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Monitoring the eradication of European mouflon sheep from the Kahuku Unit of Hawaiʻi Volcanoes National Park

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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 Hawaiʻi 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 2004–2017, 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 the 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 at attracting or detecting small numbers of remaining individuals. Effort expended to remove each mouflon increased nearly 15-fold during the last three years of eradication effort from 2013–2016. Complementary active and passive monitoring techniques allowed us to track the effectiveness of control effort and reveal the 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.

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Introduction

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 which have become feral, such as pigs (*Sus scrofa*), which were first brought by Polynesians ~800 years 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 Kahoʻolawe Island (Kramer 1971, Kahoʻolawe Island Conveyance Commission 1993). Feral sheep on Mauna Kea reached high densities and degraded watersheds and fragile subalpine woodlands (Bryan 1937, Warner 1960). Wild ungulate species which had never been previously domesticated were introduced to enhance hunting opportunities on the islands even after the detrimental effects feral livestock had been recognized. The first eradication program in Hawaiʻi began in the early 1900s on Niʻihau Island, where goats had deforested large areas (Kramer 1971). Subsequent eradications have been pursued in many natural areas to protect and recover 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 Hawaiʻi, 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 Hawaiʻi. Managers at Hawaiʻi 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 radio-telemetry 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 ha 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 Lānaʻi 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, Hawaiʻi 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 Hawaiʻi Department of Land and Natural Resources used public and staff hunting to remove >18,000 sheep from 1980–2011; nevertheless, low annual hunting yields and immigration thwarted eradication (Banko et al. 2014).

<<Figure 1 near here>>

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 Hawaiʻi. Kahuku was delineated into several management units and fences were constructed to prevent immigration.

In the present study we tracked the effort (staff hours) expended to eradicate mouflon from the 64.7 km^2 Kahuku Paddocks, which was representative of ~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.

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 Hawaiʻi (Figure 2). We tracked reduction efforts from 2004–2017 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 1,000–1,600 m asl in October of 2012. The area consisted of dry and mesic forest dominated by the native ʻōhiʻa (*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*).

<<Figure 2 near here>>

Several recent lava flows (≤750 years 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 2–5 staff to control ungulates at Kahuku from 2004–2017. 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 for each control method include:

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 2011–2017 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 Garmin T5 GPS tracking collar and their movements were tracked with Garmin Astro 320 handheld devices.

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 would conduct aerial shooting; one pilot flying a MD (Hughes) 500D helicopter, 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 helicopter on May 17, 2016. The ram was hobbled and blindfolded without sedatives while being fitted with a Telonics TGW-4470-4 GPS 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 in order to prevent sheep escaping between them. Either a helicopter or vehicles with park staff would standby during the sweep and respond 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 2004–2017 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 groundspeed and altitude above ground level (AGL) during surveys. Flight tracks and waypoints were downloaded to computer, joined to survey data, and plotted with 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 50-m^2 contiguous plots using field methods consistent with 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 were surveyed during October 1–2, 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 ArcGIS 10.2 Geographic Information System. Locations were assigned to management units by UTM coordinates.

Camera trap monitoring- A total of 24 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 of 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 SD 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 wide field of view. Surveyors could then return to locations at night and pre-dawn hours to scan areas for mouflon. Animals could be detected with FLIR until approximately two hours after sunrise. Locations of detections were immediately reported to park staff. All monitoring activities were conducted in compliance with University of Hawaiʻi IACUC Protocol 06-043.

Results

Control Effort

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

<<Figure 3 near here>>

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 d. Staff spent a total of 4,402 h 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/hour over the nine-year 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.

<<Table 1 near here>>

<<Table 2 near here>>

Baiting and trapping did not attract any mouflon or result in captures during 36 h of effort. The Judas technique also did not result in any removals; the collared ram was observed alone five times during the 63 d period prior to removal on July 19, 2016.

Two ground sweeps were conducted by field crews. The first sweep was on November 10, 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 October 6, 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 were surveyed in the entire area. Surveys began at dawn and concluded before 1000 h. 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 5.5−15.0 (Table 3). Detections decreased to 137 animals in 2011 as the eradication effort progressed, but then ranged from 188–231 from 2014–2017. There were no detections during three aerial surveys within the enclosed unit after 2012.

