Ecological restoration of Socorro Island, Revillagigedo Archipelago, Mexico: the eradication of feral sheep and cats

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Abstract Socorro Island is part of the Revillagigedo National Park, Mexico. At 132 km^2, it is the Mexican island with the highest level of endemism. It provides habitat for 117 vascular plant species, 26% of which are endemic. There is also an endemic blue lizard (*Urosaurus auriculatus*) and eight endemic terrestrial birds. Socorro's ecosystem had been heavily degraded by invasive mammals for the past 140 years. Feral sheep (*Ovis aries*) destroyed one third of the island's habitat and feral cats (*Felis catus*) severely impacted the island's avifauna and the Socorro blue lizard. Together, feral sheep and cats are responsible for the extinction in the wild of the Socorro dove (*Zenaida graysoni*) and the Socorro elf owl (*Micrathene whitneyi graysoni*) and have been a serious threat to other vulnerable species, particularly Townsend's shearwater (*Puffinus auricularis*). As such, the island's restoration is a high priority. We conducted a feral sheep eradication from 2009 to 2012, using aerial and terrestrial methods, aided by Judas sheep and trained dogs, to kill 1,762 animals. The vegetation recovery has been remarkable, as well as the improvement of soil properties such as compaction, nitrogen, organic carbon, phosphorus, and calcium. In 2011, we initiated a feral cat control programme, which soon became an eradication project. The ongoing feral cat eradication has been a challenge, due to Socorro's large size, vegetation and topographical complexity. By December 2016, 502 cats had been dispatched, using soft leg-hold traps equipped with telemetry transmitters and lethal traps: a total effort of 50,000 trap-nights. Cat abundance has decreased very significantly and catch per unit of effort indicates that the eradication is nearing completion. The abundance of the Socorro blue lizard and terrestrial birds has already increased. We estimate completing the feral cat eradication by the end of 2017, when we will shift to a verification of eradication phase.

Keywords: exotic mammals, habitat recovery, outcomes of eradications

INTRODUCTION

Mexican islands are known for their high biodiversity richness. They are home to many endemic species and are important breeding grounds for a variety of birds and marine mammals (Aguirre-Muñoz, et al., 2011). Unfortunately, these ecosystems are suffering serious impacts resulting from human activity. Exotic species are among the main causes of biodiversity loss and ecological disequilibrium in many environments (Courchamp, et al., 2003). Herbivores, like feral sheep (*Ovis aries*), have caused serious ecological impacts on insular ecosystems. In 1869, 100 sheep were introduced to Socorro Island, in Revillagigedo National Park, Mexico (Fig. 1) for ranching. Over time, they became feral, successfully adapting to island conditions (Levin & Moran, 1989; Álvarez-Cárdenas, et al., 1994; Brattstrom, 2015). In the absence of natural predators, the sheep population grew to be about 5,000 individuals by 1960 (Villa, 1960). This reduced to around 2,000 in 1988 as a result of increased hunting by the Mexican Navy (Walter & Levin, 2008), but they became the main cause of the island's poor ecological condition (Richards & Brattstrom, 1959; Veitch, 1989). Since their introduction, feral sheep have caused huge modifications to the natural habitat. Erosion rates and loss of vegetation caused by the presence of sheep were documented, along the southern-central region of the island (León de la Luz, et al., 1994; Maya-Delgado, et al., 1994; Rhea, 2000). Nearly 30% of the original soil and vegetation on Socorro Island was lost due to erosion caused by feral sheep (Ortega-Rubio, et al., 1992). Among the most significant changes to the original floral composition has been an increase in the presence of grasses and shrub species, as well as a reduction in the area covered by native flora. Sheep aid the propagation of introduced plant species, dispersing seeds in their coat and excrement. The change in native vegetation has been observed in every habitat that sheep occupied (SEMARNAT, 2004). Another serious threat is the feral cat (*Felis catus*), which have severely impacted the island's bird communities and the endemic Socorro tree lizard (*Urosaurus auriculatus*) (Arnaud, et al., 1993; Arnaud, et al., 1994). Together, feral sheep and cats are responsible for the extinction in the wild of the Socorro dove (*Zenaida graysoni*) and the Socorro elf owl (*Micrathene whitneyi graysoni*), and pose a serious threat to other vulnerable species, such as Townsend's shearwater (*Puffinus auricularis*) (Martinez-Gomez & Jacobsen 2004). The eradication of feral cats represented another serious challenge, as Socorro is a large and complex island, and little baseline information was available on the distribution and abundance of cats (Arnaud, et al., 1994). Fortunately, technologies have been developed on other islands of Mexico and the world to achieve the eradication of these predators (Bester, et al., 2002; Wood, et al., 2002; Algar, et al., 2010; Aguirre-Muñoz, et al., 2011; Luna-Mendoza, et al., 2011; Parkes, et al., 2014). The successful implementation of an eradication campaign of this type is essential to determine the basic aspects of the species, the impact of the methods applied on the native fauna, and the

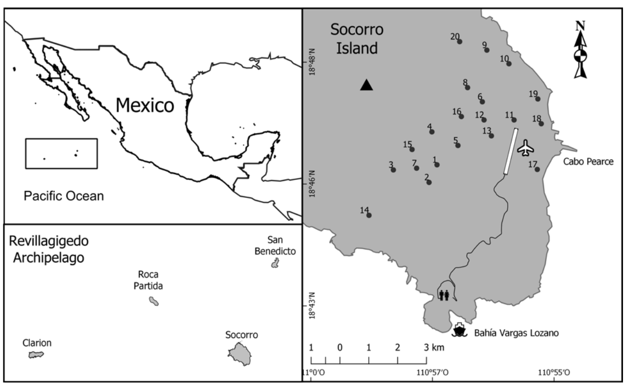

Fig. 1 Location of sampling sites of vegetation and soil.

