Monitoring Eradication of European Mouflon Sheep from the Kahuku Unit of Hawai‘i Volcanoes National Park1

Authors: Judge, Seth W., Hess, Steven C., Faford, Jonathan K., Pacheco, Dexter, and Leopold, Christina R.

Source: Pacific Science, 71(4) : 425-436

Published By: University of Hawai'i Press

URL: https://doi.org/10.2984/71.4.3

Monitoring Eradication of European Mouflon Sheep from the Kahuku Unit of Hawai'i Volcanoes National Park[1]

Seth W. Judge,[2] Steven C. Hess,[3,5] Jonathan K. Faford,[4] Dexter Pacheco,[4] and Christina R. Leopold[2]

Abstract: European mouflon (*Ovis gmelini musimon*), the world's smallest wild sheep, have proliferated and degraded fragile native ecosystems in the Hawaiian Islands through browsing, bark stripping, and trampling, including native forests within Hawai'i Volcanoes National Park (HAVO). HAVO resource managers initiated ungulate control efforts in the 469 km^2 Kahuku Unit after it was acquired in 2003. We tracked control effort and used aerial surveys in a 64.7 km^2 area from 2004 to 2017 and more intensive ground surveys and camera-trap monitoring to detect the last remaining animals within a 25.9 km^2 subunit after it was enclosed by fence in 2012. Aerial shooting yielded the most removals per unit effort (3.2 animals/hour), resulting in 261 animals. However, ground-based methods yielded 4,607 removals overall, 3,038 of which resulted from assistance of volunteers. Ground shooting with dogs, intensive aerial shooting, ground sweeps, and forward-looking infrared (FLIR)-assisted shooting were necessary to find and remove the last remaining mouflon. The Judas technique, baiting, and trapping were not successful in attracting or detecting small numbers of remaining individuals. Effort expended to remove each mouflon increased nearly 15-fold during the last 3 yr of eradication effort from 2013 to 2016. Complementary active and passive monitoring techniques allowed us to track the effectiveness of control effort and reveal locations of small groups to staff. The effort and variety of methods required to eradicate mouflon from an enclosed unit of moderate size illustrates the difficulty of scaling up to entire populations of wild ungulates from unenclosed areas.

The Hawaiian Islands have a long history of introduced mammals, which have caused detrimental effects to endemic flora and fauna (Stone 1985). Ungulates in particular have been responsible for large-scale degradation of native ecosystems (Leopold and Hess 2016). The suite of mammalian grazers includes several species of domestic livestock that have become feral, such as pigs (*Sus scrofa*), which were first brought by Polynesians ~800 yr ago; and goats (*Capra hircus*) and sheep (*Ovis aries*), which were both introduced in the late 1700s (Tomich 1986, Linderholm et al. 2016). Goats and sheep have contributed to the loss of as much as 5 m of topsoil on Kaho'olawe Island (Kramer 1971, Kaho'olawe Island Conveyance Commission 1993). Feral sheep on Mauna Kea reached high densities and degraded watersheds and fragile subalpine

[1] This research was funded by the Natural Resources Partnership Program of the U.S. Geological Survey and the National Park Service, and the U.S. Geological Survey Invasive Species Program. Portions of this research were performed under Cooperative Agreement G13AC00097 to the University of Hawai'i at Hilo. Manuscript accepted 24 April 2017.

[2] Hawai'i Cooperative Studies Unit, University of Hawai'i at Hilo, P.O. Box 44, Hawai'i National Park, Hawai'i 96718.

[3] U.S. Geological Survey, Pacific Island Ecosystems Research Center, Kīlauea Field Station, P.O. Box 44, Hawai'i National Park, Hawai'i 96718.

[4] U.S. National Park Service, Division of Resources Management, P.O. Box 52, Hawai'i National Park, Hawai'i 96718.

[5] Corresponding author (e-mail: shess@usgs.gov).

Pacific Science (2017), vol. 71, no. 4:425–436
doi:10.2984/71.4.3

woodlands (Bryan 1937, Warner 1960). Wild ungulate species that had never previously been domesticated were introduced to enhance hunting opportunities on the Islands even after the detrimental effects of feral livestock had been recognized. The first eradication program in Hawai'i began in the early 1900s on Ni'ihau Island, where goats had deforested large areas (Kramer 1971). Subsequent eradications have been pursued in many natural areas to protect and allow recovery of endangered flora and fauna (Hess and Jacobi 2011).

Control of feral ungulates is the single most expensive natural resource management activity in many natural areas of Hawai'i, requiring construction, continuous maintenance, and cyclical replacement of fences, as well as a major concurrent effort in removing ungulates through hunting, trapping, or snaring (Anderson and Stone 1993). The National Park Service (NPS) has been instrumental in developing innovative techniques to eradicate ungulates from large areas in Hawai'i. Managers at Hawai'i Volcanoes National Park (HAVO) succeeded in removing goats from a 554 km^2 area from 1967 to 1984 (Tomich 1986). In conjunction with fencing to isolate populations and prevent immigration, the now widely used Judas Goat method was developed, which employs radiotelemetry to exploit the species' herding behavior, allowing the last remaining animals to be found (Taylor and Katahira 1988, Campbell and Donlan 2005). The first eradication of a large feral pig population used intensive snaring and topographic barriers within remote areas of Haleakalā National Park in 1988 (Anderson and Stone 1993). Resource managers there also removed goats from a 45 km^2 area by fencing and shooting from ground and aircraft in 1989 (Stone and Holt 1990).

