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EVALUATING DETECTION AND MONITORING TOOLS FOR INCIPIENT AND RELICTUAL NON-NATIVE UNGULATE POPULATIONS

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ABSTRACT

Hawai'i Volcanoes National Park (HAVO) encompasses 1,308 km^2 on Hawai'i Island. The park harbors endemic plants and animals which are threatened by a variety of invasive species. Introduced ungulates have caused sharp declines of numerous endemic species and have converted ecosystems to novel grazing systems in many cases. Local ranchers and the Territorial Government of Hawai'i had long conducted regional ungulate control even prior to the establishment of HAVO in 1916. In 1995 the park's hunting team began a new hunt database that allowed managers to review hunt effort and effectiveness in each management unit. Target species included feral pigs (*Sus scrofa*), European mouflon sheep (*Ovis gmelini musimon*), feral goats (*Capra hircus*) and wild cattle (*Bos taurus*). Hunters removed 1,204 feral pigs from HAVO over a 19-year period (1996–2014). A variety of methods were employed, but trapping, snaring and ground hunts with dogs accounted for the most kills. Trapping yielded the most animals per unit effort. Hunters and volunteers removed 6,657 mouflon from HAVO; 6,601 of those were from the 468 km^2 Kahuku Unit. Aerial hunts yielded the most animals followed by ground hunt methods. Hunters completed eradications of goats in several management units over an 18-year period (1997–2014) when they removed the last 239 known individuals in HAVO primarily with aerial hunts. There have also been seven cattle and five feral dogs (*Canis familiaris*) removed from HAVO.

Establishing benchmarks and monitoring the success of on-the-ground ungulate removal efforts can improve the efficiency of protecting and restoring native forest for high-priority watersheds and native wildlife. We tested a variety of methods to detect small populations of ungulates within HAVO and the Hō'ili Wai study area in the high-priority watershed of Ka'ū Forest Reserve on Hawai'i Island. We conducted ground surveys, aerial surveys and continuous camera trap monitoring in both fence-enclosed units and unenclosed units where populations of introduced mouflon and feral pigs threatened sensitive native plants and forest bird habitats.

Beginning in June 2014, twenty infrared camera traps were positioned in areas occupied by ungulates. The cameras were active for at most 198 days, and then half of the cameras were baited with oats and salt blocks for 126 days. There were a total of 1,496 observations of mouflon captured on camera, totaling 2,592 individuals: 1,020 ewes, 900 rams, 276 lambs, and 396 sheep of unknown sex. There were no detections of the illegally introduced axis deer (*Axis axis*). There were 11 observations of feral pigs and 109 observations of other animals (birds, rats, and other small mammals), including one detection of the federally endangered Hawaiian hawk (*Buteo solitarius*). Mouflon detection rates did not increase near baited cameras until three months after the initial baiting.

Ground-based surveys for ungulate presence were conducted along six transects in Kahuku in October 2014. Evidence of ungulates were detected in 27.5% of plots surveyed within an unenclosed unit, while an enclosed unit had sign in only 3.6% of plots surveyed. An aerial survey by helicopter was conducted in October 2014. A total of 378 mouflon were detected during the survey: 192 in the Kahuku Paddocks, 186 in the Kahuku East unit and no mouflon were detected in the actively controlled Mauka unit.

Two baseline ungulate surveys have been completed at the Hō'ili Wai study area in the high-priority watershed of Ka'ū Forest Reserve adjacent to Kahuku prior to the completion of an exclusionary ungulate fence. Ground-based surveys were conducted on four transects within a 4.99 km^2 area on 5 August and 5–6 November 2014. In August, 20.71% of 565 plots surveyed

had fresh or intermediate ungulate sign. In November, 17.41% of 557 plots surveyed had fresh or intermediate ungulate sign. These surveys represent baseline levels of ungulate activity prior to management; therefore comparative inferences can be made about ungulate distribution and relative abundance, but inferences about absolute abundance cannot be made until all ungulates have been removed from the enclosed area. Additional ground-based surveys will be conducted when the fenced area has been fully enclosed, and until ungulate removals have been completed.

INTRODUCTION

Control of non-native ungulates is the single most expensive natural resource management activity in National Parks 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, and snaring (Anderson and Stone 1993). Natural Park Service (NPS) resource managers have developed highly effective control methods for feral ungulates (Taylor and Katahira 1988, Anderson and Stone 1993). To date, ungulates have been completely excluded or removed from roughly 750 km^2 of important terrestrial ecosystems throughout the Hawaiian Islands, primarily on federal lands (Hess and Jacobi 2011). Managers have also found through decades of experience that the cost of reducing ungulate populations by half is roughly the same regardless of initial abundance (B. Harry, NPS retired, pers. comm.). Reducing populations to progressively lower levels becomes increasingly more expensive because low densities of animals are difficult to detect, particularly when they become wary of extended control efforts. Also, more recently introduced species which have never been domesticated, such as European mouflon sheep (*Ovis gmelini musimon*) and axis deer (*Axis axis*) are more difficult to detect and control than domesticated species which have become feral (Hess 2008). Much of the difficulty is due to the inability to locate and monitor individuals and small groups of remaining animals.

The Kahuku Ranch was acquired by the National Park Service in 2003 and management of non-native ungulates commenced in 2004, including mouflon and feral sheep (*O. aries*), feral pigs (*Sus scrofa*), and feral cattle (*Bos taurus*). Now, after a decade of management, ungulate populations have decreased to the point where they have become locally difficult to detect, especially within enclosed management units. However, several remaining populations of regionally abundant ungulate species could increase in number and re-invade Kahuku as well as other sections of Hawai'i Volcanoes National Park (HAVO). At the same time, unauthorized introductions of new invasive ungulate species between Hawaiian Islands have recently increased in frequency. Axis deer were introduced to Hawai'i Island from Maui in 2009 (Tummons 2011). To date, four individuals have been removed from the vicinity of Kahuku's southern boundary (Hess et al. 2015). Detecting, locating, and dispatching small numbers of animals remains a costly challenge for managers.

The objective of this research is to develop and implement intensive techniques to detect and monitor low-density relictual populations of non-native ungulates within fenced management areas and recent invasions of both regionally abundant ungulates and recently introduced species increasing in the vicinity of National Park boundaries in the Pacific Islands Network. Specific goals are: 1) developing and evaluating new techniques for detecting relictual ungulate populations within managed areas and incipient invasions of newly introduced ungulate species in HAVO using Forward Looking Infrared Radar (FLIR) and remote-triggered infrared cameras; 2) building NPS capability to conduct regional landscape-scale monitoring of established non-native ungulates to help managers identify, prioritize, and evaluate the effectiveness of ungulate removal efforts; 3) improve designs and methods for indexing feral pig abundance using ground-based surveys and occupancy models with appropriate environmental covariates; and 4) provide technical assistance, training, and analysis tools for NPS staff to detect incipient invasions of newly established ungulate species and to conduct and analyze ungulate survey data. The findings of this study will be used to increase the efficiency of detecting and monitoring non-native ungulates throughout National Parks of Hawai'i and in protected natural areas throughout National Parks of the Pacific Islands Network that have been invaded by large herbivorous mammals.

Methods

Study area

Kahuku Unit of Hawai'i Volcanoes National Park

Ground-based monitoring of ungulates, aerial surveys, and control efforts by NPS staff were conducted in the 468 km^2 Kahuku Unit of HAVO on the island of Hawai'i (Figure 1). A 209 km^2 study area was delineated and divided into three management units: the Kahuku Paddocks, the Mauka unit, and the Kahuku East unit (Figure 1). The Kahuku Paddocks were improved pasture areas between 600–1600 m asl on the southern ridge of Mauna Loa. These former ranch lands were mesic forest dominated by 'ōhi'a (*Metrosideros polymorpha*) and to a lesser extent, koa (*Acacia koa*). The introduced Christmas-berry tree (*Schinus terebinthifolius*) co-dominated lower elevations (approximately 600–900 m asl). The understory had been modified to open meadows dominated by introduced grasses (*Panicum repens*, *Cenchrus clandestinus, Pennisetum setaceum,* etc.). The Mauka unit ranged between 1,600–2,100 m asl and included the upper reaches of montane 'ōhi'a/koa forest and then sharply transitioned into subalpine native shrubland near 2,000 m asl. Montane forest understory included a variety of native shrubs and trees including 'ōlapa (*Cheirodendron trigynum*), ō'helo (*Vaccinium* spp.), pūkiawe (*Leptecophylla tameiameiae*), pilo (*Coprosma montana*), and tree ferns (*Cibotium* spp.). Shrublands were dominated by short stature 'ōhi'a woodland and native shrubs such as: a'ali'i (*Dodonaea viscosa*), ō'helo, pūkiawe and native bunchgrass (*Deschampsia nubigena*). Kahuku East was comprised of mixed montane/subalpine 'ōhi'a forests near 1,600 m and entirely native sub-alpine shrublands above 1,700 m asl. Several relatively recent lava flows (≤ 750 years b.p.) extend through portions of each unit; notably the 1887, 1916, and 1950 flows which each offer ungulates escape routes and some protection from hunters or feral dogs (USGS unpubl. data). Orographic effects cause strong climatic gradients over a broad range of elevation in Kahuku (Hess et al. 2011). Mean annual precipitation from 1983–2008 at 1,570 m elevation was 975 ± 341 (SD) mm (Schlappa et al. 2011). The greatest mean rainfall occurred between November and January (1157 mm) and the least precipitation occurred between May and June (54.8 mm; Schlappa et al. 2011). Rainfall decreases westward towards the Mauna Loa southwest rift zone and the adjacent rural sub-division. The Ka'ū Forest Reserve borders the east and southeast portions of each Kahuku management unit (Figure 1).

Hō'ili Wai Unit of Ka'ū Forest Reserve

Hō'ili Wai is an important conservation area adjacent to Kahuku within the Ka'ū Forest Reserve which was identified by members of the Three Mountain Alliance for protection and management because of it forest bird population, 'Alalā (*Corvus hawaiiensis*) habitat, and watershed value. The Hō'ili Wai study area (19° 13′ 26″ N, 155° 34′ 51″ W; approximately 1,700–1,850 m asl) has an area of approximately 5 km^2 and consists primarily of a closed canopy mesic 'ōhi'a forest with understory of dense kanawao (*Broussaisia arguta*), native ferns (*Cibotium* and *Dryopteris* spp.), kāwa'u (*Ilex anomala*), kōlea (*Myrsine* spp.), 'ōlapa, and other native plant species, but relatively few non-native species aside from feral pigs. Interpolated rainfall averaged 2,510 mm/year based on regional data beginning in 1892 (Giambelluca et al. 2013).

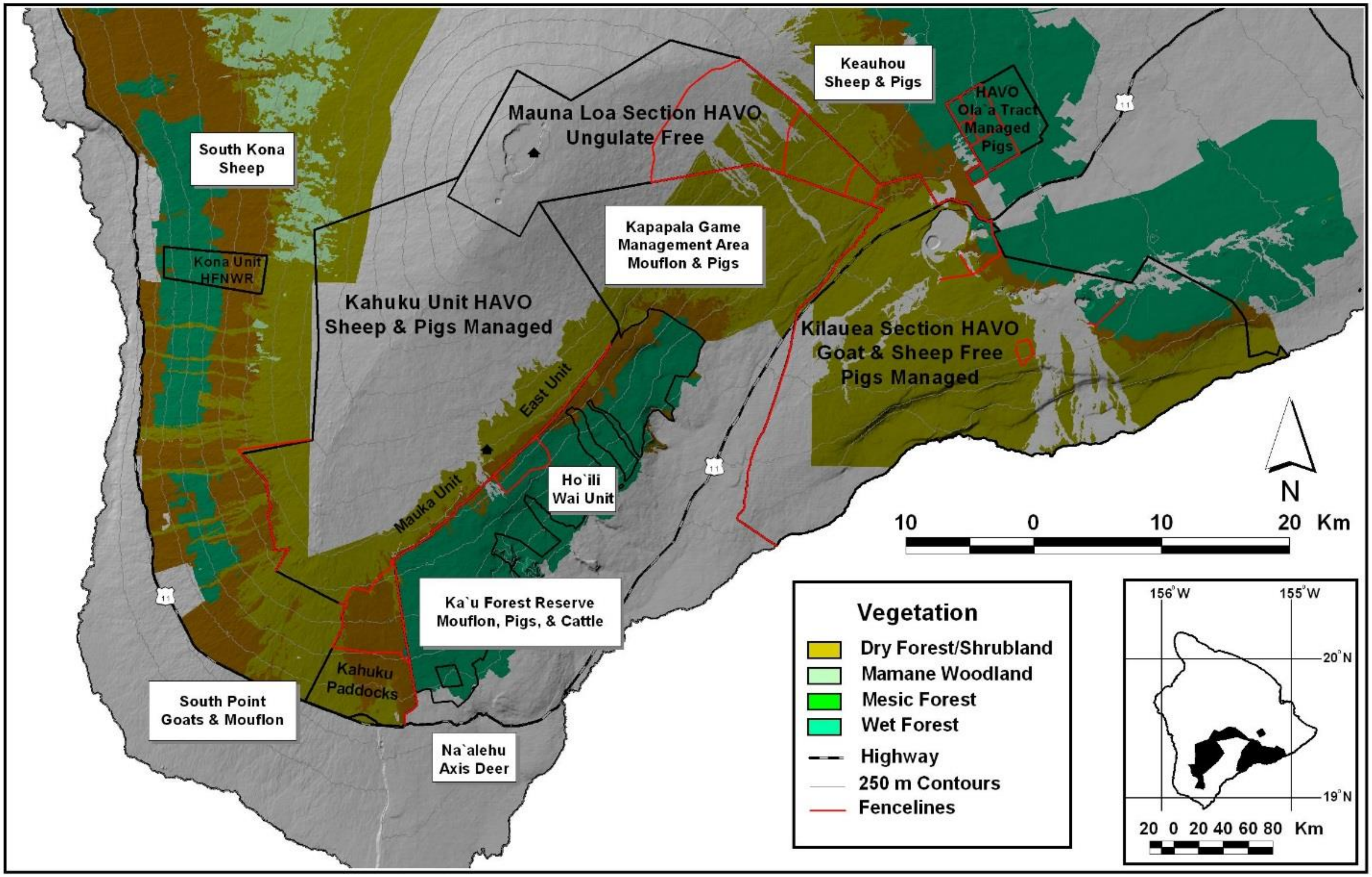

Figure 1. Hawai'i Volcanoes National Park and adjacent land management areas with respective invasive ungulates.

