 m (Fig. 3). The small size and patchy nature of upland water vole colonies makes them extremely vulnerable to the presence of even very low numbers of mink.

The analysis of mink capture rate clearly demonstrated that the level of mink activity within a focal sub-catchment was affected by the intensity of mink control and erosion of mink numbers in the rest of the catchment. Connectivity, reflecting the distance to and number of mink remaining in surrounding sub-catchments, was the dominant effect predicting within sub-catchment mink capture rate. This validates the necessity for a large scale approach to mink control in order to effectively protect focal native species at both local and wider scales. The results also suggest that small scale mink removal projects are likely to be severely compromised due to continual and rapid recolonisation by mink from surrounding uncontrolled areas, casting doubt on their cost-effectiveness. The importance of scale for the present project is illustrated by the decrease in the number of mink predicted to reinvade a given sub-catchment as an increasing fraction of a catchment is covered (Fig. 4). Thus a catchment approach as enshrined in EU and now UK legislation is beneficial when dealing with mink invasion. However, the high mobility of mink and evidence of frequent movements between catchments emphasise the need for a multi-catchment approach. Indeed the mean distance between 254 pairs of American mink identified as first degree relatives, an approximate measure of natal dispersal distance, was 15.7 km of in our study area and 26% of movements were between catchments (Oliver and Lambin et al., unpublished).

The analysis showed that the effect of connectivity was best captured with a 12 month time lag and the d' value of 10500 m implied that recolonising mink are not only sourced from immediately adjacent sub-catchments. In fact, in an otherwise average scenario, the rate of mink capture in a focal sub-catchment was predicted to be approximately equally affected by a sub-catchment 30 km away containing 10 mink, as it would by a sub-catchment 20 km away containing five mink, or an immediately adjacent sub-catchment containing one mink. The relative impact of connectivity on mink capture rate increased for sub-catchments further from the coast which is likely to reflect increased habitat structuring in inland and mountainous areas, where suitable mink habitat becomes tightly constrained to river valleys, as opposed to more continuous habitat in lowland areas. Therefore, inland sub-catchments that are well connected to mink in surrounding sub-catchments are likely to experience high colonisation by mink dispersing from neighbouring areas, which are channelled through suitable habitat in contrast to lowland sub-catchments where habitat is less of a constraint. Our findings suggest that in upland areas, where connectivity between sub-catchments is higher, removing mink from surrounding sub-catchments should have a greater impact on mink activity in a focal sub-catchment than would be the case in lowland areas. Such areas of favourable habitat also present the opportunity to create 'attractive sinks' (Delibes et al., 2001) for reducing mink in the wider area by intercepting mink dispersing along river corridors.

Immigration is prevented in the core project area owing to the large buffer area and geographical barriers (Zalewski et al., 2009) such as the coastline of NE Scotland, regions of mountainous terrain and the barrier created by sustained control on the expanding margins. Such prevention fulfils one of the criteria set out by Bomford and Obrien (1995) for the desirability of an invasive eradication program. The use of mink rafts for detection and trapping meets two further criteria; that all reproductive animals must be at risk and that they can be detected at low densities. The systematic deployment of rafts on a large scale accompanied by long term over-watch maintained by volunteers ensures the detection of individual dispersers and traps can be rapidly set in response to mink presence. The ongoing monitoring of the project area with rafts mitigates for trap shyness of some individuals, which can be especially limiting in the case of invasive mustelids (King et al., 2009).

The success of the large scale approach taken by the NE Scotland Mink Project has provided a model for sister projects. One catchment scale effort contiguous to the NE project area is now managed and funded by the Deveron, Bogie and Isla Rivers Trust, following their involvement as a partner in the NE project (Fig. 1d). The NW mink project began in 2009 to protect and expand a mink free area in the North of Scotland and is to merge with the NE project to coordinate continuous coverage over much of northern Scotland.

