Invasive mammal species on Corvo Island: is their eradication technically feasible?

Mamíferos exóticos na Ilha do Corvo: é a sua erradicação tecnicamente possível?

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ABSTRACT - The successful eradication of exotic mammals from an island depends on many factors: the number of invasive species, the number of individuals of each species, biogeography and size of the island, and the support of the government authorities and people inhabiting the island. The LIFE project "Safe Island for Seabirds" (2009-2012) attempted to investigate the feasibility of performing an eradication programme of the exotic mammals on Corvo Island. This study presents results of monitoring the black rat *Rattus rattus*, house mouse *Mus domesticus*, cat *Felis catus*, goat *Capra aegagrus hircus*, and sheep *Ovis aries*, carried out during the project. The relative abundance and distribution of rodents, goats and sheep was determined each month, and a sterilisation campaign was developed for cats. Our results showed that the eradication of rodents is technically feasible, and should be attempted in April (when the lowest peak in abundance occurred for both species). For cats, although a higher numbers of feral cats than those estimated for Corvo have been eradicated on other islands, there are several constraints that will have to be overcome - in particular, the limits of legal responsibility for the management of cats. The eradication of goats and sheep could be attempted, but due to the island's steep cliffs it would be very expensive. Education programmes must be carried out to inform the human inhabitants about the problems caused by exotic mammals for endangered species, since currently local government authorities do not see the eradication of invasive species as a political priority.

RESUMO - O sucesso da erradicação de mamíferos exóticos de uma ilha depende de vários fatores: número de espécies invasoras, número de indivíduos de cada espécie, biogeografia e tamanho da ilha, e o apoio das entidades governamentais e dos habitantes. O projeto LIFE "Ilhas Santuário para as Aves Marinhas" (2009-2012) procurou investigar a viabilidade de realizar um programa de erradicação de mamíferos exóticos na Ilha do Corvo. Este estudo apresenta resultados da monitorização do rato-preto *Rattus rattus*, do rato-caseiro *Mus domesticus*, do gato *Felis catus*, da cabra *Capra aegagrus hircus* e da ovelha *Ovis aries* levada a cabo durante o projeto. A abundância relativa e a distribuição de roedores, cabras e ovelhas foram determinadas mensalmente e foi efetuada uma campanha de esterilização dos gatos. Os nossos resultados mostraram que a erradicação de roedores é tecnicamente possível e deveria ocorrer em abril, no pico de menor abundância para as duas espécies. No caso dos gatos, apesar de a

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erradicação dos assilvestrados já ter sido feita noutras ilhas com números superiores aos estimados para o Corvo, existem vários obstáculos que terão que ser ultrapassados, nomeadamente a ausência de responsabilidade legal para a gestão dos gatos. A erradicação de cabras e ovelhas poderia ser conseguida, mas devido às íngremes falésias costeiras seria muito dispendiosa. Programas de educação deveriam ser implementados para informar a população sobre os problemas causados pelos mamíferos exóticos sobre espécies em perigo, uma vez que as atuais autoridades do governo local não consideram a erradicação de espécies invasoras como uma prioridade política.

Exotic mammals, as ecological generalists, have successfully colonized a wide range of habitats on islands and have caused irreversible damage to island biota (Atkinson 1985; Courchamp et al. 2003; Towns et al. 2006; Jones et al. 2008). The impacts of exotic mammals on native ecosystems vary among islands (Clark 1981; Fitzgerald 1988; Yabe et al. 2010) since they are influenced by the presence of other introduced species (Cuthbert 2002; Bonnaud et al. 2010). Eradication is often the preferred strategy for the removal of exotic species on islands (Brooke et al. 2007; Aguirre-Muñoz et al. 2009; Capizzi et al. 2010; Oppel et al. 2011; Veitch et al. 2011). But whether eradication is possible depends on many factors, including the support of the people inhabiting the island, which can be challenging.

The Archipelago of Azores (Portugal) provides nesting habitat for a total of eleven seabird species and some of them are now restricted to a few islets and remote coastal strips (Monteiro et al. 1996). Two of the most important threats for the current seabird populations breeding in the Azores are reduction of suitable breeding habitat due to human activities and predation by introduced mammals (Monteiro et al. 1996), which are probably causing ongoing population declines (Fontaine et al. 2011). Corvo, being the smallest island of the archipelago, it exhibits a well preserved coastal environment, contains a small population (437 inhabitants), and offers the best potential and conditions for seabird recolonization. Corvo still has important seabird colonies, including of many species that are classified as priority by the Annex I of the Birds Directive and as vulnerable by the World Conservation Union (Table 1). With only one village, Corvo has the biggest number and density of Cory's shearwaters *Calonectris diomedea* breeding in the Azores, but also smaller numbers of Little shearwater *Puffinus assimilis*, Manx shearwater *Puffinus puffinus*, Madeiran storm-petrel *Oceanodroma castro*, Roseate tern *Sterna dougallii* and Common tern *Sterna hirundo*. Besides these seabirds, there is also Azorean wood pigeons *Columba palumbus azorica* breeding on the island. As a result, Corvo has the highest percentage of appropriate areas to preserve Azorean avifauna (Rodriguez and Cunha 2012), is biosphere reserve since 2007, and the Nature Park was created the in 2008 under Regional Legislative Decree 44/2008/A, in order to conserve and protect species habitat and natural resources. It also has an Important Bird Area (IBA) which includes the coast in most of the island, two Special Protected Areas (SPAs) and one Site of Community Interest (SIC).

