Federal Collaboration in Science for Invasive Mammal Management in U.S. National Parks and Wildlife Refuges of the Pacific islands

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ABSTRACT: Some of the most isolated islands in the Pacific Ocean are home to US National Parks and Wildlife Refuges. These islands are known for flora and fauna that occur nowhere else, but also for invasive species and other factors which have resulted in the disproportionate extinction of native species. The control of invasive mammals is the single most expensive natural resource management activity essential for restoring ecological integrity to parks in the Hawaiian Islands, American Samoa, and the islands of Guam and Saipan. Science-based applications supporting management efforts have been shaped by longstanding collaborative federal research programs over the past four decades. Consequently, feral goats (*Capra hircus*) have been removed from >690 km^2 in National Parks, and feral pigs (*Sus scrofa*) have been removed from >367 km^2 of federal lands of Hawai‘i, bringing about the gradual recovery of forest ecosystems. The exclusion of other non-native ungulates and invasive mammals is now being undertaken with more sophisticated control techniques and fences. New fence designs are now capable of excluding feral cats (*Felis catus*) from large areas to protect endangered native waterfowl and nesting seabirds. Rodenticides which have been tested and registered for hand and aerial broadcast in Hawai‘i have been used to eradicate rats from small offshore islands to protect nesting seabirds and are now being applied to montane environments of larger islands to protect forest birds. Forward-looking infrared radar (FLIR) is also being applied to locate wild ungulates which were more recently introduced to some islands. All invasive mammals have been eradicated from some remote small islands, and it may soon be possible to manage areas on larger islands to be free of invasive mammals at least during seasonally important periods for native species.

Key Words: ecosystem recovery, invasive mammals, island ecosystems, predators, research, rodents, ungulates.

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INTRODUCTION

The remote oceanic islands of Hawaiʻi, often described as the most isolated on Earth, exemplify the transformative effects that introduced mammals can bring to insular terrestrial ecosystems. The founding biota of the Hawaiian Archipelago had to possess extraordinary dispersal capabilities to cross half of the Pacific Ocean, and many groups of organisms with lesser capabilities have never become naturally established (Ziegler 2002). Consequently, the Hawaiian Islands, like many other isolated oceanic islands, developed in the complete absence of all ground-dwelling mammals and their associated ecological processes (Carlquist 1970). The discovery of the Hawaiian Archipelago by ocean-voyaging Polynesians and the introductions of several mammals forever altered the ecosystems of these islands. The Polynesian or Pacific rat (*Rattus exulans*) and domestic swine (*Sus scrofa*) were among the first terrestrial mammals to be introduced to the Hawaiian Islands more than 1,000 years ago (Kirch 1982).

Archaeological evidence documented domestic pigs known as *puaʻa* which originated from Island Southeast Asia (Larson et al. 2005; 2007) at permanent Polynesian settlements on the islands of Oʻahu (Pearson et al. 1971), Molokaʻi (Kirch and Kelly 1975; Kirch 1982), and Kauaʻi (Burney et al. 2001). Both skeletal remains and early historic observers indicated that *puaʻa* were smaller than contemporary Hawaiian feral pigs, weighing only 27–45 kg (Ziegler 2002). Despite the fact that domestic swine have become one of the most widely distributed large feral mammals on most islands throughout the Pacific, there is no evidence that pigs strayed far from commensal situations in Hawaiʻi until the admixture of aggressive European strains (Maly 1998, Ziegler 2002, Larson et al. 2005). The Polynesian rat, also originating in Southeast Asia, accompanied early Polynesian voyagers to virtually every island in the Pacific (Kirch 1982, Matisoo-Smith and Robins 2004). The devastating effects of the third most widely distributed rat on Earth have only recently come to light and may have included the catastrophic disappearance of native lowland forests of Hawaiʻi in as little as 50 years (Athens 2009).