Our initial lack of knowledge concerning the size of the mink population in the study area, the dispersal ability of mink and the resources and support that would be available to us in terms of a volunteer workforce required that we adopted an adaptive strategy. The lack of mink captures in the early months of the project in montane areas caused us to shift our focus to more productive habitat downstream. We made the decision to aim for catchment-wide coverage instead of intercepting immigrants at a defined boundary. The decline of captures within sub-catchments as control was stepped up in other areas of the catchment allowed us to increase our scope and ambition with regard to the size of mink free areas we could sustainably manage; leaving controlled areas to be monitored by volunteers.

Optimising the effectiveness of the volunteer workforce was central to the use of functional participation. The technical simplicity of mink raft method is conducive to its use in a community conservation project. The time commitment required by volunteers was modest (typically 15 min per raft every 2 weeks) and allowed a gradation of involvement, from detection to trapping and dispatching mink. Over time, an increasing proportion of volunteers were encouraged to take ownership of the entire process. Retention rate of different categories of volunteers was nonetheless variable. For example, gamekeepers tended to drop out at a higher rate than other volunteers. This had the potential to allow the persistence of low density mink populations in certain areas but was countered by a changing volunteer base as the geographical focus of the project shifted from gamekeeper dominated upland areas downstream to lowland areas where the presence of fisheries staff was greater. The involvement of this body of volunteers was one factor that facilitated greater project coverage than anticipated. Local residents and land managers also made a substantial contribution to the project both numerically and owing to their high retention. Given the need to maintain a level of over-watch through the area cleared of mink so to guard against a decreasing

Please cite this article in press as: Bryce, R., et al. Turning back the tide of American mink invasion at an unprecedented scale through community participation and adaptive management. Biol. Conserv. (2010), doi:10.1016/j.biocon.2010.10.013

risk of re-invasion, it will remain essential that project officers continue supporting, motivating and engaging volunteers for the long term. One way to achieve this is to increasingly involve them in other conservation activities, including the removal of other invasive species. Volunteers in areas freed of mink will be kept informed of project developments and will have a designated officer to discuss necessary procedures should mink be detected.

A lack of public awareness and opposition to campaigns from the general public are thought to have been responsible for the failure of several attempted eradications in Europe (Genovesi, 2005). While there has been no opposition to this project, we nevertheless invested much time in increasing public awareness of the nefarious impacts of invasive species on native biodiversity and on the scope for community-led remedial action thereby ensuring a suitable socio-political environment; an additional criterion for eradication (Bomford and Obrien, 1995).

The focus of project was primarily about conserving existing upland populations of water voles rather than restoring populations decimated by mink predation. While the future of core populations appears secured, numerous volunteers report the past presence of water voles in the lowland areas now mink-free and where suitable habitat abounds. While there is some evidence of localised water vole expansions from their upland strongholds, there is an inherent lag to the recolonisation process which we expect to witness during the future phases of the project without recourse to the release of captive bred individuals (Harrington et al., 2009).

A key question is whether the model of volunteer-based invasive species management developed in North East Scotland can be transferred to other species and regions of the world. Locally, the capacity built offers an opportunity to take a multi-species approach to managing invasive species such as grey squirrel and Japanese knotweed and giant hogweed also present in the area. The high density of gamekeepers and fisheries staff with an economic interest in eradicating American mink associated with the a high reliance on natural resources as source of income characteristic of rural areas of North East Scotland are by no means unique, being replicated elsewhere in parts of upland Britain (Hudson, 1992). The breadth of motivations amongst volunteers, suggests that coalitions of volunteers can be assembled elsewhere with different aims. Biodiversity interests are widespread, and specific economic interests may provide additional incentives. For example invasive mink in Iceland and Norway have an economic impact on coastal communities relying on common eider down harvesting (Doughty, 1979). There is a large conservation focus on coastal seabirds, also severely threatened by mink (Nordstrom et al., 2003; Ratcliffe et al., 2008); partly due to their importance for ecotourism in Europe. The potential effect of pest-free status on ecotourism is viewed as an economic incentive for rat eradication on New Zealands's largest offshore island (Ogden and Gilbert, 2009). More widely, this project should contribute to overturning the prevailing lack of ambition about managing invasive species in Europe by providing a model for other programs. In the same way mainland islands in New Zealand promoted science-based management for the future protection of mainland areas, an advance from the predominant focus on offshore island pest control (Saunders and Norton, 2001).