European mouflon sheep (*O. gmelini musimon*), originally from the Mediterranean islands, were released on Lāna'i for sport hunting in 1954 (Figure 1) (Tomich 1986). Mouflon have become overabundant where they have been introduced to the Canary, Kerguelen, and Hawaiian archipelagos (Chapuis et al. 1994, Hess et al. 2006, Nogales et al. 2006). Mouflon were also crossbred with feral domestic sheep and released on Mauna Kea, Hawai'i Island, in 1962 (Giffin 1979), which contributed to further habitat degradation for the palila (*Loxioides bailleui*), an endangered Hawaiian honeycreeper (Banko et al. 2013). The Division of Forestry and Wildlife of the Hawai'i Department of Land and Natural Resources used public and staff hunting to remove >18,000 sheep from 1980 to 2011; nevertheless, low annual hunting yields and immigration thwarted eradication (Banko et al. 2014).

Eleven mouflon were introduced in Kahuku Ranch, on southern Mauna Loa volcano, between 1968 and 1974 to establish a private game herd, which proliferated in forested pastures and lava-dominated subalpine shrublands at higher elevations (O'Gara 1994). With an apparent annual population increase of 21.1%, the population reached more than 2,500 individuals by 2004 (Hess et al. 2006). HAVO acquired 469 km^2 of Kahuku Ranch in 2003, and an intensive control program was initiated to reduce and eventually eradicate the population. Local eradication of mouflon had not been previously achieved from any area in Hawai'i. Kahuku was delineated into several management units, and fences were constructed to prevent immigration.

In the study reported here we tracked the effort (staff hours) expended to eradicate mouflon from the 64.7 km^2 Kahuku Paddocks, which was representative of a ~130 km^2 area occupied by mouflon at Kahuku. We used active and passive techniques to monitor the population. Aerial surveys yielded periodic indices of abundance and provided demographic composition and geographic distribution throughout Kahuku. Ground surveys and camera-trap monitoring also yielded demographic and behavioral data, as well as information used to locate and dispatch small groups of mouflon remaining in a 25.9 km^2 fence-enclosed unit. We compared effectiveness of each method by calculating the number of removals per unit effort. This work provides the first detailed account of mouflon eradication in the Hawaiian Islands.

FIGURE 1. Three mature mouflon rams detected by infrared camera traps at the Kahuku Unit of Hawai'i Volcanoes National Park, 28 August 2015.

Study Area

Aerial surveys and ground-based ungulate control efforts by NPS staff and volunteers were initiated in 2004 at the Kahuku Unit of HAVO on the island of Hawai'i (Figure 2). We tracked reduction efforts from 2004 to 2017 in the 64.7 km^2 Kahuku Paddocks on the southern rift of Mauna Loa, where mouflon were initially introduced and occurred in highest densities (Hess et al. 2006). The upper 25.9 km^2 area was completely enclosed by fence between 1,000 and 1,600 m asl in October 2012. The area consisted of dry and mesic forest dominated by the native 'ōhi'a (*Metrosideros polymorpha*) and koa (*Acacia koa*). Understory cover, which had been highly modified by livestock grazing, was dominated by introduced grasses (*Panicum repens*, *Cenchrus clandestinus*, *Pennisetum setaceum*), but patches were dominated by native tree ferns (*Cibotium* spp.) and shrubs (*Rubus hawaiensis*, *Dodonaea viscosa*, *Styphelia tameiameiae*).

Several recent lava flows (≤750 yr b.p.) extend through portions of the unit, which may provide ungulates escape routes from control efforts (Palupe et al. 2016). Orographic effects cause strong climatic gradients over a broad range of elevation in Kahuku. Mean annual precipitation from 1983 to 2008 at 1,570 m asl was 975 ± 341 (SD) mm; the greatest mean monthly rainfall (115.7 mm) occurred between November and January and the least precipitation (54.8 mm) occurred between May and June (Hess et al. 2011).

MATERIALS AND METHODS

Control Methods

NPS resource managers deployed two to five staff to control ungulates at Kahuku from