Ungulate Removal Database

NPS resource management staff maintained a database of all ungulate removals throughout HAVO beginning in July 1995. Data were summarized through December 2014. Each record had the date, unit or area where hunters were working, hunt objective (e.g. sheep hunt, pig hunt, goat hunt, etc.), and method (e.g. trapping, aerial hunt, ground hunt, etc.). Hunters recorded start time and end time, and mode of transportation to units and other arrangements. The number of staff on hunts and hours worked were multiplied to calculate "hunt hours", or the total person hours expended each day. Total numbers of kills were divided by hunt hours to assess effectiveness by year, method, objective, and target species in each unit. NPS hunters accounted for volunteer hunt hours and kills during the Kahuku Volunteer Ungulate Control Program (KVUCP).

Monitoring Relictual Non-native Ungulate Population Distribution and Abundance

Camera Trap Monitoring

Pre-baiting period

Remote-triggered infrared (IR) cameras (Bushnell Trophy Cam™) were deployed in locations likely to detect introduced mammals based on reports of recent sightings and favorable habitats. A total of 20 IR cameras were initially deployed on June 9, 2014. Cameras were tested in several locations within the Kahuku Paddocks unit. Cameras with few or no detections were moved to more favorable locations to maximize the number of detections per camera trap day. Habitats that had wide views of potential grazing areas were targeted for camera placement, as well as natural corridors where animals may be "funneled" for ease of travel. Ultimately, 16 cameras were chosen to monitor throughout the study and four additional cameras were rotated periodically to areas where small groups of mouflon were reported, or to areas where axis deer were likely to be detected. Image and video data from each IR camera was stored on an SD card. Cards were exchanged every 3–6 weeks and images and/or videos were reviewed to tally the number of each animal detected within the camera frame. The sex of individual animals (most commonly mouflon) was determined by the presence of horns, pelage color, and external genitalia. Lambs and individuals of unknown sex were also documented. Total number of sheep per camera trap and trap day were calculated and observations were grouped in two-hour blocks over a 24-hour period to determine times of peak activity.

Bait phase-in

We baited eight of the 16 cameras in the lower paddocks on December 23, 2014 with Producers Pride® rolled oats, otherwise known as "sweet cob" because the oats are supplemented with molasses. Approximately 2 kg of oats were spread out on the ground in view of each IR camera. We also placed a 1.3 kg brick of Champions Choice® iodized salt approximately 0.5 m from the pile of sweet cob. We also baited each of the four cameras placed above the fence in the actively controlled unit; these cameras were used for rapid response search methods and were moved if no ungulates were detected over a 5–6 week period.

Ground Surveys

Ground surveys were conducted for the presence and distribution of non-native ungulate activity consisting of scat, digging, tracks, or browsed vegetation within 50-m^2 contiguous plots using field methods consistent with Stone et al. (1991). Six parallel transects oriented in a North-South direction were spaced 1 km apart. A total of 97 stations, each with approximately 20 plots were surveyed during October 1–2, 2014. Transects crossed two ungulate management units: a unit enclosed by a fence (25.9 km^2) with intensive ungulate control and an unenclosed area (38.8 km^2) where ungulates could move freely across HAVO boundaries. These data were joined to their spatial coordinates and plotted using ArcGIS 9.2 Geographic Information System. Locations were assigned to management units by UTM coordinates.

Aerial Surveys
Three ungulate management units at Kahuku totaling 209 km^2 were surveyed from a helicopter on October 8–9, 2014 following methodology and transects established by Hess et al. (2006) and Stephens et al. (2008). Flights were timed to correspond to large breeding aggregations based on ground observation, and the presence of breeding pelage to maximize the ability to identify sexes. Two observers sat on each side of the aircraft and one of the observers in the back also recorded data. On their respective sides of transects, observers announced group size, sex composition (when possible), and distance to the group over the aircraft intercom. Observers were experienced in distance estimation from piloting aircraft and marksmanship. The pilot attempted to maintain constant groundspeed and above ground level (AGL) during surveys, however, uneven and sloping terrain made this difficult. These data were therefore recorded with GPS flight tracks.

Flight tracks and waypoints were downloaded to computer, joined to survey data, and plotted with GIS. AGL was determined by subtracting ground elevation on a digital elevation model from the corresponding flight elevation at the same coordinates. Mean speed and AGL was calculated for each transect. Distance data were plotted in a histogram to determine the decay in observation reliability. Mean group size and sex composition was summarized for each survey unit.

Monitoring the Efficacy of Ungulate Removal in Hōʽili Wai of Kaʽū Forest Reserve

Surveys to monitor the presence and distribution of non-native ungulates were conducted on 5 August and 5-6 November 2014 along four transects within the area which was in the process of being fenced to exclude ungulates, thus representing baseline levels of activity prior to ungulate removal. Activity indices consisting of fresh or intermediate sign using the approach described by Stone et al. (1991) and Anderson and Stone (1994) were used to quantify the distribution and relative abundance of non-native ungulates. Ungulate sign (scat, tracks, browse) on continuous 50-m^2 plots were systematically surveyed on virtual transects established with computer Geographic Information System (GIS) and downloaded to handheld Global Positioning System (GPS) units. A total of 28 stations were surveyed, each with approximately 20 sample plots (Table 1). These data were joined to their spatial coordinates, plotted using ArcGIS 10.2 and summarized by transect.

RESULTS

Ungulate Removal Database

There were a total of 5,374 records documenting ungulate removals in HAVO. Over a 20 year period (1995–2014), hunters worked on 1,293 calendar days which totaled 5,045 staff days (Table 1). Hunters removed a total of 8,119 animals and the effort totaled 36,062 hunt hours.

Table 1. Annual hunt effort and total number of animal removals from HAVO (1995–2014).

Year	Calendar Days	Total Staff	Hunt Hours	Total Kills	Kills/Hunt Hour
1995	3	3	6.0	1	0.167
1996	5	14	50.0	12	0.240
1997	4	16	26.0	7	0.269
1998	26	69	229.3	44	0.192
1999	23	65	269.5	39	0.145
2000	59	247	904.8	90	0.099
2001	53	293	1,487.3	99	0.067
2002	83	307	1,474.5	87	0.059
2003	105	613	3,280.0	331	0.101
2004	102	696	4,032.7	561	0.139
2005	77	378	2,387.3	793	0.332
2006	68	254	1,952.5	907	0.465
2007	70	284	2,412.0	875	0.363
2008	43	113	1,099.3	327	0.297
2009	105	288	2,703.8	866	0.320
2010	125	323	3,315.8	593	0.179
2011	112	319	3,623.0	1031	0.285
2012	75	208	2,089.8	605	0.290
2013	63	202	2,443.5	455	0.186
2014	92	353	2,275.0	396	0.174
Grand Total	1,293	5,045	36,061.7	8,119	0.225

Feral Pigs

Feral pig removals were first recorded in 1996. At least 1,214 pigs (331 males, 312 females, and 571 unknown sex) have been removed from HAVO (Appendix I). Hunters worked a total of 719 calendar days totaling 16,336 hunt hours. Many kills occurred incidentally during other missions (Table 2). The most common methods of removal were ground hunts with dogs, snaring, and trapping. Trapping yielded the most animals per unit effort (Figure 2).

European mouflon sheep

A total of 6,657 animals were removed in HAVO over a 20-year period (Appendix II). The first records of mouflon kills in the hunt database occurred in 1995, when hunters removed animals from high elevation areas on Mauna Loa. Removal from the Kahuku Unit began in 2004. A total of 6,601 sheep were removed from Kahuku over an 11 year period (Figure 3). Hunters employed a variety of methods with variable success. Aerial hunts and ground hunts accounted for the most kills per hunt hour expended (Table 3; Figure 4). Hunt effort remained relatively consistent in Kahuku while the number of kills varied greatly (Figure 5). Hunters averaged 1,501 hunt hours per year and 590 mouflon kills per year.

Table 2. Feral pig hunt methods and kills per hunt hour (1996–2014).

Hunt Method	Calendar Days	Hunt Hours	Total Kills	Kills/Hunt Hour
Aerial	6	70	3	0.043
Ground	10	112	1	0.009
Ground Hunt w/ Dogs	329	7715	456	0.059
KVUCP	7	N/A	10	N/A
Lost Dog Search	15	178	9	0.051
Pig Snaring	116	1806	234	0.130
Pig Trapping	252	2571	387	0.151
Rove	188	2286	60	0.026
Telemetry	190	1599	54	0.034
Grand Total	**719**	**16336.0**	**1214**	**0.074**

Figure 2. Feral pig kills per hunt hour. Note from Table 1 that other methods do not account for the majority of the control effort and are not represented in the figure. Trapping, snaring, and ground hunts accounted for 89% of all pig kills during 1996–2014.

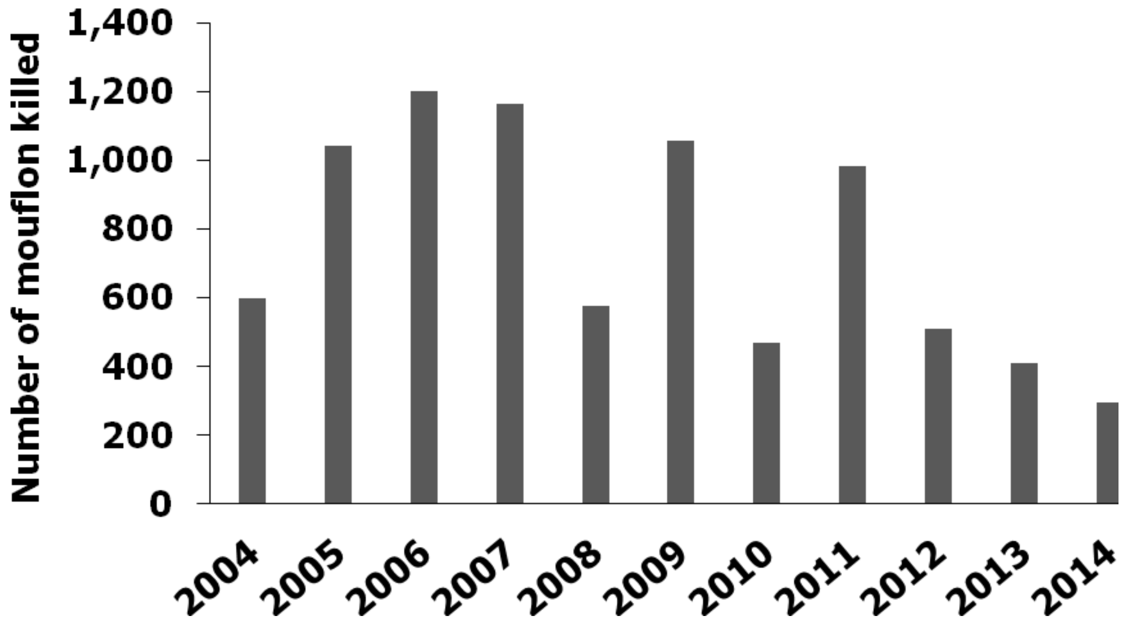

Figure 3. European mouflon sheep kills per calendar year in the Kahuku Unit of HAVO (2004–2014). A total of 6,601 sheep were removed over an 11-year period.

Table 3. Mouflon kills by hunt method in HAVO (1995–2014).

Hunt Method	Calendar Days	Staff Hours	Volunteer Hours	Total Kills	Kills/Hunt Hour
Aerial	152	1089	0	1031	0.947
Aerial with dogs	5	324	0	22	0.068
Baiting/trapping	32	362	0	7	0.019
Ground hunt w/dogs	22	814	0	79	0.097
Ground hunt	282	8157	0	1852	0.227
KVUCP	136	6454	3006	3598	N/A
Rancher hunt	7	456	0	68	0.149
Rove	16	320	0	0	0.000
Scout	4	5	0	0	0.000
Grand Total	620	17980	3006	6657	0.370

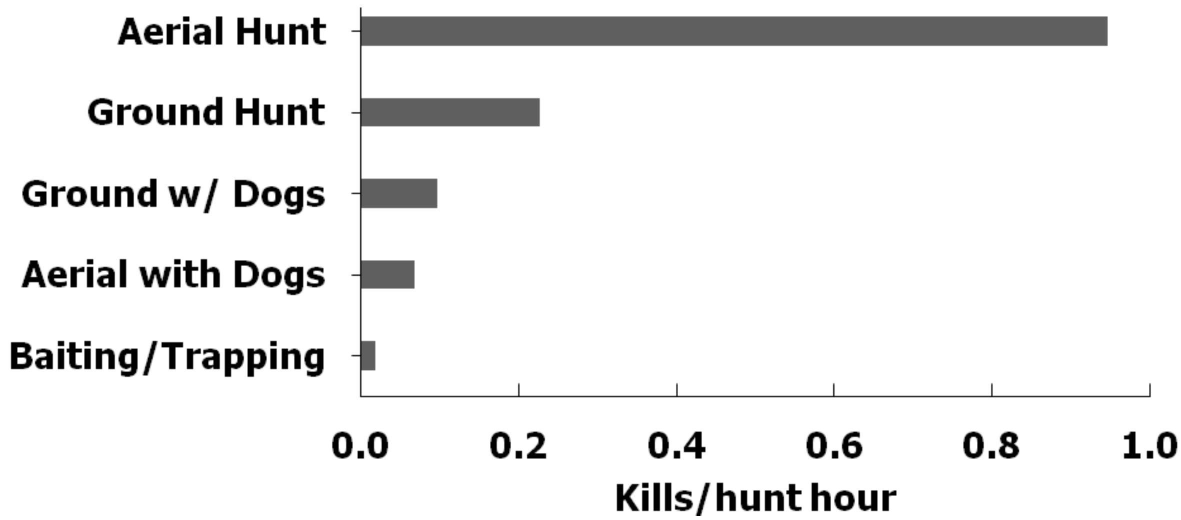

Figure 4. European mouflon sheep hunt methods and number of kills per hunt hour.