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development of an official eradication plan (Veitch 1989; Arnaud, et al., 1994; Donlan, et al., 2003; Dowding, et al., 2009).

MATERIALS AND METHODS

Study site

The volcanic Socorro Island is the largest and most diverse portion of the Revillagigedo Archipelago, a World Heritage site in Mexico that was listed by UNESCO in July 2016. It is located in the tropical eastern Pacific, 460 km from the Baja California Peninsula and 700 km from Manzanillo, Colima. It has an area of 132 km^2 and a maximum altitude of 1,040 m (18º 47´ N, 110º 58´ W). Due to its remoteness, the island is a strategic point for Mexico's military personnel (40–50 people) situated at a naval base located in the southernmost part of the island. Additionally, Socorro Island has critical biodiversity significance through a high level of endemism, due to its isolated position A remarkable number of its native biota are exclusively found in this part of the world. Approximately one third of the 118 species of native vascular plants inhabiting the island are endemic. The native fauna is comprised of one endemic reptile species and almost 101 species of birds, of which eight of the terrestrial birds are endemic (SEMARNAT, 2004).

Feral sheep eradication

Monitoring: To identify the main areas where sheep were distributed, several flights (on a Beechcraft Bonanza aircraft) were made over the island during October 2005. At the same time, Mexican Navy officers conducted land surveys on foot and in motorised vehicles (ATV´s).

Aerial hunting: The aerial hunting stage was carried out using a single turbine helicopter (model MD369D), between April 20 and 29, 2009; supported by a GPS to record the flight trajectories. Two hunters were shooting simultaneously during the flight, using semi-automatic rifles and shotguns. All flights took place between 07:00 and 11:00 h, and between 16:00 and 19:00 h; at an average speed of 42 km/h and average height of 35 m.

Judas sheep: During the aerial hunting, 12 live animals were captured, to be used as 'Judas' sheep (individuals that serve to help locate remaining herds; Taylor & Katahira, 1988). These animals were neutered and fitted with radio-telemetry collars (Telenax, Mexico). These Judas sheep were deployed back to the sites where they were captured.

Terrestrial hunting and trapping: From February 2010 to April 2012, 4–7 experienced hunters carried out terrestrial hunting. Each one was equipped with a handheld GPS to record their hunting tracks, rifles (calibre .222, .243 and .308) with telescopic sights, as well as a 12-gauge shotgun with cartridges. Supported by the Judas sheep, it was possible to identify sheep herds. Simultaneously, leg-hold traps (Oneida Victor Soft Catch # 3) and snare traps were used on previously identified sheep trails; both types of trap were checked daily.

Hunting dogs: for the last stage of the sheep eradication, we used two hunting dogs (beagle and foxhound) to track down the remaining sheep herds; the dogs were fitted with GPS collars to record their locations and movements (Ortiz, et al., 2016a).

Feral cat eradication

Trapping: The eradication method consisted mainly of catching cats using leg-hold traps (#1 ½) and lethal traps (Conibear Bodygrip traps 10": Rauzon, 1985; Twyford, et al., 2000; Phillips, et al., 2005; Rodríguez, et al., 2006; Rauzon, et al., 2008; Luna-Mendoza, et al., 2011). Leg-hold traps with pads were used in 220 sites over the duration of the expedition (21–51 days), baited with a commercial cat bait made of seafood, tuna or fried sardine (Brothers, 1982). Traps were checked daily from 7:00 to 10:00 h. Lethal and leg-hold traps were located in sites of difficult access, equipped with telemetry systems (ATS, mammal trap monitor Series M4000) to determine whether they had been activated from a distance (Will, et al., 2010). Once cats were captured, these were euthanised by intramuscular injection of an anaesthetic and lethal intracardiac injection (pentobarbital). As a secondary method, night hunting was conducted using .222 calibre rifles with telescopic sights, and lamps (Kohree 80,000 lux: Ortiz, et al., 2016a).

Soil quality assessment

Soil compaction: In 2013, soil penetration resistance measurements were taken using a penetrometer (Soil Compaction Tester Dickey-john®) within 20 vegetation transects (Fig. 1). Sites were categorised as: bare soil sites, those with 50% recovered vegetation and those with 100% recovered vegetation. Additionally, soil compaction measures were taken in sites with 100% vegetation coverage, not previously disturbed by the sheep (ND = not disturbed). Fifty replicates were obtained in each category, resulting in a total of 200 measurements. An analysis of variance and Tukey's honest significance test were performed to analyse the differences among the different categories of vegetation cover.

Physicochemical soil parameters: soil samples of approximately 1 kg each, were collected from each transect at a depth of 0–10 cm: 16 samples were obtained in each one of the soil categories (N= 64). Subsequently, the following physicochemical parameters were determined: pH and electrical conductivity, total nitrogen by the Dumas method in a LECO nitrogen analyser; organic matter by the method of Walkley-Black; phosphorus by colorimetric reading of a spectrophotometer, and calcium and magnesium by the EDTA method.

Vegetation recovery assessment

Field assessment: Prior to eradication, in 2009, vegetation data collection was started to obtain a baseline scenario of the degraded environment, with the aim of making subsequent comparisons possible, and to detect signs of recovery after sheep removal. The estimation of sheep overgrazing consequences on the island was determined by selecting 20 plot sites. Transects of 10 m × 100 m were established in the more disturbed areas, to identify pioneer species on eroded soils; all plants were identified and counted. Plot sites were categorised in: forest (six replicates), mixed scrub (six replicates) and eroded surface (seven replicates) (León de la Luz, et al., 1994). The vegetation monitoring continued from 2011 to 2016. Analysis of variance was performed (rANOVA) to analyse differences in vegetation cover and in the number of species over the years of the study (Ortiz, et al., 2016b).

