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A Preliminary Assessment of Mouflon Abundance at the Kahuku Unit of Hawaii Volcanoes National Park

Open-File Report 2006–1193

U.S. Department of the Interior
U.S. Geological Survey

About the cover: Mouflon sheep (*Ovis gmelini musimon*) during an aerial survey at the Kahuku Unit of Hawaii Volcanoes National Park in November 2004. Photograph by Ben Kawakami Jr.

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U.S. Geological Survey
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Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
hectare (ha)	2.471	acre

A Preliminary Assessment of Mouflon Abundance at the Kahuku Unit of Hawaii Volcanoes National Park

By Steven C. Hess[1], Ben Kawakami Jr.[2], David Okita[3], and Keola Medeiros[2]

Abstract

Hawaii Volcanoes National Park (HAVO) recently acquired the 115,653 acre Kahuku Ranch unit adjacent to the existing Mauna Loa section of HAVO. Kahuku contains numerous exceptional natural resources including many federally listed threatened and endangered species. An apparently large and growing population of alien mouflon sheep (*Ovis gmelini musimon*), however, threatens sensitive native plants and forest bird habitats. Population composition and abundance estimates were urgently needed to determine the magnitude of resources required to manage this species and justify costs. We surveyed 32,433 acres from helicopter over 2 days in November 2004 during breeding to determine the abundance and population structure. We estimated that there were more than 2,586 ± 705 (90% CI) mouflon at Kahuku. Overall, group sizes averaged 7.8 and the sex ratio was 1:2.4 rams:ewes, but approximately 44% of the population was concentrated in forested areas near ranching operations where group sizes averaged >15 and the sex ratio was 1:3.9 rams:ewes. The remaining 56% of the population occurred widely dispersed in subalpine shrubland and barren lava flows. Abundance estimates are likely to be conservative because they were not adjusted for detection probability. Ground-based surveys of lambs suggest upper biological limit to annual population increase of 33.1% under existing environmental conditions. Historical information used to calculate population trends indicated the apparent rate of population increase to be 21.1%. In the absence of removals, the population increment for 2004–2005, would be more than 546–856, and the population doubling time with these growth rates is 3–4 years.

Introduction

Hawaii Volcanoes National Park (HAVO) recently acquired the 115,653 acre Kahuku Ranch Unit adjacent to the existing Mauna Loa section of HAVO, encompassing portions of both Ka`ū and South Kona districts of Hawaii Island. The Kahuku Unit contains numerous exceptional natural resources including endemic Hawaiian plants and birds, many of which are federally listed threatened and endangered species. A large and growing population alien mouflon sheep (*Ovis gmelini musimon*), however, threatens sensitive native plants and forest bird habitat at Kahuku.

Mouflon were introduced to Kahuku beginning in 1968 to start a game herd (O'Gara 1994). Monthly records of the former Kahuku Ranch ranch operations indicate that 8 mouflon were brought to Kahuku in 1968 and an additional 3 mouflon were brought to Kahuku in 1974 from Honolulu Zoo. This population, which numbered only several hundred prior to 1986 (Tomich 1986), now appears to be increasing in both range and abundance, and has the potential of invading adjacent areas of HAVO which have already been cleared of large mammals. Trophy hunting prior to acquisition by NPS may have skewed the sex ratio and age structure towards heavy representation by young and prime-aged ewes, demographic characteristics that may result in rapid population growth over a short period of time, as they have on other oceanic islands. For example, a female-biased mouflon population exhibited 46.3% annual growth on Haute Island in the subantarctic Kerguelen archipelago despite severe winters (Chapuis *et al*. 1994).

In another part of Hawai`i Island, mouflon were crossbred with domestic sheep (*O. aries*) and released on Mauna Kea from 1962–1966 (Giffin 1982). These hybrid mouflon were larger in body size than wild-type mouflon released at Kahuku Ranch. Hybrid mouflon, along with feral domestic sheep and goats, have caused tremendous habitat degradation for the endangered Hawaiian finch, Palila (*Loxioides bail-*

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leui). Nearly two decades of intensive population control was required for ecological conditions to improve (Hess *et al*. 1999). Although other herbivore species have been effectively eliminated from Mauna Kea, hybrid mouflon persisted and expanded their range. Currently, two large populations exist on Hawai`i Island: hybrid mouflon that surround Mauna Kea and extend across the saddle to the northern boundaries of HAVO; and wild-type mouflon that inhabit the southern part of Mauna Loa in and outside of the Kahuku Unit. Agile jumpers, Mauna Kea mouflon invaded fenced areas in the Mauna Loa strip of HAVO, where they destroyed outplanted Ka`ū silverswords (*Argyroxiphium kauense*), damaged the threatened Hawaiian catchfly (*Silene hawaiiensis*), and stripped bark from important forest trees such as koa (*Acacia koa*) and māmane (*Sophora chrysophylla*) (Belfield and Pratt 2002).