<<Table 3 near here>>

Ground surveys - Ground surveys for sign of ungulate presence (droppings, browse, tracks, and trails) were conducted in the Kahuku Paddocks on October 1−2, 2014. Six transects were surveyed, totaling 247 stations and 4,277 plots. Substantially more sign was detected in the unenclosed unit; 27.5% of plots, while 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.

<<Table 4 near here>>

Camera trap monitoring- A total of 24 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 April 14, 2017 for a total of 10,217 trap nights. A total 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 h and 1800 h. Detections per trap night steadily declined over the monitoring period (Figure 4).

<<Figure 4 near here>>

Forward-looking infrared- Two searches were conducted with the FLIR Scout TS32r Pro on May 20 and October 13, 2015 but did not yield any detections. The search range of the unit was approximately 50 m; thus mouflon could have been missed at greater distances. Observers saw four mouflon using the FLIR Recon 3EO on September 28, 2015, which had higher sensitivity enabling detection at distances of ≤4 km. Staff removed two of the animals.

Discussion

Methods which 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 nine years of the 13-year 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 in order to achieve eradication: aerial shooting, ground shooting, ground shooting with dogs, FLIR assisted shooting, and ground sweeps with large crews. More than 532 hours were required to remove the last 27 remaining animals from January 2016−February 2017. Aerial shooting was several-fold more efficient than ground-based methods, especially when conducted in conjunction with other monitoring techniques, but 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 which 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 (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 which 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 were removed while cameras were in use, during which time 50 detections had been recorded in images. While 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 complimented each other when used in conjunction. For example, ground surveys detected sign of mouflon and informed locations for camera trap monitoring.

<<Table 5 near here>>

The mouflon control program in HAVO is the first detailed example of an eradication effort of a phenotypically pure non-domesticated ungulate in Hawaiʻi (Hess and Jacobi 2011). Few other intentional eradications of non-domesticated 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 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 which 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 Hawaiʻi represent a status which may change over time and require vigilance to maintain until animals have been removed from surrounding areas.

Acknowledgments

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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 Hawaiʻi Volcanoes National Park, 2004–2012.

	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

Table 3. Detections of mouflon during aerial surveys at the Kahuku Unit of Hawaiʻi Volcanoes National Park. The first five surveys include results of the entire 64.7 km^2 Kahuku Paddocks prior to enclosure by fence. Results from 2014 and 2015 include both the 25.9 km^2 fence enclosed unit and 38.8 km^2 unenclosed area.

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

Table 4. Number of survey stations, plots surveyed, and percent of ungulate sign detected on plots surveyed in two ungulate management units in Kahuku Paddocks of Hawaiʻi Volcanoes National Park, October, 2014.

Transect Number	Number of Survey Stations		Number of Plots Surveyed		Plots with Ungulate Sign		Percent 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

Table 5. Survey methods and an evaluation of spatial and temporal coverage, observer bias, and acquisition type. 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.

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

Figure 1. Three mature mouflon rams detected by infrared camera traps at the Kahuku Unit of Hawaiʻi Volcanoes National Park, August 28, 2015.

Figure 2. Hawai‘i Island and Hawai‘i Volcanoes National Park (outlined in black). The gray area is the total distribution of mouflon in the Kahuku Unit (approximately 130 km^2). Mouflon control was conducted in the enclosed and unenclosed units of the Kahuku Paddocks from Volcanoes National Park, 2014−2016.

