Island restoration in Mexico: ecological outcomes after systematic eradications of invasive mammals

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Abstract On Mexican islands, 20 island endemic species and subspecies of vertebrates have gone extinct in the last 100 years; all but four of these extinctions were caused by invasive mammals. To prevent more extinctions, 49 populations of 12 invasive mammals were eradicated from 30 Mexican islands. These actions protected 202 endemic taxa – 22 mammals, 31 reptiles, 32 birds, and 117 plants – as well as 227 seabird breeding colonies. An area of 50,744 ha was restored, which represents 10% of Mexico's total island territories. Techniques have ranged from the traditional – trapping and ground hunting – for 26% of the restored area, to the most sophisticated – aerial hunting, aerial broadcast of bait, DGPS and GIS use – for 74% of the restored area. These conservation actions are of high significance for Mexico. Extirpated seabirds have recolonised several islands and increased reproductive success has been documented. An ongoing seabird social attraction project facilitates recolonisation of additional islands. On Guadalupe Island, after the eradication of goats (*Capra hircus*), recruitment of three endemic trees increased from zero to more than 150,000 individuals. Six native plants, including two endemics, were rediscovered. Ecological outcomes from island restoration are expected to increase. Eradicating all invasive vertebrates from the remaining 41 Mexican islands with 83 populations of invasive mammals is a viable and strategic goal, achievable by 2025, and will set a global benchmark.

Keywords: Eradication, restoration, invasive mammals, islands, Mexico, ecological outcomes, strategic goal.

INTRODUCTION

Invasive alien species are considered second behind habitat destruction as the largest cause of biodiversity loss worldwide (Courchamp *et al.* 2003). When islands are considered alone, invasive species are the primary cause of extinctions (Baillie *et al.* 2004; Reaser *et al.* 2007). According to Ebenhard (1988), invasive species can affect native species through: 1) modification of plant populations and the animals that depend on them; 2) predation; 3) competition for local resources; 4) dispersal of micro and macro parasites; 5) genetic changes in native populations through hybridisation; and 6) prey of native predators (changing the food chain). Over time, these impacts can restrain recruitment, cause the extinction of species and modify food webs and ecological processes. Insular populations are particularly vulnerable since they have not co-evolved with invasive species and lack defence mechanisms against them (Primack 2002).

Mexican islands comprise a total area of 5127 km^2 (INEGI 2005). The northwest region is particularly important, where more than 600 islands in the Pacific Ocean off Baja California, the Gulf of California, and the Revillagigedo Archipelago significantly contribute to Mexico's megadiversity. These islands have more endemic plants and vertebrates than the Channel Islands of the USA and the Galapagos Islands of Ecuador. Compared with the endemic taxa of the Galapagos Islands (310), the northwest Mexican islands (331) have 25% more endemic species per km^2. The Mexican islands are crucial nesting and resting sites for seabirds and pinnipeds, as well as important refuges for harvested marine species that have been over-exploited on the coastal mainland. Considerable conservation and restoration efforts, especially to overcome the effects of invasive species, have been invested in Mexican islands. Most of this has been in the past two decades, with close and practical collaboration between federal government, NGOs and academic institutions.

Under the Mexican constitution all islands are part of national territory and are under federal jurisdiction, except for a few islands that are in the jurisdiction of individual states (Moreno-Collado 1991; Cabada-Huerta 2007), and very few which are communal or private property (CONANP-SEMARNAP 2000). Federal islands are administered by the Ministry of the Interior (SEGOB) and protected by the Ministry of the Navy (SEMAR). For more than 15 years, control and eradication projects have been undertaken in these territories through interpretations of the Environmental Act (LGEEPA) and the Wildlife Act (LGVS), under the mandate of the Ministry of the Environment (SEMARNAT).

In this paper we review the history of invasive vertebrate introductions to Mexican islands, the impacts of the introduced species, current progress with reversing these effects, and the responses of native species when introduced species are removed. We use Guadalupe Island to illustrate the processes of extinction and the prospects for recovery. We also update the available information on invasive vertebrates on Mexican islands.

In Mexico, island biodiversity has been seriously affected by introduced invasive species but these effects were not studied until the 1980s (Mellink 1992, 1993; Velarde and Anderson 1994). Subsequently, the situation on northwest Mexican islands as a result of introduced rodents was described by Romeu (1995) as critical. The first eradication projects were implemented in 1994 and 1995, on Asunción and San Roque islands off the Baja California Peninsula (Aguirre-Muñoz *et al.* 2008), and on Rasa Island, in the Gulf of California (Ramírez-Ruiz and Ceballos-González 1996).

More recently, research on the status and impacts of invasive vertebrates has been published and lists of the distribution of invasive species generated (Mellink 2002; Aguirre-Muñoz *et al.* 2005; Aguirre-Muñoz *et al.* 2009a; Rodríguez-Malagón 2009). As part of this review we have checked, and in some cases corrected, existing datasets, with the result that tables presented here vary from those previously published.

HISTORY OF INVASIONS OF MEXICAN ISLANDS

Flora and fauna have been moved between locations for as long as people have moved around the world. On the islands of northwest Mexico before the 20th century, introductions of invasive species were largely related to the harvesting of marine mammals and mining for guano. Subsequently, the sources of introductions diversified to include commercial and sport fishing. Examples include house mice (*Mus musculus*), presumably introduced to Guadalupe Island during marine mammal hunting trips

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Table 1 Invasive mammals still present on Mexican islands in 2010.