The defining factors underpinning the success of the project are strong volunteer involvement, efficient and systematic methods of monitoring and control, an adaptive approach to suit local conditions, the strategic use of topography to minimise recolonisation and an ambitious vision; elements that are applicable to other invasive species and areas. It is a strong testament to what can be achieved when empowering local communities to take a stake in their local biodiversity and thus reason for optimism that the tide of invasion can be rolled back on a large scale where the convergent interest of local communities can be harnessed.

Acknowledgements

We thank Laura Taylor for her contribution at the start of the project, Isla Martin and Rob Raynor from SNH for facilitating long term financial support, the Tubney Charitable Trust, Mammal Trust UK, NERC (NE/E006434/1), CNPA, Dee Spey Isla Deveron salmon fisheries and rivers Trust for funding. We also thank Jonathan Reynolds from GWCT for his guidance at the beginning of the project. Most of all, we thank all volunteers and organisations who have given freely their time for the goal of preserving biodiversity in the Cairngorms and wider North East Scotland. May their work inspire many others to take ownership of their local biodiversity.

References

Aars, J., Lambin, X., Denny, R., Griffin, A.C., 2001. Water vole in the Scottish uplands: distribution patterns of disturbed and pristine populations ahead and behind the American mink invasion front. Animal Conservation 4, 187–194.

Anonymous, 2007. Species Action Framework: Making a Difference for Scotland's Species. Scottish Natural Heritage Redgordon. pp. 81

Barreto, G.R., MacDonald, D.W., 2000. The decline and local extinction of a population of water voles, Arvicola terrestris, in southern England. Zeitschrift Fur Saugetierkunde-International Journal of Mammalian Biology 65, 110–120.

Bates, D., Maechler, M., 2010. lme4: Linear Mixed-effects Models using S4 Classes. <http://CRAN.R-project.org/package=lme4>.

Bell, K., 2003. Assessing the benefits for conservation of volunteer involvement in conservation activities. Science for Conservation 203, 5–56.

Bertolino, S., Genovesi, P., 2003. Spread and attempted eradication of the grey squirrel (*Sciurus carolinensis*) in Italy, and consequences for the red squirrel (*Sciurus vulgaris*) in Eurasia. Biological Conservation 109, 351–358.

Bester, M.N., Bloomer, J.P., van Aarde, R.J., Erasmus, B.H., van Rensburg, P.J.J., Skinner, J.D., Howell, P.G., Naude, T.W., 2002. A review of the successful eradication of feral cats from sub-Antarctic Marion Island, Southern Indian Ocean. South African Journal of Wildlife Research 32, 65–73.

Bomford, M., Obrien, P., 1995. Eradication or control for vertebrate pests. Wildlife Society Bulletin 23, 249–255.

Bonesi, L., Harrington, L.A., Maran, T., Sidorovich, V.E., Macdonald, D.W., 2006. Demography of three populations of American mink *Mustela vison* in Europe. Mammal Review 36, 98–106.

Capreolus Wildlife Consultancy, 2005. The Ecology and Conservation of Water Voles in Upland Habitats. In Scottish Natural Heritage Commissioned Report.

Craik, C., 1997. Long-term effects of North American Mink *Mustela vison* on seabirds in western Scotland. Bird Study 44, 303–309.

Craik, J.C.A., 2008. Sex ratio in catches of American mink – how to catch the females. Journal for Nature Conservation 16, 56–60.

