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ORIGINAL PAPER

Multi-species predator eradication within a predator-proof fence at Ka'ena Point, Hawai'i

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Abstract Ka'ena Point Natural Area Reserve on O'ahu hosts one of the largest seabird colonies in the main Hawaiian Islands and supports three species of endangered plants. In order to stop chronic predation by invasive alien mammals on native species, a peninsula-style predator-proof fence was constructed around a 20-ha portion of the reserve in 2011. Multi-species predator removal efforts began upon fence completion; diphacinone poison in bait boxes spaced 25 m apart was used to remove black rats, house mice, and small Indian mongooses. House mice also were removed with multiple-catch live traps spaced 12.5 m apart. Feral cats were removed with padded leg-hold traps. Feral cats and mongooses were eradicated in 1 month, black rats were eradicated in 2.5 months, and house mice were eradicated in about 9 months. Since eradication, incursions of cats and mongoose have been rare (1/7.2 months), but incursion frequency has been higher for black rats (1/56 days) and house mice (1/36–47 days). Buffer predator control was conducted to limit predator access and prevent reinvasion around the fence ends along the shoreline. Even with the high initial fence cost and ongoing predator incursion management, this method is expected to become more cost effective than previous predator control efforts after 16 years. Record numbers of Wedge-tailed shearwaters and Laysan albatrosses have fledged from the reserve after predator eradication, and regeneration of native plants and invertebrates is being observed. With careful planning and persistence, predator fences can be a cost-effective method of protecting natural resources, and multiple species of predators can be eradicated with traps and first-generation anti-coagulents.

Keywords Hawai'i · Island species · Predator eradication · Predator fence

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Introduction

Introduced mammalian predators are the most serious threat to many species, particularly on islands, and are the largest cause of animal extinctions in the past few centuries (Croll et al. 2005; Reaser et al. 2007;

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Salo et al. 2007). Predators have been eradicated from many islands and the number of eradications conducted each year has been increasing (Keitt et al. 2011), preventing the extinction of many species and leading to the recovery of others. In cases where it is impractical to remove all predators using methods currently available, predator-proof fences and large trapping grids have been used to create "mainland islands" in which predators are managed (Saunders 2001; Burns et al. 2011). Most eradications and management programs have focused on single species, most often rats (*Rattus* spp) and feral cats (*Felis catus*), but more recently, eradication efforts have begun to target multiple species simultaneously (Innes and Saunders 2011). Multi-species eradications often are more cost-effective (Griffiths 2011) and can help avoid undesirable shifts by top predators to native species that can occur when smaller predators that serve as alternate prey are eradicated (Witmer et al. 2007; Griffiths 2011; Innes and Saunders 2011).

In the Hawaiian Islands, all mammals except the Hawaiian monk seal (*Monachus schauinslandi*) and the Hawaiian hoary bat (*Lasiurus cinereus semotus*) were introduced by people, some intentionally for food, pets, or biocontrol agents, and others accidentally as stowaways (Tomich 1969). Because Hawai'i is so isolated from continental areas, the native plants and animals that evolved in the islands are naïve to mammalian predators and often lack defenses against them (Salo et al. 2007; Sih et al. 2010; VanderWerf 2012). Polynesians colonized the Hawaiian Islands about 800 years ago (Rieth et al. 2011) and brought with them several destructive predators including the Pacific rat (*Rattus exulans*), domestic dog (*Canis familiaris*), and domestic pig (*Sus scrofa*; Kirch 1982; Burney et al. 2001). Introduction of alien predators accelerated with the arrival of Europeans starting in 1778, including the black or ship rat (*R rattus*), Norway rat (*R norvegicus*), domestic cat (*F. catus*), small Indian mongoose (*Herpestes auropunctatus*), house mouse (*Mus musculus*), and European wild boar (*S. scrofa*). The suite of alien predators now present in Hawai'i presents a serious threat to the survival of many of Hawai'i's native species (Ziegler 2002; Lindsey et al. 2009), with ground-nesting birds and fruiting plants being especially vulnerable.

Ka'ena Point Natural Area Reserve (NAR) is located at the northwestern tip of the island of O'ahu and contains one of the best remaining examples of a native coastal ecosystem in Hawai'i. Ka'ena Point also hosts one of the largest seabird colonies in the main Hawaiian Islands, three species of endangered plants (one of which is endemic to the area), and is a pupping ground for the endangered Hawaiian monk seal. Exclusion of off-road vehicles in the early 1990s allowed habitat recovery to begin and encouraged two species of seabirds, the Laysan albatross (*Phoebastria immutabilis*) and Wedge-tailed shearwater (*Puffinus pacificus*), to begin nesting in the reserve. However, despite regular predator control, up to 15 % of albatross nests failed each year because of predators, hundreds of shearwaters were periodically killed, and native plants and their seeds were under constant threat (Young et al. 2009; Lohr et al. 2013). To end the chronic, and sometimes catastrophic, predation affecting the natural resources at Ka'ena Point, a peninsula-style predator-proof fence capable of excluding all mammalian predators was constructed around a 20-ha portion of the reserve in 2011 (Young et al. 2012).