Island	Area (ha)†	Common names
GULF OF CALIFORNIA		
Alcatraz (Pelícano)	50	House mouse
Almagre Chico	10	Ship rat
Ángel de la Guarda	93,068	Cat, house mouse, ship rat
Carmen	14,461	Goat, cat, bighorn sheep
Cerralvo	13,505	Goat, cat
Coyote	25	Dog, cat
El Rancho	232	House mouse, ship rat
Espíritu Santo	7991	Goat, cat
Granito	27	Ship rat
María Madre	14,388	Goat, cat, ship rat, horse, rabbit
María Magdalena	6977	Goat, white-tailed deer, cat, ship rat
María Cleofas	1963	Goat, cat, ship rat
Mejía	245	House mouse, ship rat
Melliza Este	1	Ship rat
Pájaros	82	Ship rat
Saliaca	2000	House mouse, ship rat
San Diego	56	Goat
San Esteban	3966	Ship rat
San José	18,109	Goat, donkey, cat
San Marcos	2855	Goat, cat
San Vicente	14	House mouse
Santa Catalina (Catalana)	3890	Northern Baja California deer-mouse
Tiburón	119,875	Dog, bighorn sheep
Total 1	303,790	
GULF OF MEXICO AND CARIBBEAN SEA		
Cayo Norte Menor	15‡	Ship rat
Cayo Norte Mayor	29‡	Ship rat
Cayo Centro	537‡	Ship rat, cat
Cozumel	47,000	House mouse, ship rat
Holbox	5540	Ship rat
Muertos	16‡	House mouse
Mujeres	396	House mouse, ship rat
Pérez	11‡	Ship rat
Pájaros	2‡	House mouse
Total 2	53,546	
PACIFIC		
Cedros	34,933‡	Dog, goat, cat, house mouse, ship rat, donkey
Clarión	1958	Rabbit
Coronado Sur	126‡	House mouse
Guadalupe	24,171‡	Cat, house mouse
Magdalena	27,773‡	Dog, donkey, cat, house mouse
Natividad	736‡	White-tailed antelope squirrel
San Benito Oeste	364‡	Cedros Island cactus mouse
Santa Margarita	21,504‡	White-tailed antelope squirrel, dog, goat, donkey, horse, cat
Socorro	13,033‡	House mouse, cat
Total 3	124,598	
Total 1+2+3	481,934	

Names of species listed in Table 1

Common name	Scientific name
Dog	*Canis lupus familiaris*
Bighorn sheep	*Ovis canadiensis mexicana*
Cat	*Felis catus*
Cedros Island cactus mouse	*Peromyscus eremicus cedrosensis*
Dog	*Canis lupus familiaris*
Donkey	*Equus asinus*
Goat	*Capra hircus*
Horse	*Equus caballus*
House mouse	*Mus musculus*
Northern Baja California deer-mouse	*Peromyscus fraterculus*
Rabbit	*Oryctolagus cuniculus*
Ship rat	*Rattus rattus*
White-tailed antelope squirrel	*Ammospermophilus leucurus*
White-tailed deer	*Odocoileus virginianus*

† INEGI (2005), unless indicated otherwise.
‡ Area estimated by Conservación de Islas through satellite imagery (Samaniego-Herrera *et al.* 2007; Conservación de Islas-CONANP 2009).

(Moran 1996); and ship rats (*Rattus rattus*) and house mice, which probably arrived on Cedros Island with skin hunters (Mellink 1993). In association with guano mining, invasive rodents were introduced to San Roque, San Jorge, Rasa, and San Pedro Mártir islands, among others (Knowlton *et al.* 2007). The common house gecko (*Hemidactylus frenatus*) was introduced to Socorro and María Madre islands, probably with food supplies from the mainland (Valdez-Villavicencio and Peralta-García 2008), whilst common blind snake (*Ramphotyphlops braminus*) was probably introduced to Isabel Island with invasive fruit plants that were once present there (A. Samaniego-Herrera, pers. obs.). Introductions continue, with the spread of ship rats to Mejía Island and house mice to Coronado Sur Island, in the last 5 to 10 years. The Cedros Island cactus mouse (*Peromyscus eremicus cedrosensis*) was accidentally introduced in 2007 to the nearby San Benito Oeste Island.

A wide range of mammals have been intentionally introduced to Mexican islands. Dogs were taken to Guadalupe and Cedros islands as pets (Ibarra-Contreras 1995; Knowlton *et al.* 2007). As supplies of fresh meat, goats (*Capra hircus*) were introduced to Guadalupe, San Benito Oeste, Cedros, San José, Espíritu Santo and Cerralvo islands (Mellink 1993, 2002; Donlan *et al.* 2000; CONANP-SEMARNAP 2000), merino sheep (*Ovis aries*) to the tropical Socorro Island in the middle of the 18th Century; and sheep, pigs (*Sus scrofa*) and rabbits (*Oryctolagus cuniculus*) to Clarión Island (Everett 1988; Steve *et al.* 1991; CONANP-SEMARNAT 2004). To extend food reservoirs to the Seri tribe, chuckwallas (*Sauromalus* spp.) were introduced to Alcatraz Island (Case *et al.* 2002). For sustainable use as a sport hunting resource, bighorn sheep (*Ovis canadensis*) were introduced to Tiburón and Carmen islands (Álvarez-Romero and Medellín-Legorreta 2005), although they did not become invasive.