Herbivorous mammals have been introduced to oceanic island throughout the world, often with devastating consequences for the native flora of these islands. Through the actions of browsing and bark stripping, herbivores inhibit the regeneration of native forest trees (Scowcroft 1987, Scowcroft and Giffin 1983, Scowcroft and Sakai 1983), and can cause local extinction of sensitive insular plants (Luengo and Piñero 1991, Van Vuren and Coblentz 1987). Nine percent of the native Hawaiian flora has become extinct in historic times (Sakai *et al*. 2002), but resource managers have developed highly successful strategies to protect these remaining unique plants in Hawai`i's National Parks by excluding herbivores with fences, with population control methods such as baited live-traps, and eradication techniques based on social behavior. The 'Judas goat' technique employs a radio transmitter attached to an individual that repeatedly attempts to aggregate with conspecifics, thus revealing the location of remaining groups to resource managers (Taylor and Katahira 1988). To be effective, however, groups of animals must accept collared individuals and maintain relatively fixed home ranges. These strategies were developed primarily for feral livestock species brought by early European explorers; however, truly wild species such as mouflon that were more recently introduced for large game hunting may not exhibit similar social behavior.

Non-domesticated herbivores in Hawai`i such as mouflon, axis deer (*Axis axis*), blacktail deer (*Odocoileus hemionus*) can exhibit strong differences from other feral herbivores in their spatial distribution, habitat use, evasive behaviors, population dynamics, demographic structure, and social organization. These characteristics may contribute to different patterns of colonization and range expansion, but also make it difficult to monitor population status and conduct effective control programs. Understanding population processes is critical in designing effective control programs, as well as evaluating these programs. Additionally, information on reproduction can be used to determine potential population growth rates, and serial abundance estimates can be used to determine apparent population growth trends, both of which are essential for setting *a priori* population control goals. Current population composition and abundance estimates for Kahuku mouflon were not available, but were urgently needed to begin monitoring and to determine the magnitude of resources required to control this species and justify costs.

The objective of this research was to rapidly conduct reliable aerial surveys to derive preliminary estimates of population composition, distribution, and abundance of mouflon within the Kahuku Unit. We therefore applied standardized, repeatable methodology based on line-transect protocols that are the accepted standard in wildlife science (Lancia *et al*. 1996). Surveys based on this methodology may be repeated in the future to determine trends in abundance and demographic structure. We also conducted ground-based surveys of lambs to estimate the upper biological limit to annual population increase, and used historical information on Kahuku mouflon establishment and abundance to estimate apparent rates of annual population increase with simple population models. Understanding population processes in mouflon will be important for setting effective management goals to prevent further population increases.

Study Area

This study was conducted entirely within the Ka`ū district of the Kahuku Unit of Hawai`i Volcanoes National Park on the island of Hawai`i (centered at approximately 19°18´N, 155°40´W; Figure 1). There were two major zones with abundant mouflon: the improved pasture areas between 600–1600 m on the southern ridge of Mauna Loa; and the area between 1600–2700 m above the Ka`ū Forest Reserve on the southeast flank of Mauna Loa. Improved pasture areas in mesic montane forest are dominated by `ōhi`a (*Metrosideros polymorpha*), and to a lesser extent, koa (*Acacia koa*), and have been modified to create open grassy meadows. The higher elevation areas were dominated by `ōhi`a forest and dry scrub near the boundary of Ka`ū Forest Reserve and shrublands with pūkiawe (*Styphelia tameiamaeiae*) and other shrub species on exposed pāhoehoe and a`ā lava flows in the subalpine zone. An elaborate network of good roads provided access to most of the improved pasture areas, but roads were rough and limited in higher elevation terrain.

Methods

Aerial Survey

We defined the survey area for mouflon to be the improved cattle ranch pastures at the southernmost extent of Kahuku, and areas above the Ka`ū Forest Reserve Boundary up to highest elevations inhabited by mouflon (Figure 2). This area represented 20,868 ha (51,567 acres), or approximately 45% of the entire Kahuku Unit. NPS resource managers spent time on the ground in all survey areas to study distribution and

