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# Controlling Mouflon Sheep at the Kahuku Unit of Hawai`i Volcanoes National Park

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**ABSTRACT:** Hawai`i Volcanoes National Park acquired the 115,000-acre Kahuku Ranch Unit in 2003. The Kahuku Unit contains numerous exceptional natural resources including endemic plants and birds, many of which are federally listed threatened and endangered species. Eleven European mouflon sheep were introduced to Kahuku from 1968-1974 for private trophy hunting. Because Hawaiian plants did not evolve with mammalian herbivores, managers began to control the large mouflon population with a closely directed volunteer program. Since 2004, more than 1,900 mouflon have been removed through this program. We estimated that there were 2,586 ± 705 (90% CI) mouflon at Kahuku in November 2004, but by December 2006 the population decreased 30%. Although the ram:ewe ratio did not change significantly after this population decrease, the mean (±95% CI) overall ratio in 2004 was 1:2.4 (1:2.1-1:2.7) and 1:2.7 (1:2.4-1:3.1) in 2006. We found that 82.6% of adult ewes ($n = 26$) were pregnant with a single fetus in early 2007, and there was a significant increase in the number of lambs per ewe from 2005 to 2007 consistent with a density-dependent response. The maximum (±95% CI) number of lambs per ewe was 0.484 (0.412-0.558) in 2005 and 0.667 (0.587-0.750) in 2007. The directed volunteer program has been more successful in reducing mouflon abundance at Kahuku than species such as feral pigs elsewhere on Hawai`i Island, but some population-level responses such as increased reproduction could result from density decreases.

**KEY WORDS:** aerial survey, demography, European mouflon, Hawai`i, *Ovis gmelini musimon*, population control

## INTRODUCTION

European mouflon (*Ovis gmelini musimon*) are wild sheep closely related to the early ancestors of domestic sheep (*O. aries*). They were originally brought by Neolithic people to the Mediterranean islands of Corsica, Sardinia, and Cyprus from Asia Minor, where they no longer exist (Valdez 1982). Mouflon from Corsica have been introduced widely throughout the world, including many parts of Europe, the Canary Islands, North America, the Kerguelen Archipelago, and Hawai`i (Giffin 1982, Tomich 1986, Chapuis et al. 1994, Nogales et al. 2006).

Mouflon were first released on the island of Lāna`i in 1954, and on Kaua`i in 1958 (Tomich 1986), but never became established on Kaua`i. On Hawai`i Island, mouflon and feral domestic sheep were crossbred and released on Mauna Kea beginning in 1962 (Giffin 1982). There is now a large population of hybrid mouflon on Mauna Kea that extends to northern Mauna Loa. Two releases of 11 phenotypically true mouflon occurred at the Kahuku Ranch in 1968 and 1974 to establish a private game herd (O'Gara 1994). Trophy hunting may have skewed the sex ratio and age structure of the Kahuku mouflon towards heavy representation by young and prime-aged ewes, demographic characteristics that may result in rapid population growth over a short period of time. Although mouflon numbered only several hundred prior to 1986 (Tomich 1986), this population has increased its range and abundance over a broad area of southern Mauna Loa. Hess et al. (2006) estimated that the Kahuku mouflon population had increased by 22.1% per year, resulting in doubling every 3-4 years. Hawai`i Volcanoes National Park (HAVO) acquired the 115,000-acre Kahuku Ranch Unit in 2003.

Where mouflon have been introduced to other islands lacking native ungulates, populations have grown rapidly and damaged endemic plants in native ecosystems through trampling and browsing (Chapuis et al. 1994, Nogales et al. 2006). Hawaiian plants are highly vulnerable to introduced ungulates because they did not evolve with mammalian herbivores. As a result, native vegetation has been extensively degraded (Belfield and Pratt 2002, Scowcroft 1987, Scowcroft and Giffin 1983, Scowcroft and Sakai 1983). Nine percent of the native Hawaiian flora has become extinct in historic times and >52% of taxa are at risk (Sakai et al. 2002). Floral surveys within the Kahuku Unit have documented 1 threatened, 1 candidate endangered, 7 species of concern, and 5 endangered plant species, including the Ka`ū silversword (*Argyroxiphium kauensis*) (Robichaux et al. 2000, Benitez et al. 2008).