With the exception of bighorn sheep, none of the intentional introductions have brought the expected benefits. Furthermore, when domesticated species became feral and hard to hunt, they were replaced by food imported from the continent and feral populations grew without control. Table 1 shows in detail the invasive mammals still present on Mexican islands.

LOCAL IMPACTS OF INVASIVE VERTEBRATES

Introduced mammals on the islands of northwest Mexico have had major negative impacts on biodiversity, leading to extinction from these islands of 16 endemic species, including one – the Socorro Island dove (*Zenaida graysoni*) extirpated in the wild (Table 2), and now kept only in zoos. Four species listed by Aguirre-Muñoz *et al.* (2009a) are not in Table 2 because they probably did not become extinct due to introduced species. These include Mcgregor's house finch (*Carpodacus mexicanus mcgregori*) from San Benito Island, which presumably became extinct because of excessive collecting by scientists (Jehl 1970); Pemberton's deer mouse (*Peromyscus pembertoni*) from San Pedro Nolasco Island, which became extinct presumably because of competition with other native rodents (Flannery and Schauten 2001); the Guadalupe caracara or "quelele" (*Caracara lutosa*), last recorded in 1900 (Abbott 1933) probably due to excessive hunting and collecting of specimens combined with the indirect impacts of goats and cats (Jehl and Everett 1985; Stattersfield 1998); and the Turner Island woodrat (*Neotoma varia*) which was last seen in 1977, although there are no records of introduced species on Turner Island (Álvarez-Castañeda and Ortega-Rubio 2003).

Documentation and evaluation of impacts on Mexican islands has been limited, episodic and, in most cases, recent. Below, we summarise documented impacts of the most harmful and widely spread invasive species on Mexican islands.

Rodents

On Farallón de San Ignacio and San Pedro Mártir islands in the Gulf of California, isotopic analysis of ship rat diet allowed identification of those species most heavily affected by predation. On Farallón de San Ignacio, 90.4% of analysed rats fed exclusively on seabirds; whereas on San Pedro Mártir, consumption of plants, seabirds, and terrestrial and marine invertebrates was approximately equal (Rodríguez-Malagón 2009). This difference between islands reflected local food availability and confirmed the opportunistic and adaptable habits of this species of rat (Towns *et al.* 2006).

Cats

On Mexican islands, eight rodent taxa are extinct, or nearly so, and seven of these were probably due to predation by cats (*Felis catus*) (Table 2). Seabirds have been similarly affected, with the extinction of numerous island populations and total extinction of the Guadalupe storm-petrel (*Oceanodroma macrodactyla*) (Jehl and Everett 1985). The impact of cats was illustrated on Natividad Island where, before their eradication, 25 cats killed more than 1,000 black-vented shearwater (*Puffinus opisthomelas*) every month (Keitt *et al.* 2002).

Herbivores

Goats and sheep exert strong negative pressure on plant communities. They modify their species composition, which is often followed by soil erosion. They also compete with native herbivores (Parkes *et al.* 1996; Álvarez-Romero *et al.* 2008). In Mexico, goats had dramatic effects on the vegetation of Guadalupe Island (Moran 1996; Rodríguez-Malagón 2006; Luna-Mendoza *et al.* 2007), and also Espíritu Santo (León de la Luz and Domínguez-Cadena 2006), Cerralvo (Mellink 2002), and the Marías Archipelago (CONANP-SSP 2008). Sheep introduced to Socorro Island (Castellanos-Vera and Ortega-Rubio 1994) removed vegetation cover over most of the island and reduced habitat available for native birds (Rodríguez-Estrella *et al.* 1994).

RESPONSES TO INVASIONS

Island pest eradications

The eradication of invasive fauna on Mexican islands began in 1994-1995 with successful campaigns against feral cats on Asunción Island, feral cats and rats on San Roque Island (Aguirre-Muñoz *et al.* 2008), and rats and mice in Rasa Island (Ramírez-Ruiz and Ceballos-González 1996). Mammals remain the only vertebrate group eradicated from Mexican islands, with most of the successful examples using hunting, trapping, poisoning or a combination of these. Recently, radio-telemetry and trained dogs have been used. For large mammals, terrestrial and aerial hunting has been the most efficient