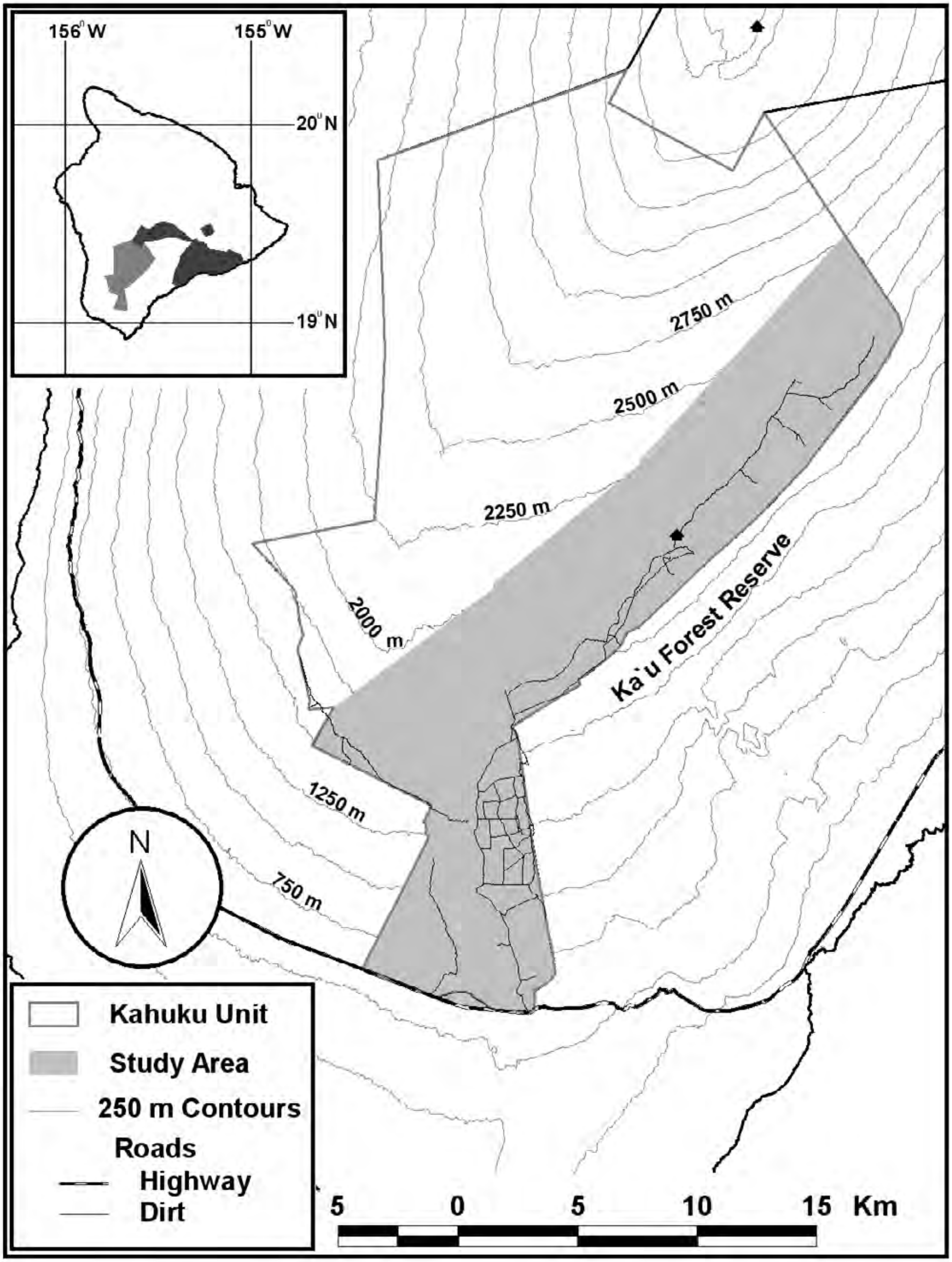

Figure 1. Mouflon study area in the Ka`ū district of the Kahuku Unit of Hawai`i Volcanoes National Park.

seasonal aggregation behavior of the species, and a preliminary survey flight was conducted on 2 October 2004 to verify geographic distribution, elevation limits, and to refine aerial survey procedures. We used geographic landmarks such as major lava flows, roads, and forest boundaries to delineate 3 survey areas. 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 in the third area were further subdivided into West and East sections by a road, hereafter designated 3W and 3E. Transects were positioned parallel to elevation contours to minimize elevation change in flight during surveys. We then plotted endpoints of these transects and uploaded coordinates to a GPS unit for in-flight navigation.

A standardized data sheet contained variables for each group of mouflon including transect, waypoint identification, sex categories (rams, ewes, unknown) and total number in group, perpendicular distance to group, habitat type, percent cover, and notes. Habitat types included; \`ōhi\`a forest, \`ōhi\`a scrub, meadow, shrubland, road, and pāhoehoe and a\`ā lava flows. Other flight data included weather conditions, flight and survey start and end times.

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 in the front of the aircraft and two recorders in the back such that they formed two observer/recorder teams. 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. Recorders noted habitat characteristics and used separate GPS units to mark waypoints. 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, 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 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 calculated for each survey unit.

Lamb Surveys

We conducted vehicle-based surveys to quantify ratios of lambs to adult mouflon on 14 March, 22 March, 29 March, and 2 May 2005. Beginning at sunrise we drove from the state cabin area to the northeast boundary of Kahuku, and then around the cattle pasture areas during early afternoon hours. We enumerated all lambs, ewes, and rams observed from the road. We classified the age of ewes as adults or yearlings, and classified rams in categories based on horn length of 30.5–61.0 cm, 61.0–76.2 cm, > 76.2 cm, or as yearlings (horns < 30.5 cm). We did not make observations on return segments of roads or in other situations where the potential existed to observe the same individuals more than once. We summarized these surveys by calculating the proportion of all ewes with lambs and lambs as the proportion of all other age/sex categories of mouflon, and reported the binomial standard error of these estimates. Lambs as a proportion of all other mouflon age/sex categories was used to estimate the maximum potential annual increment and upper biological limit to population growth.

Historical Population Trends

We searched archival records of the Kahuku Ranch to find information on the number and exact dates of mouflon introduction, abundance observations over time, and records of hunting and other removals. We projected these data in simple population models (Eberhardt 1987) to determine historical population trends and plausible rates of population growth given historical observations. We searched for minimum values of λ (annual population growth rates) corresponding to 0.1% increments, that when projected from the founding population number, simultaneously satisfied abundance observations, number of removals, and yielded terminal abundance greater than the point estimate of the 2004 aerial survey.

Results

Aerial Survey

Surveys of units 1 and 2 were conducted on November 2, and a survey of unit 3 was conducted on November 10, 2004 in a MD (Hughes) 500D helicopter (Figure 2). Weather conditions during both surveys were cloudless and visibility was unlimited in the survey areas. Transects were flown at mean ground speed of 85 kph and mean AGL of 120 m in survey units 1 and 2. Transects 1–7 in unit 3W were flown, 1–6 in unit 3E, then transect 8 in both subunits were completed. Transect 7 in unit 3E was not surveyed due to fuel shortage. Mean speed in unit 3 was 86 kph, but AGL was 86 m.