The fence is 630 m long and runs from one shoreline to the other, with the ocean acting as a barrier at each fence end (Fig. 1). The northern terminus of the fence is within 2 m of the shoreline at low tide, and at high tide is virtually at the water's edge. The southern terminus is atop a small cliff, with the ocean directly below. The fence is 2 m tall, has aluminum posts covered with a fine (6 mm × 25 mm) polymer-coated stainless steel mesh, and has a sloped aluminum hood at the top. At the bottom of the fence, a 30 cm wide horizontal skirt is cemented onto the ground to prevent animals from digging underneath. Access through the fence for pedestrians is provided by three enclosed gates with sliding double-doors. These features prevent animals ranging in size from mice to dogs from jumping or climbing over, squeezing through, or digging under the fence, and was tested in 2005 and determined to be capable of excluding all non-native mammalian predators in Hawai'i (Burgett et al. 2007). However, because the hood is only on the outside of the fence, it allows animals present inside the fence to exit by climbing out. The majority of the fence was completed by December 2010, but the gates were not installed until March 2011.

Once a predator-proof fence has been built, all predators within the fence must be removed as soon as possible to prevent their populations from growing, and an effective biosecurity program must be implemented to prevent incursions and potential

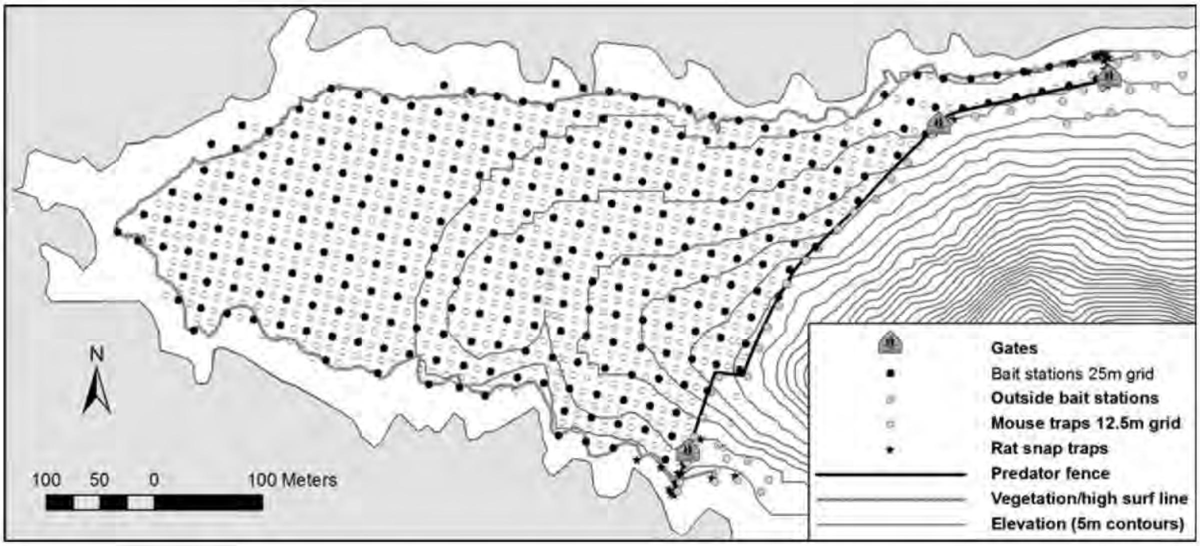

Fig. 1 Map of Ka'ena Point Natural Area Reserve showing locations of the predator-proof fence, bait stations, and traps used in predator removal and incursion detection and prevention

reinvasions. Peninsula-style fences that do not fully enclose an area are especially susceptible to reinvasion because of the gaps between the fence ends and the shoreline. If all predators are eradicated and incursions are effectively managed, the fenced area can function as a 'mainland island' that is similar in many ways to an offshore island.

Five non-native predatory mammal species were present at Ka'ena Point: feral dogs, feral cats, small Indian mongooses, black rats, and house mice. Although dogs, cats, and mongooses were primarily responsible for the conspicuous predation events on seabirds that received extensive media coverage (Honolulu Star Bulletin 2006), rats and mice are important ecosystem modifiers because they consume prey at all levels of the food chain, from plants through birds, and they can be more difficult to eradicate than larger predators (Howald et al. 2007).

The primary objectives of this study were to design and implement effective predator removal and biosecurity programs for the Ka'ena Point predator-proof fence, while considering the pest species present and the tools legally available for use in Hawai'i. To help accomplish this, we conducted two years of planning and research prior to fence construction to determine which predator species were present, their densities, and their responses to various control methods (Young et al. 2012). Because the value of predator-proof fences has been questioned recently (Scofield et al. 2011) and more information is needed on their utility (Innes et al. 2012), we also compared the costs and benefits of fence construction and predator eradication with those of the predator control methods used previously at the site. While great advances have been made in the field of multi-species predator removals, particularly in New Zealand, some of the toxicants and other tools regarded as most effective are not legal in some countries or states. The information presented in this study on the costs of predator fences and the use of trapping and first-generation anti-coagulents to eradicate multiple species of predators will be useful to biologists and managers in other locations.