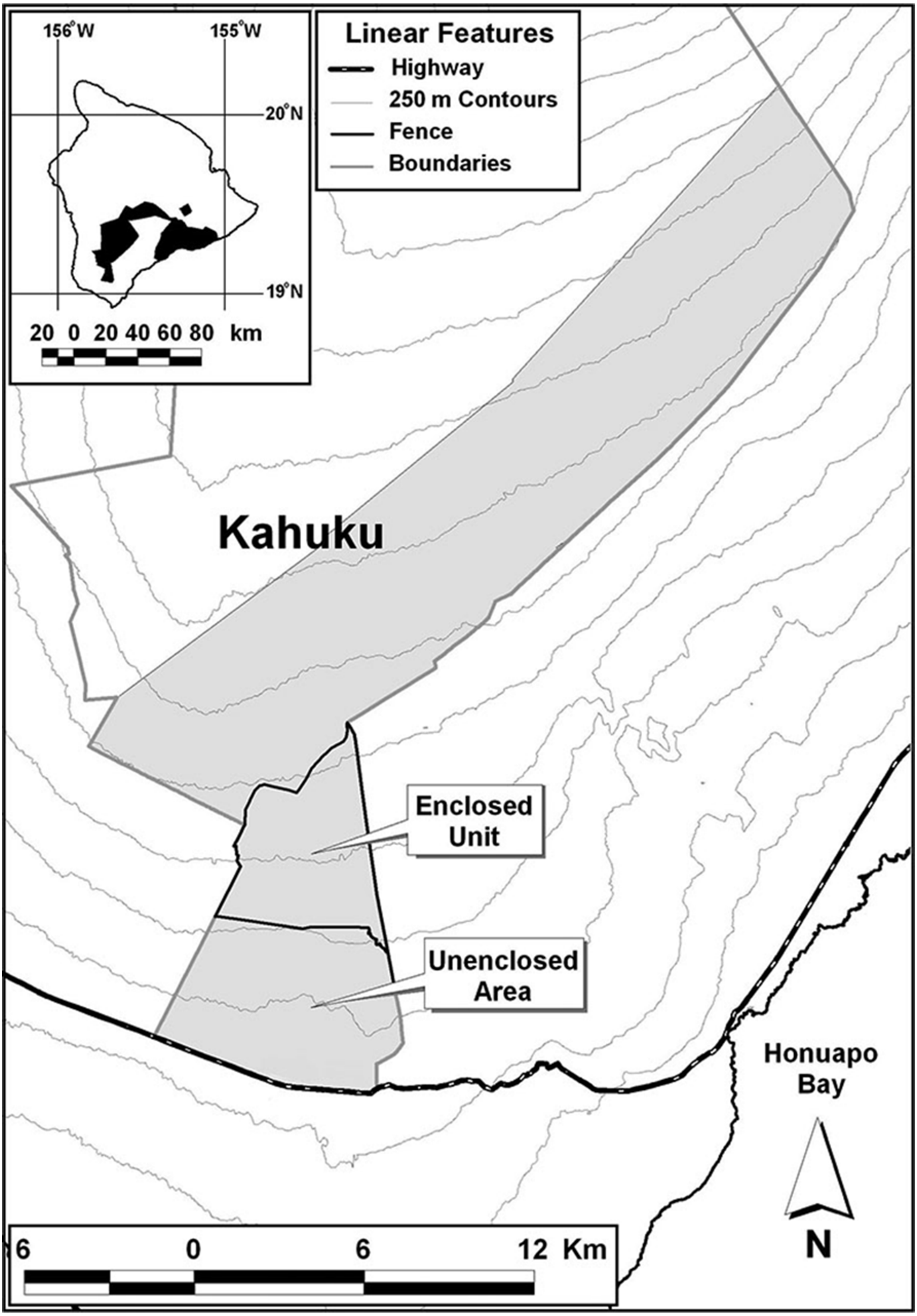

Figure 2. Hawai'i Island and Hawai'i Volcanoes National Park (in black) (inset). The gray area is the total distribution of mouflon in the Kahuku Unit (approximately 130 km^2). Mouflon control was conducted in the enclosed unit and unenclosed area of the Kahuku Paddocks from 2004 to 2016.

2004 to 2017. Staff recorded method, target species, location, time, group size, and sex of all removals. Removal effort included daily preparations and transit to control areas; thus the number of removals per hour included time spent in preparation for the actual reduction effort. Details follow for each control method.

GROUND CONTROL EFFORTS. Control efforts from the ground in Kahuku were primarily vehicle-based. Shooters also hiked to remote areas during daylight hours. Dogs were used occasionally from 2011 to 2017 to target mouflon in densely forested areas. Dogs covered great distances, flushed mouflon from dense areas, and tracked animals by scent. Each dog was equipped with a GPS (Garmin T5) tracking collar, and their movements were tracked with handheld devices (Garmin Astro 320).

VOLUNTEER-ASSISTED GROUND CONTROL EFFORTS. A volunteer ungulate control program began in 2004 (Stephens et al. 2008) and concluded in 2012. Control efforts were conducted primarily once a month and spanned a total of 136 calendar days. Three staff members typically guided four volunteers. One staff member scouted and the other two staff each guided two volunteers. Volunteers were directed to shoot all mouflon within range.

AERIAL SHOOTING. A crew of three conducted aerial shooting: one pilot flying a helicopter [MD (Hughes) 500D], one spotter, and one qualified marksman. The crew searched and attempted to shoot all mouflon observed.

TRAPPING AND BAITING. Park staff used baited traps in open areas to attempt to capture or draw mouflon into the open where they could be targeted. Traps designed to capture large mammals were baited with molasses-enriched corn and grains. A spring-loaded door was designed to capture animals alive.

JUDAS TECHNIQUE. One adult male mouflon was captured with a net gun from a helicopter on 17 May 2016. The ram was hobbled and blindfolded without sedatives while being fitted with a GPS (Telonics TGW-4470-4) collar. The ram was monitored weekly by computer and periodically in the field with a handheld device for associated mouflon.

GROUND SWEEPS. In an effort to find the last remaining mouflon in densely forested areas, field crews formed a line ~50–150 m apart and hiked downslope and attempted to flush mouflon out of hiding. Observers coordinated with each other to prevent sheep escaping between them. Either a helicopter or vehicles with park staff stood by during the sweep and responded to any mouflon sightings reported by radio. Each observer sounded an air horn frequently to flush sheep. Two ground sweeps were conducted, in 2015 and 2016.

