The history of mammal eradications in Hawai`i and the United States associated islands of the Central Pacific

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Abstract Many eradications of mammal taxa have been accomplished on United States associated islands of the Central Pacific, beginning in 1910. Commonly eradicated species are rabbits (*Oryctolagus cuniculus*), rats (*Rattus* spp.), feral cats (*Felis catus*), and several feral ungulates from smaller islands and fenced natural areas on larger Hawaiian Islands. Vegetation and avifauna have demonstrated dramatic recovery as a direct result of eradications. Techniques of worldwide significance, including the Judas goat method, were refined during these actions. The land area from which ungulates have been eradicated on large Hawaiian Islands is now greater than the total land area of some smaller Hawaiian Islands. Large multi-tenure islands present the greatest challenge to eradication because of conflicting societal interests regarding introduced mammals, mainly sustained-yield hunting. The difficulty of preventing reinvasion poses a persistent threat after eradication, particularly for feral pigs (*Sus scrofa*) on multi-tenure islands. Larger areas and more challenging species are now under consideration for eradication. The recovery of endangered Hawaiian birds may depend on the creation of large predator-proof exclosures on some of the larger islands. Large scale eradications of small Indian mongooses (*Herpestes auropunctatus*) would be beneficial to ground-nesting birds such as nēnē (*Branta sandvicensis*), but this has been achieved only in small exclosures.

Keywords: Carnivores, rabbits, recovery, rodents, ungulates, fences

INTRODUCTION

The terrestrial biota of the Central Pacific is defined by its degree of isolation. For example, the Hawaiian Archipelago is 3200 km from any continental land mass (Ziegler 2002). After tens of millions of years of evolutionary isolation from all mammals except bats, islands of the Central Pacific were besieged by rodents, carnivores and herbivores (Ziegler 2002). The first mammals were introduced by early canoe voyagers of the Pacific more than 1000 years ago (Kirch 1982). The discovery of the Hawaiian Islands by Cook in 1778, like many other islands of the Pacific, brought introductions of hoofed animals for beasts of burden, milk, hides and meat as well as additional species of rodent and predators to control rodents.

Ecological degradation ensued and groups of endemic plants and animals suffered extinctions, including flightless birds (Olson and James 1982; Steadman 1995), and nine percent of all Hawaiian flora (Sakai *et al*. 2002). After a century of settlement by westerners, the concept of eradicating non-native species came about as a solution to agricultural, public health, or economic problems (Tomich 1986), and more recently, to solve ecological problems (Hess *et al*. 2009). Reversing the effects of alien mammals has proven to be difficult, but successes have resulted in the recovery of native biota (Hess *et al*. 2009).

This paper reviews the history of invasive mammal management on United States associated islands of the Central Pacific, particularly as it involves eradications and the effects of these actions on native biota. Questions we address are: has the scale of eradications increased? Are additional species being eradicated? Are new techniques being developed and employed? We aim to provide perspective on the Central Pacific islands both in space and time, and how current and future management of invasive mammals compares to the past.

RESTORATION THROUGH ERADICATIONS

All eradications are listed in Table 1 and locations are given in Fig.1.

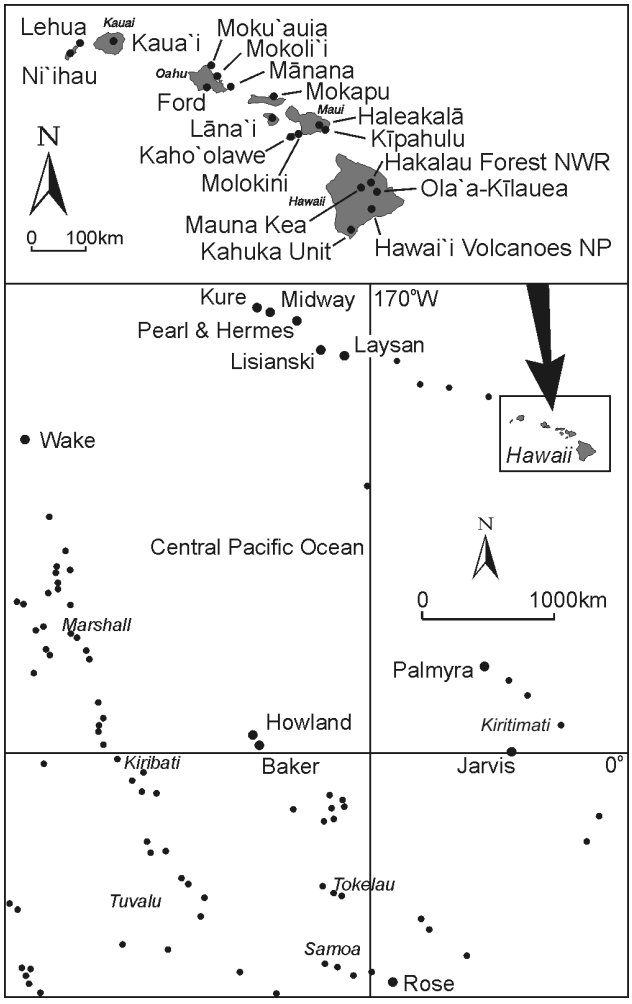

Fig. 1 Locations of mammal eradications from U.S. administered islands of the Central Pacific. Island group names (italicised) are included to provide location information.

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Table 1 Mammal eradications from U.S. administered islands of the Central Pacific.