If population growth and range expansion were to continue, the Kahuku mouflon would further degrade native ecosystems and potentially expand into adjacent areas of HAVO where large mammal species have been eradicated. National Park Service (NPS) managers began reducing the mouflon population at Kahuku with a closely directed volunteer program in May 2004 to curtail
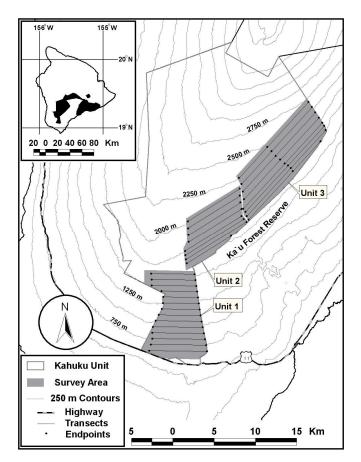
**Figure 1. Survey area and transects used during aerial surveys of mouflon in the Kahuku Unit of Hawai`i Volcanoes National Park, Hawai`i.**

further degradation of native vegetation. Public hunting, however, has not been an effective management tool for reducing some species of alien herbivores in Hawai`i (Hess et al. 2007). Our objectives were to monitor mouflon abundance and demographic processes associated with the directed volunteer program at Kahuku.

**Study Area**

There were 2 major zones with abundant mouflon within the Kahuku Unit of HAVO on the island of Hawai`i (centered at approximately 19°18′N, 155°40′W; Figure 1): improved pasture areas between 600-1,600 m on the southern ridge of Mauna Loa; and the area between 1,600-2,700 m above the Ka`ū Forest Reserve on the southeast flank of Mauna Loa. Improved pasture areas in mesic montane forest were dominated by `ōhi`a (*Metrosideros polymorpha*), and to a lesser extent, koa (*Acacia koa*). Highly modified pasture areas were open woodlands with scattered native trees and primarily alien Kikuyu grass (*Pennisetum clandestinum*) understory. Higher elevation areas were subalpine shrublands dominated by a`ali`i (*Dodonaea viscosa*), `ōhelo (*Vaccinium spp.*), pūkiawe (*Leptecophylla tameiamaeiae*), a native bunch grass (*Deschampsia nubigena*), and `ōhi`a forest near the boundary of Ka`ū Forest Reserve. We defined the mouflon study area as the modified pastures at the southernmost extent of Kahuku, and subalpine areas up to

highest elevations inhabited by mouflon, representing 20,868 ha.

**METHODS**
**Mouflon Control**

Three NPS guides and a different group of 4 closely-directed volunteers equipped with high-powered rifles attempted to remove all mouflon within range during 2 days per month beginning in May 2004. We estimated the mean and standard error (SE) of the number of mouflon removed per day by volunteers and guides, and the proportion of removed mouflon which were female with 95% confidence intervals (CI) based on binomial SE.

**Demographic Surveys**

Aerial survey flights were timed to correspond to large breeding aggregations, and the presence of breeding pelage to maximize the ability to identify sexes. We used geographic landmarks such as major lava flows, roads, and forest boundaries to delineate 3 survey areas, and subdivided the third area into East and West sections. We created transects with computer GIS at 500-m intervals in dense vegetation, and at 800-m intervals in sparse vegetation and bare lava. Transects were positioned parallel to elevation contours to minimize elevation change in flight during surveys. Transect coordinates were uploaded to a GPS unit for in-flight navigation.

Two observers sat in the front of the aircraft and 2 recorders in the back such that they formed 2 observer/recorder teams. On their respective sides of transects, observers announced group size, sex composition (when possible), and perpendicular distance to the group over the aircraft intercom. Observers were experienced in distance estimation from piloting aircraft and marksmanship. Recorders used separate GPS units to mark waypoints. The pilot attempted to maintain constant groundspeed and height above ground level (AGL) during surveys; however, uneven and sloping terrain made this difficult. A standardized data sheet contained variables for each group of mouflon including transect, waypoint, sex categories (rams, ewes, unknown) and total number in each group, distance from transect, and notes. Other flight data included weather conditions, flight, and survey start and end times.

Flight tracks and waypoints were downloaded to computer, related 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 groundspeed and AGL were calculated for each survey unit. Surveys were summarized by the total number of mouflon, mean group size, and sex composition observed in each unit. Because sex ratios were not likely to be normally distributed, and because the error distribution was unknown, we also bootstrapped empirical distributions from the data to compare overall ram:ewe composition between aerial surveys (Efron and Tibshirani 1993). For each survey, the number of ewes and rams observed in each group was sampled with replacement 1,000 times. The overall proportion of ewes in the population was calculated from the sums of ewes and rams within

replicates. Replicates were ordered and the mean and 95% CI were determined by the percentile method.