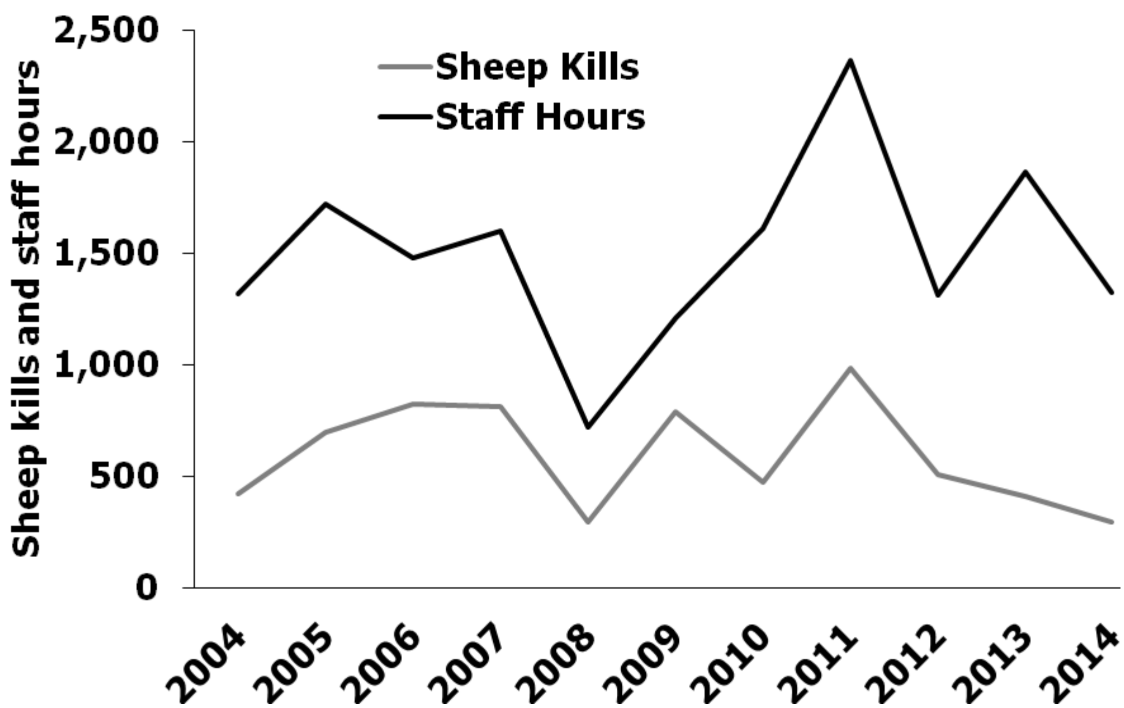

Figure 5. European mouflon sheep kills and the number of staff hours expended per year (2004–2014).

Kahuku Volunteer Ungulate Control Program

The Kahuku Volunteer Ungulate Control Program (KVUCP) hunts began in 2004 and concluded in 2012. The hunts were conducted primarily once a month and spanned a total of 136 calendar days over nine years. Typically three staff members guided four volunteers. One staff member would scout and the other two staff would guide two volunteers each. A total of 3,598 sheep were killed during the KVUCP. Staff hunters accounted for 1,527 of those kills and volunteers accounted for 2,071 kills. The earliest records may not have been reliable, especially for hunt hours and hunt days. Some hunts were summarized weekly, so daily activity is uncertain. Additionally, calculating total hunt hours is problematic; volunteer and staff hours overlap because staff were guiding volunteers. According to the database, volunteers were actively hunting for a total of 3,006 hours. Staff recorded 6,454 hours in total. There were more staff hours because transit and preparation was included. Both staff and volunteers killed a similar proportion of females among the population (Table 4).

Table 4. Numbers of male and female European mouflon sheep removed by staff and by directed volunteers at the Kahuku Unit of Hawai'i Volcanoes National Park (2004–2014).

	Male	Female	Proportion Female	95% CI
Staff	1,100	1,766	0.616	0.598–0.634
Volunteers	1,486	1,787	0.546	0.529–0.563
Total	2,586	3,553	0.579	0.566–0.591

Goats

The first records of feral goat control in the database began in 1997 although goats had been controlled in the region even before the establishment of HAVO in 1916 (Baker and Reeser 1972). HAVO staff removed seven goats that year by both aerial and ground methods. The control effort continued through 2012 and no goats were removed in 2013 and 2014. In total, at least 239 goats (45 males, 33 females, and 161 unknown) were removed over an 18-year period (Appendix III). Hunters worked on 123 calendar days totaling 324 hunt days. A total of 189 goats were removed by aerial shooting and 50 were removed from the ground. Aerial shooting consistently had a higher number of kills per hunt hour expended (Figure 6; Appendix IV).

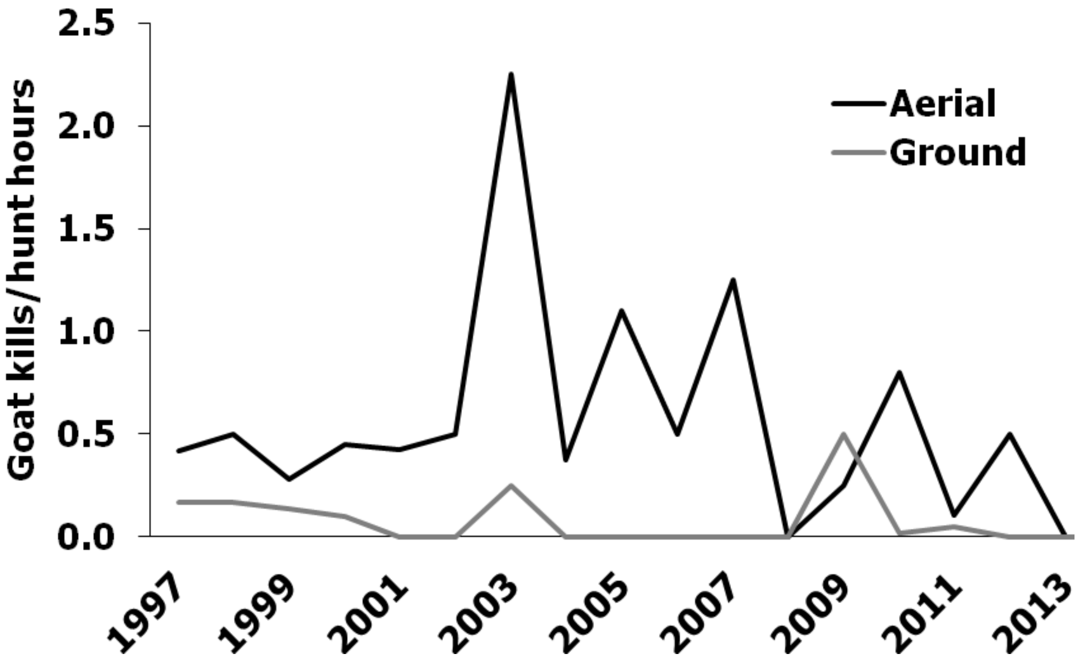

Figure 6. Goat kills per hunt hour by aerial and ground shooting within HAVO over an 18-year period (1997–2014).

Cattle
A total of seven feral cattle were removed from HAVO. Hunters opportunistically shot five animals during an aerial sheep hunt in the Kahuku Mauka Unit in 2007 (Appendix V). Hunters searched the Keauhou area from the ground in 2011, but removed no cattle. Hunters removed one male and one female cow during a ground hunt in the Kahuku Paddocks in 2011.

Feral dogs
A total of five feral dogs were removed from HAVO (Appendix VI). Three animals were removed in 2009 during an aerial hunt in the Kahuku Mauka unit. Two dogs were removed in 2011; one in Keahou while hunters were exercising dogs and the other in the Kahuku Paddocks during a ground sheep hunt.

Monitoring Relictual Non-native Ungulate Population Distribution and Abundance

Camera Trap Monitoring
Pre-baiting period
The majority of camera traps were first deployed on June 9, 2014. Additional cameras were added to the array or moved to better locations. A total of 16 cameras were positioned and monitored for baseline information regarding mouflon occurrence in the non-fenced unit of lower Kahuku. Four cameras (15, 16, 17, and 19) were "rapid response" cameras used for detecting sheep in the fenced unit of Kahuku. Cameras were not baited until December 23, 2014; thus, the pre-baiting period was ≤ 198 camera trap days (Table 5). There were 869 observations of animals detected by photo image or video; 861 were of mouflon and eight were of other animals (pigs, rats, and birds). A total of 1,800 sheep were observed on 20 different cameras (Figure 7). It is unknown how often the same animals were detected. Ewes

outnumbered rams at a ratio of 1.29:1. The number of sheep detected per camera trap day ranged between 0.005 to 1.80 sheep/day (Table 5: Figure 7). There was a declining trend in sheep detections during the pre-baiting period (Figure 8).

Table 5. Camera trap deployment and mouflon detection history during the pre-baiting period (9 June 2014–22 December 2014).

Camera Trap	Deployment Date	Rams	Ewes	Lambs	Unknown	Total Sheep	Days Active	Sheep/ Day
1	11/26/14	13	8	0	0	21	28	0.750
2	06/27/14	98	86	19	23	226	180	1.256
3	06/27/14	1	0	0	2	3	180	0.017
4	11/26/14	7	8	0	11	26	28	0.929
5	06/27/14	4	9	5	2	20	180	0.111
6	06/27/14	37	45	5	20	107	180	0.594
7	06/09/14	0	0	0	1	1	198	0.005
8	06/09/14	3	3	0	1	7	198	0.035
9	06/09/14	104	123	34	52	313	198	1.581
10	06/09/14	100	171	10	76	356	198	1.798
11	06/09/14	65	54	5	22	146	198	0.737
12	06/09/14	39	16	0	1	56	198	0.283
13	10/30/14	22	32	0	2	56	55	1.018
14	06/09/14	5	1	0	0	6	198	0.030
15	10/30/14	5	0	0	7	12	55	0.218
16	10/30/14	1	2	0	0	3	55	0.055
17	10/30/14	2	0	0	0	2	55	0.036
18	06/09/14	49	130	52	41	272	198	1.374
19	10/30/14	3	0	0	8	11	55	0.200
20	06/27/14	34	73	27	22	156	180	0.867
Grand Total		592	761	157	291	1800	2815	0.639

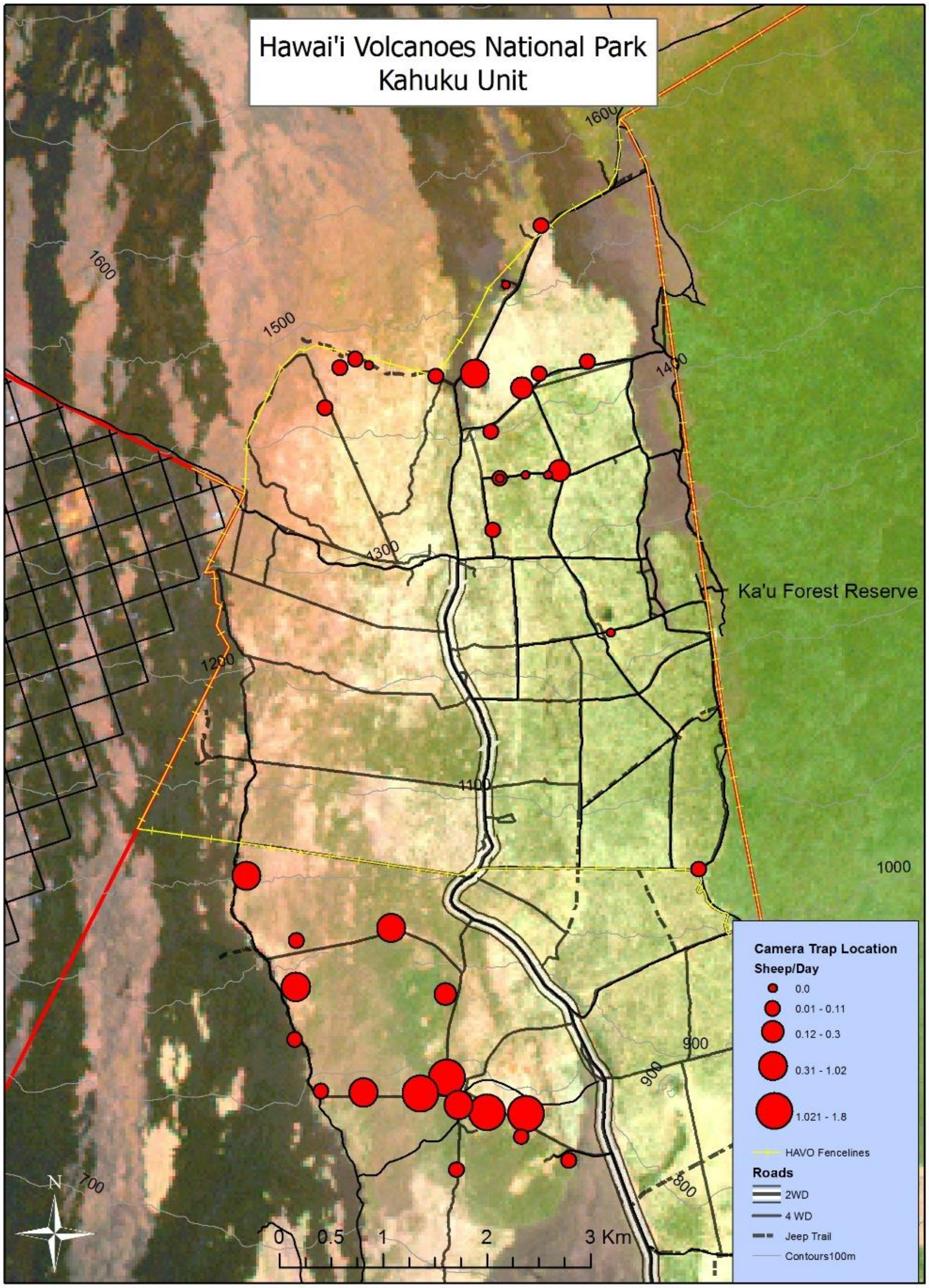

Figure 7. Camera trap locations at the Kahuku Unit of Hawaii Volcanoes National Park (June 2014–May 2015). Red circles represent the number of sheep detected per day at each camera trap location. A total of 20 cameras were used and tested at 36 locations.