Species Location	Area ha	Year Introduced	Eradicated	Method
Rabbits				
Laysan	400	1902	1923	Shooting
Lisianski	170	1903	< 1923	Starvation
Pearl & Hermes Atoll	30	< 1916	1928	Shooting
Ford, Pearl Harbor	183	< 1825	?	Starvation?
Mānana, O`ahu	25	< 1890	< 1985	Starvation
Molokini, Maui	8	< 1915	< 1965	?
Haleakalā, Maui	25	1989	1990	Snaring, shooting, and live-trapping
Kaua`i	?	2000s	2003	Trapping
Lehua Islet, Ni`ihau	110	< 1930	2006	Dogs and hunters
Total	951			
Pacific rats				
Rose Atoll, Samoa	6.3	< 1920	1992	Brodifacoum bait stns, live- & snap-traps, bromethalin
Green Island, Kure	129	?	1993	Brodifacoum bait stations, live- & snap-traps
Moku`auia, O`ahu	385	?	2000	Diphacinone bait stations, live- & snap-traps
Mokapu, Moloka`i	7	?	2008	Diphacinone aerial broadcast
Lehua Islet, Ni`ihau	110	?	--	Diphacinone aerial broadcast in 2009
Total	584			
Ship rats				
Eastern Is, Midway	134	1940s	1994	Brodifacoum bait stations, live-traps, snap-traps
Spit Island, Midway	1	1940s	1994	Brodifacoum, Live-traps
Sand Island, Midway	486	1940s	1997	Brodifacoum bait stations, live-traps
Palmyra Atoll	275	1940s	--	Brodifacoum hand broadcast in 2001
Mokoli`i, O`ahu	5	?	2002	Diphacinone bait stations
Moku`auia, O`ahu	385	2004	2006	Diphacinone bait stations, live- & snap-traps
Total	1011			
Cats				
Baker	164	1937	1960s	Direct pursuit-hunting
Howland	184	1937	1986	Shooting, trapping
Jarvis	450	1885? 1937	Died out 1990	Shooting, trapping, poisoning, virus
Wake	737	1960s	2004	Shooting, trapping
Total	1535			
Pigs				
Lāna`i	36,130	> 1911	mid-1930s	Shooting
Kīpahulu Valley, Maui	1400	1970s	1988	Snaring
HAVO, Hawai`i	7800 (16,180)	1790s	1989 (2007)	Dogs, shooting, snaring
HFNWR, Hawai`i	4450	1790s	2004	Dogs, shooting, snaring
Ola`a-Kīlauea	14,120	1790s	1995-2010	Driving, trapping, shooting, snaring
Total	72,280			
Goats				
Ni`ihau	18,910	1900s	1910–11	Contract Hunting
Jarvis	450	?	1935	Self-extirpation
Lāna`i	36,130	1800s	1981	Ground shooting
HAVO, Hawai`i	55,440	1778	1984	Drives, shooting, Judas
Haleakalā NP, Maui	13,690	> 1780	1989	Drives, shooting, Judas
Kaho`olawe	11,650	1793	1990	Helicopter & ground shooting, Judas
Mauna Kea, Hawai`i	32,110	1778	--	Drives, helicopter shooting since 1934
Total	136,270			
Sheep				
Lāna`i	36,130	mid-1800s	1980s	Ground shooting
Kaho`olawe	11,650	1858	1990s	Helicopter & ground shooting, Judas
Mauna Kea, Hawai`i	32,110	1778	--	Drives, helicopter shooting since 1936
Kahuku Unit, Hawai`i	46,800	1968	--	Ground shooting, dogs, helicopter shooting since 2004
Total	47,780			
Cattle				
HFNWR, Hawai`i	44,050	1800s	2004	Dogs, shooting, snaring, helicopter shooting

Rabbits

In the Northwestern Hawaiian Islands, European rabbits (*Oryctolagus cuniculus*) were introduced as a source of food to Lisianski and Laysan islands about 1902, and subsequently discovered on Southeast Island of Pearl and Hermes Atoll in 1916 (King 1973).

Rabbits were eradicated from Laysan and Lisianski in 1923 after a failed eradication attempt on Lisianski in 1912–1913 (King 1973). Compounding the effects of mice (present since 1846), the rabbits eliminated most of Lisianski's vegetation by 1914, which then caused starvation of the rabbits (Olson and Ziegler 1995). Eradication of rabbits on Laysan coincided with desertification and the extinction of the Laysan honeycreeper (*Himatione sanguinea freethii*), the Laysan millerbird (*Acrocephalus familiaris familiaris*), and the last observations of Laysan rail (*Porzana palmeri*) (Ely and Clapp 1973). Rabbits were also eradicated on Southeast Island of Pearl and Hermes Atoll 1928 by shooting (King 1973; Amerson *et al.* 1974).

Among the larger Hawaiian Islands, rabbits were on Ford, Mānana, and Molokini islands, but disappeared, perhaps due to starvation (Swenson 1986). An incipient rabbit population was eradicated in Haleakalā National Park (HALE) on Maui in 1990 by shooting, trapping and snaring (Loope *et al*. 1992), and another on Kaua`i was eradicated by trapping in 2003 (C. Martin pers. comm.). Intensive hunting eradicated rabbits from Lehua Islet near the island of Ni`ihau in 2005–2006 (B. Keitt and C. Swenson pers. comm.). Rabbit releases have occurred on the larger Hawaiian Islands, without establishing wild populations.