Population Monitoring

AERIAL SURVEYS. The Kahuku Paddocks were surveyed for mouflon abundance and distribution by helicopter intermittently from 2004 to 2017 following methodology established by Hess et al. (2006) and Stephens et al. (2008). Transects were spaced 800 m apart following elevation contours. Flights were timed to correspond to large breeding aggregations and the presence of breeding pelage to maximize the ability to identify sexes. Two observers sat on each side of the aircraft; one of the observers in the back recorded group size, sex composition, and distance to each group. The pilot attempted to maintain constant ground speed and altitude above ground level (AGL) during surveys. Flight tracks and waypoints were downloaded to computer, joined to survey data, and plotted with ArcGIS 10.2 Geographic Information System (GIS). Mean group size and sex composition were summarized for each survey unit.

GROUND SURVEYS. Ground surveys were conducted for the presence and distribution of ungulate activity consisting of scat, tracks, or browsed vegetation within contiguous plots (50 m^2) using field methods consistent with those of Stone et al. (1991). Six parallel transects oriented north–south were spaced 1 km apart. A total of 128 stations, each with approximately 20 plots, was surveyed during 1–2 October 2014. Transects crossed the fence-enclosed unit and the lower unenclosed area where ungulates could move freely across

HAVO boundaries. These data were joined to their spatial coordinates and plotted using GIS. Locations were assigned to management units by Universal Transverse Mercator (UTM) coordinates.

CAMERA-TRAP MONITORING. Twenty-four remote-triggered infrared cameras (Bushnell Trophy Cam, Bushnell Trophy Cam HD, and Moultrie M-990i) were deployed in widely dispersed locations throughout the paddocks to detect mouflon based on recent sightings, sign, and favorable habitat beginning in June 2014. Some cameras with wide fields of view were set to automatically record three images every 30 min. Other cameras were positioned in narrow natural corridors where animals would trigger the infrared sensor. Cameras with few or no detections were moved to more favorable locations to maximize the number of detections. Image and video data from each camera stored on Secure Digital cards were exchanged every 2–5 weeks and reviewed to tally the number, age, and sex of animals detected in images, when known. We calculated the total number of sheep per camera trap and trap night, although individual identification of sheep was not possible.

FORWARD-LOOKING INFRARED (FLIR). We used two different FLIR cameras: a FLIR Scout TS32r Pro and a FLIR Recon 3EO. Survey locations were identified during daylight hours and marked with a GPS. Locations were chosen based on evidence of recent activity and areas with a wide field of view. Surveyors could then return to locations at night and predawn hours to scan areas for mouflon. Animals could be detected with FLIR until approximately 2 hr after sunrise. Locations of detections were immediately reported to park staff. All monitoring activities were conducted in compliance with University of Hawai'i Institutional Animal Care and Use Committee Protocol 06-043.

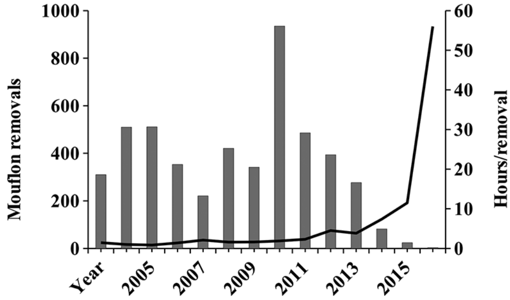

FIGURE 3. The annual number of European mouflon sheep removed (gray bars), and the effort expended (black line) to remove mouflon from the Kahuku Paddocks of Hawai'i Volcanoes National Park, 2004–2016.

RESULTS

Control Effort

Mouflon control in the Kahuku Paddocks began in 2004 and continued through February 2017. Staff worked a grand total of 10,487 hr over 310 days in this area, averaging 2–3 days per month. A grand total of 4,868 mouflon was removed over the 13-yr period. Control effort expended per mouflon removed (hours/removal) increased nearly 15-fold after 2013 (Figure 3). A total of 834 mouflon was removed during 4,320 hr of effort over 129 days within the enclosed unit after the fence was completed in 2012. Only 24 mouflon were removed with 363.5 hr of control effort in 2016. The last three known mouflon were removed on 21 February 2017.

REMOVALS BY METHOD. Ground-based shooting was the primary method for removing mouflon (Table 1). Removals were conducted by staff only, by staff with dogs, and with assistance from volunteers. Volunteer assistance began in 2004 and concluded in 2012, primarily once a month, spanning a total of 126 days. Staff spent a total of 4,402 hr guiding volunteers, leading to the removal of 3,038 sheep. Staff accounted for 1,218 of those removals, and volunteers accounted for 1,820 removals. Staff averaged 0.69 ± 0.08 (SE) removals/hr over the 9-yr period. Removals made by volunteers were 8.0% more male-biased than those of staff alone (Table 2). Aerial shooting began in 2014 and continued through February 2017, yielding 261 removals and the highest removal rate of 3.22 mouflon per hour.