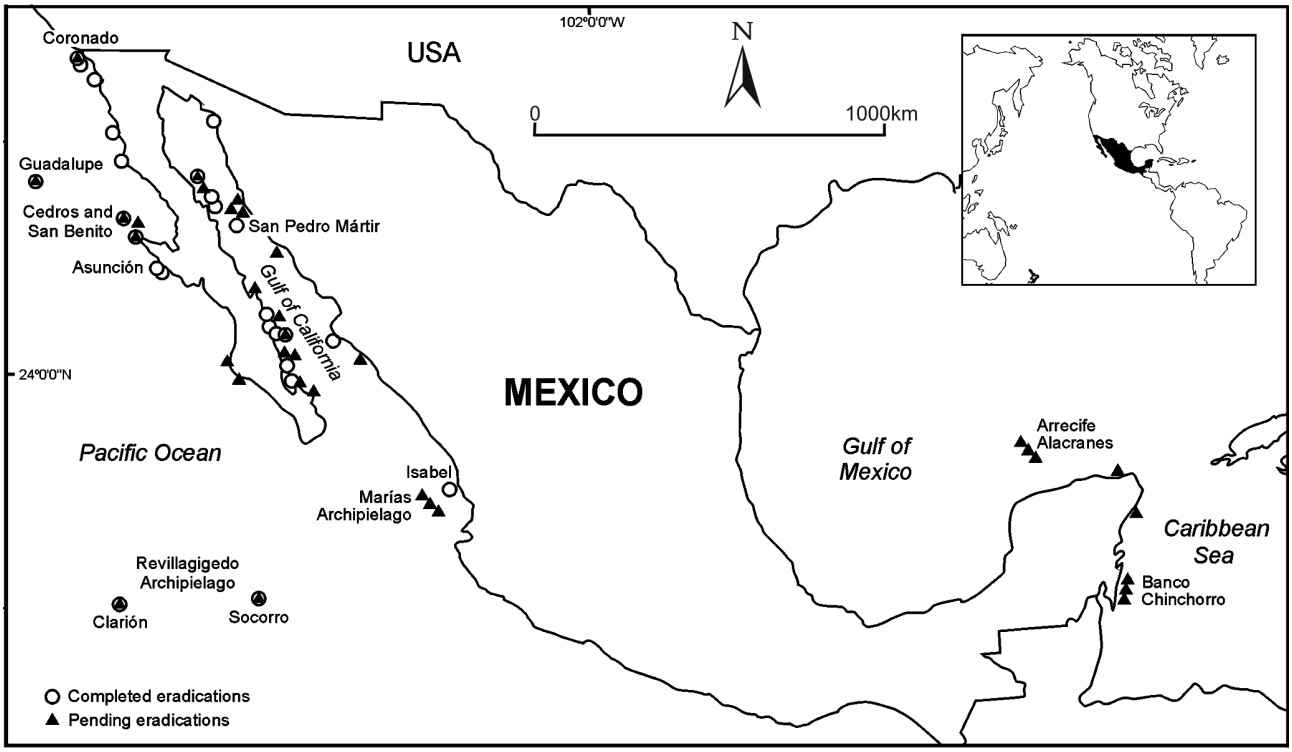

Fig. 1 Completed and pending eradications in Mexico between 1994 and 2010 (See Tables 1 and 3 for details).

Table 2 Likely extinctions of vertebrates after invasive species established on Mexican islands.

Species	Common name	Island	Year of last record	Year of last field search	Invasive species implicated and status	IUCN Category†
Birds						
Oceanodroma macrodactyla	Guadalupe storm-petrel	Guadalupe	1912 [A]	2000 [A]	Cat (SP), goat (ER) [1]	CR
Caracara lutosa	Guadalupe caracara	Guadalupe	1900 [B]	2003 [A]	Cat (SP), goat (ER) [1]	EX
*Zenaida graysoni**	Socorro dove	Socorro	1972 [O]	1981 [C]	Cat (SP), Sheep (SP)[1]	EW
Micrathene whitneyi graysoni	Elf owl	Socorro	1932 [D]	1981 [D]	Cat (SP) Sheep (SP) [1]	NE‡
Colaptes auratus rufipileus	Northern flicker	Guadalupe	1906 [B]	2003 [A]	Cat (SP) Goat (ER) [1]	NE‡
Thryomanes bewickii brevicauda	Bewick's wren	Guadalupe	1892 [B]	2003 [A]	Cat (SP) Goat (ER) [1]	NE‡
Regulus calendula obscurus	Ruby-crowned kinglet	Guadalupe	1953 [B]	2003 [A]	Cat (SP) Goat (ER) [1]	NE¥
Pipilo maculatus consobrinus	Spotted towhee	Guadalupe	1897 [B]	2003 [A]	Cat (SP) Goat (ER) [1]	NE‡
Aimophila ruficeps sanctorum	Rufous-crowned sparrow	Todos Santos	1927 [N]	2005 [L]	Cat (ER) [2]	NE‡
Mammals						
Chaetodipus baileyi fornicatus	Bailey's pocket mouse	Montserrat	1975 [E]	2003 [K]	Cat (ER) [2]	NE£
Neotoma anthonyi	Anthony's woodrat	Todos Santos	1950s [H]	2005 [L]	Cat (ER) [2]	EX
Neotoma bunkeri	Bunker's woodrat	Islas Coronado	1980s [E]	1997 [E]	Cat (ER) [2]	EX
Neotoma martinensis	San Martin Island woodrat	San Martín	1925 [I]	2006 [L]	Cat (ER) [2]	EX
Oryzomys nelsoni	Nelson's rice rat	María Madre	1898 [J]	2002 [J]	Cat (SP) ship rat (SP)[4]	EX
Peromyscus guardia harbisoni	Angel de la Guarda deer mouse	Granito	1973 [G]	1999 [G,P]	Ship rat (SP) [5]	CR
Peromyscus guardia mejiae	Angel de la Guarda deer Mouse	Mejía	1973 [G]	1999 [G,P]	Cat (ER) [2]	CR
Peromyscus maniculatus cineritius	Deer mouse	San Roque	1960's [F]	2009 [M]	Cat (ER) Ship rat (ER) [3]	NE±