It was not until European explorers discovered the Hawaiian Archipelago and initiated another wave of mammalian introductions that larger European swine interbred with *puaʻa*, the first being a boar and a sow brought to the island of Niʻihau by Captain James Cook in 1778 (Tomich 1986). Swine repeatedly interbred with multiple introduced domestic varieties and escaped European wild boars to become the most abundant large mammal throughout the Hawaiian Islands. Pigs, however, were only one of several introduced mammals that became widespread after Europeans colonized the islands. The discovery of the Hawaiian Islands, like many other islands of the Pacific, marked the beginning of introductions of many beasts of burden, animals for milk and meat on the hoof, an assortment of rodents, and small predators to keep rodents at bay. Notably among these were domestic cattle (*Bos taurus*), goats (*Capra hircus*), and sheep (*Ovis aries*) brought by Cook in 1778–1779 and Vancouver in 1793 and 1794 to establish strategic re-supply outposts for ships on worldwide voyages (Tomich 1986). Livestock became feral and proliferated without any predators or competitors. Sheep were reported at the summit of Mauna Kea, the highest peak in the Pacific, only 32 years after their introduction (Ellis 1917). House mice (*Mus musculus*) were brought unintentionally to the Hawaiian Islands by 1816 and reached the summit of Mauna Kea by 1825 (Tomich 1986). Norway rats (*Rattus norvegicus*) were noted by 1835. Tame cats that had been employed as mousers on sailing ships must have fascinated native islanders, as many were given as gifts, bartered, taken, or otherwise escaped into the wild (Baldwin 1980, King 1984), soon spreading as far as the wilderness of Kīlauea by 1840 (Brackenridge 1841), and becoming notorious predators of native birds (Rothschild 1893, Perkins 1903).

Later arrivals included black rats (*Rattus rattus*), which were not documented until 1899, apparently after the construction of shipping wharfs (Atkinson 1977). The small Indian mongoose (*Herpestes auropunctatus*) was

deliberately introduced to the Hawaiian Islands from Jamaica in 1883 and released by sugar planters to reduce rat populations in cane fields on Hawaiʻi Island, Oʻahu, Molokaʻi, and Maui, and later brought to other Pacific islands of Fiji and Japan (Hays and Conant 2007). After tens of millions of years of evolutionary isolation from all terrestrial mammals except bats, islands of the Central Pacific were quite suddenly besieged by a number of alien rodents, carnivores, and both large and small herbivores (Ziegler 2002). Rapid ecological degradation ensued and whole groups of endemic plants and animals suffered extinctions, including virtually all flightless waterfowl (Olson and James 1982, Steadman 1995), and at least nine percent of all Hawaiian flora (Sakai et al. 2002). After a century of settlement by westerners, the concept of eradication came about as a solution to primarily agricultural, public health, or economic problems (Tomich 1986), and only more recently as a solution to ecological problems (Hess et al. 2009). The devastation caused by non-native mammals was slow to be realized and addressed; however, there are now many examples of successful management efforts resulting in the dramatic recovery of native biota.

THE LEOPOLD REPORT AND FERAL GOATS

One of the most influential assessments on the management of mammals on federal lands in Hawaiʻi was the report "Wildlife Management in National Parks" by A. Starker Leopold et al. (1963), who gave national recognition to a notable overabundance of herbivores throughout the entire US national park system. Not only did this spur the removal non-native goats from national parks in Hawaiʻi, but it contributed to the restoration of ecological integrity to parks like Yellowstone where the entire suite of large predators was ultimately restored. Managers of Hawaiʻi's National Parks took action on the recommendation of the Leopold Report, which stated: "*A visitor who climbs a mountain in Hawaii ought to see mamane trees and silverswords, not goats.*" Goats had been removed from Hawaiʻi Volcanoes National Park (HAVO) on Hawaiʻi Island since 1927 but with no lasting effect due to reinvasion from the reservoir of animals in surrounding areas (Baker and Reeser 1972). 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. Managers developed specific techniques necessary to accomplish eradication from the enclosed areas such as the Judas goat method which uses radio-telemetry to take advantage of gregarious behavior in domestic ungulates (Taylor and Katahira 1988). The eradication of goats from 554 km^2 of the park during 1968 to 1984 (Tomich 1986) remained the largest area from which goats have been eradicated on any Pacific island until goats were eradicated from the 585 km^2 Galápagos Island of Santiago, Ecuador, in 2005 (Cruz et al. 2009, Chynoweth et al. 2013). After a century and a half of degradation, a previously unknown endemic plant species, ʻāwikiwiki or *Canavalia kauensis* (now *C. hawaiiensis*), was found growing on the dry lowlands of Kukalauʻula after the removal of goats (St. John 1972).