Cromarty, P.L., Broome, K.G., Cox, A., Empson, R.A., Hutchinson, W.M., McFadden, I., 2002. Eradication planning for invasive alien animal species on islands – the approach developed by the New Zealand Department of Conservation. In: Veitch, C.R., Clout, M.N. (Eds.), Turning the Tide: The Eradication of Invasive Species. Invasive Species Specialist Group, Species Survival IUCN, Cambridge, UK, pp. 85–91.

Cruz, F., Carrion, V., Campbell, K.J., Lavoie, C., Donlan, C.J., 2009. Bio-economics of large-scale eradication of feral goats from Santiago Island, Galapagos. Journal of Wildlife Management 73, 191–200.

Davis, M.A., 2009. Invasion Biology. Oxford University Press, Oxford.

Delibes, M., Gaona, P., Ferreras, P., 2001. Effects of an attractive sink leading into maladaptive habitat selection. American Naturalist 158, 277–285.

Donlan, C.J., Tershy, B.R., Campbell, K., Cruz, F., 2003. Research for requiems: the need for more collaborative action in eradication of invasive species. Conservation Biology 17, 1850–1851.

Doughty, R., 1979. Eider husbandry in the North Atlantic: trends and prospects. Polar Record 19, 447–459.

Dunstone, N., 1993. The Mink. Poyser, T., Poyser, A.D., London.

Ebbert, S.E., Byrd, G.V., 2002. Eradications of invasive species to restore natural biological diversity on Alaska Maritime National Wildlife Refuge. In: Veitch, C.R., Clout, M.N. (Eds.), Turning the Tide: The Eradication of Invasive Species. Invasive Species Specialist Group, Species Survival, Cambridge, UK, pp. 102–109.

Epanchin-Niell, R.S., Hufford, M.B., Aslan, C.E., Sexton, J.P., Port, J.D., Waring, R.M., 2010. Controlling invasive species in complex social landscapes. Frontiers in Ecology and the Environment 8, 210–216.

Genovesi, P., 2005. Eradications of invasive alien species in Europe: a review. Biological Invasions 7, 127–133.

Gosling, L.M., Baker, S.J., 1989. The eradication of muskrats and coypus from Britain. Biological Journal of the Linnean Society 38, 39–51.

Hanski, I., 1994. A practical model of metapopulation dynamics. Journal of Animal Ecology 63, 151–162.

Harrington, L.A., Harrington, A.L., Macdonald, D.W., 2008. Estimating the relative abundance of American mink *Mustela vison* on lowland rivers: evaluation and comparison of two techniques. European Journal of Wildlife Research 54, 79–87.

Harrington, L.A., Harrington, A.L., Moorhouse, T., Gelling, M., Bonesi, L., Macdonald, D.W., 2009. American mink control on inland rivers in southern England: an experimental test of a model strategy. Biological Conservation 142, 839–849.

Hudson, P., 1992. Grouse in Space and Time. The Game Conservancy Trust, Fordinbridge.

King, C.M., McDonald, R.M., Martin, R.D., Dennis, T., 2009. Why is eradication of invasive mustelids so difficult? Biological Conservation 142, 806–816.

Lambin, X., Fazey, I., Sansom, J., Dallas, J., Stewart, W., Piertney, S., Palmer, S., Bacon, P., Webb, A., 1998. Aberdeenshire Water Vole Survey: The Distribution of Isolated Water Vole Populations in the Upper Catchments of the Rivers Dee and Don. Scottish Natural Heritage.

Lorvelec, O., Pascal, M., 2005. French attempts to eradicate non-indigenous mammals and their consequences for native biota. Biological Invasions 7, 135–140.

Macdonald, D.W., Harrington, L.A., 2003. The American mink: the triumph and tragedy of adaptation out of context. New Zealand Journal of Zoology 30, 421–441.

Moore, N.P., Roy, S.S., Helyar, A., 2003. Mink (*Mustela vison*) eradication to protect ground-nesting birds in the Western Isles, Scotland, United Kingdom. New Zealand Journal of Zoology 30, 443–452.