Baiting and trapping did not attract any mouflon or result in captures during 36 hr

TABLE 1

Control Methods, Total Number of Removals, and Effort Expended during Eradication of Mouflon at the Kahuku Unit of Hawai‘i Volcanoes National Park, 2004–2017

Method	Years Employed	Total Removals	Staff Hours	Staff Days	Removals/Hour
Volunteer program	2004–2012	3,038	4,402	126	0.69
Ground shooting	2008–2017	1,498	5,323	140	0.29
Baiting and trapping	2011	0	36	3	0.00
Ground shooting w/dogs	2011–2017	68	290	6	0.28
Aerial shooting	2014–2017	261	81	25	3.22
Ground sweep	2015–2016	1	231	2	<0.01
Ground shooting w/FLIR	2015, 2017	2	88	2	0.02
Judas technique	2016	0	36	6	0.00
Grand total	—	4,868	10,487	310	0.46

TABLE 2

Numbers of Male and Female Mouflon Removed by Staff and by Directed Volunteers at the Kahuku Unit of Hawai‘i Volcanoes National Park, 2004–2012

Personnel	Rams	Ewes	Proportion Female	95% CI
Staff	535	683	0.561	0.533–0.588
Volunteers	945	875	0.481	0.460–0.504
Total	1,480	1,558	0.523	0.495–0.531

of effort. The Judas technique also did not result in any removals; the collared ram was observed alone five times during the 63-day period before removal on 19 July 2016.

Two ground sweeps were conducted by field crews. The first sweep was on 10 November 2015 when eight staff, spaced approximately 50 m apart, swept 29.5 km of transects. The sweep was assisted by helicopter with a shooter and one NPS staff on the ground. No mouflon were seen during the sweep, but sign was detected on three of eight transects. During the second sweep, on 6 October 2016, a crew of 12 swept 56.9 km of transects on the eastern half of the unit. Staff was able to flush one ewe and remove the animal.

Monitoring

AERIAL SURVEYS. Eight aerial surveys were conducted to index mouflon abundance in the Kahuku Paddocks (Table 3). A total of 14 transects totaling 84.3 km was surveyed in the entire area. Surveys began at dawn and concluded before 1000 hours. The pilot maintained an AGL of approximately 125 m, and flight speeds ranged between 74.8 kph and 87.4 kph during each survey. The maximum number of 782 and largest group size of 55 occurred in 2004. Mean group size for all surveys ranged between 5.5 and 15.0 (Table 3). Detections decreased to 137 animals in 2011 as the eradication effort progressed, but then ranged from 188 to 231 from 2014 to 2017. There were no detections during three aerial surveys within the enclosed unit after 2012.

GROUND SURVEYS. Ground surveys for sign of ungulate presence (droppings, browse, tracks, and trails) were conducted in the Kahuku Paddocks on 1–2 October 2014. Six transects were surveyed, totaling 247 stations and 4,277 plots. Substantially more sign was detected in the unenclosed area (27.5% of plots), and the enclosed unit had sign in only 3.6% of plots (Table 4). Four mouflon were observed within the enclosed unit during the survey and subsequently removed by staff.

CAMERA-TRAP MONITORING. Twenty-four camera traps were positioned at 75 different locations throughout the enclosed unit. The first cameras were deployed in October 2014, and additional cameras were added to the array in 2015 and 2016. Cameras were continually maintained, active all hours of the day, moved, and monitored until 14 April 2017, for a total of 10,217 trap nights. A total

TABLE 3

Detections of Mouflon during Aerial Surveys at the Kahuku Unit of Hawai‘i Volcanoes National Park

Year	Survey Area	Groups Detected	Mean Group Size	Total Detected	Rams	Ewes	Unknown Sex
2004	Entire	52	15.0	782	14	55	713
2006	Entire	37	7.6	282	30	103	149
2007	Entire	60	7.9	471	84	355	32
2008	Entire	41	8.8	359	62	158	139
2011	Entire	25	5.5	137	14	67	56
2014	Enclosed	0	—	0	—	—	—
2014	Unenclosed	31	6.2	192	50	114	28
2015	Enclosed	0	—	0	—	—	—
2015	Unenclosed	22	8.5	188	44	69	75
2017	Enclosed	0	—	0	—	—	—
2017	Unenclosed	34	6.8	231	31	200	—
Total		302	9.0	2,642	329	1,121	1,192

Note: The first five surveys include results of the entire 64.7 km^2 Kahuku Paddocks before enclosure by fence. Results from 2014 and 2015 include both the 25.9 km^2 fence-enclosed unit and the 38.8 km^2 unenclosed area.

TABLE 4

Number of Survey Stations, Plots Surveyed, and Percentage of Ungulate Sign Detected on Plots Surveyed in Two Ungulate Management Units in Kahuku Paddocks of Hawai‘i Volcanoes National Park, October, 2014

Transect No.	No. of Survey Stations		Number of Plots Surveyed		Plots with Ungulate Sign		% of Plots with Ungulate Sign	
	Enclosed	Unenclosed	Enclosed	Unenclosed	Enclosed	Unenclosed	Enclosed	Unenclosed
1	6	1	95	18	0	0	0.00	0.00
2	25	23	459	438	35	121	7.63	27.63
3	24	24	515	485	24	187	4.66	38.56
4	29	26	623	442	12	195	1.93	44.12
5	33	20	275	396	0	65	0.00	16.41
6	11	25	—	531	—	66	—	12.43
Total	128	119	1,967	2,310	71	634	3.61	27.45

of 48 mouflon were detected on 24 images in the enclosed unit, although individual identification of sheep was not possible. Mean group size was 2.0 ± 0.2 (SE) mouflon. Detections occurred throughout the day but the majority of detections were between 1600 hours and 1800 hours. Detections per trap night steadily declined over the monitoring period (Figure 4).