†IUCN 2010. IUCN Red List of Threatened Species. Version 2010.1. <www.iucnredlist.org>. Downloaded on 06 April 2010.
CR=Critically endangered; E=Extinct; EW=Extinct in the wild; NE=Not evaluated.
SP= Still Present; ER= Eradicated.
* Extinct in the wild but bred in captivity in Frankfurt, Germany.
‡ Listed as extinct in the Official Mexican Norm NOM-059-SEMARNAT-2001 (DOF 06-03-2002).
¥ Listed as probably extinct in the Official Mexican Norm NOM-059-SEMARNAT-2001 (DOF 06-03-2002).
£ Listed as subject to special protection in the Official Mexican Norm NOM-059-SEMARNAT-2001 (DOF 06-03-2002).
± Listed as endangered in the Official Mexican Norm NOM-059-SEMARNAT-2001 (DOF 06-03-2002).
A= Barton *et al.* 2005; B= Jehl and Everett 1985; C=Jehl and Parkes 1983; D=Jehl and Parkes 1982; E=Álvarez-Castañeda and Ortega-Rubio 2003; F= Alvarez-Castañeda and Patton 1999; G=Mellink *et al*. 2002; H=Mellink 1992; I=Cortés-Calva *et al*. 2001; J=Ceballos and Oliva 2005; K=GECI 2003; L=Samaniego-Herrera *et al.* 2007; M=Félix-Lizárraga *et al.* 2009; N=Van Rossem 1947; O=CONANP-SEMARNAT 2004; P=Álvarez-Castañeda and Ortega Rubio 2003; 1= Aguirre-Muñoz *et al.* 2009a; 2=Ortega-Rubio and Castellanos-Vera 1994; 3=Nogales *et al.* 2004; 4=Donlan *et al.* 2000; 5= CONANP-SSP 2008.

technique, in combination with radio-telemetry. For small mammals such as cats and rabbits, the combination of hunting and trapping, supported by detection dogs, has been particularly effective. For rodents, aerial spread of rodenticide has proved to be the most effective practice (Samaniego-Herrera *et al.* 2009, 2011; Table 3).

Between 1995 and 2010, 49 invasive mammal populations have been eradicated from 15 islands in the Pacific Ocean and 15 in the Gulf of California (Table 3; Fig. 1). These restoration actions have protected at least 117 species of endemic plants, 85 species of endemic vertebrates, and more than 227 populations of seabirds over a total area of 50,744 ha (Fig. 2). Feral cats have been eradicated from 18 islands, rodents and rabbits from 14 islands, and ungulates from 8 islands. The most significant contribution has been the eradication of goats and sheep from Guadalupe and Socorro islands respectively (Fig. 2 and Fig. 3). Rodent eradications also contributed to

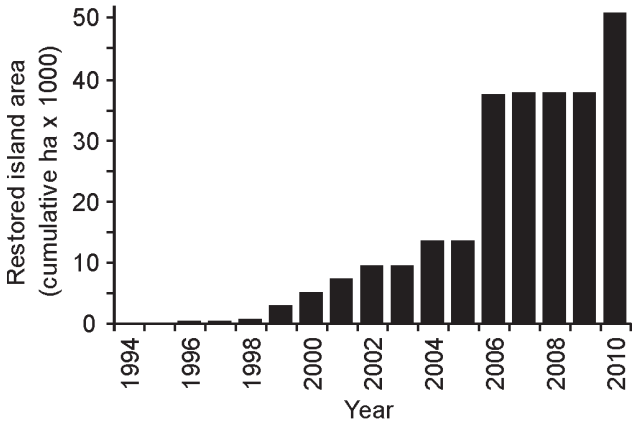

Fig. 2 Cumulative restored island area in Mexico from 1994 to 2010.

Table 3 Species, techniques and dates of eradication of invasive mammals from Mexican islands between 1994 and 2010.

Island	Area (ha)[£]	Species removed[‡]	Date of eradication	Methods	Year of last field search[‡]	References
Pacific Ocean						
Asunción	41	Cat	1994	Trap	2009	A,B,C,E,F,AA
Clarión	1958	Sheep, pig	2002	Hunt	2003	E,F
Coronado Norte	37[±]	Cats	1995-1996	Trap	2009	A,B,C,D,E,F
Coronado Sur	126[±]	Cat[1], goat[2] donkey	2003	Trap, hunt	2009	D,E,F,G,Z
Guadalupe[3]	24,171[±]	Rabbit, donkey	2002	Live removal*	2010	F,G
		Horse	2004	Live removal*		F,H
		Goat	2003-2006	Live removal*, trap, hunt and telemetry		F,I,J
		Dog[4]	2007	Live removal*, trap, hunt		E,F,I
		Goat, sheep	1997	Live removal*		A,D,E,F,K,U,V
Natividad	736[±]	Cat	1998-2000	Trap, hunt, live removal	2006	A,B,C,AB,AC
		Dog	2001	Live removal*		F
San Benito Este	146[±]	Rabbit	1999	Trap and hunt	2009	A,E,F,K,L,V
San Benito Medio	45[±]	Rabbit	1998	Trap and hunt	2009	A,E,F,K,L,V
San Benito Oeste	364[±]	Rabbit, goat	1998	Trap and hunt	2009	A,E,F,K,L,U,V
		Donkey*	2005	Live removal*		F,G
San Jerónimo	48[±]	Cat	1999	Trap and hunt	2006	B,C,D,F,K,AA
San Martín	265[±]	Cat	1999	Trap and hunt	2006	B,C,D,F,K,AA
San Roque	35	Cat[5]	1994	Trap	2009	A,B,C,D,E,F,K,AA
		Ship rat	1995	Bait stations		A,D,E,F,H,K,O,AD
Socorro	13,033[±]	Sheep	2010	Hunt and telemetry	2010	X
Todos Santos Norte	34[±]	Cat, rabbit	1999-2000	Trap and hunt	2009	A,B,C,E,F,K,V,AA,AC
		Donkey	2004	Live removal*		F,G
Todos Santos Sur	89[±]	Cat[¥]	1997-1998/ 1999/2004	Trap and hunt	2009	A,B,C,D,E,F,K,V
		Rabbit	1997	Trap and hunt	2009	A,B,C,D,E,F,K,V
Gulf of California						
Coronados	715	Cat	1998-1999	Trap	2008	B,C,K,M,N
Danzante	412	Cat	2000	Trap[€]	2008	C,F
Estanque	82	Cat	1999	Trap and hunt	2003	B,C,K,AA
Farallón de San Ignacio	17[±]	Ship rat	2007	Aerial broadcast	2009	F,P,AD
Isabel	80[±]	Cat[6]	1995-1998	Trap, hunt & bait stns	2009	A,B,C,E,F,K,Q
		Ship rat[7]	2009	Aerial broadcast		R, AD
Mejía	245	Cat	1999-2001	Trap and hunt	2005	B,C,E,F,K, AA,AB
Montserrat	1886	Cat[8]	2000-01/03	Trap and hunt	2008	B,C,E,F,K
Partida Sur	1533	Cat	2000	Live removal*	2007	B,C,E,F,K,AA,AB
Rasa[9]	57	Ship rat, house mouse	1995-1996	Bait stations	2009[§]	E,H,O,S,AD
San Jorge Este	9	Ship rat	2000-2002	Bait stations	2004	E,F,H,K,O,T,AD
San Jorge Medio	41	Ship rat	2000-2002	Bait stations	2004	E,F,H,K,O,T,AD
San Jorge Oeste	7	Ship rat	2000-2002	Bait stations	2004	E,F,K,T,AD
San Francisquito	374	Cat	2000	Trap and hunt	2005	B,C,E,F,K,AA
		Goat	1999	Hunt		F,U
San Pedro Mártir	267[±]	Ship rat	2007	Aerial broadcast	2009	F,P,AD
Santa Catalina (Catalana)	3890	Cat	2000-2004	Trap and hunt	2008	B,E,F,Y,Z
Total area	50,742					