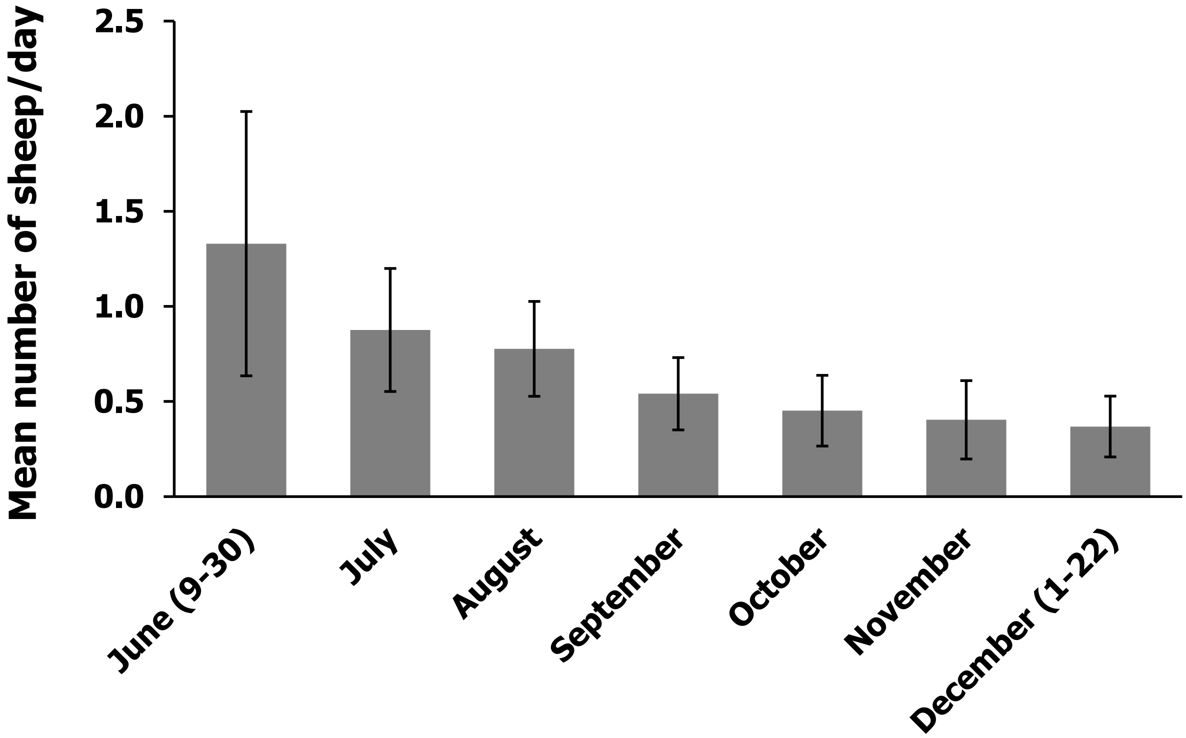

Figure 8. Mean monthly sheep detections for all cameras operating during the pre-bait period (9 June 2014–22 December 2014). There were 8 cameras operating during the first deployment in June and up to 16 cameras operating in December.

Bait phase-in

Thirteen camera traps were baited with salt and sweet cob on 23 December 2014. Cameras were re-baited every two weeks to maintain freshness and availability of bait and monitored until April 27, 2015 for a total of 126 days of operation. Each of the four rapid response cameras were baited in the fenced and managed area of Kahuku, these locations were not included in the pre-baiting period. Nine other baited cameras had information from the pre-baiting period; there was no increase in mouflon activity until three months after baiting commenced (Figure 9).

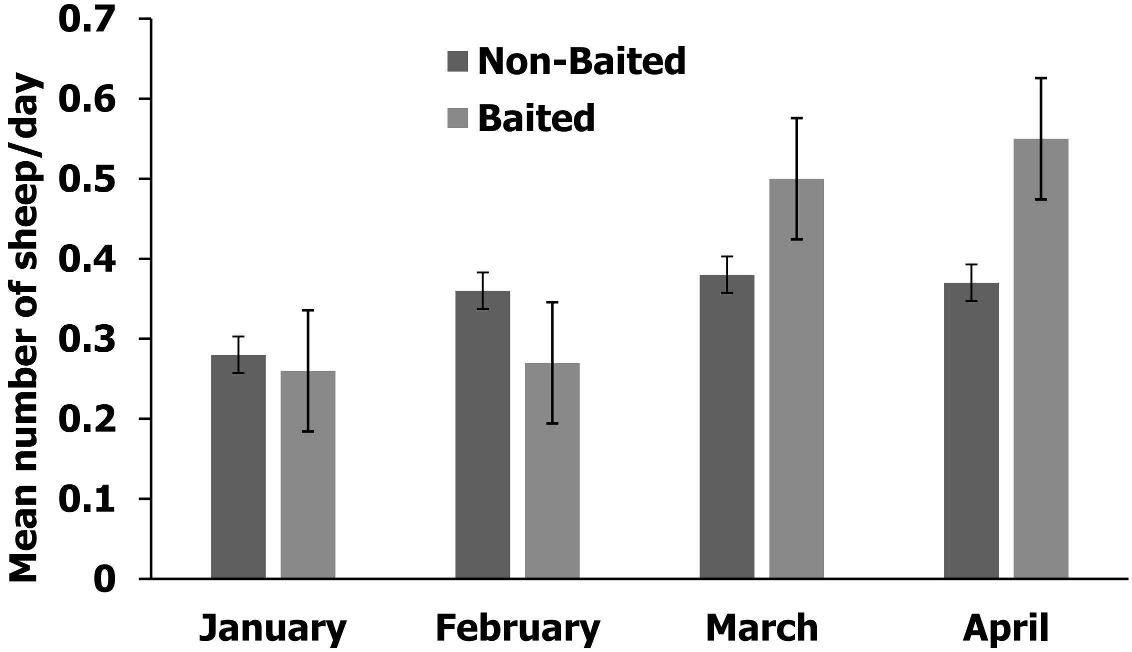

Figure 9. Mean number of sheep detected per day on cameras with and without bait during the baiting period (23 December 2014–26 April 2015).

Sex Ratio and Lambing period

There were a total of 2,592 detections of mouflon in Kahuku: 900 rams, 1,020 ewes, 276 lambs, and 396 sheep of an unknown sex. The total ratio of rams to ewes was 1:1.13, but there was variation in the ratio over the monitoring period (Figure 10). Lambs were detected on camera during the first days of deployment in June 2014 and detections began to decline in August and September (Figure 11). In 2015, the first detection of a lamb was on January 30. Consequently, the lambing period in Kahuku begins in January with peak months between April–July. By September most lambs are indistinguishable from adults.

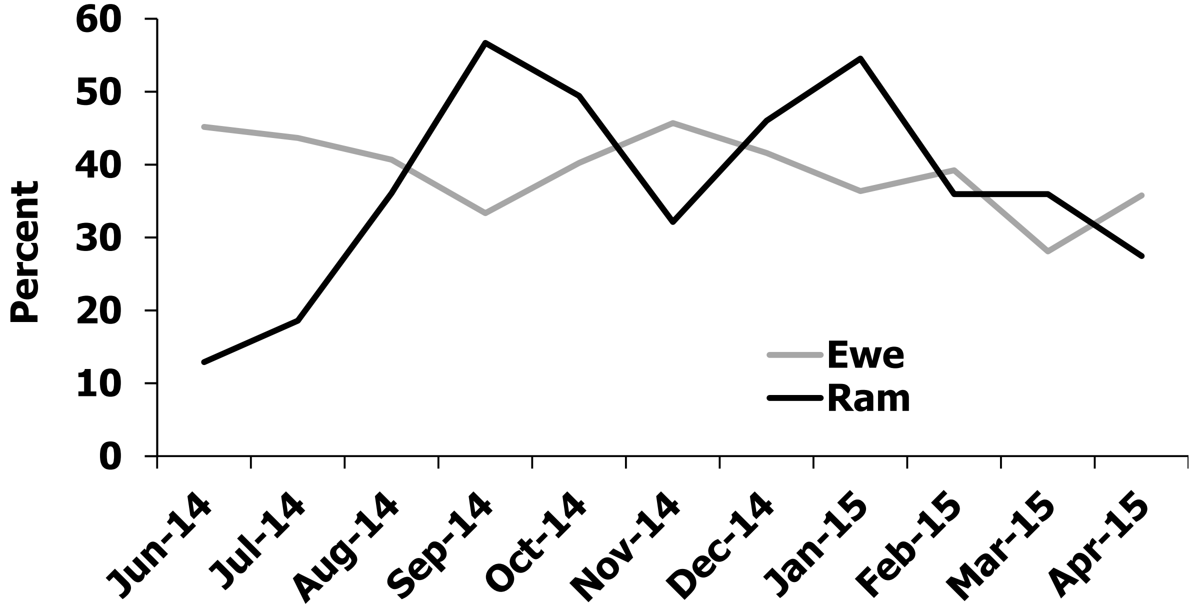

Figure 10. Percent of ewes and rams of total mouflon detected during the entire camera trap monitoring period.

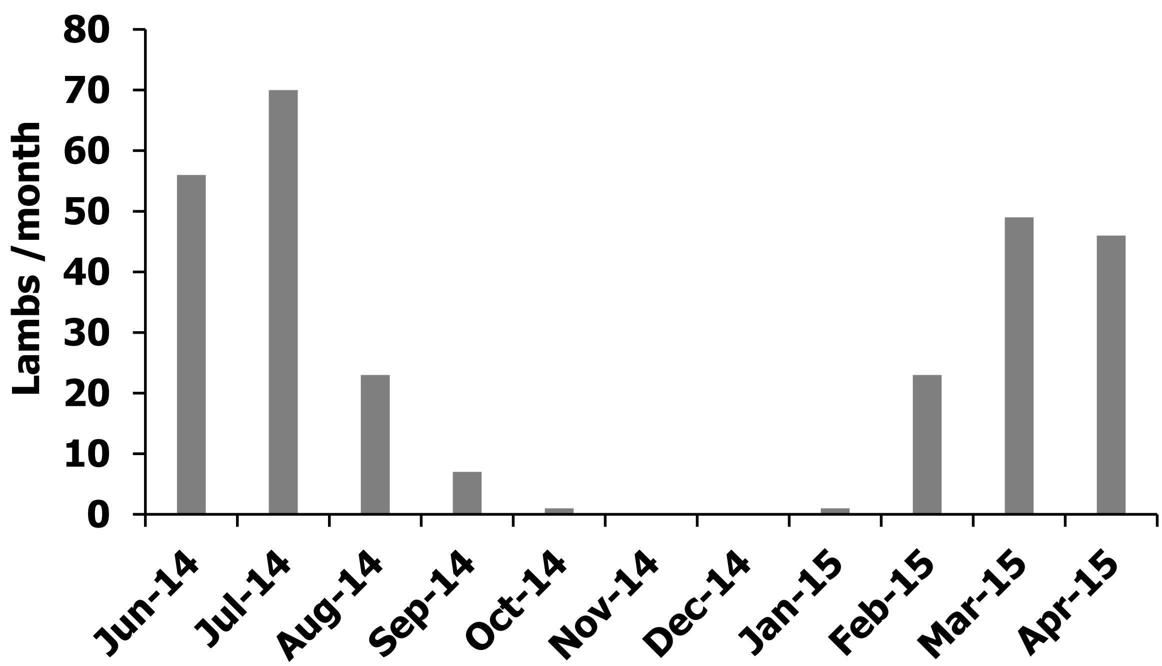

Figure 11. Mouflon lambs detected on infrared cameras in 2014 and 2015. There were a total of 276 lambs captured on camera.

Mouflon activity rates
Time of day observations were grouped into two-hour blocks. There were a total of 1,496 observations of sheep (either individuals or groups). Sheep were detected at all hours of the day but observations peaked in the morning between 06:00 h and 10:00 h; and in the late afternoon between 14:00 h and 18:00 h (Figure 12).