Rodents

The Polynesian or Pacific rat (*Rattus exulans*) was among the earliest introductions of Pacific voyagers more than 1000 years ago (Kirch 1982; Matisoo-Smith and Robins 2004). House mouse (*Mus musculus*) reached the Hawaiian Islands by 1816 aboard European ships and Norway rats (*R. norvegicus*) were noted in Hawai`i as early as 1835, but ship rats (*R. rattus*) were not documented until 1899, apparently after the construction of shipping wharfs (Atkinson 1977). Introduced rodents, particularly ship rats, prey on birds at all life history stages and compete by preying on invertebrates and seeds, often interrupting reproduction in plants (Lindsey *et al*. 2009). The effects of Pacific rats may have included the disappearance of native lowland forests of Hawai`i in as little as 50 years (Athens 2009).

The first rat eradication in 1990, by the U.S. Fish & Wildlife Service (USFWS) and the Samoan Department of Wildlife and Marine Resources, was Pacific rats on 6.3 ha Rose Atoll, American Samoa. WeatherBlok containing 0.005% brodifacoum was used in bait stations spaced 50 m apart over the entire island, along with live- and snap-traps (Morrell *et al*. 1991; Ohashi and Oldenburg 1992). This eradication failed but a subsequent treatment with Vengeance (0.01% bromethalin, an acute neurotoxin) was successful (Murphy and Ohashi 1991).

In the Northwestern Hawaiian Islands, Wildlife Services (WS) of the U.S. Department of Agriculture's Animal and Plant Health Inspection Service and the Hawai`i Department of Land and Natural Resources (DLNR) eradicated Pacific rats in 1993 from 129 ha Green Island, Kure Atoll, using brodifacoum bait stations (J. Murphy pers. comm.). In 1994 the U.S. Navy, USFWS and WS eradicated ship rats from Eastern and Spit Islands at Midway Atoll (J. Murphy pers. comm.). Trapping and baiting with WeatherBlok of 134 ha Eastern Island was completed within three months. No evidence of rats was found at bait stations after a year (Murphy 1997a). The eradication of rats from 1 ha Spit Island in 1990 was accomplished within a month with live traps, incidental baiting and rat nest removal (J. Gilardi pers. comm.; Murphy 1997a).

The successful Eastern and Spit Island eradications, combined with evidence of the impacts rats were having on Bonin petrel (*Pterodroma hypoleuca*), persuaded the U.S. Navy to fund rat eradication on Sand Island (Seto and Conant 1996). In July 1996, the 486 ha island was overlaid with two 50 m grids, one for brodifacoum bait stations and one for live traps (Murphy 1997b). The last rat sighting was in October 1997. Sand Island remains the largest island and the only permanently inhabited island in the U.S. from which rats have been removed. Growth of the Bonin petrel population from an estimated 32,000 nesting birds (Seto and Conant 1996) to more than 900,000 provides compelling evidence for the enormous benefits of rat eradication. Native vegetation on Midway, such as naupaka (*Scaevola taccada*) and nohu (*Tribulus cistoides*), also became noticeably more dense and abundant (N. Hoffman pers. comm.). Mice on Sand Island are now the only small mammal remaining in the Northwestern Hawaiian Islands.

At Palmyra Atoll in the equatorial Line Islands, rats prevent six seabird species from nesting. An attempt to eradicate ship rats from the atoll by WS failed in 2001. This was the most complex eradication attempt by Hawai`i-based wildlife managers, involving approximately 275 ha and 54 islets, some of which were densely vegetated with coconut palms (*Cocos nucifera*), naupaka bushes and pāpala kēpau (*Pisonia grandis*) trees (Ohashi 2001). Numerous factors contributed to the failure, among them high rainfall in a complex forest habitat which resulted in rat foraging ranges that were smaller than the 50 m bait station spacing, and high bait take by land crabs *Cardisonma carnifex*, *Coenobita brevimanus* and *C. perlatus*. A successful pilot eradication on several small islets using hand broadcast of brodifacoum at a rate of 90 kg/ha was conducted in July 2005 after the failure was evaluated.

The successes of rat eradication on remote islands have also brought about efforts to restore offshore islets of the main Hawaiian Islands. In 2002, the Offshore Islet Restoration Committee was formed to restore selected islets around the Hawaiian Islands. To date, rat eradications have been successful on Moku`auia and tiny Mokoli`i Islet, both near O`ahu, using traps and diphacinone in bait stations (J. Eijzenga pers. comm.). Wedge-tailed shearwaters (*Puffinus pacificus*) subsequently began fledging from Mokoli`i, although ship rats have apparently reinvaded (D. Smith pers. comm.). A joint project by the USFWS, Hawaii DLNR and WS to eradicate Pacific rats from 7 ha Mokapu Island off Moloka`i in February 2008 was the first rat eradication using an aerial application of a registered rodenticide (diphacinone) for conservation purposes in the U.S. (P. Dunlevy pers. comm.). Attempting to build on this precedent, diphacinone pellets were also broadcast by helicopter for Pacific rats in January 2009 on 110 ha Lehua Islet, but the eradication was unsuccessful (VanderWerf *et al*. 2007; P. Dunlevy pers. comm.).

Carnivores

Domestic cats (*Felis catus*) arrived with the earliest European explorers (Tomich 1986). "Wild" cats had spread as far as the wilderness of Kīlauea by 1840 (Brackenridge 1841). Feral cats continue to present challenges to managers of natural areas on islands where they are known to prey on birds, but there is little prospect for island-wide eradication (Lindsey *et al*. 2009). Cat predation of nesting wedge-tailed shearwaters on O`ahu, has caused total loss of reproductive success (Smith *et al*. 2002).