We observed a total of 1785 mouflon in 229 groups during the survey flights. We classified 749 (42.0%) individuals by sex, although 41 (2.3%) were sufficiently visible, but had intermediate sexual characteristics. The remaining 995 were too distant, obscured by vegetation, or otherwise not sufficiently visible to assign sex. Survey unit 1 had the most observed mouflon, the largest mean group size, and the highest ratio of ewes to rams (Table 1). Group sizes were dominated by observations of 3 and 4, then by observations of 1 and 2 animals (Figure 3.) The largest 10 groups observed were 55,

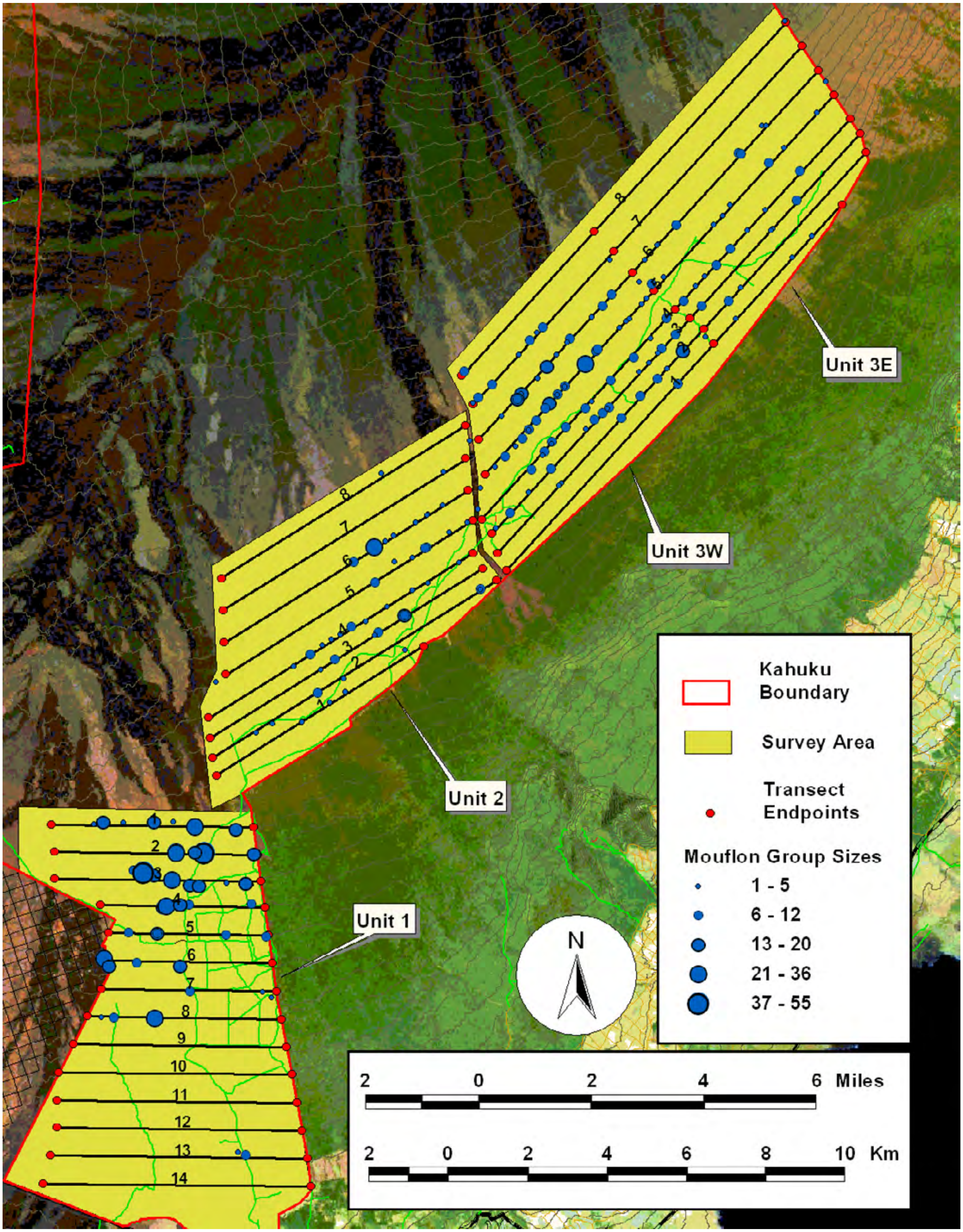

Figure 2. Survey area, transects, and locations of mouflon observed during aerial surveys of the Kahuku Unit of Hawaii Volcanoes National Park, 2 & 10 November 2004.

50, 36, 33, 30, 30, 25, 25, 25, and 23 mouflon. Of these, 9 groups were observed in unit 1; the group of 33 mouflon was observed in unit 2.

A histogram plot of distances to 226 observed groups confirmed that mouflon actively evaded the helicopter in advance of its flight path (Figure 4), which was also supported by our observations of animals running from the approaching aircraft (Figures 5 & 6). This appears to have resulted in some observed groups moving from the nearest distance interval of 0-50 m to the 50-100 m interval. These data are therefore not amenable to distance analyses because they violate the assumption that animals are detected at their initial location, prior to any movement in response to observers, particularly animals located directly on transects (Buckland *et al.* 1993).

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 1586 mouflon in 201 groups were observed within this area. We divided the total number of mouflon observed (M) within each belt transect (t) by its area (A) to determine the density (d) of mouflon on each belt transect $\left(M_t / A_t = d_t \right)$.