Ewes removed during control efforts from January-March 2007 were dissected to determine reproductive status based on lactation and the presence and the number of fetuses. Ewes were aged as adult or yearling based on dentition. Additionally, we classified the sex and age composition of all observed herds along a standardized vehicle route from March-May 2005, and throughout 2007, except for June and July. Females were classified as lambs or adults from January-May based on size, and as ewes of unspecified age for the remainder of the year. Rams were classified as juveniles (<30.5-cm horns) or adults (>30.5-cm horns). The percentile bootstrap method (Efron and Tibshirani 1993) was used to determine means and 95% CI for estimates of lambs as a proportion of ewes and rams as a proportion of ewes as described above.

**Density and Abundance Estimates**

We plotted distances to mouflon groups observed during aerial surveys and examined their decay to determine a reliable belt transect width. The total number of mouflon observed ($M$) within each belt transect ($t$) was divided by area ($A$) to determine the density ($d$) of mouflon on each belt transect [$M_t / A_t = d_t$]. We used repeated measures ANOVA to test for differences in mouflon density between aerial surveys, with survey unit and transect treated as class variables.

We assigned transects *post facto* to 3 different strata corresponding to high, medium, and low-density areas to reduce the overall transect-to-transect variance. Therefore, the true measures of SE were underestimated in this analysis. We averaged density and calculated SE of density for transects within the 3 strata. We then multiplied mean density by the proportion of transect belt area within each stratum to the total survey area, determined

SE for each stratum in the same manner, and 90% CI by multiplying SE by critical *t*-values corresponding to DF for the number of transects per stratum. The overall CI was less than the sum of the strata CIs because it was based on the pooled SE and critical *t*-value corresponding to the total number of transects.

**RESULTS**

**Mouflon Control**

The directed volunteer program removed 1,835 mouflon between March 2004 and February 2007 (Table 1). From that total, 1,507 sheep were removed from Kahuku between the November 2004 and December 2006 aerial surveys. The proportion of removed mouflon which were female ranged from 0.645 in 2005 to 0.569 in 2007, but did not decline significantly. Volunteers and staff removed 4.6±2.9 (mean±SD) and 5.2±2.5 mouflon/day, respectively.

**Demographic Surveys**

Units 1 and 2 were first surveyed in a MD (Hughes) 500D helicopter on November 2, and Unit 3 was surveyed on November 10, 2004. The second survey of Units 1 and 2 was conducted on December 19, and Unit 3 was surveyed on December 20, 2006 in the same aircraft. Transect 7 in Unit 3E was not surveyed in 2004 due to fuel shortage. Weather conditions were cloudless with unlimited visibility during both surveys.

We observed a total of 1,785 mouflon in 229 groups and classified 749 (42.0%) individuals by sex during the 2004 survey. We observed 1,234 mouflon in 203 groups and classified 1,018 (82.5%) individuals in 2006. In 2004, Unit 1 had the most observed mouflon, the largest mean group size, and the highest ratio of ewes to rams (Table 2). In 2006, however, Unit 1 had the largest mean group size and the highest ratio of ewes to rams, but Unit 3 had the most observed mouflon. The overall mean

Table 1. Removals of mouflon sheep by a directed volunteer program at the Kahuku Unit of Hawai`i Volcanoes National Park, 2004-2006 by biological year (March - February).

| Dates of Removal | Rams | Ewes | Total | Ram:Ewe Ratio | Proportion Female | 95% CI |
|---|---|---|---|---|---|---|
| Mar 2004 - Feb 2005 | 150 | 273 | 423 | 1:1.82 | 0.645 | 0.600 - 0.691 |
| Mar 2005 - Feb 2006 | 283 | 415 | 698 | 1:1.47 | 0.595 | 0.558 - 0.631 |
| Mar 2006 - Feb 2007 | 308 | 406 | 714 | 1:1.32 | 0.569 | 0.532 - 0.605 |
| Total | 741 | 1094 | 1835 | 1:1.48 | 0.596 | 0.574 - 0.619 |

Table 2. Summary of mouflon aerial surveys during November 2004 and December 2006 at the Kahuku Unit of Hawai`i Volcanoes National Park.