At Haleakalā National Park (HALE) on Maui, eradication of goats from the 137 km^2 ha park began in 1983 and was completed in 1989 using techniques developed in HAVO (Stone and Holt 1990, L. Loope pers. comm.). Goats and sheep were also eradicated from Kahoʻolawe Island in 1990 by ground shooting, helicopter hunting, and the use of Judas animals (Kahoʻolawe 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). Goat control in National Parks of Hawaiʻi proved not only the technical feasibility to eradicate ungulates from large areas of multi-tenure islands, but also resulted in the development of specific techniques which became standard operating procedures in other locations. The Judas goat method, which uses radio-telemetry to take advantage of gregarious behavior in ungulates, has been replicated in many other management operations (Taylor and Katahira 1988).

SHEEP

Feral sheep have repeatedly reached excessive densities on Mauna Kea, devastating the watershed and dry subalpine woodland environment. Foresters for the Territory of Hawaiʻi 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 but not widely known outside of Hawaiʻi (Warner 1960). Despite this knowledge, European mouflon (*Ovis gmelini musimon*) were hybridized 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. Patchy recovery of māmane has occurred after reduction of sheep numbers (Hess et al. 1999). The fence surrounding Mauna Kea has not been maintained and several hundred sheep are removed each year by aerial hunting from helicopters; however, habitat loss compounded by drought has contributed to an ongoing long-term decline of Palila (Banko et al. 2009; 2013).

European mouflon sheep from the Mediterranean Islands have become invasive where they were introduced to the Canary, Kerguelen, and Hawaiian archipelagos (Chapuis et al. 1994, Hess et al. 2006, Nogales et al. 2006). Mouflon were first introduced to the Hawaiian island of Lānaʻi in 1954 as a game species prior to their release on Mauna Kea (Tomich 1986). A third population on Hawaiʻi Island's Mauna Loa was founded by only 11 individuals between 1968 and 1974 at the Kahuku Ranch which was acquire by Hawaiʻi Volcanoes National Park in 2003 (Hess et al. 2006). As the Mauna Kea and Mauna Loa populations grew and started to merge (Ikagawa 2014), a directed volunteer program began to eliminate mouflon to prevent further degradation at Kahuku (Stephens et al 2008).

Control of non-native ungulates is the single most expensive natural resource management activity in many natural areas of Hawaiʻi. It is often difficult to detect small numbers of incipient and relictual ungulates in these areas, especially for cryptic species which have never been domesticated. Aerial surveys are the most common method for assessing ungulate populations on a large spatial scale. However, the effectiveness of aerial surveys diminishes after populations have been reduced to relictual levels. Ground-based surveys, camera trap monitoring, and aerial surveys enhanced with Forward Looking Infrared Radar (FLIR) are now being compared to detect mouflon and other ungulates in a 131 km^2 area at Kahuku. From 2004 to 2014, the number of mouflon observed during aerial surveys decreased from 1,785 to 378, and no mouflon were detected in two intensively managed subunits, despite reports of small numbers (USGS, unpubl. data). During systematic ground-based surveys, fresh sign occurred at 3.6% of plots within one of the managed units. Twenty remote triggered camera traps were positioned in Kahuku; four in the unit where sheep had been detected during ground surveys. Over a 199 day period, 863 images of sheep were collected, including seven detections in a managed unit. Each method has strengths, but is limited by effective detection distance, spatial and temporal coverage, as well as intensity of effort. Systematic survey methods coordinated with continuous camera trap monitoring complemented each other when used for detecting small numbers of ungulates.