Among all seabird species breeding on Corvo Island, only Cory's shearwater breeds in locations that are accessible to humans and thus amenable to scientific investigations. A recent study about the impacts of exotic mammals on breeding success confirmed that predation by black rats *Rattus rattus* and feral cats *Felis catus* is the main cause of nest failure (Hervías et al. 2012). Predation by exotic mammals is thus a major concern, because adults of larger species, such as Cory's shearwater and Yellow-legged gull *Larus michahellis*, are probably less vulnerable to these predators than all other seabird species for which nidification has been confirmed on Corvo, which are all significantly smaller. As adult survival is likely to have a much stronger influence on population growth rate than nest success (Fontaine et al. 2011), these species are much more vulnerable to both rodent and

Table 1. Breeding seabird species in the nine islands of the Archipelago of Azores and their IUCN Red List Category; LC = Least Concern; VU = Vulnerable; NT = Near Threatened (IUCN 2012).
Tabela 1. *Aves marinhas nidificantes nas nove ilhas do arquipélago dos Açores e seu estatuto de ameaça de acordo com a Lista Vermelha da UICN LC = Pouco preocupante; VU = Vulnerável; NT = Quase ameaçado (IUCN 2012).*

Seabird species	Corvo	Flores	Faial	Pico	São Jorge	Graciosa	Terceira	São Miguel	Santa Maria	IUCN
Bulweria bulwerii						X			X	LC
Calonectris diomedea	X	X	X	X	X	X	X	X	X	LC
Larus michahellis	X	X	X	X	X	X	X	X	X	LC
Oceanodroma castro					X	X			X	LC
Oceanodroma monteiroi						X				VU
Onychoprion fuscatus						X			X	LC
Pterodroma deserta						X				NT
Puffinus assimilis	X	X	X	X	X	X		X	X	LC
Puffinus puffinus	X	X								LC
Sterna dougallii	X	X	X	X	X	X	X	X	X	LC
Sterna hirundo	X	X	X	X	X	X	X	X	X	LC

cat predation than Cory's shearwaters. Breeding colonies of Manx shearwater are restricted to Corvo and Flores islands (Monteiro et al. 1999). Monteiro's storm petrel *Oceanodroma monteiroi*, so far only known from Graciosa, may also breed here (hot season Azores population; Bolton et al. 2008) but evidence of breeding is still lacking.

Given the high conservation interest of seabird species on Corvo, an ambitious European Commission funded LIFE Project (07 NAT/P/000649) entitled "Safe Islands for Seabirds" was carried out from January 2009 to December 2012. This project aimed to create a management plan for the exotic mammals on Corvo, providing a comprehensive basis to assist with decision-making and assess the risks, constraints and preliminary costs of eradication in the whole island.

Here we present the results of monitoring exotic mammals from Corvo Island between 2009 and 2011 and investigate the feasibility of performing an eradication programme of mammalian species. To assess whether eradication is technically feasible, we proceeded in two steps. Firstly, the relative abundance and distribution of rodents, goats and sheep was determined every month and a sterilisation campaign was developed for cats. Specifically, we examined the hypothesis that exotic mammals vary in abundance responding to seasons and habitats, and that times with lowest abundance indices would be most effective for eradication. Secondly, the detected abundance values were compared with those from other islands where eradication was successfully executed to assess whether mammals with abundance ranges similar to those on Corvo have been successfully eradicated from other islands in the past. Finally, a revision of the actions needed to overcome any risks and constraints identified to attempt the eradication of introduced mammals on Corvo, was conducted.

METHODS

» Study area

Corvo (39º 40' N, 31º 7' W), an island of volcanic origin, has an area of 1700 ha - most of which is surrounded by steep cliffs >200 m in height (maximum elevation is 718 m). The island was inhabited in approximately 1558 (Chagas 1645-1650) (Fig. 1). The invasion of exotic mammal

species occurred in the 15th century, facilitated by Portuguese settlers (Le Grand 1983; Monteiro et al. 1996). Of a total of ten terrestrial mammals introduced in the Azorean Archipelago, Corvo has five species that exist with feral populations (Table 2). They belong to three different taxonomic orders: Rodentia (black rat and house mouse *Mus domesticus*), Carnivora (feral cat) and Artiodactyla (goat *Capra aegagrus hircus* and sheep *Ovis aries*). On Corvo, one amphibian species, the Iberian water frog *Rana perezi* and one reptile species, the Madeiran lizard *Lacerta dugesii*, were also introduced. There are no native species of reptile, and only two native mammalian species are present on Corvo, the endemic Azorean *bat Nyctalus azoreum* and one *Pipistrellus* sp. bat. The native vegetation cover was almost exterminated (>90%) during the colonization process and, today, it is restricted to a few areas on the cliffs. Most areas were converted to agricultural fields and some others were forested with introduced plants (60%), mainly the African tamarisk *Tamarix africana,* Sweet pittosporum *Pittosporum undulatum* and Hydrangea *Hydrangea microphylla*. The remaining species (40%) are native to the Azores, *Erica azorica*, *Juniperus brevifolia*, *Picconia azorica*, *Morella faya*, *Laurus azorica*, *Vaccinium cylindraceum* and *Viburnum tinus*, and they are threatened through invasion of their habitats by non-native species and grazing by goats, sheep and cows.