[£] INEGI (2005), unless indicated otherwise; [±] Area estimated by Conservación de Islas through satellite imagery (Samaniego-Herrera *et al.* 2007; Conservación de Islas-CONANP 2009); [‡] Work conducted by Conservación de Islas unless indicated otherwise; *Small populations were removed alive; [§] E. Velarde. pers. comm. [€]During 2000 traps and track plots were set by CIBNOR's (Centro de Investigaciones Biológicas del Noroeste, S.C.) researchers to trap the feral cats. No cats were captured. However, during 2000 one cat was found dead on the island. Since then, no more tracks or signs have been recorded (Gustavo Arnaud pers. comm. 2010). [¥]Cats were reintroduced and eradicated in 1999 (Sánchez-Pacheco and Tershy 2000) and 2004 (Aguirre-Muñoz *et al.* 2004).

[1]First cat eradication: 2001 (Knowlton *et al.* 2007); [2]First goat eradication: 1999 (Campbell and Donlan 2005); [3]Cows were introduced in 1985 but died due to competition with goats (Rico-Cerda pers. comm.); [4]Feral population eradicated in 2005, domesticated

Footnotes to Table 3 continued:

individuals removed alive in 2007 (Aguirre-Muñoz *et al.* 2009b); [5]First cat eradication attempt: 1980s by SEDUE; [6]Project conducted by UNAM (Rodríguez *et al.* 2006); [7]First eradication attempt, conducted by UNAM, failed (Rodríguez-Juárez *et al.* 2006). [8]Two cats were reintroduced and removed during 2002 (GECI 2003). [9]Project conducted by UNAM (Ramírez Ruiz and Ceballos-González 1996).

A= Donlan *et al*. 2000; B= Wood *et al*. 2002; C= Nogales *et al*. 2004; D= Knowlton *et al.* 2007; E= Aguirre-Muñoz *et al.* 2008; F= Aguirre-Muñoz *et al*. 2009a; G= Carrión *et al*. 2006; H= Aguirre-Muñoz *et al*. 2005; I= Aguirre-Muñoz *et a*l. 2007; J= Luna-Mendoza *et al*. 2007; K= Tershy *et al*. 2002; L= Donlan *et a*l. 2002; M= Arnaud-Franco *et al*. 2000; N= Rodríguez-Moreno *et al*. 2007; O= Howald *et al*. 2007; P= Samaniego-Herrera *et al*. 2009; Q= Rodríguez *et al.* 2006; R-= Samaniego-Herrera *et al*. 2010; S= Ramírez-Ruiz and Ceballos-González 1996; T= Donlan *et al.* 2003; U= Campbell and Donlan 2005; V= Álvarez-Romero *et al*. 2008; W= Arata *et al*. 2009; X= Ortiz-Alcaraz *et al.* 2009; Y=Sánchez-Pacheco and Tershy 2002; Z=GECI 2003; AA=Sánchez-Pacheco and Tershy 2000; AB=Hermosillo-Bueno pers. comm. 2010; AC= Sánchez-Pacheco and Tershy 2001; AD= Samaniego-Herrera *et al*. 2011.

the total restored area, especially in the past three years, when aerial broadcast methods were used, supported by on-board differential GPS, satellite imagery and telemetry (Samaniego-Herrera *et al.* 2011). The efficiency of helicopter aerial broadcast and hunting is illustrated by comparison with traditional ground-based methods. Ground-based traditional methods on 25 islands represent 26% of the total area, compared with aerial-based methods on five islands, but involving 74% of the total area.