FERAL PIGS

Feral pigs differ fundamentally from that of other ungulate species because, in addition to herbivory and trampling, pigs also wallow, dig, and root in soil (Engeman et al. 2006), primarily in wetter forests. The actions of pigs are considered to disperse some alien plants (Diong 1982, Aplet et al. 1991, LaRosa 1992), inhibit regeneration of native plants (Cooray and Mueller-Dombois 1981, Diong 1982), selectively browse and destroy native plants (Ralph and Maxwell 1984, Stone 1985, Stone and Loope 1987, Drake and Pratt 2001, Murphy et al. 2013), spread plant pathogens (Kliejunas and Ko 1976), accelerate soil erosion (Stone and Loope 1987), alter soil microarthropod communities (Vtorov 1993), and alter nutrient cycling (Coblentz and Baber 1987, Singer 1981, Vitousek 1986). Feral pigs in Hawai‘i also create nutrient-rich wallows and troughs in tree fern (*Cibotium* spp.) trunks (Stone and Loope 1987). Despite the fact that feral pigs have been implicated in altered ecosystem processes in Hawai‘i and elsewhere, some important aspects of feral pig ecology in Hawai‘i are still poorly studied because of the inaccessible environments they inhabit, and because their effects cannot be disentangled from those of other sympatric ungulate species.

Several studies have examined the recovery of plant communities after landscape-scale removal of pigs. Loope et al. (1991) found that the removal of feral pigs from a montane bog on Maui reversed damage to vegetation, and the presence of alien plant species was minimal due to inherently low invisibility of native bog communities. Nonetheless, pigs had only a short history (< 20 yr) in this area. Loh and Tunison (1999) monitored vegetation changes following pig removal at 16 plots in pig-disturbed areas of the ‘Ola‘a-koa rainforest unit in Hawai‘i Volcanoes National Park. Native understory cover increased 48% from 1991 to 1998, largely in the first two years following pig removal. Alien understory vegetation increased 190%. The presence of alien banana poka (*Passiflora mollisima*), however, was reduced from 81% to 40% within plots. Hess et al. (2010) analyzed vegetation monitoring over a 16-year period concurrent with feral pig and cattle removal in a wet montane forest at Hakalau Forest National Wildlife Refuge (HFNWR) on Hawai‘i Island. Strong increases in understory cover of native ferns and slight decreases in cover of bryophytes and exposed soil occurred. Mean cover of native plants was generally higher in locations that were formerly lightly grazed, while alien grass and herb cover was generally higher in areas that were heavily grazed. In contrast to many other Hawaiian forests, widespread invasion by alien grasses and herbs did not occur after ungulate removal and may be due to dense canopy cover.

Cole et al. (2012) and Cole and Litton (2013) found that stem density and cover of native plants, species richness of groundrooted native woody plants, and abundance of native plants of conservation interest were all significantly higher where feral pigs had been removed from a Hawaiian montane wet forest over 6.5–18.5 years. The area of exposed soil was lower and cover of litter and bryophytes was greater where pigs were absent. Density of groundrooted native woody plants increased sixfold in pig-free sites over 16 years, whereas establishment was almost exclusively restricted to epiphytes at sites inhabited by pigs. Stem density of young tree ferns also increased significantly in pig-free sites, but not at sites inhabited by pigs. Abundance of invasive plants such as strawberry guava (*Psidium cattleianum*) increased fivefold at sites where they had established prior to feral pig removal. While common native understory plants recovered within 6.5 years of feral pig removal, species of conservation interest recovered only on areas that possessed remnant populations at the time of removal. Results indicated that control of nonnative plants and outplanting of rarer species may be necessary after pig removal.

Because pigs are extraordinarily prolific (Hess et al. 2007), reinvasion of from the reservoir of animals in surrounding areas is a perpetual problem, making continuous fence maintenance and population monitoring in managed areas necessary. HFNWR has intensively managed feral cattle and pigs and monitored non-native ungulate presence and distribution during surveys of all managed areas since 1988. Activity indices for feral pigs, consisting of the presence of relatively recent tracks, digging, browse, or scat was recorded at

422 stations along 17 transects, each with roughly 20 sample plots (Leopold et al. 2015). A calibrated model based on the number of pigs removed from one management unit and concurrent activity surveys was applied to estimate pig abundance in other management units (Hess et al. 2007). The resulting time series of pig abundance provides managers with a means to evaluate and refine control efforts in an adaptive management framework. The simultaneous acquisition of rigorous data on ungulate population abundance, plant communities, and ecosystems processes would further advance the scientific basis for the management of natural resources in Hawai‘i.