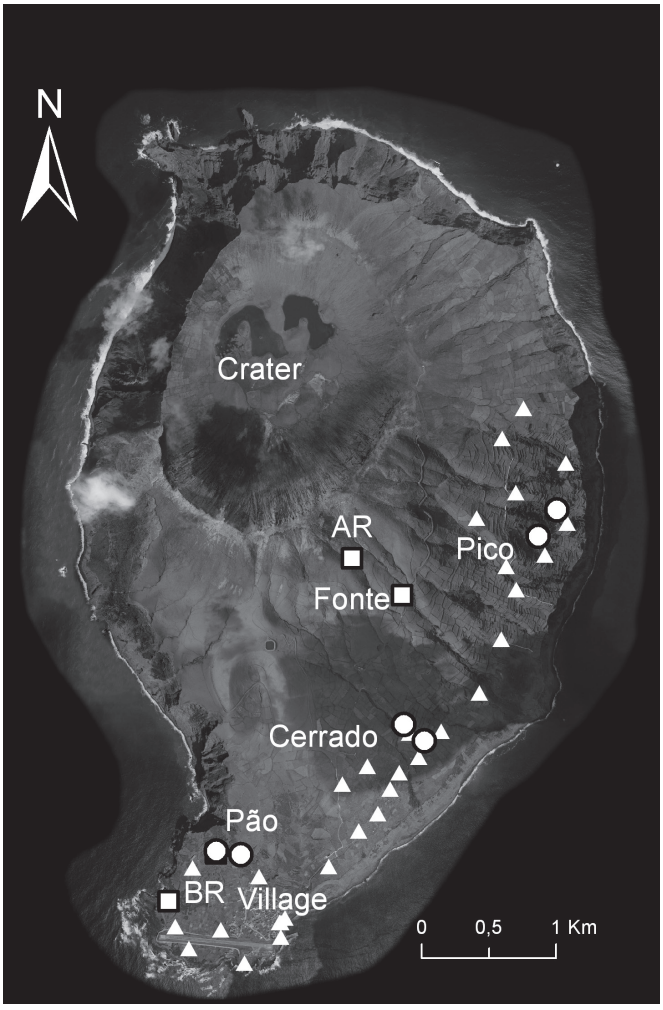

Figure 1. Spatial distribution of sampling areas for rodents (in white) at two different altitudes (squares) and in three different habitats (circles) and trapping areas for feral cats (triangles).

Figura 1. *Distribuição espacial das áreas amostradas para roedores (a branco) a duas altitudes diferentes (quadrados) e três habitats (círculos), e das áreas de captura de gatos assilvestrados (triângulos).*

Table 2. Occurrence of exotic mammalian species in the nine islands of the Archipelago of Azores.
Tabela 2. *Espécies exóticas de mamíferos presentes nas nove ilhas do arquipélago dos Açores.*

Exotic species	Corvo	Flores	Faial	Pico	São Jorge	Graciosa	Terceira	São Miguel	Santa Maria
Capra aegagrus hircus	X	X	X	X	X	X	X	X	X
Erinaceus europaeus			X				X	X	X
Felis catus	X	X	X	X	X	X	X	X	X
Mus domesticus	X	X	X	X	X	X	X	X	X
Mustela furo		X	X	X	X		X	X	X
Mustela nivalis			X				X	X	
Oryctolagus cuniculus		X	X	X	X	X	X	X	X
Ovis aries	X	X	X	X	X	X	X	X	X
Rattus norvegicus		X	X	X	X	X	X	X	X
Rattus rattus	X	X	X	X	X	X	X	X	X

» Monitoring the exotic mammalian species

Rodents

The accidental introduction of rodents was referred since the human colonisation in 1558 (Fructuoso 1591; Chagas 1645-1650; Cordeiro 1717). During the present study we identified the presence of two rodent species on Corvo, the black rat and house mouse.

The abundance index of rodents was assessed by live-traps on trapping grids for two years (2010 – 2012). During the first year, we aimed to assess differences in abundance between altitudes and identify temporal peaks in abundance. From March 2010 to February 2011, four areas were surveyed up to 10 times each (except in July and December because we were not on the island) once per month to identify abundance peaks throughout the year at two different altitudes: two grids < 250 m above sea level (asl), the Biological Reserve (BR), which is a predator proof enclosure area created by the LIFE project, and *Pão de Açúcar* (*Pão*), and two grids > 400 m asl, *Fonte da Lomba da Rosada* (*Fonte*) and the Altitude Reserve (AR), an area used by the LIFE project to restore native vegetation (Fig. 1). The trapping grids were 70 x 70 m and contained a total of 49 traps at 10 m spacing. The 49 traps were divided into 25 Sherman traps (for black rat and house mouse) and 24 Pest-stop traps (for house mouse only), which were alternated with each other throughout the grid.

During the second year, we established different study plots at similar elevation to examine differences among habitats. From September 2011 - March 2012 (5 monthly surveys, we were not able to survey the grids in October and February) we surveyed the three different habitats of Corvo: wooded riverbank in *Pico João de Moura* (*Pico*), pasture grassland in the *Cerrado das Vacas* (*Cerrado*) and urbane land in *Pão* (Fig. 1). Two 30 x 30 m grids each with 16 Sherman traps and 16 Pest-stop spaced 10 m apart were established in each habitat. Grids were 200 m apart within each habitat.

Traps were baited with peanut butter and operated for four nights each month. All captured individuals were marked. Because marks made by cutting the ear or hair were difficult to find in recaptures (most individuals had bitten ears and wet hair), animals were marked cutting a combination of a small part of their fingers. After handling, all individuals were released in their capture locations.

To compare rodent activity over time and between habitats we used an abundance index for house mice and black rats that was calculated using the number of individuals caught during each trapping session (4 nights) (Ruscoe et al. 2001). The number

of individuals for each species was divided by the total number of trap-nights, corrected for traps that were sprung and thus unavailable, and expressed as the number of individuals captured per 100 trap nights (ind/100TN) (Cunningham & Moors 1993). For each month, we report the average trapping index and standard deviation for all grids that were in the same habitat type or at the same elevation.

Because our goal was to assess whether eradication was feasible, we also estimated rodent abundance using mark-recapture techniques (Otis et al. 1978; Ruscoe et al. 2001). We used our monthly trapping sessions as primary occasions, and each trapping night as secondary occasion in a robust design approach to estimate rodent population size for each month (Pollock 1982; Kendall et al. 1995). We accounted for individual heterogeneity in capture probability (Krebs et al. 1994; Conn et al. 2006), and evaluated models that varied capture probabilities over time and between habitats. We fitted models using Program MARK (White & Burnham 1999) via the RMark library (Laake & Rexstad 2008) in R 2.13.1 (R Development Core Team 2010) using the 'RDHet' model type. We selected the most parsimonious re-capture model structure using AIC, and present abundance estimates and 95% confidence intervals for each month from the most parsimonious model.

Cats

Cats were introduced on Corvo after 1717 (Cordeiro 1717), and once they were intentionally released to control rodent populations in pasture lands they became feral. On Corvo there are domestic, stray (cats fed by humans) and feral cats, but here we use the term 'feral' to refer to both populations, stray and feral ones.