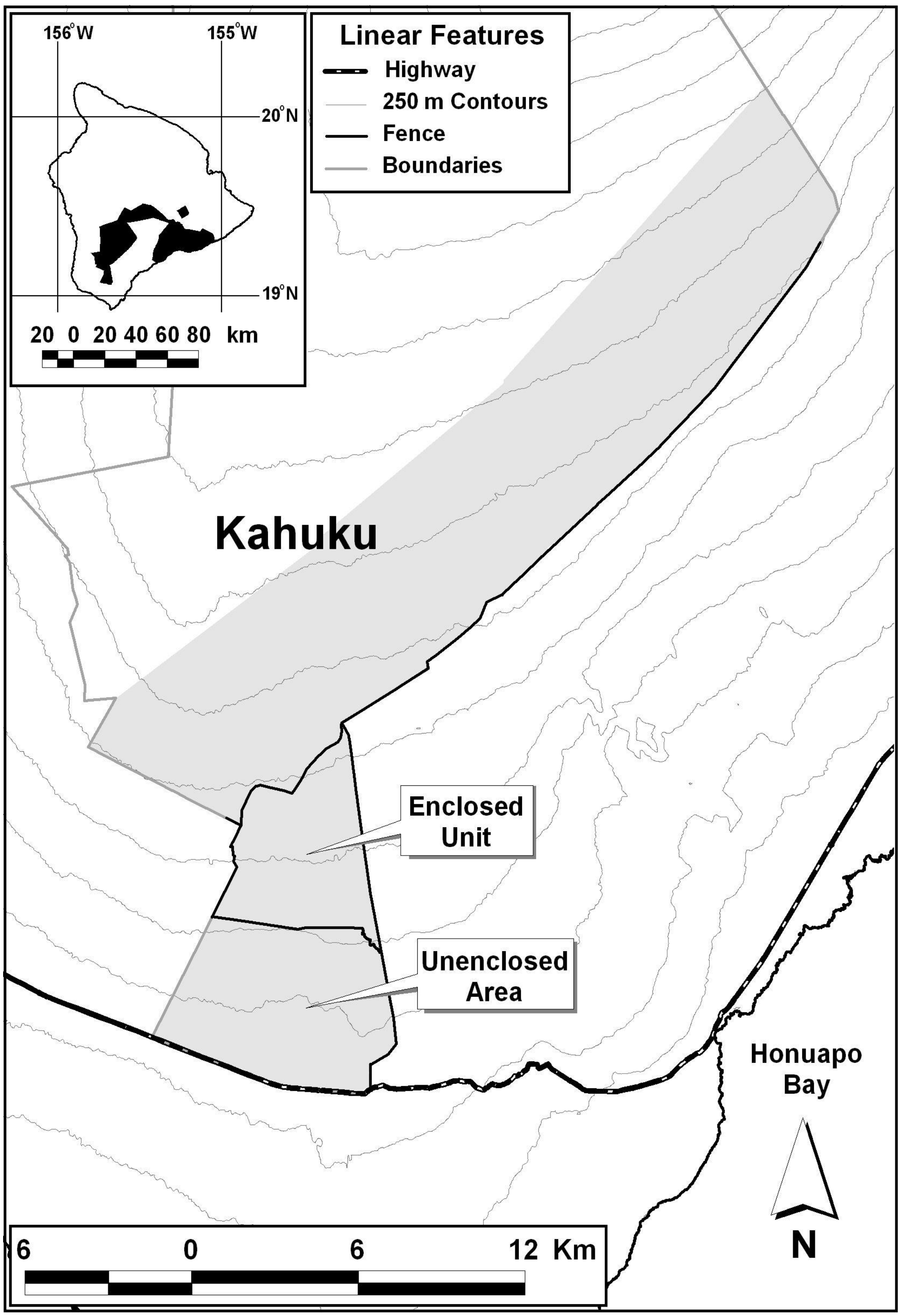


Figure 3. The annual number of European mouflon sheep removed (gray bars), and the effort expended (black line) to remove mouflon from the Kahuku Paddocks of Hawaiʻi Volcanoes National Park, 2004–2016.