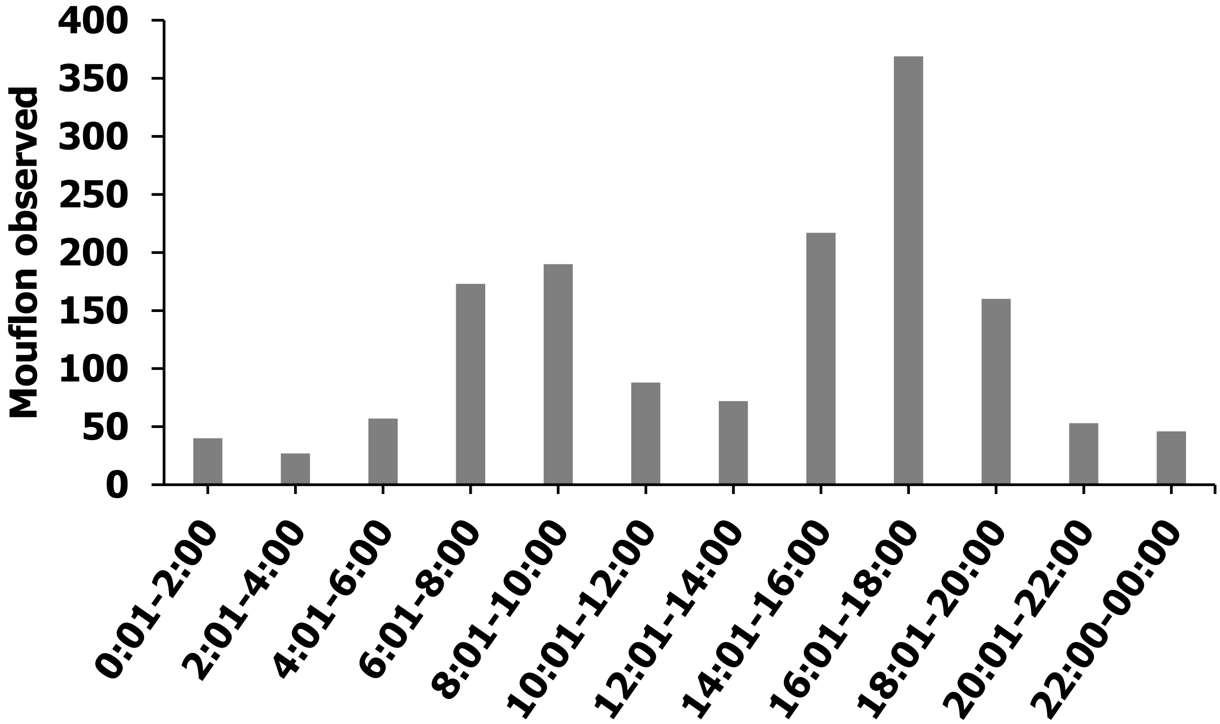

Figure 12. Mouflon detections grouped in two-hour blocks over a 24-hour period.

Ground Surveys
Ground surveys for sign of ungulate presence (droppings, browse, tracks, and trails) were conducted in the Kahuku Paddocks units on October 1 & 2, 2014. Six transects were surveyed, totaling 313 stations and 4,277 plots. Substantially more sign was detected in the unenclosed unit; 27.5% of plots surveyed, while the enclosed unit had sign in only 3.6% of plots surveyed (Table 6; Figure 13). Four mouflon were observed within the enclosed unit during the survey.

Table 6. Percent of ungulate sign detected on plots surveyed in two ungulate management units in Kahuku Paddocks area of Hawai`i Volcanoes National Park (October 1 & 2, 2014).

Transect Number	Number of Stations Surveyed		Number of Plots Surveyed		Plots with Ungulate Sign		Percent Plots with Ungulate Sign	
	Enclosed	Unenclosed	Enclosed	Unenclosed	Enclosed	Unenclosed	Enclosed	Unenclosed
2	6	1	95	18	0	0	0.00%	0.00%
3	25	23	459	438	35	121	7.63%	27.63%
4	24	24	515	485	24	187	4.66%	38.56%
5	29	26	623	442	12	195	1.93%	44.12%
6	33	20	275	396	0	65	0.00%	16.41%
7	11	25	0	531	0	66	0.00%	12.43%
Total	128	119	1967	2310	71	634	3.61%	27.45%

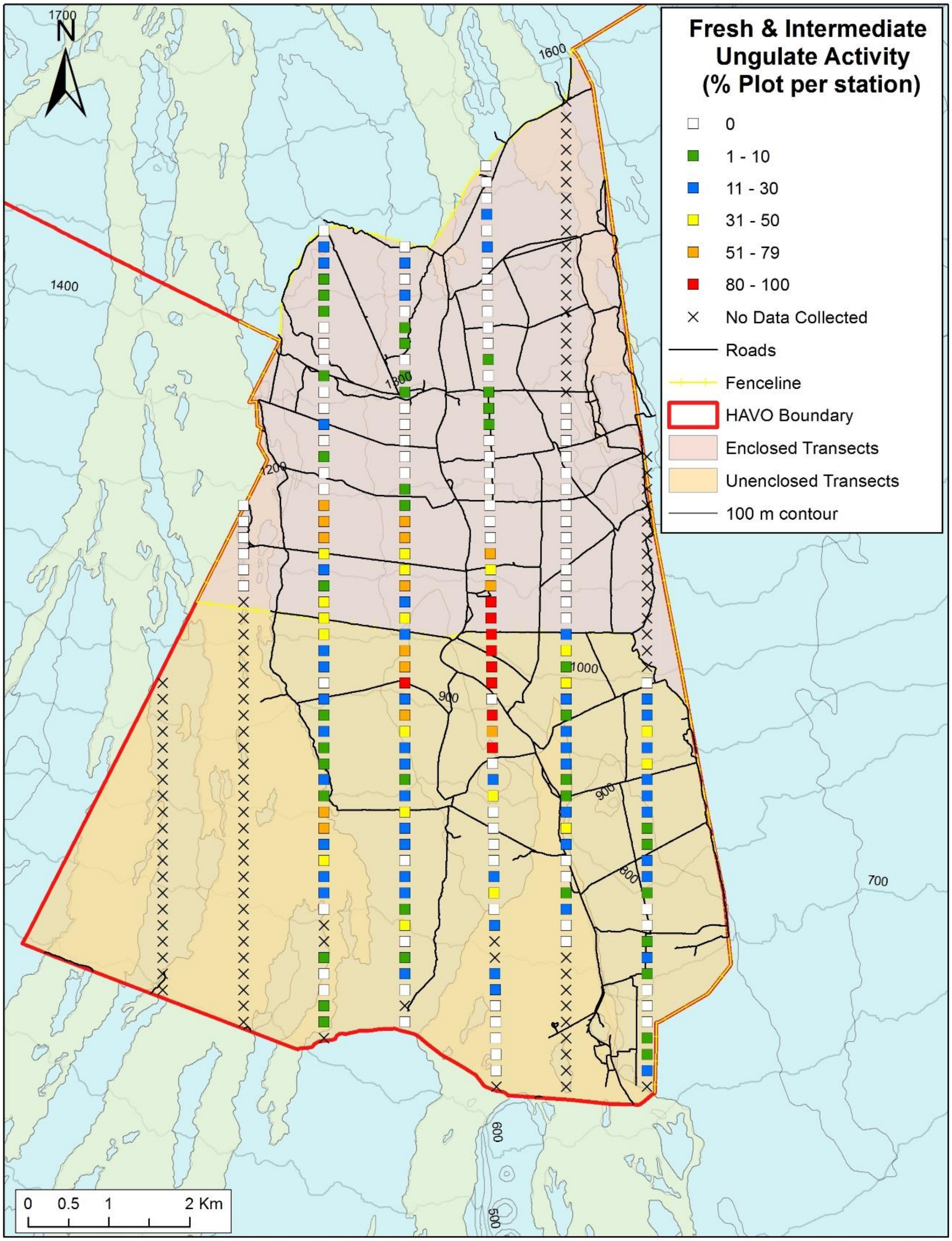

Figure 13. Ungulate sign observed on six transects in the Kahuku Unit of Hawai'i Volcanoes National Park, Hawai'i Island, (October 1 & 2, 2014).

Aerial Surveys
Aerial surveys of the East unit of Kahuku were conducted on October 8, and the Mauka unit and the Kahuku Paddocks units were both surveyed on October 9, 2014 in an MD (Hughes) 500D helicopter (Figure 14). Weather conditions during both surveys were cloudless and visibility was unlimited. Transects were flown at a mean ground speed of 74.8 KPH and a mean AGL of 120.2 m (Table 7). A total of 378 mouflon were detected during the survey: 192 in the Paddocks unit, 186 in the East unit. No sheep were detected in the Mauka unit where ungulates have been intensively controlled (Table 7). There were a total of 81 observations, or groups, counted for a mean group size of 6.19 sheep in the Paddocks unit and 3.72 sheep in the East unit (Figure 15). Mean distance from observer to sheep was 117.5 m, but was highly variable among observers (Figure 16). Total number of sheep detected was lower than any other of the five surveys conducted since 2004 except in 2011, which had the least amount of survey effort (Table 8; Figure 17).

Efficacy of Ungulate Removal in Hōʻili Wai of Kaʻū Forest Reserve
Baseline ungulate sign was recorded at all transects and stations during both surveys. The percent of plots with fresh or intermediate ungulate presence at Kaʻū Forest Reserve was 20.71% in August 2014 and 17.41% in November 2014 (Table 9). The percent of plots with ungulate sign at each station are displayed in six categories (Figure 18): 0% sign (white); 1–10% (green); 11–30% (blue); 31–50% (yellow); 51–79% (orange); 80–100% (red).

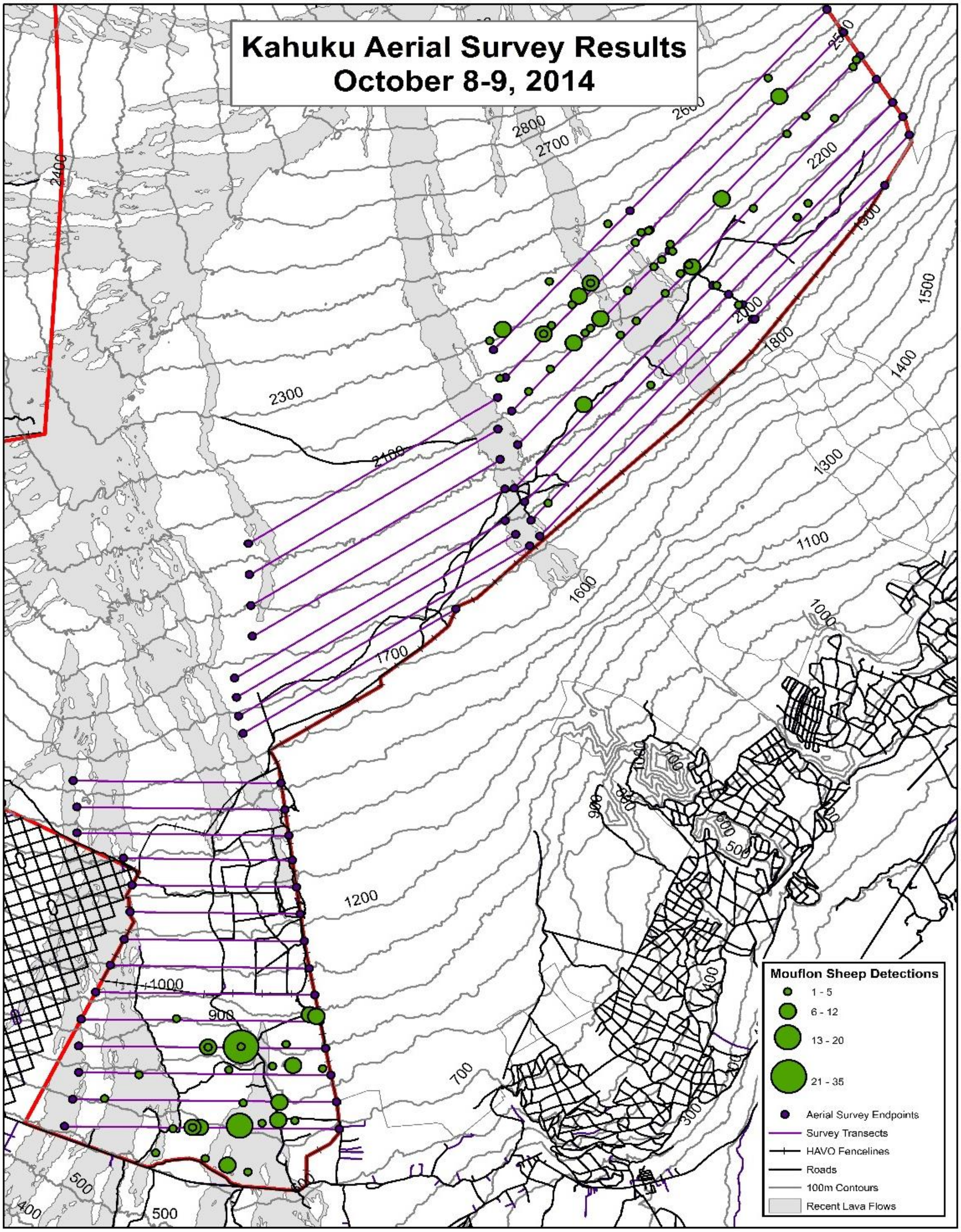

Figure 14. Survey area, transects, and locations of mouflon observed during aerial surveys of the Kahuku Unit of Hawaii Volcanoes National Park, (October 8–9, 2014).

Table 7. Summary of aerial survey for mouflon at the Kahuku Unit of Hawaiʻi Volcanoes National Park, (October 8–9, 2014).