Methods

Study site

Ka'ena Point Natural Area Reserve was established by the State of Hawai'i in 1983 to protect a remnant coastal dune ecosystem from off-road vehicles, erosion, and the spread of invasive species. The reserve encompasses 30.6 ha at the northwestern tip of the island of O'ahu. The reserve is open to the public by pedestrian access, and visitors are required to remain on a system of trails. The substrate consists of lava rock shoreline that is impacted by large waves during the winter months, a small beach of coral rubble, and shallow sandy soils overlying lava bedrock. Ka'ena means "the heat" in Hawaiian, and the climate is indeed warm and dry, with average monthly maximum temperatures of 25.9–30.1 °C and average annual rainfall of 613 mm (Western Regional Climate Center). The vegetation is mixed dry shrubland and grassland <1 m in height, with species composition varying by substrate. Native plants dominate the sandier areas near the shoreline, particularly naupaka (*Scaevola taccada*) and the endangered legume 'ohai (*Sesbania tomentosa*). Higher areas with rockier substrate support a mix of native species including naio (*Myoporum sandwicense*), 'ilima (*Sida fallax*), and pā'ū 'o hi'iaka (*Jacquemontia ovalifolia*), and alien species such as kiawe (*Prosopis pallida*) and various grasses. 'Akoko (*Chamaesyce celastroides kaenana*), an endangered euphorb endemic to Ka'ena Point, also occurs in rocky areas.

As the habitat condition improved following the exclusion of off-road vehicles, two species of seabird colonized the reserve: the wedge-tailed shearwater, a species that is widespread in the tropical Pacific and Indian oceans, nests in underground burrows and rocky crevices from May to November, and the Laysan albatross, which forages widely over the North Pacific but breeds primarily in the Hawaiian Islands, nests on the surface, with eggs laid in November–December and chicks fledging in June–July (Young et al. 2009). Predator control was initiated to protect these new seabird colonies in 2000, when the Hawai'i Division of Forestry and Wildlife contracted the US Department of Agriculture (USDA) Wildlife Services to remove feral dogs, feral cats, and mongooses with live traps and shooting. Although numbers of both seabird species were growing in response to the ongoing management, predation remained a problem, particularly for the much smaller shearwater, and reproduction was poor in some years.

Baseline predator data collection

Prior to fence construction, we compiled existing data and collected additional baseline data on each species of predator present at Ka'ena Point, and we used this information to design the predator removal program. For larger mammals (dogs, cats, and mongooses), data were available from 11 years of predator control conducted by the USDA. A total of 150 feral cats, 480 mongooses, and nine feral dogs were removed from Ka'ena Point Natural Area Reserve from 2000 to 2010, for average annual removal rates of 13.6 feral cats, 43.6 mongooses, and 0.82 feral dogs. Shooting was the most effective method of controlling dogs, and padded leg-hold traps were the most effective method of controlling cats (Young et al. 2012).

For rodents, we conducted quarterly trapping with snap traps for 1 year to determine the species present and their relative abundance at different seasons (Young et al. 2012). Black rats and house mice were the only rodent species detected. Capture rates of mice were two–eight times higher than the capture rates of rats, depending on the season, and the pattern of seasonal abundance was similar for both species, with peaks in spring and lows in late fall, suggesting a spring reproductive period. To estimate home range sizes of rats and mice, and thus the required spacing for traps and/or bait stations, we captured individuals of each species in live traps, glued a small spool of light-weight thread onto the fur of their back, and released them. The movements of each animal were traced by following the thread two–three days later, by which time the animal had groomed the spool off its back. The maximum distance moved was 45 m for rats and 12 m for mice. More detailed methods used for rodent baseline data collection are provided in Young et al. (2012).

Predator removal

Regular control programs conducted by USDA for feral dogs, feral cats, and mongooses were continued during fence construction to prevent predation on nesting seabirds. Feral cats were removed with a combination of leg hold traps (Victor #15 padded or Bridger offset leg hold traps) and cage-traps (9 × 9 × 26-inch single door Tomahawk traps) baited with commercial cat food. Traps set for cats also were suitable for capturing mongooses, although no mongooses were caught in traps during fence construction. Up to 29 cage traps were placed throughout the reserve, and up to nine leg-hold traps were placed strategically in locations most likely to intercept predators, particularly cats (Young et al. 2012). To help inform removal efforts and improve trap placement, four remote cameras with infra-red motion-activated triggers (Scoutguard SG550) were used to identify individual cats and determine areas of high cat activity. Inspection of sandy areas for tracks provided additional information on the presence and movement patterns of cats and mongooses and aided in trap placement.