Cats were eradicated from Baker Island in 1964, Howland Island in 1987, and Jarvis Island in 1990 (Rauzon *et al*. 2011). Hunting on Baker and Howland sufficed, but Jarvis also required trapping, poisoning, and feline panleucopaenia virus to a limited extent (Rauzon 1985). These eradications resulted in the recolonisation of five extirpated seabird species (Rauzon *et al*. 2002). Feral cat eradication was completed on Wake Atoll in 2004 by Marine Endeavors. Seabird diversity and abundance as well as Pacific rats increased in the absence of cats (Rauzon *et al*. 2008), and rat eradication by Island Conservation is planned.

The small Indian mongoose (*Herpestes auropunctatus*) was introduced to the Hawaiian Islands from Jamaica in 1883 and released to reduce rat populations in sugar cane fields on Hawai`i Island, O`ahu, Moloka`i, and Maui (Hays and Conant 2007). Mongooses may have been effective at reducing damage to sugarcane by Norway rats for a short period of time prior to the arrival of ship rats in Hawai`i (Atkinson 1977). Mongooses are now regarded only as pests and predators of ground-nesting birds, particularly nēnē (Hawaiian goose; *Branta sandvicensis*) and waterbird species (Stone and Loope 1987; Banko 1992). Without adequate prevention, mongooses may yet colonise Kaua`i and Lāna`i, the fourth and sixth largest Hawaiian Islands. Mongoose eradication has been achieved only in small exclosures.

Ungulates

Pigs (*Sus scrofa*) from Island Southeast Asia were the first ungulates introduced to Central Pacific islands by the earliest colonists more than 1000 years ago (Kirch 1982; Larson *et al*. 2005). The effects of pigs are widespread in Hawai`i, and throughout the Pacific region. In Hawai`i, pigs may have remained near commensal situations until the admixture of other strains brought by Europeans beginning in 1793 (Ziegler 2002).

Goats were established on Ni`ihau in the early 1900s and eradication by contract hunting became warranted by 1910 or 1911 (Kramer 1971). Lāna`i was also affected by excessive browsing and, by 1900, large areas were deforested by sheep and goats introduced in the mid-1800s (Hobdy 1993). Charles Gay began goat and sheep eradication on his Lāna`i ranch in 1902 and fenced the summit cloud forest to protect the watershed. The ornithologist George C. Munro came to run Gay's ranch in 1911 and spent much of his first decade there shooting sheep and goats. He also began eliminating pigs that had been released in 1911. Munro eradicated pigs from Lāna`i by the mid-1930s, feral goats by 1981, and feral sheep in the 1980s. Introductions of axis deer (*Axis axis*) in 1920, and European mouflon sheep (*Ovis gmelini musimon*) in 1954, continue to limit vegetation recovery on Lāna`i.

Feral sheep have repeatedly reached excessive densities on Mauna Kea, devastating the watershed and dry subalpine woodland environment. Foresters for the Territory of Hawai`i conducted sheep drives starting in 1934 that eliminated tens of thousands. The Mauna Kea Forest Reserve (MKFR) was fenced in 1935-1937 (Bryan 1937a) and nearly 47,000 sheep and over 2200 other ungulates were removed in the following 10 years by foresters and Civilian Conservation Corps workers using drives on foot and horseback (Bryan 1937b, 1947). Populations rebounded when sport hunting became a management goal of wildlife biologists after World War II and by 1960, the dire condition of the Mauna Kea forest was decried (Warner 1960). Despite this knowledge, European mouflon were hybridised with feral sheep and released between 1962 and 1966 to improve hunting opportunities (Giffin 1982). Scowcroft (1983), Scowcroft and Giffin (1983), and Scowcroft and Sakai (1983) used exclosures, aerial photography and studied tree size classes to demonstrate the effects of browsing and bark-stripping by sheep, cattle, and goats on the subalpine vegetation. U.S. Federal District court orders of 1979 and 1986 mandated the removal of goats and sheep to protect the endangered palila (*Loxioides bailleui*) that feed and raise their nestlings on māmane (*Sophora chrysophylla*) seed pods. More than 87,000 sheep have been removed from the MKFR over a 75-year period, but sheep are still far from being eradicated. The fence surrounding Mauna Kea has not been maintained and several hundred sheep are removed each year by aerial hunting from helicopters (Banko *et al*. 2009).

Goats had been removed from Hawai`i Volcanoes National Park (HAVO) on Hawai`i Island since 1927 but with no lasting effect due to reinvasion from the reservoir of animals in surrounding areas (Baker and Reeser 1972). Managers of Hawai`i's National Parks took action on the recommendation of the Leopold Report on Wildlife Management in National Parks (1963), which stated: "A visitor who climbs a mountain in Hawaii ought to see mamane trees and silverswords, not goats." The eradication of goats from 55,400 ha of the park took place from 1968 to 1984 (Tomich 1986). Goat eradication in HAVO proved the technical feasibility of eradicating ungulates from large areas of multi-tenure islands and developed specific techniques necessary to accomplish the task. The Judas goat method, which uses radio-telemetry to take advantage of gregarious behaviour in ungulates, has been replicated in many other management operations (Taylor and Katahira 1988). The re-invasion problem was solved by dividing areas into fenced units of manageable size, a difficult logistical process at the time for large areas and dense tropical forests on volcanic substrates. After a century and a half of degradation, a previously unknown endemic plant species, `āwikiwiki or *Canavalia kauensis* (now *C. hawaiiensis*), was found growing on the dry lowlands of Kukalau`ula in the absence of goats (St. John 1972).