Normalised Difference Vegetation Index (NDVI): To identify changes in vegetation cover the photosynthetic vegetation vigour of the island was obtained, quantified with the Normalized Difference Vegetation Index (NDVI). Supported with QGIS software, two maps were generated. A "pre-eradication" map, created using a QuickBird satellite image, dated on May 11, 2008; and a "post-eradication" map, generated with a WorldView 2 satellite image, dated on May 9, 2013. Finally, the change in vegetation cover between the two dates was determined by subtracting the 2008 image NDVI raster pixel image values from the image of 2013, considering only differences exceeding 0.2 (bare soil).

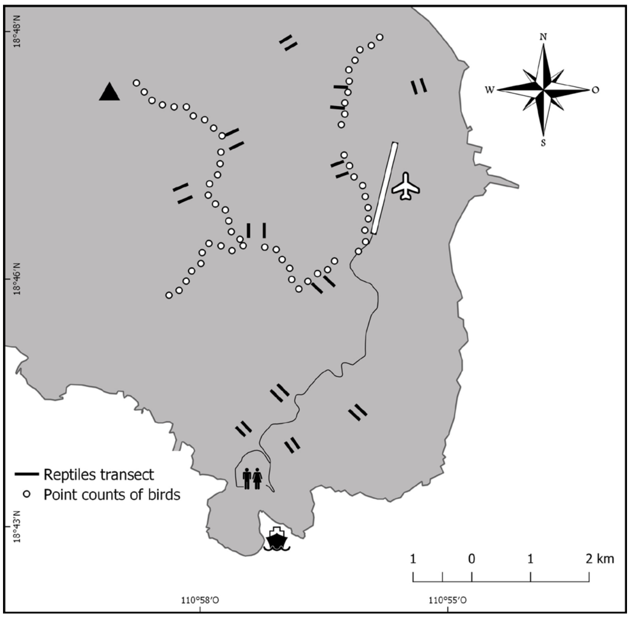

Fig. 2 Location of transects of Socorro tree lizard (lines) and count-points for birds (quadrats).

Monitoring of native fauna

Socorro Island tree lizard: To evaluate if the vegetation recovery was promoting any improvement of native animal populations, we monitored the Socorro Island tree lizard, during April and October, from 2012 to 2017. Twenty-four transects were set up in three different types of habitats (eight replicates per habitat type): forest, deciduous scrubland and eroded surfaces or areas impacted by sheep (León de la Luz, et al., 1994), each measuring 6 m × 100 m (Fig. 2). Transects were each visited on three consecutive days, between 10:00 and 12:00 h, during two different seasons (dry and rainy). Density (D) was estimated using the formula: $D = (n/2wL)$, where n is the number of individuals recorded, L is the total transect length, and w is the width of the transect on each side of the line (Gallina & López-González, 2011). A one-way repeated measure analysis of variance (rANOVA) was conducted to determine differences in seasonality and in habitat type on tree lizard density, the statistical software R (Version 3.2.2) was used for the analysis.

Terrestrial birds: Terrestrial birds were also monitored, using the point-count technique. Six transects were established during April and October (two seasons per year) from 2012 to 2017 (Fig. 2). The monitoring was carried out from 6:30 to 9:30 h and was repeated on three consecutive days, during the dry and rainy season, respectively. At each site, all birds observed within a radius of 25 m in a time span of five minutes were counted. Subsequently, the observer moved to the next counting point, located 250 m away, with a five-minute break before starting the next count. The statistical test rANOVA was run to determine the effect of season and habitat type on the total number of birds, plus Student t-tests for paired samples with a Bonferroni adjustment, to compare sightings during the different seasons.

RESULTS

Sheep eradication

Aerial hunting: a total of 35 flight hours was achieved in one week during the aerial hunting stage, in which most of the island was covered, with an average flight time of 1h 20 min per event; this resulted in removal of 1,257 individuals. The aerial hunting ceased when sheep became difficult to locate, and relatively few animals were being shot within a flight event. This method was selected due to its proven effectiveness in achieving rapid eradication (Campbell & Donlan, 2005) and was ideal on this island owing to its tropical conditions, which allowed the carcasses to decompose rapidly.

Ground hunting and trapping: 505 sheep were dispatched during the ground hunting stage, which comprised a nine-month period of hunting, over two years (March 2010–April 2012). Judas sheep were mostly effective when there were more remaining sheep, due to an increased probability of aggregation. Hunting dogs were used only at the final stage of eradication to locate the last ten remaining animals, which were difficult to locate for hunters. A total of 1,762 sheep were dispatched from Socorro Island in a three-year eradication campaign (Table 1).

Feral cat eradication

By December 2016, 502 cats had been removed, using soft leg-hold traps equipped with telemetry transmitters and lethal traps (body grip). Traps were placed in more than 250 sites on the island. Up to that date, there was an effort of more than 50,000 trap-nights. The success of cat capture during the trapping period fluctuated throughout the year (greater catch in January–May, dry season; and lower catch in June–October, rainy season). However, a clear trend to a smaller population was noted at a multi-year timescale (Fig. 3). In general terms, the success of capture is greater in the dry season and decreases during the rainy season. It is expected that cat eradication will cease in 2018; if that is the case, absence confirmation monitoring will be carried out in 2019.

Soil quality assessment

The results of the soil compaction assessment showed that eroded soils were the most compacted and a trend towards compaction reduction on areas with recovered

Table 1 Feral sheep dispatched on Socorro Island.