We targeted rodents and mongooses with Ramik mini-bars® containing 0005 % diphacinone (HACCO Inc., Randolph, Wisconsin, USA). Diphacinone is widely used for rat control (VanderWerf 2009; Parkes et al. 2011), and also is effective for small Indian mongooses (Smith et al. 2000; Barun et al. 2011). We placed bait in tamper-resistant Protecta® plastic bait stations (Bell Laboratories, Madison, Wisconsin, USA) to shield them from rain and reduce the risk of poisoning to non-target species. Entrances to the stations were large enough to allow access by mice, rats, and mongooses. Bait stations were positioned throughout the fenced area in a 25-m grid pattern (the closest spacing allowed under the product label; Fig. 1) using laser rangefinders and were filled with up to 11 one-oz blocks per station. The maximum allowable amount of bait specified on the product label is 16 oz per station, but we placed no more than 11 oz in each station because that was the maximum number that could be secured to prevent bait from being shaken out of the station. We did not place bait stations below the vegetation line on the coast to reduce the possibility of them being washed away by high surf. With 25-m spacing, there were 289 stations inside the fence (Fig. 1). We stocked bait in the stations on 23–24 February 2011, 1 month prior to the completion of the fence gates, to ensure that the majority of rodents were removed before their breeding season began, which was expected to occur in March. We serviced bait stations twice per week during the first month; after that we adjusted the frequency depending on the level of take to ensure that an adequate supply of bait was available at all times. Frequency of maintenance was once per week during the second month, once every two weeks for the next three months, and once a month thereafter. Application of diphacinone bait was conducted in compliance with US Environmental Protection Agency registration number 61282-26 and special local need registration HI-980005.

We were not confident that the 25-m bait station grid alone would be sufficient to eradicate mice because there is some uncertainty about the efficacy of diphacinone on mice (Parkes et al. 2011), and because the small distances travelled by mice tracked at Ka'ena Point (~12 m; Young et al. 2012). Therefore, on 10 March 2011, 14 days after the commencement of baiting, we placed Catchmaster™ multiple-catch mouse traps baited with peanut butter and roasted peanuts at 12.5 m intervals throughout the fenced area, except where a bait station already was present. These traps have openings too small for seabirds to enter and are thus safe to use in seabird colonies. This resulted in rows containing only mouse traps alternating with rows that contained mouse traps and bait stations (Fig. 1). On transects that already contained bait stations, mouse traps were alternated with bait stations, so that mouse traps were 25 m apart, but with a method of control every 12.5 m. We checked the traps with the same frequency as bait stations; twice weekly during the first month and less often thereafter as needed.

We measured progress of rodent removal in several ways. First, we compared the capture rate of mice over time with baseline data that had been collected immediately before removal efforts commenced using the same Catchmaster™ multiple catch live-traps placed every 10 m along 200 m transects inside the reserve. Second, we used tracking tunnels with inked cards baited with peanut butter to detect the presence of mice, rats, and mongoose and measure their relative abundance. We placed the tunnels in a 50-m grid pattern throughout the fenced area (N = 73). We first deployed tracking tunnels on 2 March 2012, one week after baiting began and one week before mouse traps were deployed, and we ran them at approximately monthly intervals during the remainder of the removal operation.

We used several criteria to judge whether eradication of each predator species had been achieved because the species differed in their incursion potential and we used different methods to detect them. Feral dogs, feral cats, and mongooses were relatively easy to detect and incursions proved to be rare (see "Results" section), so eradication was determined to be the first instance when no detections were made with any method, including traps, tracking tunnels, cameras, droppings, or observations of animals or their tracks. For rodents, determining an exact eradication date was more problematic because it was difficult to distinguish the last remaining survivors from new animals that had re-invaded. Data from other projects suggest that rodents do not venture further than about 100 m in their first few days in a new area (Innes et al. 2011), so all rodents detected

>100 m from the fence ends or gates were judged to be survivors.

Incursion prevention and detection

We defined an incursion as the detection of a predator inside the fence subsequent to the eradication of that species. For rodents, we counted as an incursion any evidence in traps, bait stations, or tracking tunnels inside the fence after the eradication date, particularly within 100 m of the fence ends. For larger mammals, we counted as an incursion any evidence in tracking tunnels, remote cameras, scat, tracks in the sand, or direct observation. We calculated the incursion rate for each species as the number of detections divided by the number of days post-eradication.