At Haleakalā National Park (HALE) on Maui, 51 km of the 6920 ha Crater District was fenced between 1983 and 1987. Goats were also eliminated from the 4542 ha Kīpahulu District by the late 1980s (Stone and Holt 1990), and eradication of goats from the 13,700 ha park was completed in 1989 using techniques developed in HAVO (L. Loope pers. comm.).

Goats and sheep were eradicated from Kaho`olawe Island in 1990 by ground shooting, helicopter hunting, and the use of Judas animals (Kaho`olawe Island Conveyance Commission 1993). Goats and sheep had contributed to the loss of as much as 5 m of soil and interfered with livestock operations before the island became a bombing and shelling range after World War II (Kramer 1971).

The National Park Service was also the first to eradicate pigs from large areas of the Hawaiian Islands. Due to the steep terrain of Maui, feral pigs did not begin to invade the remote Kīpahulu Valley until the 1970s (Anderson and Stone 1993). Conventional control methods such as trapping and hunting dogs were precluded because helicopters were needed for access. Snaring was used to eradicate pigs from a 1400 ha area of Kīpahulu during a 45-month period beginning in 1978. Hunting dogs, shooting and snaring were also used to remove pigs from 7800 ha of HAVO from 1980–1989 (Katahira *et al*. 1993). The area from which pigs have been removed in HAVO increased to 16,200 ha by 2007 (D. Benitez pers. comm.). Native understory in the `Ōla`a Forest koa unit of HAVO increased 48% from 1991 to 1998, largely in the first two years following pig removal (Loh and Tunison 1999).

Hakalau Forest National Wildlife Refuge (HFNWR), also on Hawai`i Island, employed similar methods to remove pigs from a 4500 ha area in 1988–2004. Cattle were eradicated concurrently. The long period of time to complete removal was due in part to the large size of one management unit (> 2000 ha), interspersed areas of continued sustain-yield hunting, high densities of pigs, and relatively late use of snares (Hess *et al*. 2007). Preventing reinvasion into pig-free areas requires maintenance in perpetuity. Fences must be inspected monthly for damage and corrosive volcanic environments require fence replacement every 5–15 years.

The Nature Conservancy of Hawai`i (TNCH), the Natural Area Reserve System of the Hawai`i Division of Forestry and Wildlife, East Maui Watershed Partnership and the Three-Mountain Alliance of Hawai`i Island have all adopted and refined techniques for managing ungulates across larger landscapes. Many of these lands adjoin each other, thereby creating buffers or blocks of ungulate-free areas with high conservation value. While techniques to control and remove ungulates are well-established, some pose additional new threats. European mouflon have not yet reached their full distribution on Hawai`i Island and may invade conservation areas that have fences < 2 m tall. Axis deer populations are growing on Maui where they were introduced in 1960 (Tomich 1986). Game farms and ranches may inadvertently (and illegally) release additional ungulate species.

Perspective on Size of Eradications

We examined the area from which alien mammals have been eradicated to determine trends and consider whether eradications are increasing, decreasing, or unchanged over time. There has been no significant increase in the area from which rats (linear regression; coefficient = 0.018, F_{10} = 0.04, p = 0.851), rabbits (coefficient = -0.021, F_6 = 2.26, p = 0.193) and cats (coefficient = 0.150, F_3 = 6.62, p = 0.124) have been eradicated but cats show the strongest positive trend (r^2 = 0.77). The number of islands from which rabbits can be eradicated is now virtually zero. Rodent eradications have only recently begun in earnest. Despite the small number of islands from which cats have been eradicated, there appears to be an incipient pattern of application of successful techniques to larger islands. The trend in ungulates is more difficult to interpret because of incremental removal of contiguous populations on larger islands, repeated reinvasion, and lack of documentation (coefficient = -0.862, F_{13} = 0.36, p = 0.562). There were some unprecedented large-area ungulate eradications at a relatively early time, but later eradications have been of smaller areas.

Table 2 Areas from which ungulates have been eradicated in the Hawaiian Islands based on unpublished data from The Nature Conservancy of Hawai`i (TNCH). Other agency acronyms are: East Maui Watershed Partnership (EMWP), Hawai`i Division of Forestry and Wildlife (DOFAW), Kaho`olawe Island Reserve Commission (KIRC), National Park Service (NPS), National Tropical Botanical Garden (NTBG), Natural Area Reserve System (NARS), Three-Mountain Alliance (TMA), U.S. Fish & Wildlife Service (USFWS) and West Maui Mountains Watershed Partnership (WMMWP).