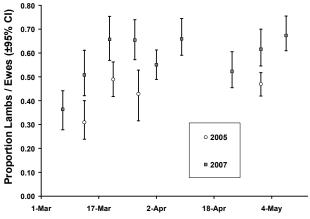| Survey Unit | Kilometers Surveyed | | Total Mouflon Observed | | Mean Group Size | | Ram:Ewe Ratio | | Ground Speed (km/hour) | | AGL (m) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2004 | 2006 | 2004 | 2006 | 2004 | 2006 | 2004 | 2006 | 2004 | 2006 | 2004 | 2006 |
| Unit 1 | 84.3 | 83.6 | 782 | 282 | 15.04 | 7.62 | 1:3.93 | 1:3.43 | 85 | 81 | 120 | 131 |
| Unit 2 | 67.8 | 67.5 | 227 | 262 | 4.73 | 4.52 | 1:3.32 | 1:1.99 | 85 | 74 | 120 | 67 |
| Unit 3 | 110.4 | 117.7 | 776 | 690 | 6.02 | 6.51 | 1:2.02 | 1:2.98 | 86 | 98 | 86 | 86 |
| Overall | 262.5 | 268.8 | 1,785 | 1,234 | 7.79 | 6.08 | 1:2.36 | 1:2.73 | 85 | 84 | 109 | 95 |

**Figure 2. Lambs as a proportion of ewes observed during ground during the 2005 and 2007 lambing season of mouflon in the Kahuku Unit of Hawai`i Volcanoes National Park, Hawai`i.**
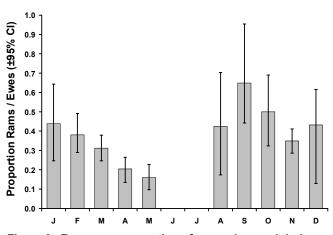


**Figure 3. Rams as a proportion of ewes observed during ground surveys in 2007 of mouflon in the Kahuku Unit of Hawai`i Volcanoes National Park, Hawai`i.**
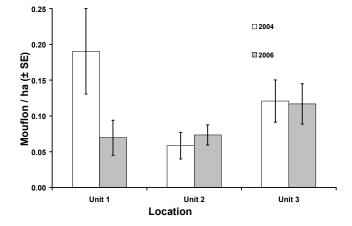


**Figure 4. Mouflon density during the 2004 and 2006 aerial surveys in 3 areas of the Kahuku Unit of Hawai`i Volcanoes National Park, Hawai`i before and after a directed volunteer program began removals in 2004.**

proportion of ewes (±95% CI) from 1,000 bootstrap replicates for 157 groups in 2004 was 0.703 (0.673 -0.730). For 187 groups in the 2006 survey, the mean proportion of ewes was 0.732 (0.705 - 0.754). Overlapping CIs indicated the proportion of ewes in the population did not differ significantly between surveys at $\alpha = 0.05$ level.

We dissected 23 adult and 8 yearling ewes in 2007 and found that 82.6% of adult ewes were pregnant with a single fetus, but no yearlings were pregnant. The proportion of ewes observed with lambs increased significantly from 2005 to 2007. The maximum proportion of ewes with lambs (±95% CI) was 0.484 (0.412-0.558) in 2005 and 0.667 (0.587 - 0.750) in 2007 (Figure 2). The composition of sexes changed significantly within 2007. Rams as a proportion of ewes ranged from 0.160 (0.096 - 0.228) in May to 0.649 (0.442 - 0.955) in September (Figure 3).

**Density and Abundance Estimates**

Based on visual examination of plotted distances to groups, reliability appeared to decay rapidly at distances greater than 125 m, becoming unreliable at distances greater than 250 m. We therefore truncated observations greater than 250 m and treated each transect as a fixed-width 500-m belt. A total of 1,586 mouflon in 201 groups were observed within this area in 2004. In 2006, we observed a total of 1,044 mouflon in 188 groups within this area.

In repeated measures ANOVA of mouflon density, tests of hypotheses for between subject effects were significant for survey unit ($F_{2, 20} = 6.69$, $P < 0.006$) and transect ($F_{14, 20} = 3.00$, $P < 0.013$). Univariate tests of hypotheses for within subject effects, however, were not significant for time ($F_{1, 20} = 0.51$, $P > 0.481$), or for the interaction of time and transect ($F_{14, 20} = 0.87$, $P > 0.601$), but the interaction of time and unit ($F_{2, 20} = 4.78$, $P < 0.021$) was significant. The density of mouflon in Unit 1 decreased from 2004 to 2006 while other units did not change (Figure 4). We estimated there were 2,586 ± 705 (90% CI) mouflon in November 2004, but by December 2006, the population decreased by approximately 30% to 1,797 ± 688 (Table 3).