As part of the biosecurity plan to keep pest pressure off the fence and reduce the chance of predator incursions and re-invasion, we conducted weekly predator control outside the fence using diphacinone bait stations and snap traps. We placed bait stations at 25 m intervals along the entire length of the exterior fence and up to 50 m out from the fence (Fig. 1). On the fence ends, we placed bait stations in a fan-shaped pattern extending 125 m from the fence. We also monitored the fence weekly for breaches and holes, and we swept rocks, sand, and other debris from inside the gates, particularly the tracks of the sliding doors, to ensure the gates opened and closed properly. To prevent rats from approaching the fence ends and possibly gaining access to the reserve, we placed rat snap traps in covered boxes to prevent seabird injury at 10–15 m intervals along the outside of each fence end (Fig. 1). In case rats or mice did make it around the fence end, we placed rat traps and mouse traps at 6.5–12.5 m intervals along the inside of the fence end and along the shoreline inside the fence up to 100 m from the end. The 100 m extent was largely determined by the local topography, but also followed recommendations by Innes et al. (2011) based on the behavior of rats re-invading a fenced area. This system of traps outside and inside the fence formed a "gauntlet" through which predators would have to pass in order to reach the interior of the reserve. Rodents have been shown to use fences and shorelines as movement corridors, so targeting these areas increased the chance of interception (Innes et al. 2011). In addition, tracking tunnels located <100 m from each fence end were run weekly at the same time the biosecurity traps were checked to provide an additional method of detection for rodents that may be trap shy.

If we detected rodents in the interior of the reserve (>100 m from the ends), this triggered an incursion response using additional traps and fresh bait in the area immediately around the area of detection for up to one month (i.e., a 'spot treatment' following protocols suggested by Maitland 2011). If no rodents were detected after one month, or if the animal was captured in a trap, this incursion response was withdrawn. Feral cats, feral dogs, and mongooses could be readily tracked in the sandy soil present in much of the reserve. If a cat or mongoose was detected in the reserve, we deployed cage traps and leg hold traps in the area until the animal was caught, or until it was determined that it had left the reserve.

Results

Large mammal removal

When the gates were installed on 29 March 2011, thereby completing the fence construction, there was no evidence of dogs or mongooses inside the fence. It is possible that any feral dogs present had been scared away by the construction activity and exited through the gate openings. Mongooses had likely consumed

Table 1 Summary of predator eradications and incursions by species at Ka'ena Point

Species	Control start date	Perceived eradication date	# Days to eradicate	Incursion rate (days)
Feral cat	23 February 2011	30 March 2011	35	1/217
Mongoose	23 February 2011	30 March 2011	35	1/217
Black rat	23 February 2011	10 May 2011	74	1/57
House mouse	23 February 2011[a]	19 Oct–29 Nov 2011	237–278	1/36–47

[a] Mouse live traps were deployed on 3 March 2012

the diphacinone bait and perished during the month of baiting that occurred before the gates were installed, since none were captured in traps during that period. A single feral cat was captured in a padded leg-hold trap one day after the gates were installed. This cat, and no others, had been detected with trail cameras for over a month before it was trapped. If any other cats were present they likely exited the fenced area shortly thereafter (Table 1).

Rodent removal

Take of diphacinone bait from stations was high for the first two weeks, then declined rapidly and remained low for the remainder of the removal operation (Fig. 2). A total of 9,341 oz (264 kg) of bait was deployed in the 289 stations inside the fence over a period of 252 days, for an average take of 0.13 oz (0.0036 kg) per station per day. Rat droppings and mouse droppings were observed inside many stations during the first few weeks. The low level of bait consumption that occurred later appeared to be from remaining mice and insects. Tracking tunnel data collected one and three weeks after baiting began showed a decrease in abundance of rats (5 % presence to 0 %) and mice (45 % presence to 25 %). A rat caught in a snap trap near the southern fence end on 10 May 2011, 74 days after control efforts began, was judged to be the last resident.

The diphacinone bait greatly reduced mouse abundance; the capture rate of mice in live traps declined from 0.38 mice/trap-night before baiting began to 0.014 mice/trap-night after two weeks of baiting, a 96 % decline. The mouse capture rate in live traps continued to decline, but mice persisted for several more months. The first trap check that resulted in zero mouse captures was on 13 October, and the last detection of mice on tracking tunnels in the interior of the reserve was on 19 October, 223 days after live trapping began and 237 days after baiting began (Fig. 3). It is possible no resident mice remained in the reserve after that date, but single mice were caught in the snap trap gauntlet near the northern fence end on 26 October and 3, 11, and 29 November (Fig. 4). The fact that these mice were captured along the shoreline close to the fence end suggests they entered the reserve along the shoreline and were re-invaders, but it is also possible they were the last survivors attempting to exit the reserve. No mice were detected subsequently by any method in the interior of the reserve, lending support to the conclusion that mice captured near the fence ends were re-invaders. The exact date of mouse eradication is thus difficult to determine, but likely occurred 237–278 days after removal efforts began.

Incursion rates

Two cats were detected inside the fence between 30 March 2011 (considered the eradication date) and 14 June 2012, resulting in an incursion rate of approximately one every 217 days or 7.2 months One of these cats was detected on a trail camera near the fence line 70 days after eradication, but it was not detected again on camera or by any other method and is assumed to have left the fenced area on its own. On 5 January 2012, a cat and cat tracks were observed in the interior of the reserve, and trapping was immediately initiated. The cat was caught in a padded leg-hold trap on 12 January 2012 before any evidence of seabird predation was observed.