Island/Location	Agency	Area ha
Hawai`i		
HAVO NP	NPS	23,910
Hakalau NWR	USFWS	4240
Ōla`a-Kīlauea	TMA	35,030
Kona Hema	TNCH	3270
Pōhakuloa Training Area	U.S. Army	3000
Pu`u Maka`ala	NARS	1170
Kīpāhoehoe	NARS	580
Pu`u Wa`awa`a	DOFAW	100
Manukā	NARS	40
Pu`u O Umi	NARS	30
Ka`ūpūlehu	NTBG	30
Total		39,920
Maui Nui		
Kaho`olawe	KIRC	11,550
Haleakalā NP	NPS	10,610
West Maui	WMMWP	5760
East Maui	EMWP	2710
Waikamoi	TNCH	2180
East Maui	NARS	810
Auwahi	`Ulupalakua Ranch	10
Olokui, Moloka`i	NARS	680
Kūka`iwa`a Pen, Moloka`i	NPS	60
Total		34,340
Kaua`i		
Alaka`i	DOFAW	70
O`ahu		
Wai`anae Range	NARS	110
Wai`anae Range	U.S. Army	70
Pe`ahināi`a, Ko`olau Range	U.S. Army	50
Honouliuli	TNCH	70
Total		300
Grand Total		74,620

THE NEAR FUTURE FOR RECOVERY AND REINTRODUCTIONS

Eradications of rodents, cats, and rabbits from smaller islands of the Central Pacific have been beneficial to seabirds but there are a limited number of such islands. The restoration of landbirds and terrestrial biota depends on our ability to manage pests at the landscape level of larger islands. Societal values for hunting ungulates and harbouring outdoor pets necessitates expensive barriers to exclude these animals from pest-free refuges on multi-tenure islands. Careful planning and multiple pest management strategies may be used to maximise the area of pest-free refuges in relation to boundary perimeter that must be fenced. There is roughly 75,000 ha of ungulate-free area in the larger Hawaiian Islands (TNCH, unpubl. data; Table 2), but this comprises only about 19% of all forest bird habitat (Price *et al*. 2009). There is no significant area from which all mammalian pests have been eradicated. This presents obstacles to the reintroduction of native species which today exist only in captivity, such as the `alalā (Hawaiian crow; *Corvus hawaiiensis*) which requires large areas with diverse native understory food plants, and is susceptible to predation by rats and toxoplasmosis hosted by feral cats (Work *et al*. 2000). Successful reintroductions of species like `alalā back into the wild will depend on the ability of landowners and management agencies to establish and maintain large pest-free areas across ownership boundaries for the indefinite future.

CONCLUSION

The concept of eradication arose independently and at a relatively early time in the Central Pacific due to the necessity to protect fragile small-island ecosystems, forested watersheds and ranching operations on larger islands. Techniques of worldwide significance have been developed here, particularly during the eradication of ungulates. In their review of feral goat eradications on islands, Campbell and Donlan (2005) acknowledged the development of the Judas goat technique in Hawai`i (Taylor and Katahira 1988), but they made no mention of the goat-free areas created by this technique in the National Parks of Hawai`i, which are larger than the combined area of Ni`ihau, Lāna`i and Kaho`lawe. Although there is a negligible amount of area that is entirely pest-free on the larger Hawaiian Islands, many conservation agencies and landowners are developing methods and capacity for this goal and proposing larger island-wide eradications, such as cats and rodents from Kaho`olawe. There are now few remaining uninhabited small islands with alien mammals in the Central Pacific. Regulation of toxicants in the U.S. (Fagerstone *et al*.1990; Poché 1992) and conflicting societal interests between conservation, sustained-yield hunting and free-ranging pets continue to present challenges for the management of larger natural areas on multi-tenure islands. Future prospects for eradications over the entire area of the largest islands are limited, but there is potential for creating fenced areas free from ungulates on public lands, which are inhabited by much of the endemic Central Pacific biota.

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REFERENCES

Amerson, Jr, A.B.; Clapp, R.B. and Wirtz, II, W.O. 1974. The natural history of Pearl and Hermes reef, Northwestern Hawaiian Islands. *Atoll Research Bulletin 174*: 1-306.

Anderson, S. J. and Stone, C.P. 1993. Snaring to remove feral pigs *Sus scrofa* in a remote Hawaiian rain forest. *Biological Conservation 63*: 195-201.

Athens, S.J. 2009. *Rattus exulans* and the catastrophic disappearance of Hawai`i's native lowland forest. *Biological Invasions 11*: 1489-1501.

Atkinson, I.A.E. 1977. A reassessment of factors, particularly *Rattus rattus* L., that influenced the decline of endemic forest birds in the Hawaiian Islands. *Pacific Science 31*: 109-133.

Baker, J.K. and Reeser, D.W. 1972. Goat management problems in Hawaii Volcanoes National Park: A history, analysis, and management plan. U.S. Department of the Interior National Park Service Natural Resources Report Number 2. Office of the Chief Scientist, Washington D.C.

Banko, P.C. 1992. Constraints on productivity of wild Nene or Hawaiian Geese *Branta sandvicensis*. *Wildfowl 43*: 99-106.

Banko, P.C.; Brinck, K.W.; Farmer, C. and Hess, S.C. 2009. Recovery programs: palila. In: Pratt, T.; Banko, P.; Atkinson, C.; Jacobi, J. and Woodworth, B. (eds.). *Conservation biology of Hawaiian forest birds: implications for island avifauna*, pp. 513-532. New Haven, CT, Yale University Press, U.S.A.

Brackenridge, W.D. 1841. Journal kept while on the U.S. exploring expedition, 1838-1841. Unpublished manuscript at the Maryland Historical Society, U.S.A.

Bryan, L. W. 1937a. The big fence on the Big Island. *Paradise of the Pacific 49*: 15, 30.

Bryan, L. W. 1937b. Wild sheep in Hawaii. *Paradise of the Pacific 49*: 19, 31.

Bryan, L. W. 1947. Twenty-five years of forestry work on the Island of Hawaii. *Hawaii Planters' Record 51*: 1-80.

Campbell, K. and Donlan, C.J. 2005. Feral goat eradications on islands. *Conservation Biology 19*: 1362-1374.