Year	Months	Personnel	Hunter hours	Distance (km)	Judas sheep	Trap nights	Captured sheep	Dog hours	Sheep removed
2009	May		35 (helicopter)						1,257
2010	Mar–Apr	7	1,323	815	53	900	41	-	355
	Jul	6	588	460	18	-	-	-	48
2011	Apr	5	512	433	11	650	8	-	67
	Aug–Sep	4	728	644	4	-	-	-	25
	Nov–Dec	4	420	385	-	-	-	49	8
2012	Apr	4	240	216	-	-	-	-	2
Total			3,811	2,953	86	1,550	49	49	1,762

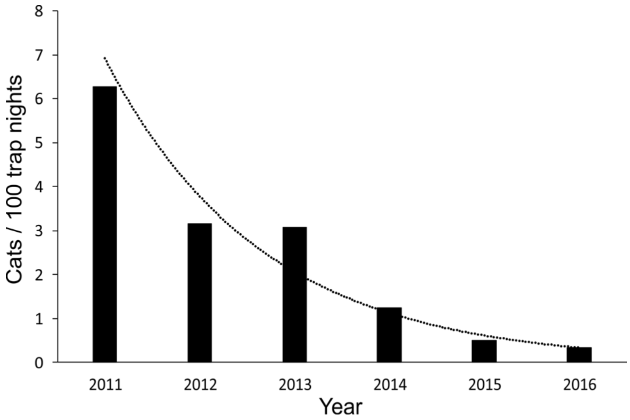

Fig. 3 Success of capture of feral cats.

vegetation was observed (50% and 100% recovered vegetation cover). Transects that retained eroded soils (0% vegetation) because of the sheep trampling, showed greater penetration resistance (>300 pounds-force per square inch, or psi, to 12 inches deep); at sites with 50% and 100% recovered vegetation cover, soils were also compacted and shallow (100–120 psi to three inches deep) and became more compacted at greater depths (300 psi to 24 inches deep); at sites with 100% coverage without disturbance (ND), the soil showed little variation (230–300 psi until 21 inches depth), which was in the optimal range for the growth of most plants (from 200–400 psi to 24 inches), which could be due to the constant, stable conditions. Significant differences ($p < 0.001$) were observed among sites with 0% and those with 50% and 100% recovered vegetation cover. The results of physicochemical analyses of soil samples showed increased nutrients: pH values remained close to neutral, showing a significant difference ($p < 0.021$) between sites without vegetation and 50% vegetation cover (results in Ortiz, et al., 2016b). Electrical conductivity, which is an indicator of salt presence in soil, was also significantly different ($p < 0.013$) between the eroded and 100% vegetation covered sites, although no difference was observed between eroded soils and those that were not disturbed. In the case of total nitrogen, organic carbon, phosphorus and calcium, sites with recovered vegetation were significantly different ($p < 0.001$) to those with erosion. Both nitrogen and organic carbon doubled, while phosphorus and calcium values almost tripled in places with increased vegetation cover compared to the eroded sites. Meanwhile, magnesium showed significant differences among the eroded sites (0%, 50%, and 100% recovered vegetation cover) and undisturbed sites (100% ND; Ortiz, et al. 2016b). The sites that were never altered by the presence of sheep exhibited a magnesium concentration twice that of disturbed sites.

Vegetation recovery assessment

Calculations (comparison of the images from 2008 and 2013) showed a difference of 1452 ha, which is equivalent to vegetation recovery of 11% of the island surface. The eastern part of the island was the area with the greatest habitat disturbance (Álvarez-Cárdenas, et al., 1994), and where the greatest vegetation recovery seemed to have occurred within the analysed period. Due to the presence of sheep, most of the evaluated sites lacked vegetation, and few species were present in 2009 (Fig. 4). Additionally, trails made by the sheep were observed to have compacted soils. Statistical tests showed significant differences from 2009 to 2013 in the number of species present in the eroded sites as well as in percentage cover. It was possible to record obvious recovery in all the habitats in 2013, i.e. the forest habitat with the highest values, followed by the mixed scrub, and then the eroded surface.

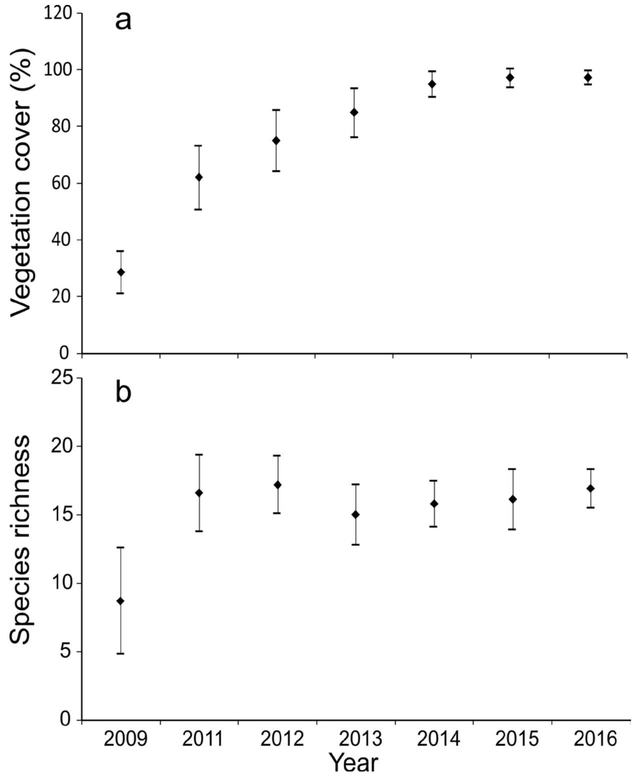

Fig. 4 Increase in vegetation cover (a) and species richness (b) on Socorro Island.