Observations	Survey Unit			Overall
	East	Mauka	Paddocks	
Kilometers surveyed	110.4	67.8	84.3	262.5
Flight speed (KPH)	55.4	92.5	76.6	74.8
Above Ground Level (m)	110.1	--	130.4	120.2
Number of mouflon groups	50	0	31	81
Mean distance detected (m)	120.4	--	114.7	117.5
Number of rams	44	0	50	94
Number of ewes	135	0	114	249
Number of unknown sex	7	0	28	35
Ram: ewe ratio	1:3.1	--	1:2.3	1:2.6
Mean group size	3.7	--	6.2	4.7
Total number of mouflon	186	0	192	378

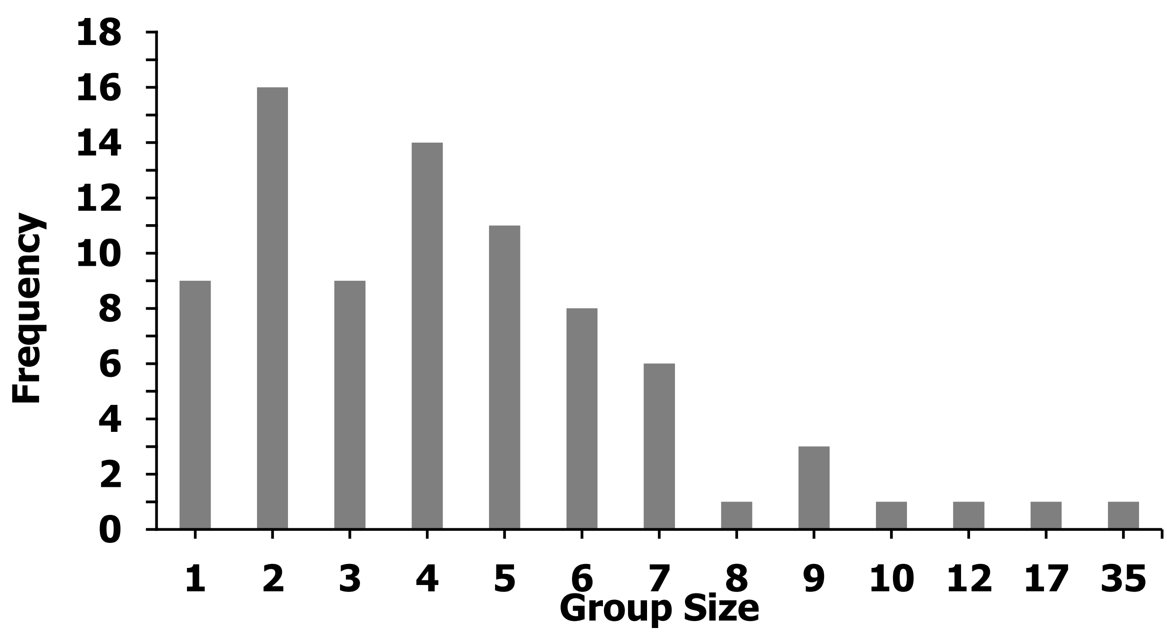

Figure 15. Histogram of 81 mouflon groups observed during aerial surveys on 8 & 9 October 2014 at the Kahuku Unit of Hawaiʻi Volcanoes National Park.

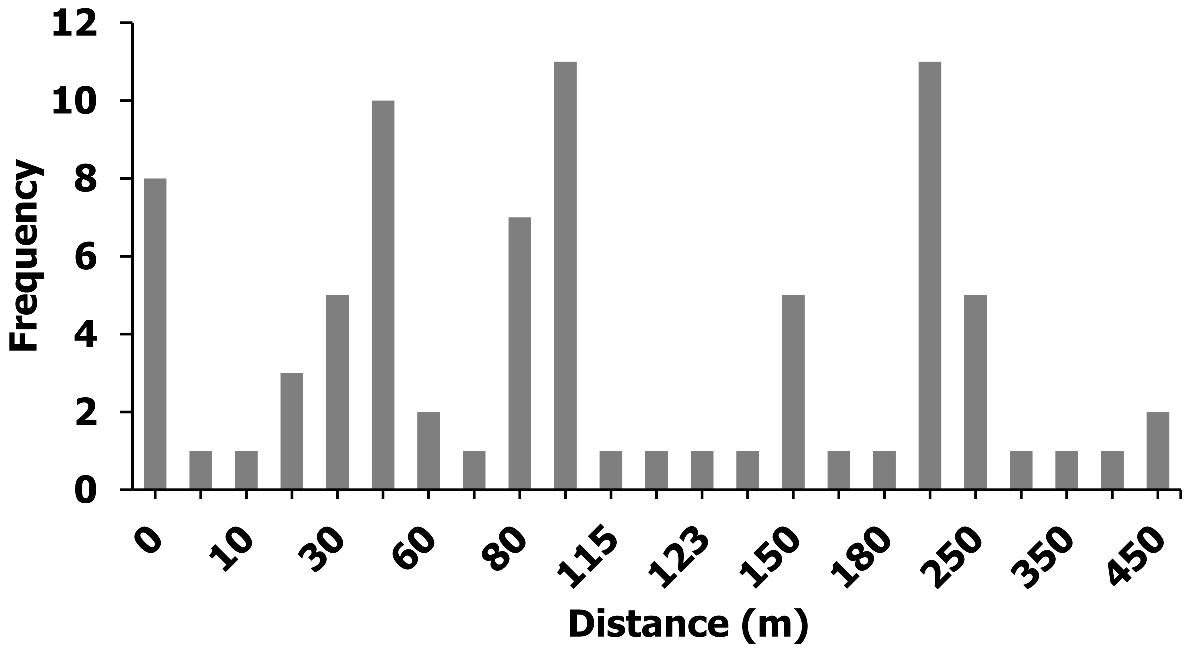

Figure 16. Histogram of distances for 81 mouflon groups observed during aerial surveys on 8 & 9 October 2014 at the Kahuku Unit of Hawaiʽi Volcanoes National Park.

Table 8. Number of European mouflon sheep observed by management area during aerial surveys of the Kahuku Unit of Hawaiʽi Volcanoes National Park (2004–2015).

Management Area	Number of mouflon observed						
	2004	2006	2007	2008	2011	2014	2015
Paddocks	782	282	471	359	137	192	188
Mauka	227	262	244	177	16	0	--
East	776	690	489	290	86	186	332
Total	1,785	1,234	1,204	826	239	378	520

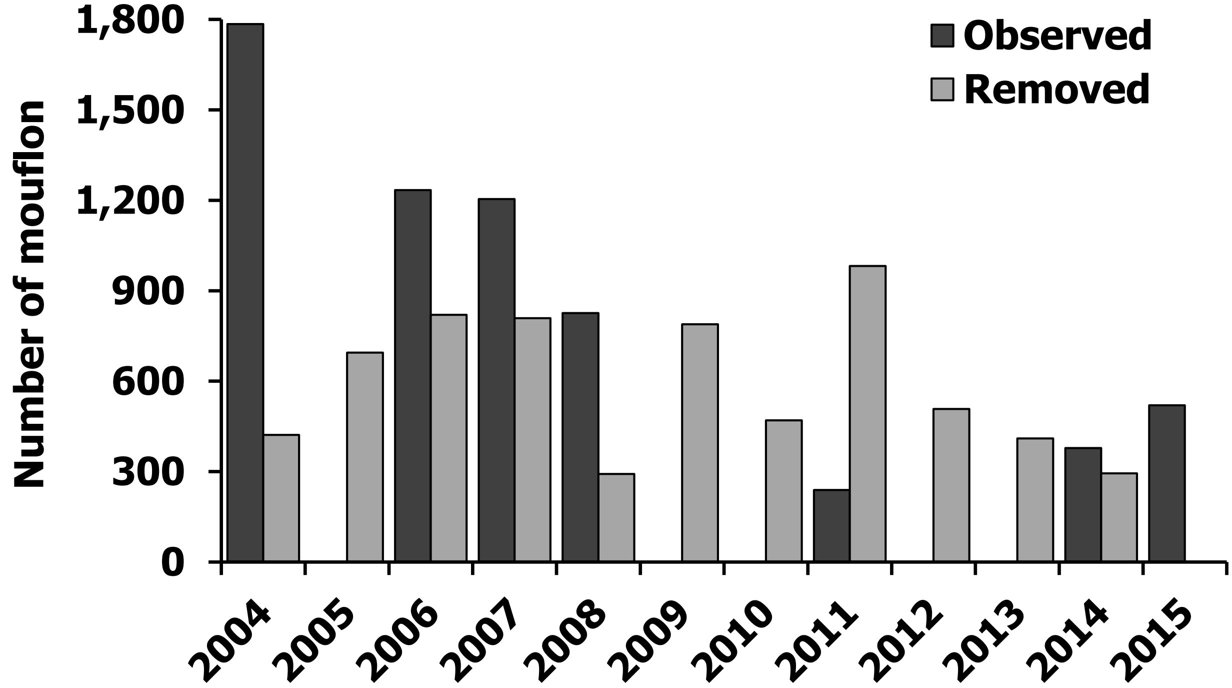

Figure 17. Total number of European mouflon sheep observed during aerial surveys and the annual number removed at the Kahuku Unit of Hawaiʻi Volcanoes National Park (2004–2015).

Table 9. Summary of transects, number of stations, number plots surveyed, and the percent of plots with fresh or intermediate pig sign within the unenclosed 4.99 km^2 Hōʻili Wai management unit in Kaʻū Forest Reserve, Hawaiʻi Island, during August and November of 2014.

Transect Number	Number of Stations	Number of Stations Surveyed		Number of Plots Surveyed		Percent of Plots with Fresh or Intermediate Pig Sign	
		Aug 2014	Nov 2014	Aug 2014	Nov 2014	Aug 2014	Nov 2014
1	8	7	7	138	139	22.5	32.4
2	8	7	7	142	138	15.5	18.8
3	8	7	7	145	140	9.7	6.4
4	8	7	7	140	140	35.7	12.1
Total	32	28	28	565	557	20.7	17.4

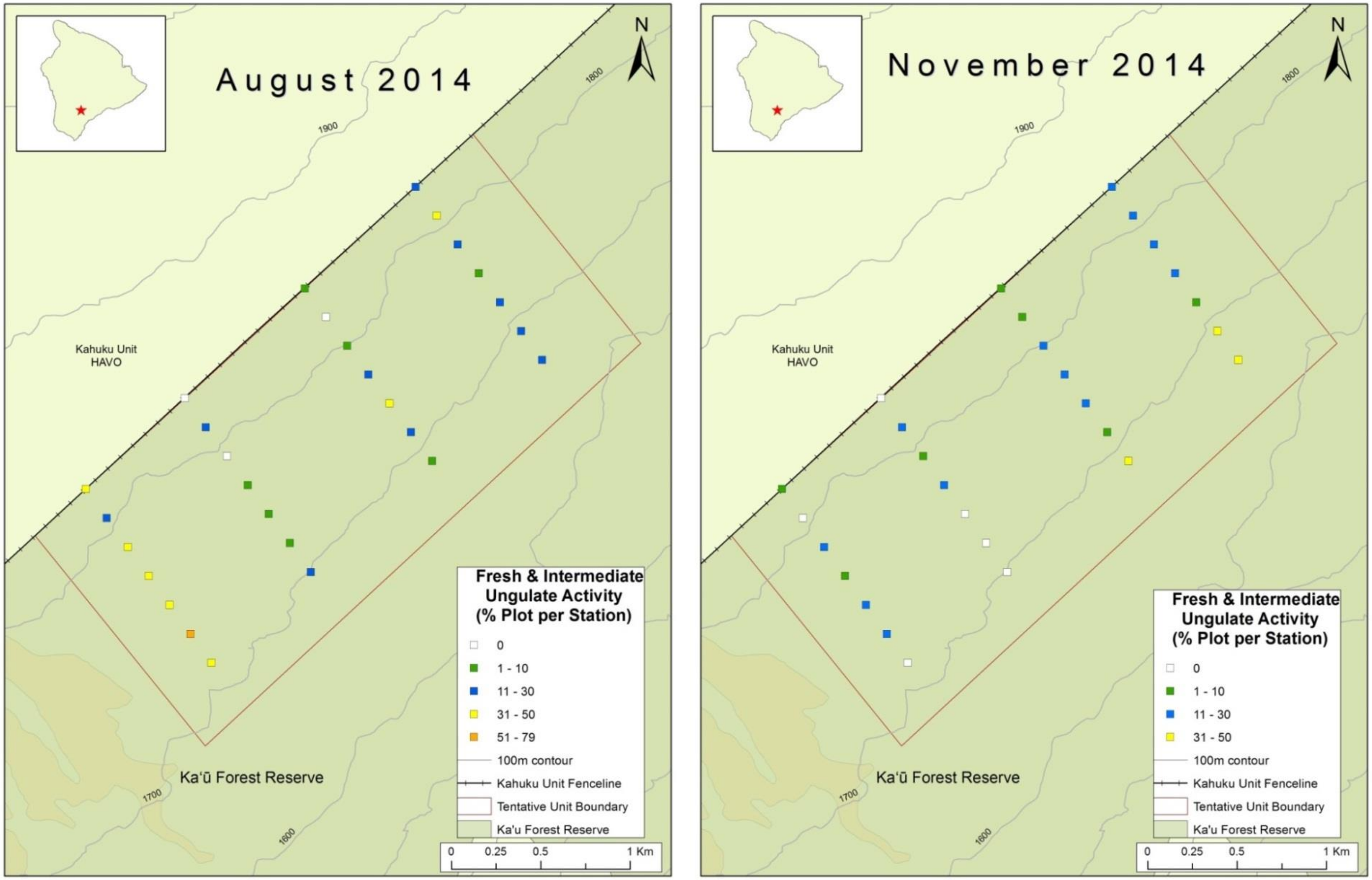

Figure 18. Ungulate sign from the unenclosed 4.99 km2 Hōʻili Wai management unit in Kaʻū Forest Reserve, Hawaiʻi Island, August and November 2014. Values presented are the maximum recorded from each sample station.