FORWARD-LOOKING INFRARED (FLIR). Two searches were conducted with the FLIR Scout TS32r Pro, on 20 May and 13 October 2015, but did not yield any detections. The search range of the unit was approximately

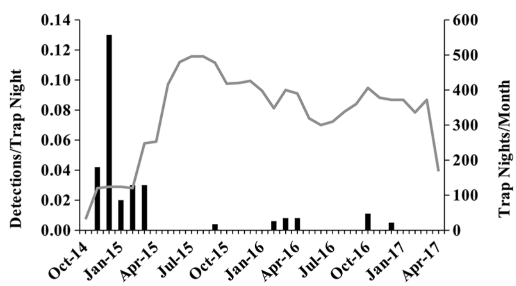

FIGURE 4. Monthly sum of mouflon per trap night (gray bars) detected by 24 camera traps and total number of camera trap nights per month (black line) in the Kahuku Paddocks of Hawai‘i Volcanoes National Park, 2014–2016.

50 m; thus mouflon could have been missed at greater distances. Observers using the FLIR Recon 3EO saw four mouflon on 28 September 2015; it had higher sensitivity, enabling detection at distances of ≤4 km. Staff removed two of the animals.

DISCUSSION

Methods that resulted in the most removals included volunteer-assisted shooting, ground shooting by staff, and aerial shooting, which was the most effort-effective method overall. Volunteer-assisted shooting accounted for 62% of all removals over the first 9 yr of the 13-yr effort, when mouflon were at high population density. The program had the benefit of involving the public in protecting NPS resources and facilitated a positive relationship with the public. However, volunteers preferentially targeted rams, which may distort the sex ratio of a population and result in increased population growth rates after density has been reduced in polygynous species such as mouflon (Stephens et al. 2008). Although ground shooting by staff, both with and without the use of dogs, also resulted in large numbers of removals, these methods became less efficient after densities had been reduced.

The effort required to remove the last remaining mouflon increased nearly 15-fold after the fenced unit was enclosed in 2012. After enclosure, NPS staff developed and refined five methods to achieve eradication: aerial shooting, ground shooting, ground shooting with dogs, FLIR-assisted shooting, and ground sweeps with large crews. More than 532 hr were required to remove the last 27 remaining animals from January 2016 to February 2017. Aerial shooting was severalfold more efficient than ground-based methods, especially when conducted in conjunction with other monitoring techniques but was limited by high expense and safety concerns. Aerial shooting may lose effectiveness as mouflon become increasingly wary of helicopters but may be warranted when presence is confirmed by monitoring. Ground sweeps were the most effort-intensive technique but one of few means for locating small numbers of remaining animals.

Other methods that did not result in the removal of animals included baiting and trapping, and the Judas technique. The Judas technique has been proven highly effective for feral livestock such as domestic sheep and goats (Taylor and Katahira 1988), but strong behavioral differences limit its utility for wild ungulate species. Small group sizes and low group cohesion, especially during pursuit, may render the method of little use for mouflon, although it has been used successfully to control hybrid sheep on Mauna Kea (Banko et al. 2014), and it was considered useful in locating small numbers of remaining axis deer (*Axis axis*) at Point Reyes National Seashore, California (N. Gates, NPS, pers. comm.). The Judas technique may be improved by collaring females to attract multiple mature rams. Furthermore, inducing permanent estrus would increase the likelihood of mature rams finding collared ewes (Campbell et al. 2007). Other attempts to attract mouflon by baiting required several months of consistent effort, perhaps because of neophobia or competitive use of bait by other animal species (Judge et al. 2016).

Our results are consistent with practical observations by NPS resource managers, who found through decades of experience that the effort to reduce ungulate populations by half is roughly the same regardless of initial abundance (B. Harry, NPS retired, pers. comm.). Although large numbers of animals can readily be removed from populations at high density, the effort to monitor, detect, and control remaining animals increases substantially when populations have been reduced to low densities because they become wary of repeated culling and extended control efforts (Côté et al. 2014). Moreover, habitat use of remaining animals may also change in response to control activities (Palupe et al. 2016), and species that have never been domesticated, such as mouflon and deer, are more difficult to detect and control than feral livestock (Hess 2008).

Although FLIR was instrumental in detecting and removing four axis deer that were illegally introduced to Hawai‘i Island (Hess et al. 2015), it resulted in the removal of only two mouflon at Kahuku. Continuous camera-trap monitoring was used to greater extent for locating remaining mouflon at Kahuku. A total of 130 mouflon was removed while cameras were in use, during which time 50 detections had been recorded in images. Although this represents the detection of ~38% of remaining individuals, it was the single most effective monitoring method. In contrast, no mouflon were detected from aerial surveys during the same period, which may have resulted from wariness of aerial shooting. Although methods are available for correcting incomplete detection in aerial surveys, they cannot be applied in this case where no groups were detected (Lancia et al. 1996).