RECENT ILLEGAL INTRODUCTIONS: AXIS DEER

Among the wild ungulates introduced to Hawai‘i that had never been domesticated were axis deer (*Axis axis*), which are native to India, Sri Lanka, and Nepal (Graf and Nichols 1966). Axis deer from India were given to King Kamehameha V in 1867 and released in early 1868 (Kramer 1971). Several deer from Moloka‘i were moved to Lāna‘i in 1920. Axis deer were later released on Maui in 1959 where they have become widespread (Anderson 2003). The introduction of axis deer to Hawai‘i Island was debated for many years, but opposed by ranchers and environmentalists (Titcomb 1969, Walker 1969). Nonetheless, illegal introductions of deer and mouflon between islands have occurred recently. The U.S. Fish and Wildlife Service launched an investigation after sightings were reported, which revealed that in December 2009, a helicopter pilot and rancher from Maui had covertly transported four deer in exchange for about a dozen European mouflon sheep (Tummons 2011a, b). Because neither species was established in the wild on either of the islands, in June 2012, state lawmakers responded by specifically banning “the intentional possession or interisland transportation or release of wild or feral deer” (Honolulu Star-Advertiser 2012). Two individuals were prosecuted under the Lacey Act for transporting wildlife between islands with the intent to guide hunting for out-of-state residents (Associated Press 2012), while the individual who provided the mouflon was sentenced to community service. Further, the helicopter pilot agreed to provide 500 hours of flight time to locate and eradicate the Hawai‘i Island deer population in restitution (Hess et al., in press). FLIR has been used to locate and dispatch four individuals to date.

RODENTS

Introduced rodents, particularly black rats, have become superabundant on most of the world’s inhabited islands, causing widespread ecological damage and tremendous human health problems. Rodents 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). Rodents also carry several diseases that are communicable to humans, domestic mammals, and native wildlife. The bacteriological diseases murine typhus and bubonic plague caused by the organisms *Rickettsia typhi* and *Yersinia pestis* are hosted by many rodent species (Tomich et al. 1984). These diseases have a long history of causing human illness and mortality in Hawai‘i. Although plague has not occurred in the archipelago since 1957 (Tomich et al. 1984), murine typhus outbreaks still occur periodically, with 47 confirmed human cases in a 2002 outbreak (Manea et al. 2001, Sasaki et al. 2003). Leptospirosis, caused by the spirochete *Leptospira interrogans*, is one of the most widespread, sometimes fatal zoonoses worldwide, having an annual incidence of 1.29 per 100,000 people in Hawai‘i (Middleton et al. 2001, Katz et al. 2002). Other diseases associated with rodents, such as cryptosporidiosis, giardiasis, and salmonellosis, pose persistent and serious public health problems (Sasaki and Ikeda 2000, Katz et al. 2002).

Recognizing the severe problems rats cause to nesting seabirds, the U.S. Fish & Wildlife Service (USFWS) and the Samoan Department of Wildlife and Marine Resources eradicated Polynesian rats from 6.3 ha Rose Atoll, American Samoa, in 1990 using brodifacoum, a second generation anticoagulant, in bait stations, live- and snap-traps, and subsequent treatment with bromethalin (Morrell et al. 1991, Murphy and Ohashi 1991, Ohashi and Oldenburg 1992). In the Northwestern Hawaiian Islands, Wildlife

Services (WS) of the U.S. Department of Agriculture's Animal and Plant Health Inspection Service and the Hawaiʻi Department of Land and Natural Resources (DLNR) eradicated Poynesian rats in 1993 from 129 ha Green Island, Kure Atoll, using brodifacoum bait stations (J. Murphy pers. comm.). In 1994–1996 the U.S. Navy, USFWS and WS eradicated black rats from three islands of Midway Atoll using brodifacoum, live traps, incidental baiting and rat nest removal (J. Gilardi and J. Murphy, pers. comm.; Murphy 1997a,b). Sand Island of Midway Atoll remains one the largest permanently inhabited islands 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 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 prevented six seabird species from nesting. The first attempt to eradicate ship rats from the atoll by WS failed in 2001 due to the complexity of the 275 ha area with 54 islets, and dense coconut palms (*Cocos nucifera*), and *Pisonia grandis* trees (Ohashi 2001). Notable factors contributing to the failure included bait taken by land crabs (*Cardisonma* and *Coenobita* spp.). A more intensive second attempt was successful by 2013, benefitting coconut palms and *Pisonia* trees.