Monitoring of native fauna

The results of tree lizard monitoring reveal that the population is increasing, taking into consideration both the dry and rainy seasons (Fig. 5). Lizard density fluctuated significantly between seasons since the trapping of cats started on Socorro Island ($p = 0.014$). The number of birds sighted from 2012 to 2015 also showed significant differences between seasons ($p = 2.2 \times 10^{-4}$). Although population fluctuation is evident over the years of the study, there is an increase of birds in the dry seasons of 2014 and 2015 (Fig. 6). Significant differences were found between November 2012 and the rest of the monitoring time points (except November 2014). No significant differences were found between dry seasons during the years 2013 to 2015. The most abundant species was the Socorro tropical warbler (*Setophaga pitiayumi graysoni*), followed by the Socorro wren (*Troglodytes sissonii*), and the towhee (*Pipilo maculatus socorrensis*), all of them endemic to the island.

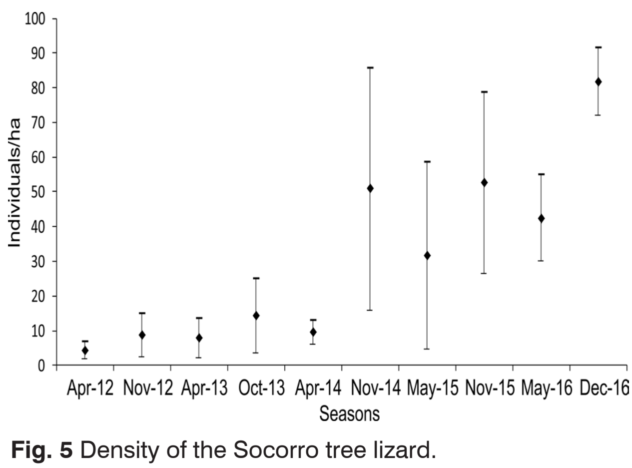

Fig. 5 Density of the Socorro tree lizard.

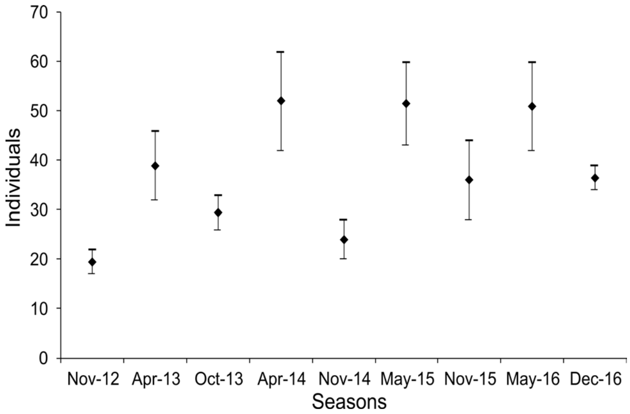

Fig. 6 Numbers of birds sighted.

DISCUSSION

Compared with other islands where goats or sheep have been eradicated (Van Vuren, 1992), the Socorro Island feral sheep eradication can be considered highly effective as it was completed in three years, when similar projects have taken 3–5 years, and even decades, to conclude (Campbell & Donlan, et al., 2005). Moreover, the methods used reduced project cost, which was US$ 38/ha, while other sheep eradication projects, such as that developed on Santa Cruz Island, California, cost US$ 80/ha, due to capture and transport of sheep to the continent (Faulkner & Kessler, 2001).

The capture of cats increases during the dry season (January–May) and decreases in the rainy season (June–October). The results differ between wet and dry seasons, since moist land interferes with the installation of leg-hold traps, and dry substrate is unavailable to cover them. Rain also compacts and hardens the substrate covering the traps, hence restraining their activation. At the same time, another key factor that affects trapping in the rainy season is the higher abundance of land crabs (*Gecarcinus planatus*), which consume the bait placed in traps, or activate traps when attempting to reach the bait. The combination of lethal traps and telemetry devices is essential during trapping in the most remote areas of the island. In this way, traps do not have to be checked daily but every five to seven days any bait lost to insects (mainly ants) and crabs is replenished (Parkes, et al., 2012).

The changes in soil physicochemical properties on Socorro Island seem to be related to the gradual recovery of vegetation after the eradication of feral sheep. Prostrate *Chamaesyce* sp. and *Erigeron socorrensis* have been observed to have a great capacity to retain soil. *Hyptis pectinata* and *Pteridium caudatum* established in high densities; in addition to retaining soil, they have generated much organic matter. Possibly the most successful species to colonise disturbed areas has been *Dodonaea viscosa*, which has a great ability to germinate in eroded soil (Campa-Molina, 1989), generating organic matter and preventing the germination of other species (Castellano & Valone, 2007). In the absence of trampling, soil aggregate stability increases, which enhances permeation, reduces erosion, and may promote nutrient accumulation and soil retention (Allington & Valone, 2010). As pioneer plants began to establish, the ground became less compacted because the roots of plants, particularly annual grasses in this instance, act as biological perforators, also incorporating organic matter into the soil. Once the roots die and shrink, these pores are large enough to allow the roots of perennial shrubs to penetrate (Sellés, et al., 2012). Greater ease of water movement in the soil matrix, coupled with heavy rainfall, could be causing leaching and replacing cations with H+ ions, acidifying the soil.

Both the results obtained with the NDVI calculation and field observations suggested that some pioneer plants had the ability to germinate on eroded soils and were instrumental in the succession process by providing the right conditions for seeds of tree species to germinate. The progressive increase in vegetation cover reduces soil compaction and restores the biogeochemical cycles of essential nutrients, such as nitrogen, phosphorus, and calcium, which are essential for the recovery of communities and the ecosystem in general, as well as the incorporation of carbon on the ground, which is essential for the proper functioning of important microbiological components. Any change in the habitat that produces changes in litter production, soil aeration, or any other factor affecting microorganisms will be reflected in changes in biogeochemical cycles, such as those of carbon and nitrogen (Hartmann, et al., 1997).