Table 1. Summary of 229 mouflon groups observed during aerial surveys on 2 & 10 November 2004 at the Kahuku Unit of Hawaii Volcanoes National Park.

Survey Unit	Kilometers Surveyed	Total Mouflon Observed	Mean Group Size	Ram: Ewe Ratio
Unit 1	84.26	782	15.04	1:3.93
Unit 2	67.80	227	4.73	1:3.32
Unit 3	110.44	776	6.02	1:2.02
Overall	262.50	1785	7.79	1:2.36

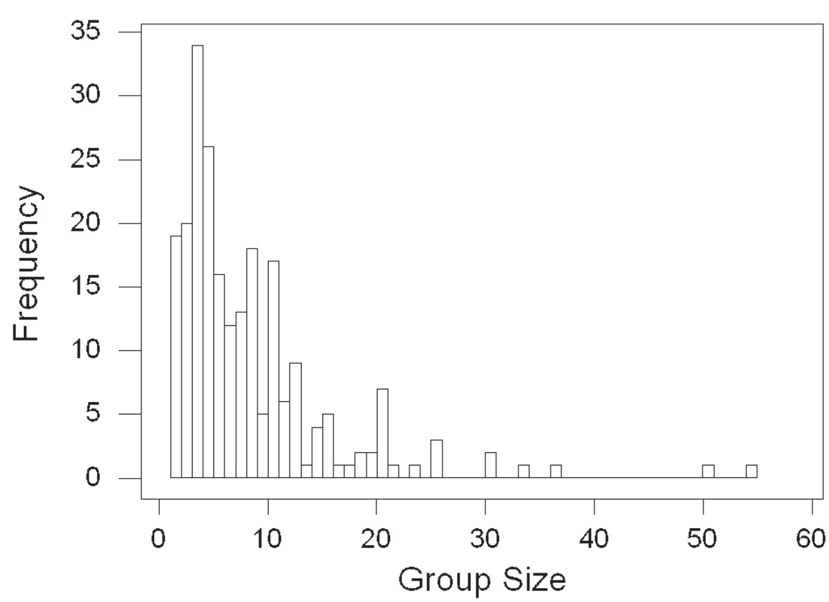

Figure 3. Histogram of 229 mouflon group sizes observed during aerial surveys on 2 & 10 November 2004 at the Kahuku Unit of Hawaii Volcanoes National Park.

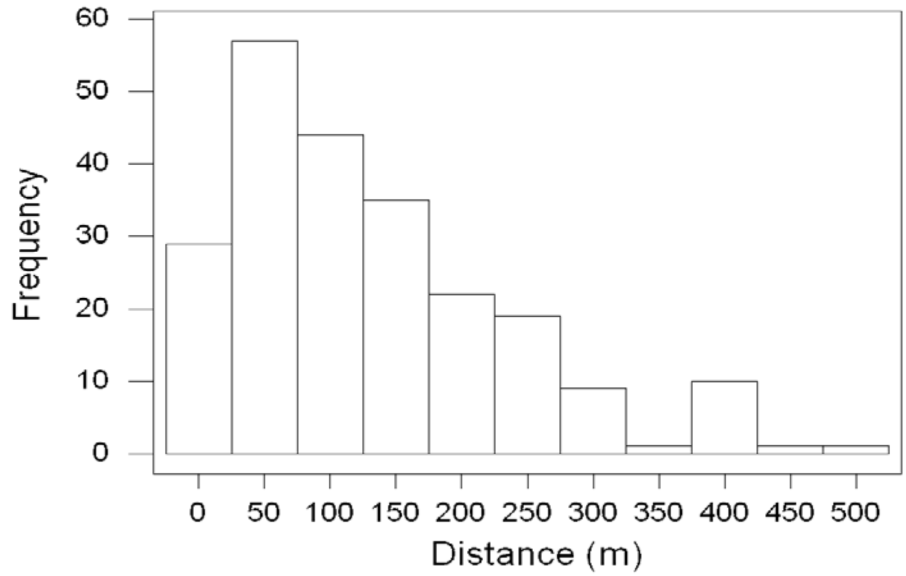

Figure 4. Histogram of distances for 226 mouflon groups observed during aerial surveys on 2 & 10 November 2004 at the Kahuku Unit of Hawaii Volcanoes National Park.

Transects were then stratified by mouflon density within survey units such that 3 different strata were created corresponding to high, medium and low density areas. Stratification reduces the overall error in abundance estimation because transect-to-transect variation in density is reduced within strata. Since little was known of the distribution of mouflon prior to these surveys, this is technically considered a post-stratification process (i.e., the number of transects within each stratum was not a random variable; they were determined *post facto*). Therefore, the true measures of standard error were underestimated in this analysis. Nonetheless, the process of stratification by density was instructive in itself because it revealed areas of dense concentration. This particular stratification designation may be also used in subsequent breeding-season surveys to determine valid measures of survey error.

To determine abundance estimates, we averaged density and calculated the standard error (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 (Table 2). We determined SE for each stratum in the same manner, and 90% confidence interval (CI) by multiplying standard error by critical *t*-values corresponding the degrees of freedom 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.

Table 2. Mouflon population estimates by stratum at the Kahuku Unit of Hawaii Volcanoes National Park.

Stratum	Transects	Area (ha)	Estimated Mouflon	90% CI
High	Unit 1; 1–8 Unit 3W; 2–7	6,956	2,002	± 549
Medium	Unit 2; 2–7 Unit 3E; 2–6	7,136	533	± 160
Low	Unit 1; 9–14 Units 2 & 3; 1 & 8	6,777	51	± 34
Total	37	20,869	2,586	± 705

Photograph by Ben Kawakami Jr.