Nordstrom, M., Hogmander, J., Laine, J., Nummelin, J., Laanetu, N., Korpimaki, E., 2003. Effects of feral mink removal on seabirds, waders and passerines on small islands in the Baltic Sea. Biological Conservation 109, 359–368.

Ogden, J., Gilbert, J., 2009. Prospects for the eradication of rats from a large inhabited island: community based ecosystem studies on Great Barrier Island, New Zealand. Biological Invasions 11, 1705–1717.

Oliver, M., Luque-Larena, J.J., Lambin, X., 2009. Do rabbits eat voles? Apparent competition, habitat heterogeneity and large-scale coexistence under mink predation. Ecology Letters 12, 1201–1209.

Parkes, J.P., Robley, A., Forsyth, D.M., Choquenot, D., 2006. Adaptive management experiments in vertebrate pest control in New Zealand and Australia. Wildlife Society Bulletin 34, 229–236.

Pretty, J.N., 1995. Participatory learning for sustainable agriculture. World Development 23, 1247–1263.

Ratcliffe, N., Craik, C., Helyar, A., Roy, S., Scott, M., 2008. Modelling the benefits of American Mink *Mustela vison* management options for terns in west Scotland. Ibis 150, 114–121.

Reynolds, J.C., Short, M.J., Leigh, R.J., 2004. Development of population control strategies for mink *Mustela vison*, using floating rafts as monitors and trap sites. Biological Conservation 120, 533–543.

Saffer, V.M., Calver, M.C., 2001. Chemotherapy for ecosystems: use of selective toxins to control invasive vertebrate pests. Ecosystem Health 7, 297–306.

Saunders, A., Norton, D.A., 2001. Ecological restoration at Mainland Islands in New Zealand. Biological Conservation 99, 109–119.

Saunders, G.R., Gentle, M.N., Dickman, C.R., 2010. The impact and management of foxes *Vulpes vulpes* in Australia. Mammal Review 40, 181–211.

Simberloff, D., 2001. Eradication of island invasives: practical actions and results achieved. Trends in Ecology & Evolution 16, 273–274.

Stokes, K.E., O'Neill, K.P., Montgomery, W.I., Dick, J.T.A., Maggs, C.A., McDonald, R.A., 2006. The importance of stakeholder engagement in invasive species management: a cross-jurisdictional perspective in Ireland. Biodiversity and Conservation 15, 2829–2852.

Strachan, R., Jefferies, D.J., 1993. The Water Vole Arvicola Terrestris in Britain 1989–1990: Its Distribution and Changing Status. The Vincent Wildlife Trust, London.

Strachan, C., Strachan, R., Jefferies, D., 2000. Preliminary Report on the Changes in the Water Vole Population of Britain as Shown by the National Survey of 1989–1990 and 1996–1998. The Vincent Wildlife Trust, London.

Tyler, C., Clark, E., Pullin, A.S., 2005. Do management interventions effectively reduce or eradicate populations of the American Mink, *Mustela vison*? Systematic In Review No. 7. Collaboration for Environmental Evidence.

White, G.C., Burnham, K.P., 1999. Program MARK: survival estimation from populations of marked animals. Bird Study 46 (Supplement), 120–138.

WildCRU, O.U., 2004. Water Vole Surveys in Fife and Central Cairngorms. In Scottish Natural Heritage Commissioned Report.

Woodroffe, G.L., Lawton, J.H., Davidson, W.L., 1990. The impact of feral mink *Mustela vison* on water VOLES *Arvicola terrestris* in the North-Yorkshire-Moors-National-Park. Biological Conservation 51, 49–62.

Zalewski, A., Piertney, S.B., Zalewska, H., Lambin, X., 2009. Landscape barriers reduce gene flow in an invasive carnivore: geographical and local genetic structure of American mink in Scotland. Molecular Ecology 18, 1601–1615.

Zuberogoitia, I., Zabala, J., Martinez, J.A., 2006. Evaluation of sign surveys and trappability of American mink: management consequences. Folia Zoologica 55, 257–263.