The number of feral cats on Corvo was estimated at 163 individuals in 2011 using camera traps and spatially explicit capture-recapture models (Oppel et al. 2012). Here, we determined the trapping rate of feral cats to assess the amount of effort that would be required in a future eradication of cats on Corvo. Moreover, we developed a sterilisation programme of domestic cats to assess their number, and thus to evaluate the participation of cat owners to prevent the re-establishment of a feral cat population after their potential eradication.

In 2010, cat owners were individually contacted by house visits in a public awareness campaign. Domestic cats were micro-chipped and neutered with their owners' permission. This sterilisation programme was supported by the LIFE project and the local veterinarian, and was free of charge for owners. The acceptance rate of this sterilisation scheme was 90%, leading to the sterilisation of many domestic cats in 2010.

To assess the effort required for feral cat trapping, traps were deployed in areas known to be frequented by cats. From a previous study to assess their diet on Corvo, we knew that cats explored all habitats (*unpublished data*), and that higher densities were observed in the lower areas of the island (Oppel et al. 2012). Feral cats were captured using two Eezicatch and four Eeziset traps each night, in 56 trapping nights from February to August 2010. Traps were baited with fish after sunrise and then checked early in the morning. At the veterinary clinic, captured individuals were anesthetized, neutered and marked by cutting ¼ inch of their left ear. Once the cats had regained consciousness they were released in their captured locations.

Goats and sheep

Goats and sheep were introduced on Corvo along with the first inhabitants, to serve as a food resource (Fructuoso 1591). Wool production was an important activity until the 1960's, when meat production using bovines increased in popularity, and goats and sheep were restricted to inaccessible areas (coastline cliffs) of the island where they have established feral populations. Because their restricted distribution, transects by boat were conducted monthly along the coast of the island from September 2009 to August 2010, to estimate their number. During each survey, the entire island was circumnavigated and the cliffs were scanned with 10 x 40 binoculars to detect any goats and sheep. The number of all sheep and goats observed during a survey were summed to estimate an index of abundance for these species on the island of Corvo.

In addition, in November 2010 we conducted interviews with local farmers (n = 40) in order to ascertain the distribution and number of goats and sheep in the interior area of the island.

RESULTS

» Rodents

A total of 691 house mice and 44 ship rats were captured. Rodent abundance varied substantially over time, and was generally lower at higher elevation (Fig. 2). In the first year of monitoring, the highest abundance indices of house mice (13.5 ± 9.7 ind/100TN) and black rats (4.1 ± 5.8) were reached in November 2010 (Fig. 2). The lowest index of house mouse occurred from April to June 2010 (3.1 ± 0.7) and we did not capture any black rat in April and October 2010 and in January and February 2011.

Due to the low number of captures and recaptures of rats we were not able to estimate their abundance. The abundance estimation of house mice was limited to a grid at lower elevation, because few mice were captured and recaptured at the higher elevation site (Fig. 2). The temporal fluctuation in estimated abundance resembled the temporal fluctuation in the trapping index. The most parsimonious abundance model included a mixture component for capture probability that indicated heterogeneity in capture probability between 0.85 (95% CI: 0.21 - 0.99) for 5% of individuals and 0.28 (0.21 - 0.37) for the remaining individuals. Mouse abundance estimation for the grid covering approximately 0,5 ha ranged from 9 (7 - 17) individuals in May and June 2010 to 52 (45 - 66) individuals in November 2010 (Fig. 3).

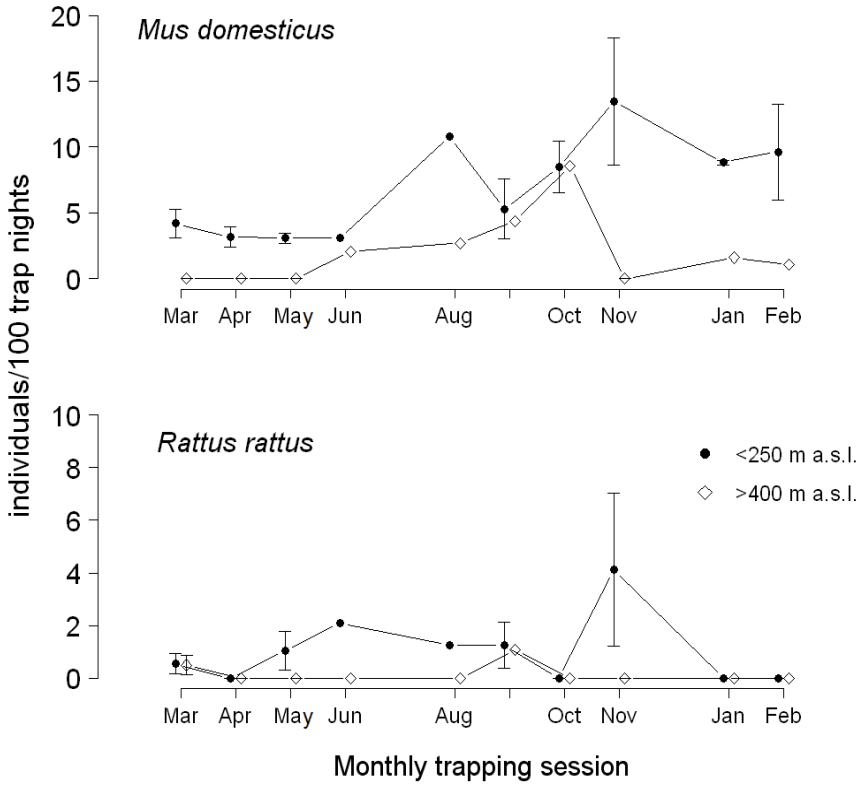

Figure 2. Mean trapping index (individuals captured per 100 trap nights) of house mouse *Mus domesticus* and black rat *Rattus rattus* captured on four grids in pasture grassland at two different altitudes from March 2010 to February 2011, on Corvo Island. Error bars represent standard deviation of mean trapping index across the two grids at each elevation and lack of error bars indicates that only one grid was operated in a given month.