**DISCUSSION**

The directed volunteer program at Kahuku has been relatively successful in controlling mouflon compared to similar efforts to remove other nonnative mammals in Hawai`i. The average annual removal was 611 ± 163 (SD) mouflon during the 3 years of the Kahuku program. Reported removals of hybrid mouflon sheep on Mauna Kea by public hunters averaged only 249 ± 88 per year from 1998 - 2002 (Banko et al. *In Press*). Volunteers and guides removed an average of 4.6 and 5.2 mouflon/ day at Kahuku, respectively, whereas the average removal of feral pigs by public hunters and staff was 0.25 and 0.80 pigs/day, respectively, at Hakalau Forest National Wildlife Refuge (HFNWR) (Hess et al. 2007). The wide disparity in removal rates can be attributed to differences in habitat, behavior between species, lack of prior conditioning to the control program, and the close supervision by guides at Kahuku that was not provided at Mauna Kea or at HFNWR. Feral pigs at HFNWR occur

**Table 3. Mouflon population estimates by stratum at the Kahuku Unit of Hawai`i Volcanoes National Park in 2004 and 2006.**

| Stratum | Transects | Area (ha) | 2004 Estimated Mouflon | 2004 90% CI | 2006 Estimated Mouflon | 2006 90% CI |
|---|---|---|---|---|---|---|
| High | Unit 1; 1-8 Unit 3W; 2-7 | 6,956 | 2,002 | ±549 | 991 | ±403 |
| Medium | Unit 2; 2-7 Unit 3E; 2-6 | 7,136 | 533 | ±160 | 547 | ±189 |
| Low | Unit 1; 9-14 Units 2 & 3; 1 & 8 | 6,777 | 51 | ±34 | 259 | ±135 |
| **Total** | **37** | **20,869** | **2,586** | **±705** | **1,797** | **±688** |

in dense montane forest whereas mouflon at Kahuku occupy more open forest and woodland, which makes them vulnerable to skilled marksmen at long distances. A volunteer program at HAVO from 1971 - 1980 removed >4,000 pigs at a mean rate of 0.6 pigs/12-hour day, but eradication was not achieved because efforts were not sufficiently systematic and ingress from surrounding forests continued (Katahira et al. 1993). Eradication was later achieved by NPS staff after closed fenced units were systematically controlled and monitored.

Aerial surveys were useful for monitoring population dynamics related to the directed volunteer program even though abundance estimates lacked precision, particularly in 2006. There was high variability in density between transects within survey units, and also in the distribution of group sizes during our aerial surveys. Nonetheless, Garel et al. (2005b) reported that helicopter surveys of mouflon provide a better trade-off between cost and precision over pedestrian surveys. Our aerial surveys in 2004 and 2006 revealed that the directed volunteer program had reduced the overall population and altered the distribution of mouflon in Kahuku. We detected an approximate 30% reduction between these surveys with a significant decrease in density in Unit 1 while density in the other survey units remained unchanged. The directed volunteer program was likely most effective in Unit 1 because this area had the highest initial mouflon density, the closest proximity to access, and the highest road density. The proportion of females in the population was exclusively greater, however, in our 2006 aerial survey than that of removals for 2006 and 2007, indicating selective removal of rams in these years.

The proportion of ewes in the population, consequently, has not declined during the directed volunteer program. Such a reduction in the overall proportion of ewes could curtail the population growth rate; however, the removal data also indicated a non-significant decrease in the proportion of ewes removed over time. We found that 82.6% of these adult ewes were pregnant in 2007, which is similar to the results of Garel et al. (2005a) where >80% of adult ewes were pregnant in 3 populations in France. Our age composition surveys revealed that reproduction in the Kahuku mouflon population increased significantly after density was reduced. Such a response is consistent with density dependence in reproduction. As the Kahuku mouflon population is further reduced in density, lamb survival may remain high or increase due to the concomitant increase in forage available to remaining mouflon. If the female segment of the population increases, and the number of lambs per ewe continues to increase, the potential per capita population growth rate may also increase correspondingly. We also found that the male segment of the population changed strongly over the annual cycle. Rams apparently moved away from ewe/lamb family groups during lambing season in March-May to some unknown location. They returned to join ewes prior to the rutting season in September.

The directed volunteer program has been more successful in reducing mouflon abundance at Kahuku than unsupervised public hunting programs have been for species such as feral pigs elsewhere on Hawai`i Island, but some population level responses such as increased reproduction could result from density decreases. Control efforts may therefore become more difficult as the population declines to remnant levels. The population could be more quickly reduced by focusing control on ewes. One strategy to maximize control of ewes is to step up the directed volunteer program during the March-May lambing season when rams are not as abundant in the area.

## ACKNOWLEDGMENTS

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