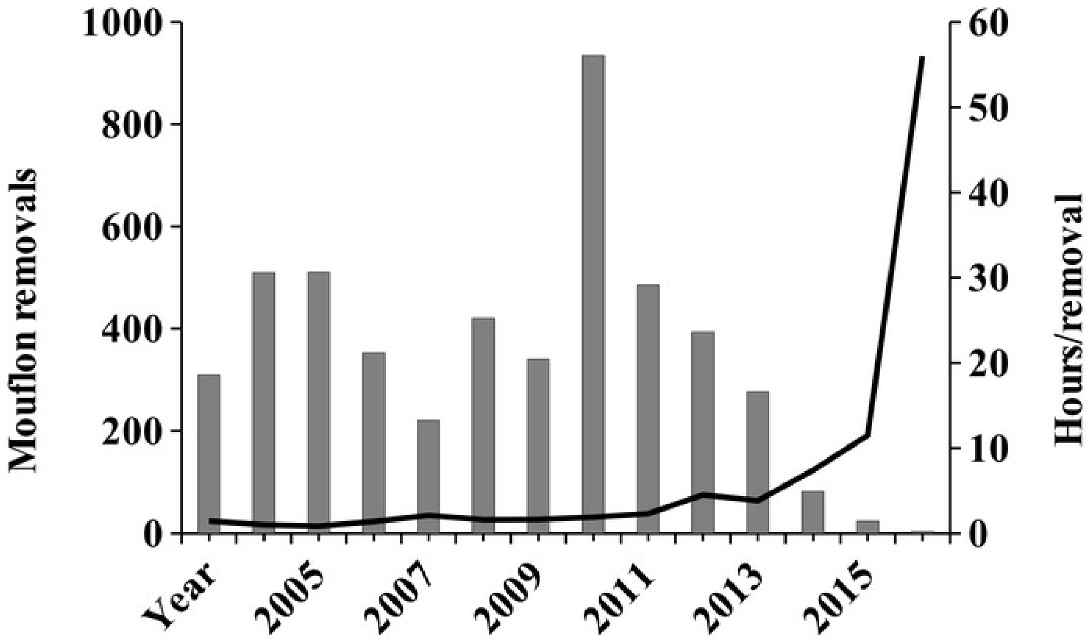
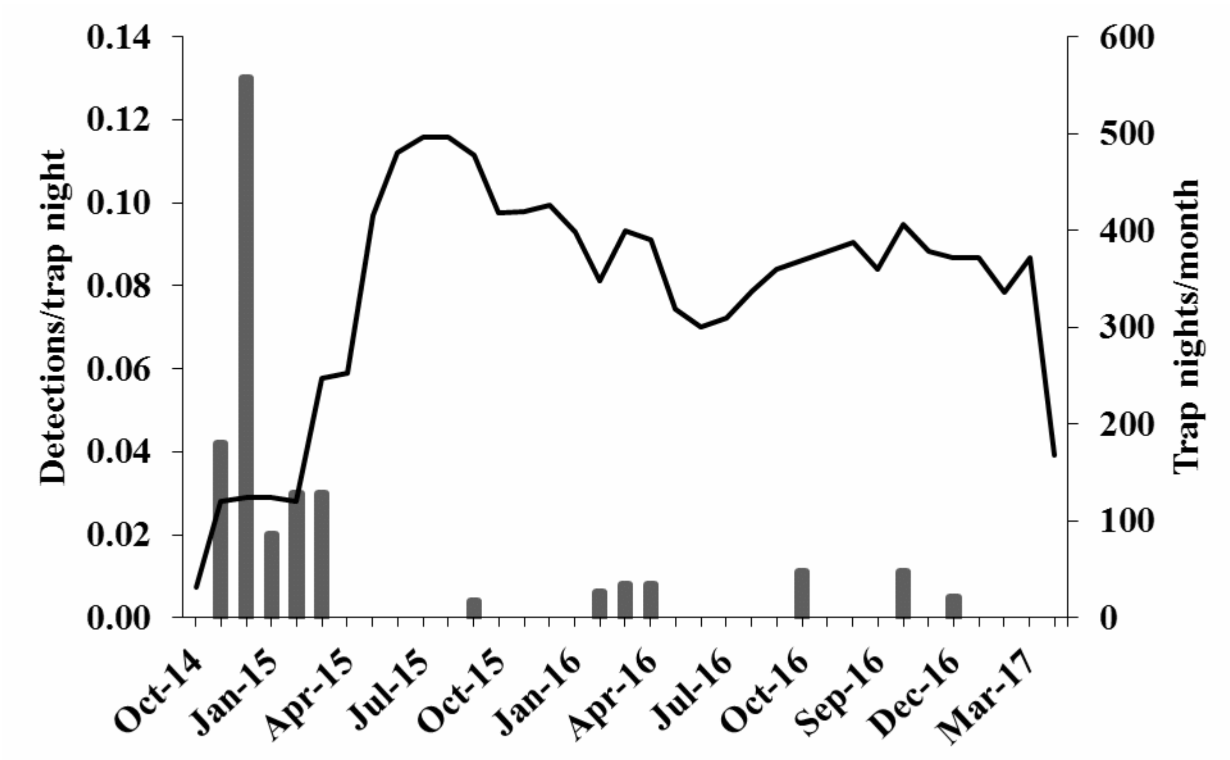


Figure 4. Monthly sum of mouflon per trap night (gray bars) detected by 24 camera traps and total number of camera trap nights per month (black line) in the Kahuku Paddocks of Hawai‘i



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