DISCUSSION

Ungulate Removal Database

Compilation of long-term ungulate removal data can provide useful insights into the overall efficacy of ungulate control programs for the restoration of native ecosystems. Analyses of species-specific control techniques can identify the most effort-effective techniques and how the efficacy of each technique may change over a range of different ungulate densities.

A rigorous hunt program commenced in 2004 after the acquisition of the Kahuku. Mouflon were abundant and widely distributed throughout the entire unit. Staff averaged nearly 600 kills/year over an eight-year period. Yield began to decline in 2011 and subsequent years as the mouflon population became reduced; however, hunt effort remained relatively constant, reaffirming that the continued reduction of mouflon populations, regardless of size, will cost approximately the same amount over the course of eradication. An adaptive strategy that takes on multiple approaches for finding small populations may lead to successful eradication and potentially expedite the time to complete eradication.

Mouflon sheep are polygynous and exhibit a male dominated hierarchy, where a single ram can breed with several females. Trophy hunting in Kahuku prior to NPS acquisition has likely caused a female biased sex ratio (Stephens et al. 2008). In HAVO, 62% of all kills were ewes, but there may still be a male bias because as much as 75% of the population may be female (Hess et al. 2006). Removal of both sexes is beneficial for the eradication effort, but specifically targeting ewes is more important for curtailing population growth. Furthermore, an intensive hunt effort after the lambing season may more effectively reduce the population by removing reproducing females. The mouflon population in Kahuku experienced an annual growth rate of more than 21% (Hess et al. 2006). It will be necessary to maintain a consistent control effort for this species, which has demonstrated rapid population growth over a short period of time.

HAVO hunters were successful at removing pigs with a combination of methods. Trapping, snaring and ground hunts with dogs were each productive. Trapping yielded the most animals with the least amount of effort because hunters only need to bait, check, and maintain traps. Similarly, snares remained active and effective without constant attendance. However, eradications may not be possible without hunters and dogs tracking down animals that have become wary of snares and traps. The feral pig removals in units of HAVO have demonstrated a successful multi-faceted management strategy of ungulates in Hawai'i.

HAVO resource managers have the opportunity to demonstrate the successful eradication of mouflon for the first time in Hawai'i. At what point do managers declare eradication and cease the hunt effort? Demonstrating a successful eradication beyond doubt is essentially impossible because there is always a chance that the search effort has been inadequate (Elphick et al. 2010). The challenge then is to conduct an effective search and hunt effort. HAVO staff have expended nearly 18,000 hunt hours controlling mouflon in HAVO. Resource managers have documented the frequency of kills since the control effort began and have a detailed record of removal rates. Eventually the number of kills and frequency of sightings will drop to zero. Once there are zero sightings, there is the trade-off between the costs of continued searching and the ecological benefit of confirmed eradication (Gotelli et al. 2012). Thus, managers have the opportunity to save money and resources by confirming eradication in a well-timed manner. A variety of hunt strategies and monitoring tools will lend confidence to resource managers and provide data for determining the probability of detecting mouflon in HAVO. A blend of systematic searches and hunter knowledge will be necessary for finding the last mouflon in Kahuku. The units are often bisected by a series of roads, which define "paddocks" in the area. Each paddock can be searched by either passive or active methods. Passive searches entail a system of camera traps and on the ground surveys for fresh sign. Active search methods include ground hunts, aerial hunts and forward looking infrared searches for mouflon. A successful eradication may be considered once each area is searched and there is a consistent record of zero detections.

Monitoring Relictucal Non-native Ungulate Population Distribution and Abundance
Camera trap monitoring was effective for detecting mouflon and other wildlife in Kahuku. Mouflon behavior did not appear to be affected by the cameras and observer bias was limited to locations where cameras were set. By having a combination of camera placement strategies we were able to locate small populations of sheep. The cameras had an infrared detection range of 15 m, where the heat signature of an animal is effectively detected. The cameras could be placed near natural corridors where animals can move unimpeded by thick vegetation. Outside of 15 m, animals were often detected by duty cycle, when the camera automatically takes a picture or video at designated times. Animals at approximately 150 m from the camera could be seen on these images. The placement of sweet cob and salt was marginally effective at attracting animals to camera trap locations. Mouflon did not exhibit interest in the bait until three months after the initial baiting (with only seven direct observations). Mouflon may be deterred by bait because of their wariness of other animals (USGS unpubl. data). Moving cameras frequently and placing them in strategic areas may be the best method for detecting mouflon.

Ground surveys are a valuable but effort-intensive tool for detecting ungulates in both open pasture and closed canopy rainforests. Experienced observers can record evidence of animals in dense forests where aerial surveys would be ineffective. In this case, four mouflon were also observed during our survey of an enclosed management unit thought to have few remaining animals. Nonetheless, ground surveys provide only a snapshot of ungulate activity unless they are repeated over time. It might also be difficult to detect ungulate sign in conditions where grasses are thick or in lava flows with no soft substrates.

Aerial survey data was valuable for mapping the distribution of mouflon in HAVO. Mouflon were observed in remote areas on vast lava flows where hunters and surveyors are unlikely to travel. However, sheep may become wary of helicopters as a consequence of aerial hunt efforts. Mouflon will either flee or hide during aerial hunts, the latter may avoid detection; thus observers will miss a significant portion of the population. Aerial surveys also provide only a snapshot in time; however, the series of six repeated surveys shows a substantial decrease in mouflon abundance since 2004.

Each monitoring tool can be evaluated by its capacity to detect animals over a spatial and temporal scale (Table 10). Aerial and ground surveys acquire data from a single point in time and thus only provide a snapshot of the population during the survey. However, each method benefits from acquiring data from a large spatial scale, especially aerial survey methods that can effectively map the distribution of a species. Alternatively, camera traps acquire data continuously, but are limited in spatial scale. Each survey type had strengths and weaknesses, but the tools complimented each other when used in conjunction. For example, with the combination of ground surveys and camera trap monitoring we were able to locate small numbers of mouflon in the enclosed area of Kahuku and to monitor them over time. We expanded the search near stations where ungulates were detected by placing camera traps in an array nearby. In turn, we were able to detect mouflon that were likely missed during hunt efforts and aerial surveys. By collecting and replacing camera trap data cards regularly, hunters are provided with locations and descriptions of animals promptly.

Table 10. 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 can be classified as a single point in time or continuously. Similarly, temporal coverage is evaluated by the size of the area the survey encompasses, either extensive or intensive. 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	Intensive	Active	Negative
Camera	Continuous	Intensive	Passive	Negligible

Metrics of mouflon activity in the unfenced unit of Kahuku provide estimates of distribution, sex ratio, group size, and sheep per unit measured. This data can be referred to as the baseline index of the frequency of sheep detections before an aggressive control program is commenced. Camera traps, aerial surveys and ground surveys applied in conjunction with the control efforts will provide a proxy for effectiveness; as we would expect sheep detections to decline as a result of removals.

Monitoring the Efficacy of Ungulate Removal in Hōʽili Wai of Kaʽū Forest Reserve
These surveys represent baseline levels of ungulate activity prior to management; therefore comparative inferences can be made about ungulate distribution and relative abundance, but not about absolute abundance. The absolute abundance of ungulates can be determined retrospectively after all ungulates have been removed from the enclosed management unit. A model can then be developed to relate surveys of ungulate activity to absolute abundance. This model can be applied to estimate ungulate abundance in other areas adjacent to Kaʽū Forest Reserve outside of the enclosed management unit. Ungulate distribution and abundance estimates are important for land managers because as population numbers are reduced, removal strategies may need to concentrate effort in areas with ungulate activity and accommodate for increased wariness among remaining animals.

ACKNOWLEDGEMENTS

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APPENDIX I. FERAL PIG HUNT HISTORY IN HAVO (1996–2014).

Year/Unit	Hunt Days	Hunt Hours	Total Kills	Kills/Hour
1996	**2**	**40**	**7**	**0.175**
East Rift	2	40	7	0.175
1998	**1**	**46**	**4**	0.087
East Rift	1	46	4	0.087
2000	**23**	**641**	**47**	**0.073**
East Rift	2	64	5	0.078
Koa	1	24	1	0.042
New Unit	20	553	41	0.074
2001	**35**	**1384.75**	**82**	**0.059**
New Unit	35	1384.75	82	0.059
2002	**50**	**1232**	**62**	**0.050**
East Rift	3	84	0	0.000
Kipuka Puaulu	2	34	2	0.059
New Unit	45	1114	60	0.054
2003	**77**	**2530.25**	**158**	**0.062**
Ainahou	6	23	9	0.391
Kipuka Puaulu	3	112	2	0.018
Koa	4	219	0	0.000
New Unit	65	2176.25	147	0.068
2004	**81**	**2680.5**	**132**	**0.049**
Ainahou	16	26.5	22	0.830
East Rift	2	82	14	0.171
Kipuka Puaulu	2	49.5	1	0.020
New Unit	63	2522.5	95	0.038
2005	**46**	**638.25**	**83**	**0.130**
Ainahou	31	108.5	48	0.442
Koa	1	42	0	0.000
New Unit	13	473.5	34	0.072
Small Tract	1	14.25	1	0.070
2006	**37**	**470.5**	**86**	**0.183**
Ag Unit	4	159.5	8	0.050
Ainahou	31	244	52	0.213
New Unit	2	32	24	0.750
Puhimau	1	35	2	0.057

Feral pig hunt history in HAVO (1996–2014) continued.

Year/Unit	Hunt Days	Hunt Hours	Total Kills	Kills/Hour
2007	**30**	**808.5**	**61**	**0.075**
Ag Unit	8	335.5	14	0.042
Kahuku Paddocks	1	0	1	N/A
New Unit	18	299	44	0.147
Pu'u Unit	1	10	1	0.100
Small Tract	4	164	1	0.006
2008	**21**	**378**	**29**	**0.077**
Ag Unit	4	150	0	0.000
Kahuku Mauka	2	25	1	0.040
Kahuku Paddocks	3	0	6	N/A
Keanakakoi	1	8	1	0.125
New Unit	10	184	19	0.103
Small Tract	2	11	2	0.182
2009	**69**	**1469**	**72**	**0.049**
Ag Unit	1	32.5	0	0.000
East Rift	1	20	0	0.000
Kahuku Mauka	29	729.5	22	0.030
Keanakakoi	29	389.25	29	0.075
Kipuka Ki	2	15.75	0	0.000
Koa	4	100	1	0.010
New Unit	10	182	20	0.110
2010	**74**	**1550.25**	**109**	**0.070**
Ag Unit	9	172.5	0	0.000
Ainahou	4	3.25	8	2.462
East Rift	2	18	0	0.000
Horse Corral	1	10	0	0.000
Kahuku Mauka	3	129	2	0.016
Kahuku Paddocks	4	47.5	4	0.084
Keanakakoi	10	122	2	0.016
Koa	1	46	0	0.000
New Unit	46	1002	93	0.093
2011	**48**	**1066**	**41**	**0.038**
Ag Unit	2	32.5	1	0.031
Ainahou	4	7	9	1.286
East Rift	3	74.5	1	0.013
Kahuku East	1	20	0	0.000
Kahuku Mauka	1	39	1	0.026
Kahuku Paddocks	14	247	23	0.093
Kipuka Puaulu	2	30	0	0.000
Koa	1	20	1	0.050
New Unit	22	596	5	0.008

Feral pig hunt history in HAVO (1996-2014) continued.

Year/Unit	Hunt Days	Hunt Hours	Total Kills	Kills/Hour
2012	**40**	**755.25**	**94**	**0.124**
Ag Unit	1	39	4	0.103
Ainahou	13	16.5	38	2.303
Hilina Pali	3	3.5	8	2.286
Horse Corral	2	28	1	0.036
Kahuku Paddocks	11	269.75	40	0.148
Kipuka Nene	1	1.5	1	0.667
KMC Highway	4	44.5	1	0.022
New Unit	7	352.5	1	0.003
2013	**31**	**569.25**	**45**	**0.079**
Ag Unit	1	30	0	0.000
Ainahou	8	34.75	18	0.518
East Rift	1	33	0	0.000
Hilina Pali	1	1	1	1.000
Kahuku Paddocks	9	157.5	12	0.076
Keanakakoi	3	65	0	0.000
Kipuka Ki	1	20	1	0.050
New Unit	5	170	4	0.024
Puhimau	3	58	9	0.155
2014	**54**	**888**	**102**	**0.115**
Ag Unit	3	46.5	0	0.000
Ainahou	6	107.5	25	0.233
Kahuku East	2	65	5	0.077
Kahuku Mauka	1	25	0	0.000
Kahuku Paddocks	5	73.5	7	0.095
Keanakakoi	16	69.75	10	0.143
Koa	4	45	0	0.000
Mary Ellen	2	4	0	0.000
Mauna Ulu	1	1	0	0.000
New Unit	15	355.5	53	0.149
Peter Lee	1	10.5	0	0.000
Small Tract	10	84.75	2	0.024
Grand Total	**719**	**17147.5**	**1214**	**0.071**

APPENDIX II. MOUFLON HUNT HISTORY IN HAVO (1995–2014).