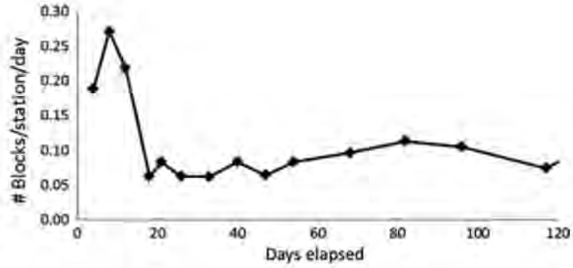

Fig. 2 Take of diphacinone bait from stations at Ka'ena Point Natural Area Reserve. High levels of take during the first 2 weeks were by rats and possibly mongoose; low bait take thereafter was by mice and insects

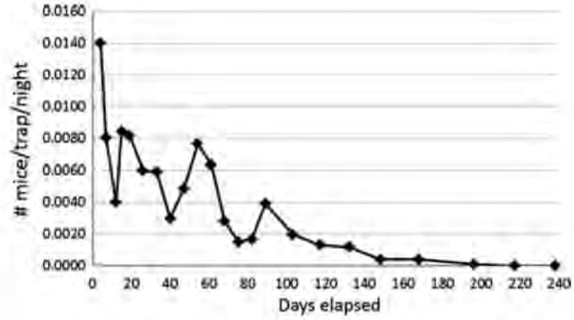

Fig. 3 Capture rate of mice in live traps during the eradication over time

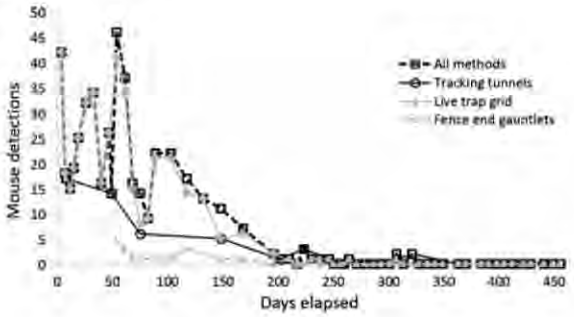

Fig. 4 Number of mice detected over time by method. Eradication probably was achieved between days 252–278; see text for explanation. Subsequent detections were considered incursions

Two mongooses were detected inside the fence from 30 March 2011 to 14 June 2012, resulting in the same incursion rate as for cats, one every 217 days or 7.2 months. One of these mongooses was detected from scat 128 days after eradication, immediately following a weekend when one of the gates was inadvertently stuck open. The scat was on top of a bait station, and enough bait had been taken from the station to constitute a lethal dose; the animal was not detected again. The second mongoose was detected visually and by tracks 254 days post-eradication, and was caught in a leg-hold trap 29 days after it was first detected. No seabird predation was observed as a result of these incursions.

The incursion rate of rats was higher. Seven rats were detected inside the fence during the period after rats were judged to have been eradicated (10 May 2011–8 June 2012; 394 days), resulting in an incursion rate of one every 56 days. Five of the seven rats that made it past the fence were captured in traps immediately inside the fence ends, all of which were *R. rattus*. Two rats survived the gauntlet and were detected with tracking tunnels in the interior of the reserve 162 and 302 days post-eradication, respectively. In those instances, snap traps were placed in the area of detection and bait stations in the area were refreshed. Although neither individual was trapped, there was evidence of bait take and no subsequent detections on tracking tunnels, suggesting that the rats had either died from consuming the bait or exported themselves.

For mice, the incursion rate was more difficult to measure, but probably was about once every 36–47 days. If the eradication date was judged to be 3 November 2011 (the first occasion after no mice were captured in the interior of the reserve), then six incursions occurred during the 217 days between then and 8 June 2012, resulting in an incursion rate of one every 36 days. If two mice that were captured in snap traps near the northern shoreline on 11 and 29 November 2012 are counted as the last survivors instead of invaders, then four incursions occurred during the 191 days between then and 8 June 2012, resulting in an incursion rate of one every 47 days. The final four mouse detections were in traps or on tracking tunnels within 100 m of the fence ends. No mice have been detected in the interior of the reserve (>100 m from the fence ends) since being eradicated.

Cost-benefit analysis

The predator control efforts conducted from 2000 to 2011 by USDA under contract from DOFAW cost $35,000 per year, not including administrative staff time to oversee the contracting. This work entailed three visits per week to check cat and mongoose traps, occasional supplemental visits for night-shooting, and sporadic rat control. In comparison, construction of the predator fence cost $290,000, including materials, labor, and travel from New Zealand and living expenses of the fencing crew in Hawai'i (Table 2), and not including administration, regulatory compliance documents, or public outreach efforts conducted before the fence was constructed. Materials cost included 40 m of spare parts for fence maintenance. Eradication of predators from the fenced area cost approximately $55,500, including supplies, labor, and expenses (Table 2). Labor consisted of 1,240 worker-hours during 30 visits by 5–7 workers over a 9 month period at an average rate per worker of $30 per hour (including benefits). After predator eradication, implementation of the biosecurity plan cost $10,000 per year, including weekly checks of bait stations and traps along the shoreline at the fence ends, inspecting the fence for breaches, and sweeping and maintaining the gates. Fence maintenance costs have been about $2,000 per year thus far but are not well known yet and may rise as the fence ages; $4,000 per year over the life of the fence might be more realistic and we used this to calculate cumulative costs. Some of the predator removal and biosecurity work was conducted simultaneously with other management and research activities (e.g., VanderWerf and Young 2011), so their