Figura 2. *Índice médio de captura (indivíduos capturados por 100 noites de armadilhagem), de rato-caseiro* Mus domesticus *e rato-preto* Rattus rattus*, obtido em 4 grelhas com pastagem a duas altitudes diferentes de março a fevereiro de 2011, na Ilha do Corvo. As barras de erro representam o desvio padrão do índice médio de captura nas duas grelhas a diferentes altitudes e a ausência de barras de erro indica que foi amostrada uma única grelha nesse mês.*

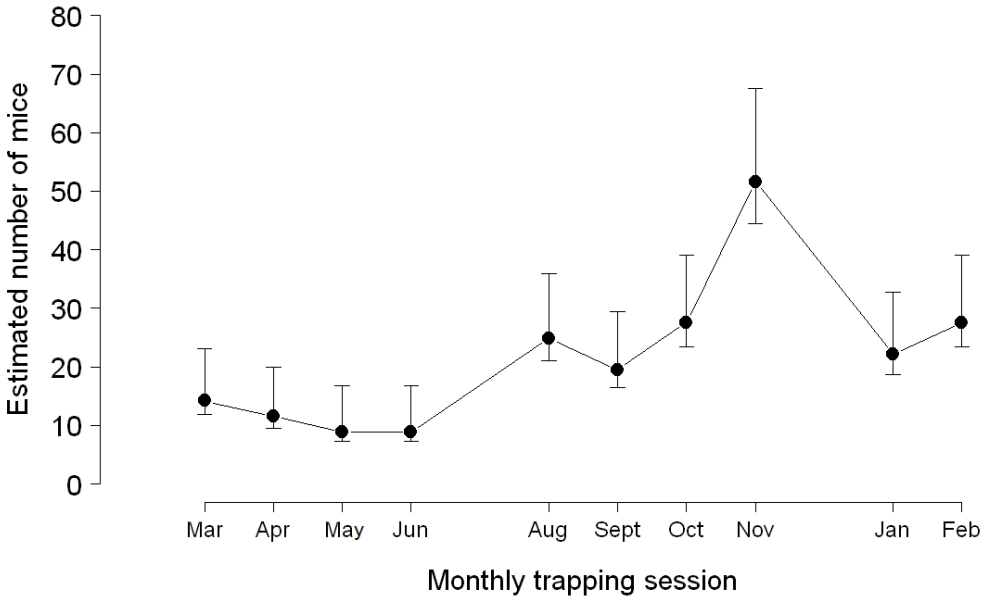

Figure 3. Estimated abundance (± 95% confidence intervals) of house mouse *Mus domesticus* in 0.5 ha of pasture grassland between March 2010 and February 2011 on Corvo Island.
Figura 3. *Abundância de rato-caseiro* Mus domesticus *(± 95% intervalo de confiança) estimada em 0,5 ha de pastagem, desde março de 2010 a fevereiro de 2011 na Ilha do Corvo.*

The comparison among habitats indicated similar temporal trajectories across the three studied habitats, but with lower amplitude in wooded riverbanks (range 12.3 - 16.8 ind./100TN) than in pasture grassland (range 6.3 - 22.8, Fig. 4). The highest abundance index of house mouse (22.8 ± 3.7) was obtained in pasture grassland in November 2011, and the lowest index occurred in urban land (5.2 ± 2.5) in March 2012. The most parsimonious abundance model included temporally varying capture probability that ranged from 0.14 (95% CI: 0.10 - 0.19) in September 2011 to 0.30 (0.23 - 0.38) in March 2012. Mouse abundance estimation for two grids covering approximately 0,4 ha ranged from 105 (86 - 137) individuals in pasture grassland in November 2011 to 17 (14 - 23) individuals in urban land in March 2012 (Fig. 5).

The highest abundance index of black rat was in wooded riverbank (11.4 ± 6.7 ind./100TN) in September 2011, but we did not capture any black rat in this habitat in December 2011 and January 2012, or in pasture grassland in November 2011, January, and March 2012 (Fig. 4).

» Cats

Feral cats were present in all studied habitats. During 336 trap nights, a total of 60 feral cats were captured, and only 4 of them were recaptured, leading to a total capture success rate of 0.08 cats per trap night. No domestic cats were captured in cat traps.

A total of 113 domestic cats were identified during the house visits. Of these domestic cats, the local veterinarian had already neutered 19% and most of them were micro-chipped. During our project an additional 51% were neutered and tagged between January and August 2010. Less than 10% of the owners (but owning 30% of total domestic cats) did not approve of sterilisation and a small minority did not approve that their cats be equipped with a microchip.

» Goats and sheep

The maximum number of 92 sheep was counted in January 2010, but other surveys had often substantially lower numbers (range 4 - 45), indicating that even the maximum count may have

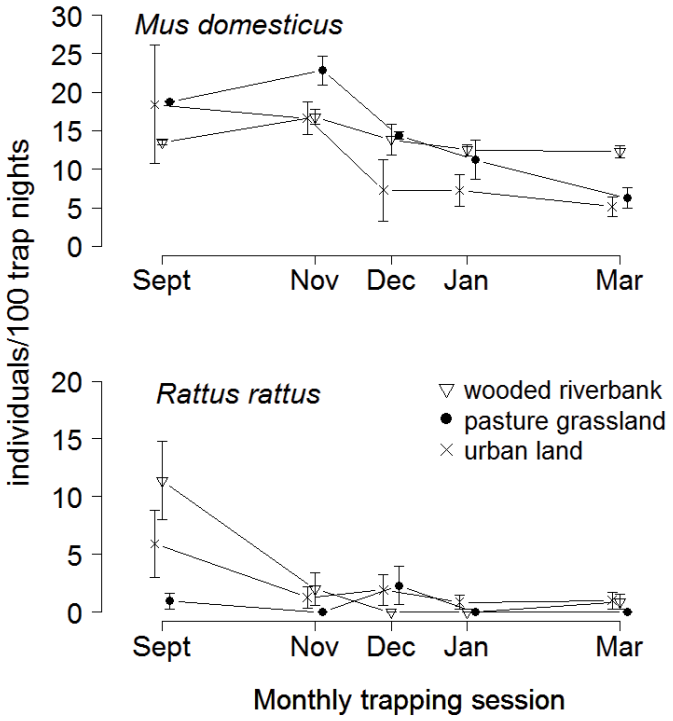

Figure 4. Mean trapping index (individuals captured per 100 trap nights) of House mouse *Mus domesticus* and Black rat *Rattus rattus* in three different habitats: wooded riverbank, pasture grassland and urban land between September 2011 and March 2012 on Corvo Island. Error bars represent standard deviation of mean trapping index across two grids in each habitat.