Ely, C.A. and Clapp, R.B. 1973. The natural history of Laysan Island, Northwestern Hawaiian Islands. *Atoll Research Bulletin 171*: 1-361

Fagerstone, K.A.; Bullard, R.W. and Ramey, C.A. 1990. Politics and economics of maintaining pesticide registrations. *Proceedings of the Vertebrate Pest Conference 14*: 8-11.

Giffin, J.G. 1982. Ecology of the mouflon sheep on Mauna Kea. State of Hawaii, Department of Land and Natural Resources, Division of Forestry and Wildlife, Honolulu, Hawaii.

Hays, W.S.T. and Conant, S. 2007. Biology and impacts of Pacific island invasive species. 1. A worldwide review of effects of the small Indian mongoose, *Herpestes javanicus* (Carnivora: Herpestidae). *Pacific Science 61*: 3-16.

Hess, S.C.; Jeffrey, J.; Ball, D.L. and Babich, L. 2007. Efficacy of feral pig removals at Hakalau Forest National Wildlife Refuge. *Transactions of the Western Section of The Wildlife Society 42*: 53-67.

Hess, S.C.; Swift, C.E.; Campbell III, E.W.; Sugihara, R.T. and Lindsey, G.D. 2009. Controlling small mammals. In: Pratt, T.; Banko, P.; Atkinson, C.; Jacobi, J. and Woodworth, B. (eds.). *Conservation biology of Hawaiian forest birds: implications for island avifauna*, pp. 425-447. New Haven, CT, Yale University Press, U.S.A.

Hobdy, R. 1993. Lāna`i - A case study: The loss of biodiversity on a small Hawaiian Island. *Pacific Science 47*: 201-210.

Kaho`olawe Island Conveyance Commission. 1993. Kaho`olawe Island: restoring a cultural treasure. Kaho`olawe Island Conveyance Commission, Wailuku, HI, U.S.A.

Katahira, L.K.; Finnegan, P. and Stone, C.P. 1993. Eradicating feral pigs in montane mesic habitat at Hawaii Volcanoes National Park. *Wildlife Society Bulletin 21*: 269-274.

King, W.B. 1973. Conservation status of birds of Central Pacific islands. *Wilson Bulletin 85*: 89-103.

Kirch, P.V. 1982. The impact of the prehistoric Polynesian on the Hawaiian ecosystem. *Pacific Science 36*: 1-14.

Kramer, R.J. 1971. *Hawaiian land mammals*. Rutland, Vermont, Charles E. Tuttle Company, Inc. 347 pp.

Larson, G.; Dobney, K.; Albarella, U.; Fang, M.; Matisoo-Smith, E.; Robins, J.; Lowden, S.; Finlayson, H.; Brand, T.; Willerslev, E.; Rowley-Conwy, P.; Andersson L., and Cooper, A. 2005. Worldwide phylogeography of wild boar reveals multiple centers of pig domestication. *Science 307*:1618-1621.

Leopold, A.S.; Cain, S.A.; Cottam, C.M.; Gabrielson, I.M. and Kimball, T.L. 1963. Wildlife management in the national parks. *Transactions of the North American Wildlife Conference 24*: 28-45.

Lindsey; G.D.; Hess, S.C.; Campbell III, E.W. and Sugihara, R.T. 2009. Small mammals as predators and competitors. In: Pratt, T.; Banko, P.; Atkinson, C.; Jacobi, J. and Woodworth, B. (eds.). *Conservation biology of Hawaiian forest birds: implications for island avifauna*, pp. 274-292. New Haven, CT, Yale University Press, U.S.A.

Loh, R.K. and Tunison, J.T. 1999. Vegetation recovery following pig removal in `Ola`a-Koa rainforest unit, Hawaii Volcanoes National Park. Pacific Cooperative Studies Unit Technical Report 123. University of Hawai`i, Honolulu, HI, U.S.A.

Loope, L.L.; Medeiros, A.C.; Minyard, W.; Jessel, S. and Evanson, W. 1992. Strategies to prevent establishment of feral rabbits on Maui, Hawaii. *Pacific Science 46*: 402- 403.

Matisoo-Smith, E. and Robins, J.H. 2004. Origins and dispersals of Pacific peoples: Evidence from mtDNA phylogenies of the Pacific rat. *Proceedings of the National Academy of Sciences 101*: 9167-9172.

Morrell, T.E.; Ponwith, B.; Craig, P.; Ohashi, T.; Murphy, J. and Flint, E. 1991. Eradication of Polynesian rats (*Rattus exulans*) from Rose Atoll National Wildlife Refuge, American Samoa. DMWR Biological Report Series No. 20.

Murphy, J.G. 1997a. Rat eradication on Eastern and Spit Island, Midway Atoll National Wildlife Refuge. Unpublished Report. USDA, APHIS ADC. Honolulu, HI, U.S.A.

Murphy, J.G. 1997b. Rat eradication on Sand Island, Midway Atoll National Wildlife Refuge. Unpublished Report. USDA, APHIS ADC. Honolulu, HI, U.S.A.

Murphy, J.G. and Ohashi, T.J. 1991. Report of rat eradication operations conducted under specific emergency exemption to use Talon-G containing brodifacoum in a field situation on Rose Atoll National Wildlife Refuge, American Samoa. USDA, APHIS ADC. Honolulu, HI.

Ohashi, T.J. 2001. Environmental assessment for the rat eradication on Palmyra Atoll. Prepared by the U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, Honolulu, HI U.S.A.