Table 2 Breakdown of predator fence construction and predator eradication costs at Ka'ena Point Natural Area Reserve, Hawai'i

Item	Cost
Fence construction	
Materials	$290,000
Labor	$109,000
Travel + living expenses	$44,000
Total	$443,000
Predator eradication	
Bait boxes + bait	$6,090
Mouse traps	$6,046
Bait for mouse traps	$275
Tracking tunnels + cards	$1,500
Vehicle mileage	$3,713
Helicopter time	$680
Labor	$37,200
Total	$55,504

actual cost was somewhat lower than reported here (Table 2).

We anticipate that the "break even point" of the fence cost will occur in about 16 years (Fig. 5). At that time, the cumulative cost of annual predator control would have been about the same as the cumulative costs of fence construction, predator eradication, and annual fence maintenance and biosecurity. The life-span of the fence is projected to be about 20–25 years, though parts of the fence near the northern shoreline that experience more salt spray may require replacement earlier.

Discussion

To our knowledge, this is the first successful eradication of this suite of predators, including mice in particular, that used a combination of diphacinone bait and trapping. Other successful multi-species eradications typically have used aerial broadcast application of second generation anti-coagulents, such as brodifacoum, which are more effective than first-generation anti-coagulents like diphacinone, because they require only a single feeding for an animal to ingest a lethal dose (Parkes et al. 2011). Broadcast methods and other toxicants were not available for use in this project because of regulatory restrictions in Hawai'i.

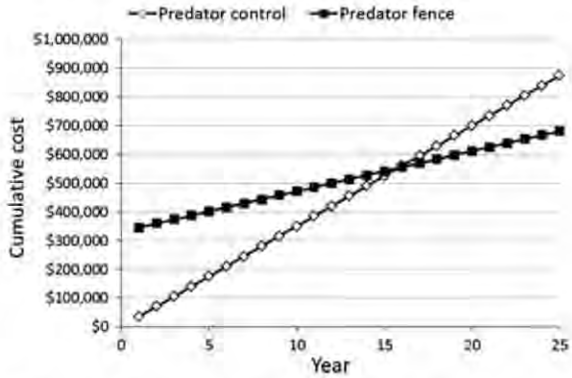

Fig. 5 Cumulative costs of protecting natural resources at Ka'ena Point Natural Area Reserve using a predator fence versus annual predator control. Cost of the predator fence includes costs of fence construction, predator eradication, annual fence maintenance, and weekly biosecurity checks

Although the predator removal methods we used may not be those generally preferred or regarded as most effective, they were most feasible given the scope of the project and the constraints we faced, and our results demonstrate that a multi-species eradication can be achieved with these methods.

The general criteria which must be met for an eradication to succeed are that: (1) All animals must be put at risk by the eradication technique; (2) The animals must be put at risk at a rate exceeding their rate of increase; and (3) Immigration must be zero (Parkes 1993). The last criterion is inherently violated at Ka'ena Point because the fence ends were open, and we recognize that peninsula-style fences may never be considered true eradications for this reason. Confirming eradication can be difficult in many circumstances, and Solow et al. (2008) attempted to address the issue of how to confirm the absence of something. The current standard to determine the success of an offshore island rodent eradication is two years without rodent sign (Parkes et al. 2011), which isn't applicable in a case such as this where immigration can be continual.

Eradicating cats, mongooses, and even rats was relatively straightforward at Ka'ena Point, and determining when eradication had been achieved for these species also was fairly straightforward. The number of feral cats and mongooses present in the reserve before fence construction probably was small, and their presence was easily detected with remote cameras, tracks in sand, and tracking tunnels. Judging when rats had been eradicated was a little more difficult, but again, few rats were present and the frequency and distribution of detections made it more clear when eradication had been achieved. Mice, however, took substantially more effort to eradicate and determining an eradication date was not possible because it was not clear whether some mice detected were the last survivors or the first re-invaders. Future studies would be well-served to use biomarking of individuals outside the fenced area in order to distinguish survivors from re-invaders. Never the less, we are confident that all predators, including mice, have been eradicated or reduced to negligible levels for conservation purposes, and that this status can be maintained.