We found differences in the number of species and vegetation cover in the sampling area between 2009 and 2013. The forests and mixed scrub areas showed the greatest recovery, probably favoured by their vegetal components and the permanence of seed banks, due to a more stable landscape, water availability, and precipitation patterns. The endemic tree species recovering were *Guettarda insularis* and *Psidium socorrense*. The smaller number of plant species found in the isolated patches of mixed scrub included in large expanses of erosion could be due to the steepness of slopes and wind exposure. Gravity also makes the permanence of naturally occurring soil seed banks difficult. Some species of exotic grasses have increased with sheep eradication because they are no longer grazed.

The Socorro Island tree lizard was found at higher densities in the deciduous scrubland, being less abundant in forests at higher altitudes. The results of this particular study show that the density of lizards on eroded surfaces was as high as 43 individuals/ha after cat abundance was reduced, however Galina et al. (1994) reported not having observed lizards in these areas. This may be due to a gradual recovery of the vegetation resulting from the recent eradication of sheep (Ortiz-Alcaraz, et al., 2016a; Ortiz-Alcaraz, et al., 2016b) and to the sustained trapping of cats in these areas. Lizard abundance was slightly higher during the rainy season, likely due to greater food availability. As the cat eradication programme in the eastern area of the island has progressed, the predation pressure of cats on the lizard population has decreased. Lizards are a major component of the cats' diet (50% of faecal samples of cats analysed contained lizard remains; Arnaud, et al., 1993). The vegetation type where the highest number of birds was observed was the forest (*Ficus-Guettarda-Ilex*), especially in the highest parts of the island, where the recovery of vegetation resulting from the absence of grazing sheep has led to greater availability of food and shelter against predators (Rodríguez-Estrella, et al., 1994). On the other hand, special efforts have also been made to eradicate cats in the forest, aiming to protect the native bird species, such as the Townsend´s shearwater (Ratcliffe, et al., 2009).

The plans developed by Veitch (1989), Arnaud, et al. (1993) and Parkes, et al. (2012) are all in agreement that feral cats can be eradicated using traditional techniques: trapping and night hunting. However, the experience on the island has shown the importance of using detection dogs to locate the remaining cats, either during the day, in their dens (placing traps to catch them), or at night, killed by hunting (Tortora, 1982; Veitch, 2001), as well as the statistical confirmation of absence (Ramsey, et al., 2011).

CONCLUSION

The aerial hunting method proved to be an ideal technique for the eradication of sheep from Socorro Island. It enabled the eradication team to dispatch a high number of animals in a few days of work, while allowing the hunters to access difficult terrain. The use of Judas sheep and hunting dogs was crucial for completing the eradication.

Removing the exotic herbivorous species from the island is a conservation tool, which is evident in recovery of the natural environment. Habitat fragmentation and degradation caused by the presence of sheep was evident on the island, where the main impact was on vegetation. The resistance of native species has been important, not only in the relatively rapid recovery of the vegetation cover, but also in offering the possibility of recovering the former island vegetation. The results reflect the important role of vegetation in erosion control, both for establishing mechanical support due to plant roots in the soil structure and in capturing water flow and nutrients, providing fresh organic matter to the soil and restoring biogeochemical cycles and ecosystem processes.

With habitat recovery and progress in the feral cat eradication, wildlife recovery is expected as food availability and resources for the native species of the island gradually increase and predation decreases. Socorro Island seems resilient enough to recover over a relatively small-time scale, after the removal of the pressures caused by exotic mammals.

REFERENCES

Aguirre-Muñoz, A., Samaniego-Herrera, A., Luna-Mendoza, L., Ortiz-Alcaraz, A., Rodríguez-Malagón, M., Méndez-Sánchez, F., Félix-Lizárraga, M., Hernández-Montoya, J.C., González-Gómez, R., Torres-García, F., Barredo-Barberena, J.M. and Latofski-Robles, M. (2011). 'Island Restoration in Mexico: Ecological outcomes after systematic eradications of invasive mammals'. In: C.R. Veitch, M.N. Clout and D.R. Towns (eds.) *Island invasives: eradication and management,* pp. 250–258. Occassional Paper SSC no. 42. Gland, Switzerland: IUCN and Auckland, New Zealand: CBB.

Algar, D., Angus, G.J., Brazell, R.I., Gilbert, C. and Withnell, G.B. (2010). 'Eradication of feral cats on Faure Island, Western Australia'. *Journal of the Royal Society of Western Australia* 93: 133–140.

Allington, G.R.H. and Valone, T.J. (2010). 'Reversal of desertification: The role of physical and chemical soil properties'. *Journal of Arid Environments* 74: 973–977.

Álvarez-Cárdenas, S., Castellanos-Vera, A., Galina-Tessaro, P. and Arnaud, G. (1994). 'Aspectos de la Población y el Hábitat del Borrego Doméstico (*Ovis aries*)'. In: A. Ortega-Rubio and V. Castellanos (eds.) *La Isla Socorro, Reserva de la Biosfera Archipiélago de Revillagigedo, México*, pp. 301–317. México: Centrode Investi-gaciones Biológicas del Noroeste.

Arnaud, G., Rodríguez, A., Ortega-Rubio, A. and Álvarez, C.S. (1993). 'Predation by cats on the unique endemic lizard of Socorro Island (*Urosaurus auriculatus*), Revillagigedo, México'. *The Ohio Journal of Science* 93(4): 101–104.