Year/Unit	Calendar Days	Total Kills	Staff Hours	Vol. Hours	Kills/Staff Hour
1995	**3**	**1**	**6**	**0**	**0.167**
Mauna Loa	3	1	6	0	0.167
1996	**3**	**5**	**10**	**0**	**0.500**
Mauna Loa	3	5	10	0	0.500
1997	**1**	**0**	**2**	**0**	**0.000**
Mauna Loa	1	0	2	0	0.000
1998	**13**	**2**	**51.25**	**0**	**0.039**
Kulalio	11	2	46	0	0.043
Mauna Loa	2	0	5.25	0	0.000
1999	**17**	**4**	**63.5**	**0**	**0.063**
Boys School	1	4	3	0	1.333
Kulalio	16	0	60	0	0.000
Mauna Loa	1	0	0.5	0	0.000
2000	**33**	**7**	**111.75**	**0**	**0.063**
Boys School	1	4	6	0	0.667
Kapapala	4	0	8.5	0	0.000
Kulalio	32	3	97.25	0	0.031
2001	**13**	**0**	**60.5**	**0**	**0.000**
Kulalio	10	0	49.5	0	0.000
Mauna Loa	3	0	10	0	0.000
Nene Cabin	1	0	1	0	0.000
2002	**33**	**11**	**182.5**	**0**	**0.060**
Boys School	6	5	28	0	0.179
Kipuka Ainahou	1	0	3	0	0.000
Kulalio	23	4	109.25	0	0.037
Nene Cabin	13	2	42.25	0	0.047
2003	**31**	**118**	**721.75**	**0**	**0.163**
Boys School	2	0	22.5	0	0.000
Half-Way House	5	8	51	0	0.157
Kahuku	10	107	586	0	0.183
Keawewai Cabin	1	0	10	0	0.000
Kipuka Ki	1	0	3	0	0.000
Kulalio	10	3	38.75	0	0.077
Sheep pen	2	0	10.5	0	0.000

Mouflon hunt history in HAVO (1995–2014) continued.

Year/Unit	Calendar Days	Total Kills	Staff Hours	Vol. Hours	Kills/ Staff Hour
2004	**26**	**423**	**1336.16**	**0**	**0.317**
Boys School	1	0	1.83	0	0.000
Kahuku	22	422	1318.84	0	0.320
Keahou	4	0	12	0	0.000
Nene Cabin	1	0	1.49	0	0.000
Peter Lee	1	1	2	0	0.500
2005	**32**	**699**	**1739**	**0**	**0.402**
Boys School	1	0	0	0	0.000
Kahuku	29	695	1719	0	0.404
Kulalio	1	0	5	0	0.000
Mauna Loa	2	0	12	0	0.000
Ocean View	1	4	3	0	1.333
2006	**31**	**820**	**1480**	**0**	**0.554**
Kahuku	29	751	1402	0	0.536
Kahuku Mauka	3	69	78	0	0.885
2007	**43**	**809**	**1599.5**	**239**	**0.506**
Kahuku	19	431	752	0	0.573
Kahuku Mauka	17	299	423.5	0	0.706
Kahuku Paddocks	6	79	194	239	0.407
Kahuku West	5	0	230	0	0.000
2008	**27**	**298**	**718.25**	**501.25**	**0.415**
Kahuku Mauka	12	71	241.75	0	0.294
Kahuku Paddocks	13	221	464.5	501.25	0.476
Kahuku West	1	0	10	0	0.000
Peter Lee	1	6	2	0	3.000
2009	**63**	**789**	**1206.75**	**616**	**0.654**
Kahuku Mauka	48	362	457.25	0	0.792
Kahuku Paddocks	14	421	676	616	0.623
Kahuku West	4	6	72.5	0	0.083
Peter Lee	1	0	1	0	0.000
2010	**55**	**471**	**1700.5**	**537**	**0.277**
Kahuku East	5	20	163	0	0.123
Kahuku Mauka	29	105	623.5	0	0.168
Kahuku Paddocks	12	341	551	537	0.619
Kahuku West	10	4	273	0	0.015
Mauna Loa	3	1	80	0	0.013
Peter Lee	1	0	10	0	0.000

Mouflon hunt history in HAVO (1995–2014) continued.

Year/Unit	Calendar Days	Total Kills	Hunt Hours	Vol. Hours	Kills/Hour
2011	**66**	**985**	**2435**	**474.5**	**0.405**
Kahuku East	1	2	4.5	0	0.444
Kahuku Mauka	20	45	424.75	0	0.106
Kahuku Paddocks	39	935	1776.75	474.5	0.526
Kahuku West	5	0	160	0	0.000
Peter Lee	4	3	69	0	0.043
2012	**46**	**508**	**1324**	**638**	**0.384**
Kahuku Mauka	8	22	171.5	0	0.128
Kahuku Paddocks	36	486	1122.5	638	0.433
Kahuku West	1	0	20	0	0.000
Peter Lee	1	0	10	0	0.000
2013	**42**	**410**	**1871.25**	**0**	**0.219**
Kahuku Mauka	7	16	81	0	0.198
Kahuku Paddocks	37	394	1780.25	0	0.221
Kahuku West	1	0	0	0	0.000
Peter Lee	1	0	10	0	0.000
2014	**41**	**294**	**1321.25**	**0**	**0.223**
Kahuku East	3	2	177.75	0	0.011
Kahuku Mauka	4	17	81.5	0	0.209
Kahuku Paddocks	35	274	1056	0	0.259
Kahuku West	1	1	6	0	0.167
Grand Total	**619**	**6654**	**17940.91**	**3005.75**	**0.371**

APPENDIX III. FERAL GOAT HUNT HISTORY (1997–2014)

Feral goat hunt history (1997–2014).

Year/Unit	Calendar Days	Male Kills	Female Kills	Unknown	Total Kills	Hunt Hours	Kills/ Hunt Hour
1997	**4**	**4**	**0**	**3**	**7**	**24**	**0.292**
East Rift	3	2	0	0	2	14	0.143
Great Crack	2	1	0	1	2	4	0.500
Mauna Loa	2	1	0	2	3	6	0.500
1998	**19**	**5**	**6**	**27**	**38**	**132**	**0.288**
East Rift	9	3	1	4	8	62	0.129
Great Crack	3	0	0	5	5	6	0.833
Mauna Loa	11	2	5	18	25	64	0.391
1999	**20**	**3**	**5**	**27**	**35**	**206**	**0.170**
East Rift	2	0	0	0	0	2	0.000
Kue'e	2	1	0	0	1	4	0.250
Kulani	1	0	0	4	4	16	0.250
Mauna Loa	19	2	5	23	30	184	0.163
2000	**27**	**12**	**8**	**16**	**36**	**152**	**0.237**
East Rift	2	1	0	3	4	10	0.400
Kue'e	6	0	0	6	6	16	0.375
Mauna Loa	23	11	8	7	26	126	0.206
2001	**11**	**4**	**3**	**10**	**17**	**42**	**0.405**
East Rift	3	0	0	0	0	6	0.000
Kue'e	5	1	1	4	6	8	0.750
Mauna Loa	6	3	2	6	11	24	0.458
Pu'u O'o	2	0	0	0	0	4	0.000
2002	**7**	**2**	**0**	**12**	**14**	**60**	**0.233**
Boys School	1	0	0	8	8	2	4.000
East Rift	1	0	0	0	0	32	0.000
Great Crack	3	1	0	0	1	6	0.167
Keauhou Ranch	2	0	0	0	0	4	0.000
Kue'e	2	0	0	0	0	4	0.000
Mauna Loa	4	1	0	4	5	12	0.417
2003	**8**	**3**	**1**	**51**	**55**	**28**	**1.964**
Kahuku	2	0	0	41	41	16	2.563
Kipuka Maunaiu	1	0	0	0	0	2	0.000
Kue'e	3	1	0	1	2	3	0.667
Mauna Loa	1	0	1	0	1	2	0.500
Mauna Loa Mauka	3	1	0	9	10	4	2.500

Nene Cabin	1	1	0	0	1	1	1.000
2004	**4**	**2**	**0**	**4**	**6**	**16**	**0.375**
Kahuku	1	0	0	3	3	10	0.300
Keahou	1	0	0	0	0	1	0.000
Kole Flats	1	0	0	1	1	1	1.000
Kue'e	1	1	0	0	1	1	1.000
Mauna Loa	2	0	0	0	0	2	0.000
Nene Cabin	1	1	0	0	1	1	1.000
2005	**3**	**0**	**0**	**11**	**11**	**10**	**1.100**
Kaone	1	0	0	3	3	4	0.750
Keahou	1	0	0	0	0	1.5	0.000
Kue'e	2	0	0	4	4	2	2.000
Mauna Loa Mauka	2	0	0	4	4	2.5	1.600
2006	**1**	**1**	**0**	**0**	**1**	**2**	**0.500**
Keahou	1	0	0	0	0	1	0.000
Kue'e	1	1	0	0	1	1	1.000
2008	**1**	**0**	**0**	**0**	**0**	**3**	**0.000**
Kalapana Coast	1	0	0	0	0	3	0.000
2009	**4**	**2**	**0**	**0**	**2**	**24**	**0.083**
Kalapana Coast	4	2	0	0	2	24	0.083
2010	**8**	**4**	**9**	**0**	**13**	**65**	**0.200**
Great Crack	2	1	9	0	10	4	2.500
Kahuku Mauka	1	1	0	**0**	1	0	0.000
Mauna Ulu	6	2	0	0	2	61	0.033
2011	**2**	**1**	**0**	**0**	**1**	**9.5**	**0.105**
East Rift	1	0	0	0	0	0	0.000
Great Crack	2	1	0	0	1	7	0.143
Mauna Ulu	1	0	0	0	0	2.5	0.000
2012	**2**	**2**	**1**	**0**	**3**	**6**	**0.500**
East Rift	1	1	1	0	2	6	0.333
Great Crack	1	1	0	0	1	0	0.000
2013	**1**	**0**	**0**	**0**	**0**	**3**	**0.000**
Kau Desert	1	0	0	0	0	3	0.000
2014	**1**	**0**	**0**	**0**	**0**	**28.5**	**0.000**
Great Crack	1	0	0	0	0	28.5	0.000
Grand Total	**123**	**45**	**33**	**161**	**239**	**811**	**0.295**

APPENDIX IV. GOAT KILLS AND HUNT METHOD WITHIN HAWAII VOLCANOES NATIONAL PARK (1997–2014).

Year/Method	Male Kills	Female Kills	Unknown Sex	Total Kills	Calendar Days	Hunt Days	Kills/Hunt Day
1997	**4**	**0**	**3**	**7**	**4**	**14**	**0.500**
Aerial	2	0	3	5	2	12	0.417
Ground	2	0	0	2	2	2	1.000
1998	**5**	**6**	**27**	**38**	**19**	**39**	**0.974**
Aerial	3	3	18	24	8	27	0.889
Ground	2	3	9	14	11	12	1.167
1999	**3**	**5**	**27**	**35**	**20**	**38**	**0.921**
Aerial	2	1	10	13	6	17	0.765
Ground	1	4	17	22	14	21	1.048
2000	**12**	**8**	**16**	**36**	**27**	**48**	**0.750**
Aerial	10	6	11	27	16	35	0.771
Ground	2	2	5	9	11	13	0.692
2001	**4**	**3**	**10**	**17**	**11**	**32**	**0.531**
Aerial	4	3	10	17	10	31	0.548
Ground	0	0	0	0	1	1	0.000
2002	**2**	**0**	**12**	**14**	**7**	**26**	**0.538**
Aerial	2	0	12	14	6	22	0.636
Pig Snaring	0	0	0	0	1	4	0.000
2003	**3**	**1**	**51**	**55**	**8**	**48**	**1.146**
Aerial	3		51	54	7	45	1.200
Ground		1	0	1	2	3	0.333
2004	**2**	**0**	**4**	**6**	**4**	**24**	**0.250**
Aerial	2	0	4	6	4	24	0.250
2005	**0**	**0**	**11**	**11**	**3**	**14**	**0.786**
Aerial	0	0	11	11	3	14	0.786
2006	**1**	**0**	**0**	**1**	**1**	**4**	**0.250**
Aerial	1	0	0	1	1	4	0.250
2008	**0**	**0**	**0**	**0**	**1**	**2**	0.000
Aerial	0	0	0	0	1	2	0.000
2009	**2**	**0**	**0**	**2**	**4**	**6**	**0.333**
Aerial	1	0	0	1	2	2	0.500
Ground	1	0	0	1	1	1	1.000
Rove	0	0	0	0	1	3	0.000
2010	**4**	**9**	**0**	**13**	**8**	**13**	**1.000**
Aerial	3	9	0	12	4	6	2.000
Ground	1	0	0	1	4	7	0.143

2011	**1**	**0**	**0**	**1**	**2**	**7**	**0.143**
Aerial	1	0	0	1	2	7	0.143
2012	**2**	**1**	**0**	**3**	**2**	**4**	0.750
Aerial	2	1	0	3	2	4	0.750
2013	**0**	0	0	**0**	**1**	**2**	**0.000**
Aerial	0	0	0	0	1	2	0.000
2014	**0**	0	0	**0**	**1**	**3**	**0.000**
Rove	0	0	0	0	1	3	0.000
Grand Total	**45**	**33**	**161**	**239**	**123**	**324**	**0.738**

APPENDIX V. FERAL CATTLE HUNT HISTORY IN HAVO

Year/Unit/Method/Objective	Male Kill	Female Kill	Unknown	Total Kills
2007	**0**	**0**	**5**	**5**
Kahuku Mauka Unit	**0**	**0**	**5**	**5**
Aerial	0	0	5	5
Sheep Hunt	0	0	5	5
2011	**1**	**1**	**0**	**2**
Kahuku Paddocks	**1**	**1**	**0**	**2**
Ground	1	1	0	2
Cattle Hunt	1	1	0	2
Grand Total	**1**	**1**	**5**	**7**

APPENDIX VI. WILD DOG HUNT HISTORY IN HAVO.

Year/Unit/Method/Objective	Male Kill	Female Kill	Unknown	Total Kills
2009	**0**	**0**	**3**	**3**
Kahuku Mauka Unit	0	0	3	3
Aerial	0	0	3	3
Live Capture	0	0	3	3
2011	**0**	**1**	**1**	**2**
Kahuku Paddocks	0	1	0	1
Ground	0	1	0	1
Sheep hunt	0	1	0	1
Keahou	0	0	0	1
Ground	0	0	0	1
Exercise dogs	0	0	0	1
Grand Total	**0**	**1**	**4**	**5**