Regardless of the methods used, the ultimate objective of an eradication project is restoration of ecosystems. Each project carefully evaluates the risks to non-target species and ensures that the long-term benefits are greater than the short term impacts that can derive from those activities.

Seabird restoration

When introduced species have extirpated populations of seabirds, action may be required to attract birds to return. There has been no natural recolonisation by six species on Asunción and San Roque Islands after 14 years without introduced predators. Attempts are now being made to attract the birds back using sound systems, decoys, and mirrors (Félix-Lizarraga *et al.* 2009), simultaneously with systematic and long term monitoring. These methods have been used successfully elsewhere (Kress 1978; Podolsky 1990; Gummer 2003)

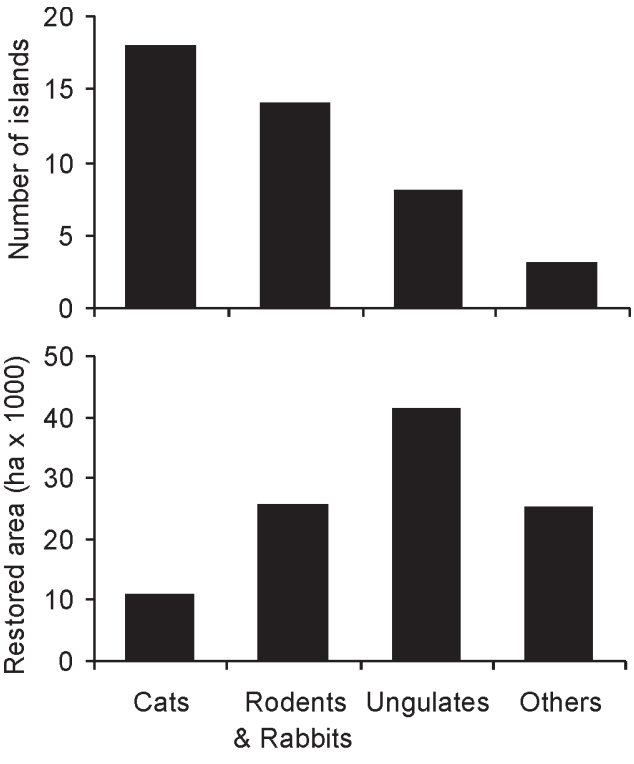

Fig. 3 Relationship between the number of islands with eradications and the restored island areas, by group of introduced species (see text and Table 3 for details).

ECOLOGICAL OUTCOMES OF ERADICATIONS

A lack of ecological information and the inherent richness of many island communities, pose challenges when evaluating, measuring and comparing the outcomes of eradications. Recovery may be documented for some species, but often the data are scarce and non systematic. Elsewhere, information has come from informal or anecdotal observations. Recently, there have been improvements in pre– and post–eradication monitoring, which allows more systematic evaluation of ecosystem recovery. The associated increase in cost remains a limiting factor.

Recovery of native species

On the Baja California Pacific islands, extirpated species such as Cassin's auklet (*Ptychroramphus aleuticus*), brown pelican (*Pelecanus occidentalis*) and Brandt's cormorant (*Phalacrocorax penicillatus*) have returned to breed (Wolf *et al.* 2006; Félix-Lizárraga *et al.* 2009). Four seabird species that have colonised islands represent new records; however, they could also have been extirpated long ago by cats and rats, before anyone recorded them. Vegetation also recovers. In the San Benito Archipelago, for example, two endemic species, the bush mallow (*Malva pacifica*) and the succulent live-forever (*Dudleya linearis*) are no longer at critical status after introduced rabbits were eradicated (Donlan *et al.* 2002, 2003).

In the Gulf of California, recolonisation by Craveri's murrelet (*Synthliboramphus craveri*) has been reported on San Pedro Mártir Island. Increased seabird reproductive success has also been documented, including a 60% increase in the nests of red-billed tropicbird (*Phaethon aethereus*) at Farallón de San Ignacio Island. There have also been new reports of plants, terrestrial birds, reptiles, and bats (Samaniego-Herrera *et al.* 2011, GECI unpublished data).

The bird attraction techniques used during the last two years are producing results. There are recorded interactions between elegant terns (*Thalasseus elegans*) and Heermann's gulls (*Larus heermanni*) and the attraction systems. During recent seasons these included placing nests with eggs among the decoys (Félix-Lizárraga *et al.* 2009).

The Socorro dove (*Zenaida graysoni*), endemic to Socorro Island, has been declared extinct in the wild. Merino sheep introduced to the island in the 1800s changed vegetative cover and structure. Later, cats and house mice were introduced. In combination, these introduced species are implicated in the extinction or endangerment of the endemic elf owl (*Micrathene whitneyi graysoni*), Socorro mockingbird (*Mimodes graysoni*), and Socorro dove. However, doves have been successfully breeding in zoos since 1987. The restoration process for reintroduction of Socorro doves to their native habitat is now under way.

Case study: Guadalupe Island

Guadalupe is a 24,171 ha volcanic island 250 km off the Baja California Peninsula (Fig. 1), being one of the most biodiverse and unique islands in the Pacific. The island has been the habitat for 223 species of vascular plants (17.5% endemic), eight species of seabirds (one extinct), eight

species of endemic terrestrial birds (five extinct) and three species of pinnipeds. Its surrounding marine environment is also unique and diverse.