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 Mokuʻauia and tiny Mokoliʻi Islet, both near Oʻahu, using traps and diphacinone, a first generation anticoagulant, in bait stations (J. Eijzenga pers. comm.). Wedge-tailed shearwaters (*Puffinus pacificus*) subsequently began fledging from Mokoliʻi (D. Smith pers. comm.). A joint project by the USFWS, Hawaiʻi DLNR and WS to eradicate Pacific rats from 7 ha Mokapu Island off Molokaʻi in February 2008 was the first rat eradication using an aerial application of a rodenticide (diphacinone) which was registered by the Environmental Protection Agency (EPA) in 2007 for conservation purposes in the U.S. (P. Dunlevy pers. comm.). Diphacinone pellets were also broadcast by helicopter for Polynesian rats in January 2009 on 110 ha Lehua Islet, but the eradication proved unsuccessful (VanderWerf et al. 2007; P. Dunlevy pers. comm.).

Larger areas of multi-tenure islands are now under consideration for the use of registered broadcast rodenticides for rodent control. Rodenticide treatment grids are being established in Hawaiʻi Volcanoes National Park where hand and aerial broadcast trials of diphacinone pellets were conducted in support of EPA registration (Spurr et al. 2013). Several native and non-native species will be monitored to examine ecosystem responses. Reinvasion of from the reservoir of animals in surrounding areas is inevitable; however, this type of seasonal management regime may benefit nesting forest birds and other species during important life history stages, thereby providing an important conservation tool.

FERAL CATS

Domestic cats have been introduced to many of the world's islands where they have frequently become the dominant apex predator in the absence of other predatory mammals. The consequences have been particularly devastating for native wildlife, including the decline, extirpation, and extinction of numerous vertebrate populations, particularly ground-nesting and burrowing landbirds and seabirds, as well as many herptile and small mammal species which, in most cases, evolved in the absence of predatory mammals and feline diseases. The depredation of endangered bird species in Hawaiʻi has been frequently documented and attributed to cats based on the characteristic condition of carcasses (Hess et al. 2007, Lindsey et al. 2009, Judge et al. 2012). Remains have also been recovered from stomach contents of feral cat and from cat scats, but dietary studies cannot differentiate between prey killed by feral cats and scavenged food items. Other types of evidence including mortality attributed to

pathogens are also often short of conclusive. Photographic or videographic documentation provides direct 'smoking gun' evidence that confirms depredation by cats (Judge et al. 2012). The most direct and compelling proof of the effects of feral cats on wildlife populations come from examples where cats have been entirely removed from islands and comparisons of areas with and without cats (Smith et al. 2002). In many cases, several species of extirpated seabirds as well as other wildlife have recovered after the complete removal of cats (Hess, in press and references therein).

In the Central Pacific, five species of seabirds have recolonized the islands of Baker, Howland, Jarvis, and Wake after the removal of feral cats (Rauzon et al. 2011). Worldwide, feral cats have been removed from more than 50 islands, many of which are remote and inaccessible. In cases where follow-up monitoring has been conducted and published, recovery of 22 species of birds on 11 islands has been documented on islands including Ascension, Juan de Nova (Mozambique), Marion, and several Islands of Mexico (Hess, in press and references therein). Where possible, the experimental removal of cats would provide the most conclusive proof of effects on wildlife populations.