Camera traps proved to be effective for detecting elusive mouflon and for providing staff with locations of remaining animals that could subsequently be removed. Mouflon behavior did not appear to be affected by the cameras and observer bias was limited to locations chosen for camera placement. By having a combination of camera-placement strategies and frequent checks, we were able to locate small numbers of remaining sheep and direct staff to remove these animals promptly. We were also able to provide age and sex data that enabled staff to know when an entire group of mouflon had been removed. We expanded the search near ground survey stations where ungulates were detected by placing camera traps in nearby arrays, thereby finding mouflon that had not been detected during control efforts and aerial surveys. Camera traps were also valuable for confirming the absence of mouflon in the enclosed unit after the last known individuals were removed.

Monitoring methods differed strongly in their temporal and spatial coverage, observer bias, and acquisition type, affecting the ability to detect animals at different densities (Table 5). Aerial and ground surveys acquired data from a single point in time and thus represented snapshots of the population. Aerial surveys provided data from large spatial scales, providing an index of abundance, demographic composition, and geographic distribution at high densities, but they were not effective for detecting small groups of mouflon at low population density. Consequently, the method could provide misleading interpretations of abundance as animals became wary and eluded aircraft. Ground surveys covered intermediate spatial scales, were effective at detecting low densities of animals, but provided no demographic information except when animals were observed directly. Camera traps acquired data continuously, but were limited in spatial scale. Active and passive survey tools complemented each other when used in conjunction. For example, ground surveys detected sign of mouflon and informed locations for camera-trap monitoring.

The mouflon control program in HAVO is the first detailed example of an eradication effort of a phenotypically pure nondomesticated ungulate in Hawai‘i (Hess and Jacobi 2011). Few other intentional eradications of nondomesticated ungulate species have been documented aside from six species of deer on at least 14 islands throughout the world and one other population of mouflon in the Kerguelen archipelago (Database of Island Invasive Species Eradications 2015). The effort

TABLE 5

Survey Methods and an Evaluation of Spatial and Temporal Coverage, Observer Bias, and Acquisition Type

Survey Type	Time	Space	Acquisition	Bias
Aerial	Point	Extensive	Active	Negative
Ground	Point	Intermediate	Active	Negative
Camera	Continuous	Intensive	Passive	Negligible

Note: Each method's capacity to detect animals on a temporal scale represents a single point in time or continuous coverage. Spatial coverage differs by the size of survey area. Observers may introduce bias by affecting animal behavior during surveys, which should be considered when interpreting data.

and variety of methods required to eradicate mouflon from an enclosed unit of moderate size illustrates the difficulty of scaling up to entire populations of wild ungulate species. More intensive eradication methods may become necessary as populations are reduced in number and restricted to areas that are difficult to access. Such an enclosed unit essentially represents an ungulate-free island surrounded by mouflon and other ungulates. It is unlikely that eradication can be achieved in adjacent high population density areas without additional fenced enclosures because of continued immigration from surrounding areas. Nonetheless, these fences are also vulnerable to breaches from many sources that may allow periodic ingress. In contrast to the eradication of an entire population, this example of local eradication, as well as many other cases throughout Hawai'i, represents a status that may change over time and require vigilance to maintain until animals have been removed from surrounding areas.

ACKNOWLEDGMENTS

We thank K. Awong, D. Hu, J. Leialoha, and R. Loh for facilitation and guidance, D. Okita of Volcano Helicopters for skillful piloting, and three reviewers for helpful comments. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Literature Cited

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

Banko, P. C., R. J. Camp, C. Farmer, K. W. Brick, D. L. Leonard, and R. M. Stephens. 2013. Response of palila and other subalpine Hawaiian forest bird species to prolonged drought and habitat degradation by feral ungulates. Biol. Conserv. 157:70–77.

Banko, P. C., S. C. Hess, P. G. Scowcroft, C. Farmer, J. D. Jacobi, R. M. Stephens, R. J. Camp, D. L. Leonard Jr., K. W. Brinck, J. O. Juvik, and S. P. Juvik. 2014. Evaluating the long-term management of introduced ungulates to protect the palila, an endangered bird, and its critical habitat in subalpine forest of Mauna Kea, Hawai'i. Arct. Antarct. Alp. Res. 46:871–889.

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

Campbell, K. J., G. S. Baxter, P. J. Murray, B. E. Coblentz, and C. J. Donlan. 2007. Development of a prolonged estrus effect for use in Judas goat. Appl. Anim. Behav. Sci. 102:12–23.

Campbell, K. J., and C. J. Donlan. 2005. Feral goat eradications on islands. Conserv. Biol. 19:1362–1374.

Chapuis, J. L., P. Boussès, and G. Barnaud. 1994. Alien mammals, impact and management in the French sub-Antarctic islands. Biol. Conserv. 67:97–104.

Côté, I. M., E. S. Darling, L. Malpica-Cruz, N. S. Smith, S. J. Green, J. Curtis-Quick, and C. Layman. 2014. What doesn't kill you makes you wary? Effect of repeated culling on the behaviour of an invasive predator. PLoS One 9 (4): e94248.

Database of Island Invasive Species Eradications. 2015. Island Conservation, Coastal Conservation Action Laboratory, UCSC, IUCN SSC Invasive Species Specialist Group, University of Auckland and Landcare Research New Zealand. http://diise.islandconservation.org. Accessed 28 November 2016.

Giffin, J. G. 1979. Biology of the mouflon sheep on Mauna Kea. State of Hawai'i, Department of Land and Natural Resources, Division of Forestry and Wildlife, Honolulu.