Figure 5. Mouflon behavior during aerial surveys at the Kahuku Unit of Hawaii Volcanoes National Park, November 2004.

Photograph by Ben Kawakami Jr.

Figure 6. Mouflon behavior during aerial surveys at the Kahuku Unit of Hawaii Volcanoes National Park, November 2004.

Lamb Surveys

The first lamb of the 2005 season was reported on 22 February at about 750 m elevation near the 1868 lava flow (E. Tweed, pers. comm.). The proportion of females accompanied by lambs increased from the 14 March survey, apparently peaking by the 22 March survey (Table 3). Although there appeared to be a slight decline in this proportion on 29 March, this survey was complicated by unfavorable weather and poor visibility conditions resulting in relatively small sample sizes. The last survey of 2 May had the largest sample sizes. The proportion of ewes with lambs decreased little between the reliable surveys of 22 March–2 May. There was some indication that rams had formed groups and moved out of the survey area; therefore, lambs as a proportion of all other mouflon age/sex categories was likely a biased indicator of overall annual increment to the population.

Historical Population Trends

Monthly records of Kahuku Ranch operations for June-July of 1968 (Appendix I) stated that mouflon had arrived and were placed in Number III Kona Paddock. The 1968 Annual Summary of Operations (Appendix II; p. 4) stated that, 'Eight mouflon were released on the ranch and have made their home in the pastures at 3,500 feet elevation.' The August 1974 Kahuku Ranch operation report (Appendix III) stated that an additional 3 mouflon (1 ram, 2 ewes) from Honolulu Zoo were placed in the Keokeo paddock. We assumed an initial population of 8 mouflon in 1968, augmented with 3 in 1974. Giffin (1982) cited personal communication with ranch manager M. Waddoups that there were 30–60 mouflon at Kahuku in 1976. A simple projection of the entire number of founding animals to 30–60 in 1976 required annual rates of increase between 16.0–27.2% respectively (Figure 7). Tomich (1986) stated that there were 'several hundred' mouflon at Kahuku in 1986. A memo to the Trustees of Damon Estate dated 17 August 1993 (Appendix IV) implied that C. Wakida, chief of Division of Forestry and Wildlife on the Island of Hawaii had observed '…upwards of 2,000…' mouflon from aircraft, although no details of such surveys were located. O'Gara (1994) cited personal communication with E. Yap that 'about 800 head' was culled between January 1993 and June 1994 as a result of O'Gara's 'suggestion … that culling of females and inferior rams seemed in order'. Detailed hunting records, however, were available only for years 1995 (52), and 1996 (79).

In simple population models, values of $\lambda < 1.194$ (i.e., annual population growth of 19.4%) were not sufficient to overcome the removal event of 1993–1994 (Figure 7). Values of $\lambda > 1.211$ were necessary to produce terminal abundance greater than the point estimate of 2,586 mouflon from our aerial survey. The lowest value of λ required to produce terminal abundance greater than the upper 90% CI limit of the aerial survey was 1.214. A value of $\lambda > 1.243$ was necessary to produce abundance of $\lambda > 2{,}000$ in 1993 as per the 1993 memo to Damon Estate; however, values of $\lambda > 1.22$ produced terminal abundance > 5,000 individuals in year 2004.

Discussion

We observed dense concentrations of large mouflon groups from 1,100–1,600 m elevation in the upper pastures of the ranch areas unit 1, and to a lesser extent, from 2,000–2,200 m elevation above the Ka`ū forest reserve in units 2 and 3. The largest observed group sizes and most female-biased sex ratios were also observed in the upper pasture areas of unit 1. The highly skewed sex ratio in the same area may be a result of rams guarding harem groups, or greater road access to trophy hunting opportunities in the past. Large groups and breeding activity in the upper ranch pastures may be a result of traditional movement patterns of these animals to the vicinity of their original location of liberation. The frequency of human disturbance, topography, and tree distribution were related to movements of hybrid mouflon on Mauna Kea, determining differences between areas in browsing pressure and bark stripping (Scowcroft and Sakai 1983).

We estimated a total of 2,586 ± 705 (90% CI) mouflon within the Ka`ū district of the Kahuku Unit. The majority of this population was concentrated in the upper ranch pastures of unit 1 and the western half of unit 3. The density of unit 2 was greater than that of the eastern half of unit 3, and both

Table 3. Mouflon lambs as a proportion of ewes, and lambs as a proportion of all other age/sex categories observed during 4 road-based surveys at the Kahuku Unit of Hawaii Volcanoes National Park, 2005. Binomial standard error is reported.