Arnaud, G., Rodríguez, A. and Álvarez, S. (1994). 'El Gato Doméstico (*Felis catus*), Implicaciones de su Presencia y Alternativas para su Eradicación'. In: A. Ortega-Rubio and A. Castellanos-Vera (eds.) *La Isla Socorro, Reserva de la BiosferaArchipiélago de Revillagigedo, México,* pp. 341–359. S. C. La Paz, Mexico: Centro de Investigaciones Biológicas del Noroeste.

Bester, M.N., Bloomer, J.P., Van Aarde, R.J., Erasmus, B.H., Van Rensburg, P.J., Skinner, J.D. Howell, P.G. and 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.

Brattstrom, B. (2015). 'Food webs and feeding habits on the Revillagigedo Islands, Mexico'. *Pacific Science 69*: 181–195.

Brothers, N.P. (1982). 'Feral cat control on Tasman Island'. *Australian Ranger Bulletin* 2: 9.

Campa-Molina, M.A. (1989). 'Flora y Potencial Apícola de Isla Socorro, Archipiélago de las Revillagigedo'. MSc thesis. Jalisco, México: Universidad de Guadalajara.

Campbell, K. and Donlan, J. (2005). 'A review of feral goat eradication on islands'. *Conservation Biology* 198: 1362–1374.

Castellano, M.J. and Valone, T.J. (2007). 'Livestock, soil compaction and water infiltration rate: Evaluating a potential desertification recovery mechanism'. *Journal of Arid Environments* 71: 97–108.

Courchamp, F., Chapuis, J.L. and Pascal, M. (2003). 'Mammal invaders on islands: Impact, control, and control impact'. *Biological Reviews* 78: 347–383.

Donlan, C.J., Tershy, B.R., Campbell, K.J. and Cruz, F. (2003). 'Research for requiems: The need for more collaborative action in eradication of invasive species'. *Conservation Biology* 17: 1–2.

Dowding, J.E., Murphy, E.C., Springer, K., Peacock, A.J. and Krebs, C.J. (2009). 'Cats, rabbits, myxoma virus, and vegetation on Macquarie Island: A comment on Bergstrom et al. (2009)'. *Journal of Ecology* 46: 1129–1132.

Faulkner, K.R. and Kessler, C.C. (2011). 'Live capture and removal of feral sheep from Eastern Santa Cruz'. In: Veitch, C. R.; Clout, M. N. and Towns, D. R. (eds.). 2011. *Island invasives: eradication and management*, pp. 295–299. Occassional Paper SSC no. 42. Gland, Switzerland: IUCN and Auckland, New Zealand: CBB.

Gallina, S. and C. López-González (eds.) (2011). *Manual de Técnicas para el Estudio de la Fauna. Volumen I*. Querétaro, México: Universidad Autónoma de Querétaro–Instituto de Ecología, Civil Association.

Hartmann, A., Assmus, B., Kirchhof, G. and Schloter, M. (1997). 'Direct Approaches for Studying Soil Microbes'. In: J.D. van Elsas, J.T. Trevors and E.M.H. Wellington (eds.) *Modern Soil Microbiology*, p. 172. New York: Marcel Dekker Inc.

León de la Luz, J.L., Breceda, A., Coria-Benet, R. and Cancino-Hernández, J. (1994). 'Asociaciones Vegetales'. In: A. Ortega-Rubio and V. Castellanos (eds.) *La Isla Socorro, Reserva de la Biosfera Archipiélago de Revillagigedo, México*, pp. 115–141. Mexico: Centro de Investigaciones Biológicas del Noroeste.

Levin, J.A. and Moran, R. (1989). *The Vascular Flora of Isla Socorro, México.* University of Michigan, USA: San Diego Society of Natural History.

Luna-Mendoza, L., Barredo-Barberena, J.M., Hernández-Montoya, J.C., Aguirre-Muñoz, A., Méndez-Sánchez, F., Ortiz-Alcaraz, A. and Félix-Lizárraga, M. (2011). 'Planning for the eradication of feral cats on Guadalupe Island, México: home range, diet, and bait acceptance'. In: C.R. Veitch, M.N. Clout and D.R. Towns (eds.) *Island invasives: eradication and management*, pp. 192–197. Occassional Paper SSC no. 42. Gland, Switzerland: IUCN and Auckland, New Zealand: CBB.

Maya-Delgado, Y., Salinas-Zavala, F. and Troyo-Diéguez, E. (1994). 'Estado Actual del Suelo y Propuestas para su Conservación'. In: A. Ortega-Rubio and V. Castellanos (eds.) *La Isla Socorro, Reserva de la Biosfera Archipiélago de Revillagigedo, México*, pp. 63–75. Mexico: Centro de Investigaciones Biológicas del Noroeste.

Ortega-Rubio, A., Castellanos-Vera, A., Arnaud, G., Maya-Delgado, Y., Rodríguez, R., León de la Luz, J.L., Cancino, J., Jiménez, C., Llianas, J., Álvarez, S., Galina, P., Breceda, A., Troyo, E., Salina,s F., Díaz, S., Servín, R., Romero, H., Rodríguez, A. and Coria, R. (1992). 'Estudio de los recursos naturales de la Isla Socorro, Revillagigedo'. *Ciencia* 43: 175–184.

Ortiz-Alcaraz, A., Aguirre-Muñoz, A., Méndez-Sánchez, F. and Ortega-Rubio, A. (2016a). 'Feral sheep eradication at Socorro Island, Mexico: A mandatory step to ensure ecological restoration'. *Interciencia* 41: 184–189.

Ortiz-Alcaraz, A., Maya-Delgado, Y., Cortés-Calva, P., Aguirre-Muñoz, A., Rojas-Mayoral, E., Cordoba -Matson, M. and Ortega-Rubio, A. (2016b). 'Recovery of vegetation cover and soil after the removal of sheep in Socorro Island, Mexico'. *Forests* 7: 91.