Hess, S. C. 2008. Wild sheep and deer in Hawai'i: A threat to fragile ecosystems. USGS Fact Sheet FS 2008-3102. http://pubs.usgs.gov/fs/2008/3102/. Accessed 28 November 2016.

Hess, S. C., and J. D. Jacobi. 2011. The history of mammal eradications in Hawai'i and the United States associated islands of the central Pacific. Pages 67–73 *in* C. R. Veitch, M. N. Clout, and D. R. Towns, eds. Island invasives: Eradication and management. IUCN, Gland, Switzerland.

Hess, S. C., B. Kawakami Jr., D. Okita, and K. Medeiros. 2006. A preliminary assessment of mouflon abundance at the Kahuku Unit of Hawaii Volcanoes National Park. U.S. Geological Survey Open File Report OF 2006-1193. USGS, Reston, Virginia.

Hess, S. C., J. Muise, and J. Schipper. 2015. Anatomy of an eradication effort: Removing Hawaii's illegally introduced axis deer. Wildl. Prof. 9 (2): 40–43.

Hess, S. C., R. M. Stephens, T. L. Thompson, R. M. Danner, and B. Kawakami Jr. 2011. Survival of European mouflon (Artiodactyla: Bovidae) in Hawai'i based on tooth cementum lines. Pac. Sci. 65:59–67.

Judge, S. W., S. C. Hess, J. K. Faford, D. Pacheco, C. R. Leopold, C. Cole, and V. DeGuzman. 2016. Evaluating detection and monitoring tools for incipient and relictual non-native ungulate populations. Hawai'i Cooperative Studies Unit Technical Report 069. University of Hawai'i at Hilo, Hilo, Hawai'i.

Kaho'olawe Island Conveyance Commission. 1993. Kaho'olawe Island: Restoring a cultural treasure. Kaho'olawe Island Conveyance Commission, Wailuku, Hawai'i.

Kramer, R. J. 1971. Hawaiian land mammals. Charles E. Tuttle Co., Rutland, Vermont.

Lancia, R. A., J. D. Nichols, and K. H. Pollock. 1996. Estimating the number of animals in wildlife populations. Pages 215–253 *in* T. A. Bookhout, ed. Research and management techniques for wildlife and habitats. The Wildlife Society, Bethesda, Maryland.

Leopold, C. R., and S. C. Hess. 2016. Conversion of native terrestrial ecosystems in Hawai'i to novel grazing systems: A review. Biol. Invasions doi:10.1007/s10530-016-1270-7.

Linderholm, A., D. Spencer, V. Battista, L. Frantz, R. Barnett, R. C. Fleischer, H. F. James, D. Duffy, J. P. Sparks, D. R. Clements, L. Andersson, K. Dobney, J. A. Leonard, and G. Larson. 2016. A novel MC1R allele for black coat colour reveals the Polynesian ancestry and hybridization patterns of Hawaiian feral pigs. R. Soc. Open Sci. 3:160304. http://dx.doi.org/10.1098/rsos.160304.

Nogales, M., J. L. Rodríguez Luengo, and P. Marrero. 2006. Ecological effects and distribution of invasive non-native mammals on the Canary Islands. Mammal Rev. 36:49–65.

O'Gara, B. W. 1994. Report to trustees of the Damon Estate concerning mouflon on the Kahuku Ranch. Unpubl. manuscript at the K. Ross Toole Archives, Mansfield Library, University of Montana, Missoula. (Available upon request from the University of Montana Library.)

Palupe, B., C. R. Leopold, S. C. Hess, J. K. Faford, D. Pacheco, and S. W. Judge. 2016. Changes in mouflon habitat use and distribution in the Kahuku Unit of Hawai'i Volcanoes National Park. Pac. Conserv. Biol. 22:308–311.

Stephens, R. M., S. C. Hess, and B. Kawakami Jr. 2008. Controlling mouflon sheep at the Kahuku Unit of Hawai'i Volcanoes National Park. Proc. Vertebr. Pest Conf. 23:304–309.

Stone, C. P. 1985. Alien animals in Hawai'i's native ecosystems: Toward controlling the adverse effects of introduced vertebrates. Pages 251–297 *in* C. P. Stone and J. M. Scott, eds., Hawai'i's terrestrial ecosystems: Preservation and management. University of Hawai'i Cooperative National Park Resources Studies Unit, Honolulu.

Stone, C. P., P. K. Higashino, L. W. Cuddihy, and S. J. Anderson. 1991. Preliminary survey of feral ungulate and alien and rare plant occurrence on Hakalau Forest National Wildlife Refuge. Technical Report 81. University of Hawai'i Cooperative National Park Resources Studies Unit, Honolulu.

Stone, C. P., and R. A. Holt. 1990. Managing the invasions of alien ungulates and plants in Hawaii's natural areas. Monogr. Syst. Bot. 32:211–221.

Taylor, D., and L. Katahira. 1988. Radio telemetry as an aid in eradicating remnant feral goats. Wildl. Soc. Bull. 16:297–299.

Tomich, P. Q. 1986. Mammals in Hawai'i. Bishop Museum Press, Honolulu.

Warner, R. E. 1960. A forest dies on Mauna Kea. Pac. Discovery 13:6–14.