During the 19th and 20th centuries, 46 species of plants and eight species of mammals were introduced to the island; four of the mammals became feral (Moran 1996). Overgrazing by goats decreased forest coverage from 3850 ha to 85 ha (Rodríguez-Malagón 2006), desert scrub was decreased from 10,550 ha to 800 ha (Oberbauer 2005), and some vegetation communities completely disappeared. Invasive plants spread throughout the island. Feral cats were probably responsible for the extinction of six of the nine species of endemic birds and reduced populations of other birds and invertebrates. The hunting of pinnipeds during the 18th and 19th centuries almost destroyed populations of the northern elephant seal (*Mirounga angustirostris*) and Guadalupe fur seal (*Arctocephalus townsendi*) (Hanna 1925).

The eradication of goats from Guadalupe Island in 2003-2006 provided the first step towards restoration of the native vegetation, with spectacular responses by some native plants. Seedlings of endemic trees, which were absent in 2003, appeared, and by 2009 included the endemic cypress (*Cupresssus guadalupensis guadalupensis*), pines (*Pinus radiata var. binata*), palms (*Brahea edulis*) and native oaks (*Quercus tomentella*). Species of plants believed extinct have reappeared, including the western tansymustard (*Descurainia pinnata*), coyote tobacco (*Nicotiana attenuata*), dense false gilia (*Allophyllum gilioides*), Guadalupe savroy (*Satureja palmeri*), redflower currant (*Ribes sanguineum*), bruckbush (*Ceanothus crassifolius*) and common woolly sunflower (*Eriophyllum lanatum* var. *grandiflorum*) (Junak *et al.* 2005; Luna-Mendoza *et al*. 2007; W. Henry pers. comm.; J. Hernández-Montoya pers. comm.). The eradication of feral dogs in 2007 has helped to protect birds and pinnipeds from predation. Invasive mammals remaining on the island are cats and mice (Table 1). To prevent more extinctions, cats have been controlled around seabird nesting areas since 2003. The eradication of cats and mice poses a major challenge because of Guadalupe's size and complexity. Conservación de Islas, a Mexican NGO, is working with Federal Government agencies to assess the best options for the eradication of these mammals.

Guadalupe Island is now a Biosphere Reserve. Environmental education and social work has been undertaken with the local community to demonstrate how conservation actions help to improve quality of life. Future advances in restoration of this island should be of national and international significance.

DISCUSSION

Public policies and government involvement

There has been growing cross-institutional collaboration for island management, especially between agencies of the Federal Government and Conservación de Islas. SEMAR has provided invaluable and sustained logistic support, transportation and accommodation. Beyond a regulatory role, the Ministry of Environment (SEMARNAT), through the Wildlife General Direction (DGVS) has facilitated documentation and permitting. The National Institute of Ecology (INE) has supported restoration work with significant economic resources, especially for Guadalupe Island, the Marías and Revillagigedo Archipelagos. CONANP plays a key role in the implementation of eradication programs, and along with the US Fish and Wildlife Service and the National Commission for the Knowledge and Use of Biodiversity (CONABIO), managed significant economic resources in 2008-2009 for the restoration of Mexican islands.

Government involvement is now taking a step forward. Island restoration and conservation is now a national priority to preserve the country's natural heritage. In 2010, CONABIO published the "National Strategy on Invasive Species: Prevention, Control and Eradication", a document which highlights the priority tasks for the future. Furthermore, INE, SEGOB, CONANP and Conservación de Islas are integrating the "National Strategy on Island Conservation and Sustainable Development", which will complement with the one on invasive species (Karina Santos del Prado pers. comm.).

Challenges for the restoration of Mexican islands

Given the level of institutional support now being provided, the eradication of all introduced mammals from Mexican islands is a strategic goal that could be achieved by 2025. There are at least 41 islands with 832 populations of 12 species of introduced mammals, with rodents, cats, and goats being the most widespread. The greatest challenges are provided on bigger islands with complex terrain and ecosystems, the presence of native mammals, and interaction with human activities. One such example is Cedros Island (34,933 ha) with six species of introduced mammals, 12 endemic species (including five mammals), and a human population of 4500 inhabitants. Another challenge is the implementation of new techniques such as hunting methods, toxins, and viruses which may currently be illegal in Mexico. Success will also require the retention of skilled operators and specialised scientists, the development of new lines of research, and an appropriate legal framework.

Information is now being collected on introduction pathways, distribution of invasive species, and actions required to mitigate their effects through prevention, control and eradication. The advances outlined in this review represent unprecedented action to preserve and conserve the country's natural heritage. Eradication projects against other introduced species such as birds, reptile, amphibians, invertebrates, and plants have not yet been implemented, and the effects of such species remain unknown. There is an urgent need to create or update the inventories of invasive alien species on islands, and identify the ecological and economical impacts they have. There is also an urgent need to promote research on the ecology of invasions and methods for eradication. Interdisciplinary research is also essential to establish the relationship between the people and the uses and movements of invasive organisms. Preventing introductions of new invasive species as well as containing the spread of those already in the country both pose big challenges. Success will require the consolidation of the collaboration approach between government and academic institutions, NGOs, local communities and funders. Ecotourism must also be critically analysed and its regulations enforced.

Finally, if all Mexican islands are to be restored, a long-term and sustainable funding scheme, and appropriate legislation and policies will be needed to facilitate the control and eradication of invasive species.

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