Figura 4. *Índice médio de captura (indivíduos capturados por 100 noites de armadilhagem) de rato-caseiro* Mus domesticus *e rato-preto* Rattus rattus *em três habitats diferentes: ribeira arborizada, pastagem e urbano, de setembro de 2011 a março de 2012 na Ilha do Corvo. As barras de erro representam o desvio padrão do índice médio de captura nas duas grelhas de cada habitat.*

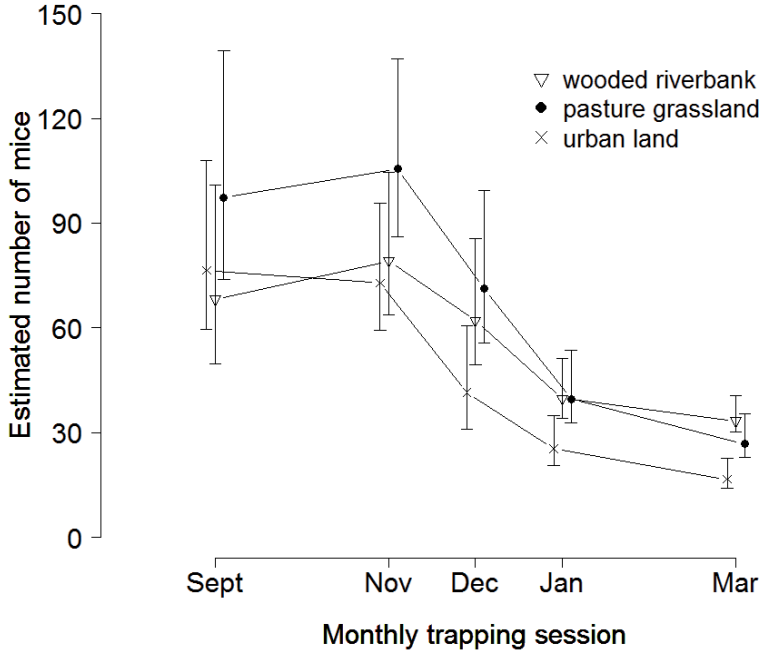

Figure 5. Estimated abundance (± 95% confidence intervals) of House mouse *Mus domesticus* in three different habitats: wooded riverbank, pasture grassland and urban land between September 2011 and March 2012 on Corvo Island. In each habitat, 2 grids were sampled that together encompassed an area of approximately 0.4 ha.

Figura 5. *Abundância de rato-caseiro* Mus domesticus *(± 95% intervalo de confiança) estimada em três habitats diferentes: ribeira arborizada, pastagem e urbano, de setembro de 2011 a março de 2012 na Ilha do Corvo. Em cada habitat foram amostradas duas grelhas, abrangendo no total uma área aproximada de 0,4 ha.*

missed some individuals. Likewise, the maximum count of goats was 93 in August 2010, and other surveys also did not detect substantial proportions of goats (range 25 – 90). Both sheep (65%) and goats (64%) were mainly distributed on the west side of the island.

Livestock data from farmers (50 – 100 sheep along the cliffs) matched the number obtained in our surveys. The number of goats and sheep observed in the interior part of the island varied between one to seven individuals, and they were mainly in the southwestern area.

DISCUSSION

» Is invasive mammal eradication justified and feasible?

Rodents

Based on our results, the eradication of rodents on Corvo should be attempted in April when the lowest peak in abundance occurred for both species. We found only minor differences in abundance indices or estimated abundance between different habitats, suggesting that equally high effort would be required in all habitats. However, the lower amplitude of temporal mouse abundance fluctuations in wooded riverbank habitat suggests that either food is more consistently available (e.g. trees bearing fruit throughout the year), or that sufficient shelter protects mouse populations from severe weather. Therefore wooded riverbanks on Corvo may require the most ground-based effort during a rodent eradication. We captured pregnant or lactating female mice in all sampled months, thus suggesting that mice breed all year around on Corvo, and that would also complicate a successful eradication.

Black rats with higher abundance index than on Corvo have been eradicated from a variation of island size, e.g. Buck Island with 59.3 ind./100TN (Witmer et al. 2007) and Bird Island with 141 ind./100TN (Merton et al. 2002). However, the design of our trapping grids may have been too small to be comparable to trapping indices from other studies. Our trapping grids were only 70 x 70 m in size, and may have therefore harboured only 1 – 3 rat home ranges, thus limiting the number of rats available for capture. The low abundance indices of black rats reported in this study must therefore be interpreted with caution; nonetheless, if the density of black rats on Corvo exceeded the density of rats on other inhabited islands from where these species were successfully eradicated (e.g. Great Barrier Island Ogden & Gilbert 2009), we would have expected much higher densities even in our very small trapping grid. Thus, we cautiously conclude that rat eradication is likely to be technically feasible.

Mice are harder than rats to eradicate from islands because of their movement behaviour and small home range sizes (MacKay et al. 2011), dietary neophobia, reduced access to bait where rats co-occur, and toxin resistance (Howald et al. 2007). House mice can reach higher densities (Howald et al. 2007) and successes and failures of mouse removal have occurred across the full range of island sizes and some eradications required more than one attempt (MacKay et al. 2007). In the Macaronesian islands, the only successful eradication of house mice was in the Selvagens Islands (200 ha) (Oliveira et al. 2008).Therefore, house mouse eradications require more meticulous planning than rat eradications (Martins et al. 2006). Factors such as bait application method, toxicant (first or second generation anticoagulant), and the presence of other introduced mammals should be taken into account for eradication attempts of both black rat and house mouse. Nevertheless, gaps in poison coverage (Micol & Jouventin 2002), low attractiveness of bait resulting in non-consumption despite encounter (Humphries et al. 2000), or resistance to the toxin used (Billing 2000) are more common reason for eradication failure of mice. MacKay et al. (2011) collected information about the population and individual behaviour of mice prior to their successful eradication from Saddle Island (New Zealand).