Ohashi, T.J. and Oldenburg, J.G. 1992. Endangered species in the Pacific islands: the role of Animal Damage Control. *Proceedings of the Vertebrate Pest Conference 15*: 32-35.

Olson, S.L. and James, H.F. 1982. Fossil birds from the Hawaiian Islands: Evidence for wholesale extinction by man before western contact. *Science 217*: 633-635.

Olson, S.L. and Ziegler, A.C. 1995. Remains of land birds from Lisianski Island, with observations on the terrestrial avifauna of the Northwestern Hawaiian Islands. *Pacific Science 49*: 111-125.

Poché, R.M. 1992. How GLP provisions influence costs of rodenticide field evaluations. *Proceedings of the Vertebrate Pest Conference 15*: 245-248.

Price, J.P.; Jacobi, J.D.; Pratt, L.W.; Warshauer, F.R. and Smith, C.W. 2009. Protecting forest bird populations across landscapes. In: Pratt, T.; Banko, P.; Atkinson, C.; Jacobi, J. and Woodworth, B. (eds.). *Conservation biology of Hawaiian forest birds: implications for island avifauna*, pp. 381-404. New Haven, CT, Yale University Press, U.S.A.

Rauzon, M.J. 1985. Feral cats on Jarvis Island: Their effects and their eradication. *Atoll Research Bulletin 282*: 1-32.

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*: 1-23.

Rauzon, M.J.; Forsell, D.J. and Flint, E.N. 2002. Seabird re-colonisation after cat eradication on equatorial Jarvis, Howland, and Baker Islands, USA, Central Pacific. In: Veitch, C.R. and Clout, M.N. (eds.). *Turning the tide: the eradication of invasive species,* pp. 79-84. IUCN, SSC, Invasive Species Specialist Group, IUCN, Gland, Switzerland and Cambridge, U.K.

Rauzon, M.J.; Forsell, D.J.; Flint, E.N. and Gove, J. 2011. Howland, Baker and Jarvis Islands 25 years after cat eradication: Recovery in a bio-geographical context. In: Veitch, C. R.; Clout, M. N. and Towns, D. R. (eds.). *Island invasives: eradication and management*, pp. 345-349. IUCN, Gland, Switzerland.

St. John, H. 1972. *Canavalia kauensis* (Leguminosae) a new species from the island of Hawaii. Hawaiian Plant Studies 39. *Pacific Science 26*: 409-414.

Sakai, A.K.; Wagner, W.L. and Mehrhoff, L.A. 2002. Patterns of endangerment in the Hawaiian flora. *Systematic Biology 51*: 276-302.

Scowcroft, P.G. 1983. Tree cover changes in mamane (*Sophora chrysophylla*) forests grazed by sheep and cattle. *Pacific Science 37*: 109-119.

Scowcroft, P.G. and Giffin, J.G. 1983. Feral herbivores suppress the regeneration of mamane and other browse species on Mauna Kea, Hawaii. *Journal of Range Management 36*: 638-645.

Scowcroft, P.G. and Sakai, H.F. 1983. Impacts of feral herbivores on mamane forests of Mauna Kea, Hawaii: Bark stripping and diameter class structure. *Journal of Range Management 36*: 495-498.

Seto, N.W. and Conant, S. 1996. The effects of rat predation on the reproductive success of the Bonin Petrel on Midway Atoll. *Colonial Waterbirds 19*: 171-185.

Smith, D.G.; Polhemus, J.T. and VanderWerf, E.A. 2002. Comparison of managed and unmanaged Wedge-tailed Shearwater colonies on O`ahu: Effects of predation. *Pacific Science 56*: 451-457.

Steadman, D.W. 1995. Prehistoric extinctions of Pacific island birds: Biodiversity meets zooarchaeology. *Science 267*: 1123-1131.

Stone, C.P. and Holt, R.A. 1990. Managing the invasions of alien ungulates and plants in Hawaii's natural areas. *Monographs in Systematic Botany from the Missouri Botanical Garden 32*: 211-221.

Stone, C.P. and Loope, L.L. 1987. Reducing negative effects of introduced animals on native biotas in Hawaii: What is being done, what needs doing, and the role of National Parks. *Environmental Conversation 14*: 245-258.

Swenson, J. 1986. Is Manana Island now "Rabbitless Island?" *`Elepaio 46*: 125-126.

Taylor, D. and Katahira, L. 1988. Radio telemetry as an aid in eradicating remnant feral goats. *Wildlife Society Bulletin 16*: 297-299.

Tomich, P.Q. 1986. Mammals in Hawai`i: *A Synopsis and Notational Bibliography*, 2nd Ed. Honolulu, Bishop Museum Press.

VanderWerf, E.A.; Wood, K.R.; Swenson, C.; LeGrande, M.; Eijzenga, H. and Walker, R.L. 2007. Avifauna of Lehua Islet, Hawai`i: Conservation value and management needs. *Pacific Science 61*: 39-52.

Warner, R.E. 1960. A forest dies on Mauna Kea. *Pacific Discovery 13*: 6-14.

Work, T.M.; Massey, J.G.; Rideout, B.A.; Gardiner, C.H.; Ledig, D.B.; Kwok, O.C.H. and Dubey, J.P. 2000. Fatal toxoplasmosis in free-ranging endangered `Alala from Hawaii. *Journal of Wildlife Diseases 36*: 205-212.

Ziegler, A.C. 2002. Hawaiian natural history, ecology, and evolution. Honolulu, University of Hawai`i Press, U.S.A.