The incursion rates at Kaʻena Point were similar to those at another peninsula-style predator-proof fence at the Tawharanui open sanctuary in New Zealand, despite differences between the sites in the size of the gap between the fence end and shoreline (2 m at Kaʻena Point vs. up to 60 m at Tawharanui; Maitland 2011). These results suggest that Kaʻena Point either has significantly more predators immediately outside the fence, resulting in higher pressure on the fence, that the shoreline at Kaʻena Point is more attractive to predators than that at Tawharanui, or that incursions aren't detected as readily at Tawharanui. At Kaʻena Point, the bait take in buffer predator control areas just outside the fence is sometimes quite high, suggesting the pest pressure on the fence is high. The rocky intertidal area along the shoreline at Kaʻena Point supports many marine invertebrates, and this rich foraging habitat may be more attractive to rodents than the sandy substrate at Tawharanui and cause them to unintentionally bypass the fence. The narrow gap between the fence end and water line at Kaʻena Point provides an excellent opportunity to intercept rodents as they enter the fence, and most rodents are caught within a few meters of the fence end, often in the first trap.

We encountered several complications during predator removal efforts that warrant discussion. Before predator control commenced, heavy rainfall had resulted in unusually lush vegetation growth and an ample supply of food and water was available for rodents, which potentially could have discouraged them from consuming bait or entering traps. A similar scenario occurred during an attempted eradication of Pacific rats (*R. exulans*) using aerial broadcast of diphacinone on Lehua Islet, Hawaiʻi in 2009, and the abundance of natural food was thought to have contributed to the failure of that eradication (Parkes and Fisher 2011). However, use of bait stations and ability to restock them as needed for several months allowed us to outlast the boom in natural food and achieve eradication. If a broadcast bait application had been attempted at Kaʻena Point, it would have involved two drops of 5.7 kg (12.5 lb) of bait per ha over the 16.3-ha area above the high surf line, or a total of 185 kg of bait versus the 264 kg that was ultimately used in bait stations. If the two drops had been spaced five–seven days apart as prescribed on the product label, the eradication attempt may have failed due to the unusually abundant natural food supply.

Supporting the idea that eradications within fenced areas should occur soon after construction, the initial mouse trapping rate outside the fence was much lower than that inside the fence (0.06 mice/trap-night vs. 0.38), probably because large predators were present in higher densities outside the fence where they were not controlled and were suppressing mouse numbers. Several of the live traps that caught mice outside the fence had mongoose scat on them and had been damaged, suggesting that larger predators were trying to access the mice caught in the traps. Delaying control of predators inside the fence likely would have caused intolerable damage to nesting seabirds and native plants. If only larger predators are controlled, rodents may experience predator release and increase in abundance. Thus, the timing of fence completion, predator removal, and seasonal variation in predator abundance must all be considered together to optimize removal effort and chances for successful eradication.

The results of this study are encouraging for future projects using first generation anti-coagulents on this suite of predators. The baiting program resulted in a substantial decline in abundance of mice after two weeks (45 % decline in tracking tunnels, 96 % decline in live-trapping). Since multiple tracking tunnels can be marked by the same individual, the live trap catch rates are likely to be a better index of abundance. Thus, diphacinone alone appeared to have eliminated up to 96 % of the mice in just two weeks even though the spacing of bait stations (25 m) was larger than the average travel distance of the mice (~12 m). It is likely that as mice were removed, home ranges of remaining animals expanded and thus allowed more individuals access to bait. If the pesticide label allowed closer bait box spacing so that the range of every mouse overlapped with at least one bait station, the diphacinone could have eliminated even more mice and possibly all of them, which is worth investigating for future eradications. We suggest that our methods (a combination of first-generation anti-coagulent bait and traps) could be used to eradicate similar suites of predators at other sites that are comparable in size and topography.

The predator fence thus far appears to be a cost-effective method of protecting the natural resources at Ka'ena Point. The projected long-term cost savings may not be as large as originally forecast, but the cost of fence construction and predator eradication still is anticipated to compare favorably with the cumulative cost of annual predator control. Whether the fence actually results in a long-term cost savings will depend on the lifespan of the fence and fence maintenance costs, which are not yet known. However, we emphasize that the fence and predator eradication have provided a higher level of protection to native species, and that comparing the costs alone is insufficient. Previous predator control efforts helped to increase the reproduction of albatrosses and shearwaters (Young et al. 2009), but some birds were still lost to predators every year. Furthermore, previous predator control focused only on feral dogs, feral cats, and mongooses, it did not ameliorate the effects of rats and mice and thus provided little protection for native plants and invertebrates. In contrast, the fence excludes all predators and provides greater protection to all native species in the reserve and not just seabirds.

Despite the ongoing incursions, there is no evidence of reinvasion by any predator in the reserve interior, and the biological outcome achieved with the fence has already exceeded the protection provided by predator control that was conducted before fence construction. Record numbers of Laysan albatross and Wedge-tailed shearwater chicks fledged from the reserve after predators were eradicated (LCY and EAV, unpubl. data). We also anticipate regeneration of native plants and invertebrates, and recolonization by other seabirds Ka'ena Point also can serve as a site for active restoration, including translocation of endangered seabirds such as the Hawaiian petrel (*Pterodroma sandwichensis*) and outplanting of endangered plants.

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