	Lambs	Lambs/ Ewes			Lambs/All Others		
		N	Proportion	SE	N	Proportion	SE
14-Mar-05	35	113	0.310	0.044	137	0.255	0.037
22-Mar-05	64	131	0.489	0.044	174	0.368	0.037
29-Mar-05	39	91	0.429	0.052	111	0.351	0.045
2-May-05	131	279	0.471	0.030	335	0.391	0.027

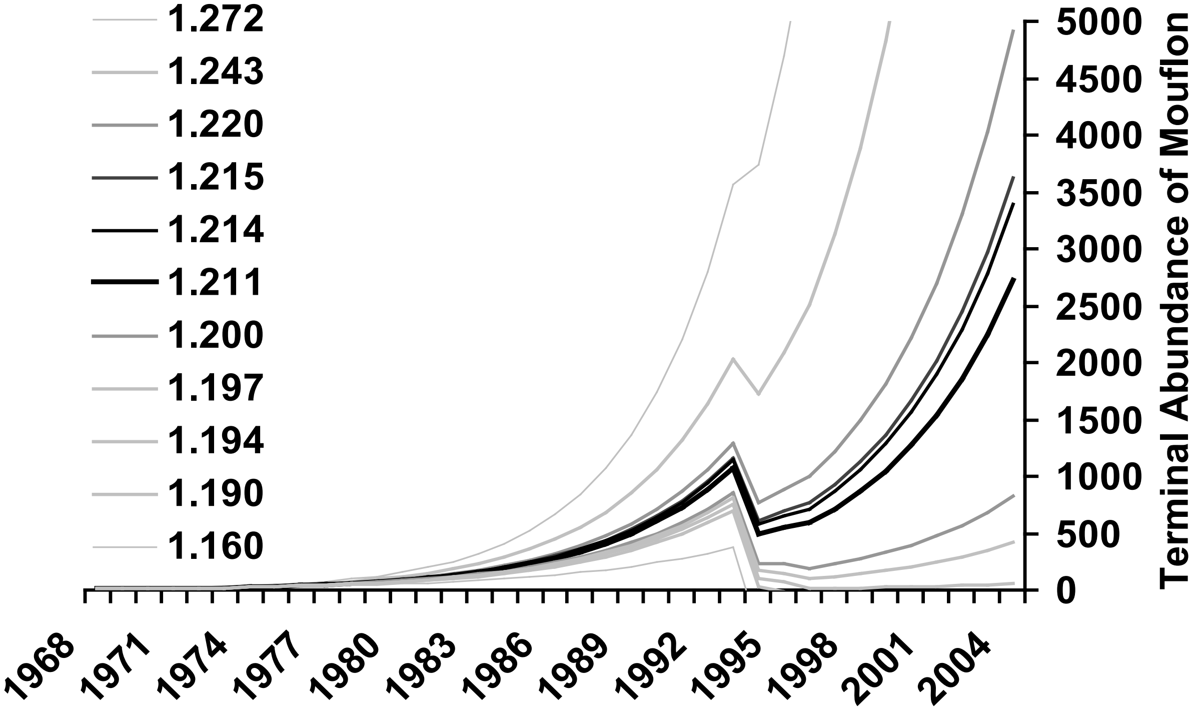

Figure 7. Population projections of mouflon at the Kahuku Unit of Hawaii Volcanoes National Park 1968–2004. Different values of annual population increase (λ) were projected for plausibility given known removals and terminal abundance estimates. Darker and bolder lines indicate more plausible values.

of these units contained more mouflon than the lower ranch pastures of unit 1. This distribution was highly aggregated due to breeding behavior and likely to be dispersed over a more extensive area at other times of the year.

Our analysis did not account for reduced detection probability where animals were obscured by vegetation or other factors. In fact, because the reliability of observations deteriorated rapidly at distances greater than 125 m, our observations underrepresented the actual number of mouflon from this distance to the truncation point of 250 m from the aircraft. Abundance estimates were therefore conservative and the actual number of mouflon was likely greater. Furthermore, our results applied to only 34% of the land area of Kuhuku. Although this area represents most of the suitable habitat for mouflon, there may also have been more mouflon west of the area we surveyed and small numbers at higher elevations.

Stratification improved the abundance estimate of mouflon because there was high variability in density within each of the survey units. The upper and lowermost transects of units 2 and 3 should continue to be designated in the low-density stratum because the uppermost transects are near the upper elevation limits of mouflon and the lower transects are obscured by dense forest vegetation. The lower pasture areas of unit 1 may contain higher densities of mouflon, particularly at other times of year, and high and medium density areas may also change seasonally. Therefore, reconnaissance of these areas from either air or ground is essential in planning future surveys to determine appropriate stratification immediately prior to flight. This information can also be used to substantially reduce sampling effort in the low-density stratum without affecting the overall precision of abundance estimates.

There is not likely to be a single ideal method for estimating the abundance of Kahuku mouflon given their evasive behavior and the variety of habitats in which they are found. Although aerial surveys allow rapid assessments of large geographic areas, they are complicated by forested habitats, which greatly reduce detection probability. Garel *et al.* (2005) found that helicopter surveys provided better precision-to-cost benefits than pedestrian surveys to determine population count statistics for mouflon in mountainous areas of southern France. Few other methodological improvements can be implemented to overcome the fundamental problem of evasion in this species. Therefore, it is not likely that distance analyses will be suitable for future surveys, especially if mouflon become more wary of aircraft. Nonetheless, distance data should be recorded for each group to better understand factors affecting detection probability, particularly in dense vegetation. Photographs should also be made of a large sample of groups to verify sex composition data taken during survey observations. In addition, transects in units 1 and 2 should be extended westward to cover area above Hawaiian Ocean View

Estates, and a few high elevation transects may be augmented to better determine densities in the alpine zone.

The 2005 lambing season began in late February at Kahuku. In years with more favorable environmental conditions, lambing may begin as early as mid-January (E. Yap, pers. comm.). Bon *et al*. (1993) reported a 9 week lambing period beginning in late March in southern France, substantially later than lambing we observed in the less seasonal climate at Kahuku. Langbein *et al*. (1998) also reported parturition dates in late March for mouflon in northeast Germany. Garel *et al*. (2005) found marked differences in the age at first reproduction and twinning rates that affected reproductive output between two populations of mouflon in France. Such differences may have been due to the interactions between the quality of the local environment and hybridization between wild and domestic sheep during the recent history of these populations.