Our study indicated substantial fluctuations in house mouse abundance over the course of our study, and individual heterogeneity in the probability of capture. Such heterogeneity is well known in mice (Krebs et al. 1994), and would complicate any eradication, because for eradication to succeed every single individual must be removed regardless of its probability to enter a trap or consume bait. In order to increase the likelihood of success for house mouse and black rat eradication on Corvo,

hand-spreading bait in conjunction with aerial drop and the use of at least two different toxins should be taken into consideration in the operational plan. Most people on Corvo are supportive of a rodent eradication campaign and recognise the potential advantages of a rodent-free status to the island's economy. Rodent populations on Corvo have been controlled for decades, using Difenacoum since 2006 (average of 500 kg per year). Because individuals could become resistant to certain toxins previously used on Corvo, the efficacy of different toxins should be tested before the bait for eradication of house mouse and black rat is chosen.

Black rats have higher impact on seabird population than brown rat *Rattus norvegicus* and Pacific rat *Rattus exulans* and prey mainly on burrow-nesting species (Jones et al. 2008). On three of the Macaronesian archipelagos (the Azores, Madeira and the Canaries), rodents mainly affect seabird species, although their effects have been observed as well on terrestrial bird and plant species in Madeira (Oliveira 2008) and the Canaries (Nogales et al. 2006; Traveset et al. 2009). On Corvo, eggs and chicks of Cory's shearwaters are relatively important in the diet of Black rat and House mouse (*unpublished data*). Rats have some impact on Cory's shearwater breeding success on Corvo (Hervías et al. 2012), on several islands in the Mediterranean (Lavezzi Island, Thibault 1995; Chafarinas Island, Igual et al. 2006) and in the Atlantic Ocean (Berlenga Island, Granadeiro 1991). All other seabird species breeding on Corvo are smaller than Cory's shearwater, breed in burrows and are likely vulnerable to both rats and mice; especially the two smallest seabirds, little shearwater and Madeiran storm petrel. When food resources are scarce for rodents, black rats can prey on these burrowing seabird species at all life stages (Jones et al. 2008). For these reasons, measures to control the population of rodents on this island is justified and could generate benefits for the entire island biodiversity including native plants (Meyer & Butaud 2009), mammals (Harris 2009), birds (Towns 2009) and invertebrates (Angel et al. 2009).

Cats

Cats were distributed among all habitats we studied on Corvo, which is in agreement with their generalist and opportunist trophic behaviour (Fitzgerald & Karl 1979; Liberg 1980; Natoli 1985; Barratt 1997; Alterio et al. 1998; Edwards et al. 2002), and has also been observed in the Canaries where a study on habitat use was conducted (Medina & Nogales 2007). On Corvo, as well as many other insular environments successfully colonized by cats (Van Aarde & Skinner 1981), they occupy the top of the terrestrial food chain. Feral cat eradications have succeeded on 83 islands in all oceans (Campbell et al. 2011). On the Canary Islands, two successful feral cat eradications have been carried out in two small non-permanently inhabited islets (Alegranza 10.2 km^2, and Lobos 4.4 km^2) where some important seabird colonies have been seriously affected by this predator (Ardura & Calabuig 1993; Rodríguez Luengo & Calabuig 1993; Martín et al. 2002a; Martín et al. 2002b). The biggest island where cat eradication has been successful is Marion Island, with a surface area of 290 km^2 (Campbell et al. 2011), and feral cats have also been eradicated from islands permanently inhabited by >300 people (Ratcliffe et al. 2010). Higher numbers of feral cats than those estimated in April 2011 for Corvo (range 123 - 228 individuals, Oppel et al. 2012) have been eradicated on other islands (e.g. Ascension, Macquarie, Marion, and Great Dog; Nogales et al. 2004; Ratcliffe et al. 2010). Judging from previous accomplishments, we suggest that a successful eradication of feral cats from Corvo Island (17 km^2 and 400 citizens) is technically feasible. However, domestic cats are currently not being sterilised and releases of unwanted kittens from domestic cats are not being prevented; therefore, the eradication of feral cats on Corvo is currently not feasible due to the almost certain re-establishment of a feral population from unwanted domestic progeny. Moreover, we found that some human cat lovers provide an excess of food around the village for feral cats. We did not find opposition to reduce the number of feral cats through sterilisation, but a few owners controlling 30% of domestic cats did not support the sterilisation of their cats.

Cats are generalist predators whose impacts have been reported in 120 different islands and on 175 vertebrates (Medina et al. 2011). In Macaronesia, particularly in the Canary Islands, cats prey on 68 species; of these, three giant lizards, three land-birds and two seabirds are threatened either

globally or locally (Medina & Nogales 2009). On Corvo, cats prey upon several native Passeriformes (*unpublished data*) and accounted for an average of 80% of Cory's shearwater nest failures from 2009 to 2011 (Hervías et al. 2012). We were unable to monitor breeding success of other seabird species than Cory's shearwater because of their inaccessible nests; however during our project we found three recently fledged little shearwaters with incisor-marks of predation, which suggests that these species may currently be threatened by cats or restricted to breeding areas that are inaccessible to cats. For these reasons, the control of domestic cats and the eradication of feral populations are biologically justified.

We believe that eradication of feral cats would only be feasible after public education campaigns, as well as the establishment and enforcement of policies against feeding feral cats. Unfortunately, the main constraints we found are the lack of responsibility and political will by authorities to pass or enforce any legislation relating to cats, which renders a successful eradication highly unlikely at this time. As a first step, Corvo would need a veterinarian to record and sterilise all domestic cats and to keep an updated record of all domestic cats on the island.