Parkes, J., Fisher, P. and Robinson, S. (2012). *Eradication of Feral Cats on Large Mexican Islands: A Discussion of Options and Feasibility*. Lincoln, New Zealand: Invasive Species International, Landcare Research New Zealand.

Parkes, J., Fisher, P., Robinson, S. and Aguirre-Muñoz, A. (2014). 'Eradication of feral cats from large islands: An assessment of the effort required for success'. *New Zealand Journal of Ecology* 38: 307–314.

Phillips, R.B., Cooke, B.D., Campbell, K., Carrion, V., Marquez, C. and Snell, H.L. (2005). 'Eradicating feral cats to protect Galápagos land iguanas: Methods and strategies'. *Pacific Conservation Biology* 11: 57–66.

Ramsey, D.S.L., Parkes, J.P., Will, D., Hanson, C.C. and Campbell, K.J. (2011). 'Quantifying the success of feral cat eradication, San Nicolas Island, California'. *New Zealand Journal of Ecology* 35: 163–173.

Ratcliffe, N., Bell, M., Pelembe, T., Boyle, D., Benjamin, R., White, R., Godley, B., Stevenson, J. and Sanders, S. (2009). 'The eradication of feral cats from Ascension Island and its subsequent recolonization by seabirds'. *Oryx* 44: 20–29.

Rauzon, M.J. (1985). 'Feral cats on Jarvis Island: Their effects and their eradication'. *Atoll Research Bulletin* 282: 1–30.

Rauzon, M.J., Everett, W.T., Boyle, D., Bell, L. and Gilardi, J. (2008). 'Eradication of feral cats at Wake Atoll'. *Atoll Research Bulletin* 560: 1–21.

Rhea, M. (2000). 'Distribution of the Endangered Socorro Mockingbird, *Mimodes graysoni*, in Relation to Habitat Availability'. University Thesis. Villanova, Pennsylvania: Biology Department, Villanova University.

Richards, A.F. and Brattstrom, B.H. (1959). 'Bibliography, cartography, discovery and exploration of the Islas Revillagigedo'. *Proceedings of the California Academy Sciences* 29: 315–360.

Rodríguez, C., Torres, R. and Drummond, H. (2006). 'Eradicating introduced mammals from a forested tropical island'. *Biological Conservation* 130: 98–105.

Rodriguez-Estrella, R., Rivera, L. and Mata, E. (1994). 'Avifauna Terrestre'. In: A. Ortega-Rubio and A. Castellanos-Vera (eds.). *La Isla Socorro, Reserva de la Biosfera Archipiélago de Revillagigedo, México*, pp. 199–224. La Paz, Mexico: Centro de Investigaciones Biológicas del Noroeste S.C.

Sellés, G., Fereyra, R., Ruíz, R., Ferreyra, R. and Ahumada, R. (2012). *Compactación de Suelos y su Control: Estudio de Casos en el Valle de Aconcagua.* Boletín INIA 234. Santiago, Chile: Instituto de Investigaciones Agropecuarias.

SEMARNAT. (2004). *Programa de Conservación y Manejo, Reserva de la Biósfera Archipiélago de Revillagigedo*. México: Secretaría de Medio Ambiente y Recursos Naturales.

Taylor, D. and Katahira, L. (1988). 'Radiotelemetry as an aid in eradicating remnant feral goats'. *Wildlife Society Bulletin* 16: 297–299.

Tortora, D.F. (1982). 'Understanding electronic dog-training. 1'. *Canine Practice* 9: 17–22.

Twyford, K.L., Humphrey, P.G., Nunn, R.P. and Willoughby, L. (2000). 'Eradication of feral cats (*Felis catus*) from Gabo Island, south-east Victoria'. *Ecological Management and Restoration* 1: 42–49.

Van Vuren, D. (1992). 'Eradication of Feral Goats and Sheep from Island Ecosystems'. In: J.E. Borrecco and R.E. Marsh (eds.) *Proceedings of the 15th Vertebrate Pest Conference*, pp. 377–381. Davis, USA: University of California.

Veitch, C.R. (1989). *The Eradication of Cats and Sheep from Socorro Island: A Report to the Socorro Island Project*. Northern Region Technical Report Series No. 11. Auckland, New Zealand: Department of Conservation.

Veitch, C.R. (2001). 'The eradication of feral cats (*Felis catus*) from Little Barrier Island, New Zealand'. *New Zealand Journal of Zoology* 28: 1–12.

Villa, B. (1960). 'La Isla Socorro. Vertebrados terrestres'. *Monografías Instituto de Geofísica* 2: 203–206.

Walter, H.S. and Levin, G.A. (2008). 'Feral sheep on Socorro Island: Facilitators of alien plant colonization and ecosystem decay'. *Diversity and Distributions* 14: 422–431.

Will, D., Hanson, C.C., Campbell, K.J. Garcelon, D.K. and Keitt, B.S. (2010). 'A Trap Monitoring System to Enhance Efficiency of Feral Cat Eradication and Minimize Adverse Effects on Non-target Endemic Species on San Nicolas Island'. In: R. M. Timm and K. A. Fagerstone (eds.) *Proceedings of the 24th Vertebrate Pest Conference*, pp. 79–85. Davis, CA: University of California.

Wood, B., Tershy, B.R., Hermosillo, M.A., Donlan, C.J., Sánchez, J.A., Keitt, B.S., Croll, D.A., Howard, G.R. and Biavaschi. N. (2002). 'Removing cats from islands in North-west Mexico'. In: C.R. Veitch and M.N. Clout (eds.) *Turning the tide: the eradication of invasive species*, pp. 374–380. Occasional Paper SSC no. 28. IUCN SSC Invasive Species Specialist Group. IUCN, Gland, Switzerland and Cambridge, UK.