MULTI-SPECIES PREDATOR EXCLOSURES

On multi-tenure islands where the eradication of feral cats and other predators may not be possible, predator exclosures provide the best prospects for the recovery of seabirds and other endangered bird species. Four such projects have been planned or undertaken in Hawai'i. Predator-proof fences have been developed and refined in New Zealand to exclude a wide variety of mammalian predators from vulnerable native bird species. They typically consist of a tall fence mesh fine enough to exclude mice, buried skirt to prevent burrowing, and a curved or floppy top to prevent predators from climbing over (Hess et al. 2009). One of the first predator-proof exclosures in Hawai'i was a relatively small (~0.7 ha) area in Hawai'i Volcanoes National Park to protect endangered Nēnē (Hawaiian Goose; *Branta sandvicensis*) goslings from feral cats, feral pigs, and mongooses (Hess 2011). Ka'ena Point on O'ahu became the first site in the Hawaiian Islands to get a predator-proof fence to exclude all mammals from mice to dogs (Young et al. 2013). The fence spans 640 meters and encloses an area of approximately 24 ha. Removal of dogs, feral cats, and mongooses has been particularly beneficial to nesting seabirds like Wedge-tailed Shearwaters, but also to Laysan Albatross (*Phoebastria immutabilis*). Dogs frequently do a substantial amount of damage to shearwater populations by killing nesting adults. Another 3.2 ha predator-proof fence was completed at Kīlauea Point National Wildlife Refuge in December of 2015 to protect Nēnē, Laysan Albatross, and Newell's Shearwater (*Puffinus newelli*). The American Bird Conservancy is currently supporting the construction of a much larger exclosure to protect the largest colony of endangered Hawaiian Petrels on Mauna Loa in Hawai'i Volcanoes National Park.

PROGNOSIS

Federal agencies have been highly successful by collaborating in scientific research and management of invasive mammals on federal lands, culminating in the removal of several destructive species across large landscapes and many entire islands, and resulting in demonstrated ecosystem recovery (Hess and Jacobi 2011). Additional multi-species eradications of invasive mammals from larger single-tenure islands would benefit numerous species of wildlife. Kaho'olawe (117 km^2) would not be the largest island in the world from which feral cats have been eradicated, but it would be nonetheless logistically challenging because of unexploded ordnance left after decades of military training, and it would also require coordinated eradication of Polynesian rats and mice. Aerial broadcast of brodifacoum could be highly effective for eradicating rodents and simultaneously reducing feral cats on Kaho'olawe, but it presents higher risks to non-target animals than diphacinone, which may be less effective, particularly against feral cats and mice (Parkes 2009). While some research may be necessary to develop the best methodological strategy, there is little question that a pest-free Kaho'olawe would be important for restoration

of native seabirds and potentially other native species of plants and animals, including some that do not occur outside the northwest Hawaiian Islands, such as Laysan Teal (*Anas laysanensis*). The future conservation value of Kahoʻolawe may become increasingly important as feral cat colonies continue to become established on other large islands, threatening the viability of native wildlife (Winter 2003).

Multi-tenure islands where rights prevail are substantially more challenging for invasive mammal management, however, and the pace of new introductions is increasing. Better prevention strategies, early detection techniques, and control methodology for incipient invasive species would benefit the environment, agriculture, and economy of the entire Hawaiian archipelago. For example, small Indian mongooses (*Herpestes auropunctatus*), which have infested nearly all of the other Hawaiian Islands, were first discovered and captured on Kauaʻi in 2012, threatening endangered ground-nesting bird populations. Abundant source populations of these and other invasive vertebrates throughout the archipelago present a growing risk for accidental and intentional introductions to cross-contaminate islands. As with deer on Hawaiʻi Island, detection and control is dependent on the trust and cooperation of landowners, who can deny access at any time. Successful eradication cannot be declared yet in many cases because it is virtually impossible to know if the last individual of a population has been removed from such large, populated islands. Therefore, the best chance for stopping additional invasions includes prevention, early detection, and rapid response before newcomers have a chance to reproduce. Vigorous enforcement of existing importation laws would aid in the prevention of additional introductions, while outreach would inform the public of both ecological and legal consequences. Solid engagement from natural resource agencies would improve early detection and rapid response. Once a small population of invaders starts to reproduce and becomes established, long-term commitment to monitoring and removal in partnership with landowners is the best shot for ensuring successful eradication—particularly for cryptic species.

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