Goats and sheep

Successful eradication programmes have been performed on different types of islands, ranging from 1 to > 100,000 ha (Campbell & Donlan 2005), with a high number of goats removed (> 40,000 on Pinta Island, Galápagos) (Campbell et al. 2004). So, in the case of goats and sheep on Corvo Island, where a total of 246 animals were counted, their eradication could be attempted, although due to the rough terrain conditions and the steep cliffs it can prove to be very expensive and may require aerial support to hunt and shoot remaining goats hiding in inaccessible places. Although goats and sheep are not of high economic importance for the island, some people enjoy shooting and eating these animals and may be opposed to eradication.

These herbivorous species affect not only endemic plants by predation and, consequently, their associated invertebrate fauna (Desender et al. 1999), they also destroy habitat for endemic and endangered seabird species such as Zino's petrel *Pterodroma madeira*, Fea's petrel *Pterodroma feae*, Cory's shearwater, Bulwer's petrels *Bulweria bulwerii* and Madeiran storm petrel (Oliveira 2008). For some of these reasons, goats were eradicated from Desertas Islands (Oliveira 2008). Therefore, although assessment of the impacts of goats and sheep on native species has not yet been attempted on Corvo, their pernicious effects on native and endangered plant species have been mentioned from other Macaronesian islands (Nogales et al. 2006).

» What actions are needed to overcome risks and constraints and to attempt mammal eradication on Corvo?

Our study of exotic mammals suggests that, according to the small size of the island and the densities of exotic species, their eradication should be technically feasible (Courchamp et al. 2003; Genovesi 2005). However, there are socio-political factors impeding the success of eradication attempts. There are at least three constraints to perform an effective eradication (Myers et al. 2000; Simberloff 2001): (1) Socio-political factors. Community opposition (Genovesi 2005) or releases of new exotic individuals from captive populations (Bomford & O'Brien 1995) are obstacles to eradication and will need to be solved before attempting an eradication. Any eradication on Corvo would be complicated by an inadequate legal basis, as regional laws do not regulate exotic species nor mitigate their impacts. The airport and harbor would need bio-security measures legally enforced to guarantee a successful implementation and therefore prevent new introductions (Oppel et al. 2011). Moreover, there are no measures to prevent immigrations and releases of new exotic individuals from existing captive populations. Education programmes must be carried out to inform the human inhabitants about the problems caused by exotic mammals for endangered species. On Corvo, good success has been achieved with the younger generation, but the older ones that makes up the majority of local government authorities, currently do not see the eradication of invasive species as a political priority. (2) Protection of non-target species will need to be implemented: Several native birds are likely to be at risk directly by eating

poison bait if an open distribution was chosen for eradication. Azores wood pigeon, common chaffinch *Fringilla coelebs*, Atlantic canary *Serinus canaria*, blackbird *Turdus merula azorica*, common starling *Sturnus vulgaris granti* and yellow-legged gull. No other significant risks to non-target wild species have currently been identified. Among domestic animals, cows are the most significant non-target animals, because they occupy all parts of the island except cliffs, and are of economic importance to the inhabitants. Minimising accidental consumption of bait by cows is the greatest logistical challenge for a full rodent eradication on Corvo. The use of carefully selected methods for each exotic species (trapping, poisoning and shooting), along with some mitigations measures (antidotes, restricted areas for baiting and temporary captive populations), should be sufficient to avoid irreversible effects on non-target species. (3) Food availability: The attempt to eradicate black rat, house mouse and cats from Corvo Island could be a difficult task, unless food availability in the village, around livestock farms and in the uncontrolled dump place could be reduced to zero. The year-round availability of alternative food for exotic mammals could potentially lead to poor acceptance rates of poison bait among rodents and thus reduce the likelihood of success of a rodent eradication campaign.

Finally, the remoteness and usually bad weather condition is an unmanageable constraint on Corvo. An island which is generally windy with a high incidence of fog and rain, which may cause logistical complications in an eradication campaign that relies on an aerial spread of poison bait.

CONCLUSION

From the results obtained in this study we can conclude that the eradication of all exotic mammalian species from Corvo is technically feasible. However, especially for rodents, goats and sheep, sufficient information should be gathered prior to eradication to ensure an operational implementation that maximises the chances of success. There are also several constraints that will have to be overcome, mainly the limits of legal responsibility of authorities for management of exotic species, the risks of reinvasion and the accidental consumption of bait by cows which are very high and difficult to manage.

In the case of eradication, we strongly recommend community involvement in meeting and project-implementation activities and community consultation as being essential to generate support. Inhabitants should be actively involved in the implementation phase of the project and an expert should train some local community members in eradication methodologies.

Because unexpected and undesired secondary effects are, in general, more likely to occur when ecosystems contain more than one invasive species, the alternatives to eradication should be taken into account. For example, the removal of cats can increase the impact of rodents on seabirds. The eradication of rodents alone could lead to prey-switching in feral cats and thus seriously affect alternative cat prey such as seabirds (Dumont et al. 2010; Hervías et al. 2012). Furthermore the removal of herbivorous species such as goats and sheep can lead to the invasion of exotic plants that, in the absence of browsing, are more competitive than native plants, leading to an explosion of such weeds (Zavaleta et al. 2001). A large-scale and well-planned eradication campaign of all exotic mammals simultaneously would avoid such complications, but will require years of preparation to garner community support (Ogden & Gilbert 2009; Oppel et al. 2011).

Acknowledgments: This work was included in project LIFE07 NAT/P/000649 'Safe Islands for Seabirds', funded by the European Commission. It was coordinated by the Portuguese Society for the Study of Birds in partnership with the Royal Society for the Protection of Birds, the Regional Secretary of the Environment and the Sea and Corvo Municipal Council. A. Díez, J. Benedicto, J. García, J. Katzenberger, J. Landschoff, J. Roma, K. Cunningham, K. Puttick, P. Domingos, S. Monforte and V. Piacentini helped with fieldwork. J. Ramos, M. Nogales, P. Oliveira, D. Menezes and J. Bried provided stimulating discussions on the design and analysis.

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