Results of lamb surveys may be used to determine upper biological limits to annual population increases under particular environmental conditions. Sexual segregation of adults during the lamb season, however, has the potential to confound these results. Various aspects of social structure have been described for mouflon in Europe (Dubois *et al*. 1994, Le Pendu *et al*. 1995). Social organization structured around different sex and age classes, presence of lambs, and breeding activity has a strong basis in mouflon sheep (Le Pendu 1996). Cransac *et al.* (1998) found segregation not only between the sexes, but also segregation between young (2–3 years) and old rams ≥ 4 years, as well as some differences in patterns of habitat use in the mid-rutting and lambing seasons. This type of segregation between sexes, however, was only associated with differences in habitat use during 3 of 8 months outside the rut. The frequency of rams in forest was greater than ewes, while ewes with new born lambs were more often sighted on steep rocky slopes generally considered to be escape terrain. Le Pendu *et al.* (1996) also found that lambs and females were closer to each other than to the other individuals on average throughout the year at two sites in southern France and eastern Germany. Lambs tended to be central to the groups and females peripheral. Nearest neighbors were close when both were engaged in the same activity other than feeding, they kept a medium distance when both were feeding and they were more distant when only one of them was feeding.

It was reasonable to assume at Kahuku that lambs as a proportion of all other adults was likely biased due to the possibility that rams formed groups and moved into forested areas at lower elevation. A better estimate of lambs as a proportion of all other age/sex categories could be obtained by using the overall sex ratio from our aerial survey. From the last lamb survey of 2 May 2005, the proportion of females accompanied by a lamb was approximately 0.471. From aerial survey data, the proportion of females in the population was approximately 0.702. Therefore, the population increment may be as high as 0.471 x 0.702 = 0.331, or a 33.1% annual increment. If we apply this estimate of population increment to the estimated population of 2,586 mouflon during the 2004 rut, we could expect approximately 856 lambs to be born into the population during the 2005 season. Given that the population estimate was probably biased low (i.e., an underestimate), the actual number of lambs born was likely to be in excess of 856. When the estimate of lambs as a proportion of all other mouflon was applied to the upper 90% CI of 3,291 mouflon from our 2004 aerial survey, it resulted in an annual increment of 1,089 lambs.

These estimates did not account for natural mortality in any age class. Nonetheless, in a heavily hunted population such as the Kahuku mouflon, mortality may be largely compensatory (i.e., removing large numbers of mouflon may result in negligible additional mortality due to starvation or other density dependent factors). For example, we observed little decline in the proportion of ewes with lambs from 22 March–2 May, suggesting high survival through this 6 week period. O’Gara (1994) documented lungworm, probably *Muellerius capillaris*, in Kahuku mouflon and hypothesized this pathogen could lead to death in lambs by 6 weeks of age. O’Gara also stated in a cover letter enclosed with his report to Damon Estate (Appendix V), ‘Obviously, the mouflon population has outgrown its habitat, and parasites are reducing reproduction.’ We observed no obvious evidence, however, that pathogens, parasites or any other major cause of lamb mortality such as predation by feral dogs occurred during the course of any of our surveys. Garel *et al.* (2004) found that lamb mortality in southern France exceeded 25% during a severe drought period, although it was < 10% in a previous study of the same population during normal environmental conditions over a 9-year period (Cransac *et al.* 1997).

Historical population trends provided information on the minimum population growth rates required to produce observed values of terminal abundance. This could also be considered the ‘apparent’ population increase, based solely on the observed population size at different intervals, without knowledge of any vital rates such as recruitment or mortality. Population growth rates produced by this method underestimated the true population growth rate because: 1) historical hunting records were poorly represented; 2) our estimate of terminal abundance did not account for the entire population, and; 3) terminal abundance was not corrected for detection probability. If more complete records of hunting removals were discovered and if abundance of the entire population could be measured more accurately, estimates of annual growth rates would probably be higher than we report here. Nonetheless, minimum population growth rates represent the annual increase in mouflon that can be ‘seen’ at Kahuku after hunting. Documentation of the large removal event of 1993–1994 was fortuitous in that it allowed us to rule out small values of λ and account for a major correction in population trajectory. Although abundance of 2,000 prior year 1993 cannot be reconciled with our estimates of terminal abundance and the removal data at hand, this scenario cannot be ruled out if hunting were substantially greater after the removal event than before, if strong density dependence operated above this level, or if mass emigration to areas outside Kahuku occurred after 1994. Our estimated minimum apparent annual population increase of 21.1% is consistent with other species of large mammals (Eberhardt 1987), but lower than that of mouflon introduced to another oceanic island (Chapuis *et al*. 1994).

In conclusion, lamb surveys and historical trends taken together indicate that the per capita increase in 2004–2005 should lie between 21.1–33.1%. Assuming a population of 2,586 and an apparent annual population increase of 21.1% observed from the historical trends, 546 mouflon *in addition to the unknown mean annual per capita harvest* would need to be removed to maintain the population at or near its 2004 level. Assuming population increase near the upper biological capability of 33.1%, however, a minimum of 856 mouflon would need to be removed to achieve the same management goal. Although the latter rate of increase is likely to be an overestimate because it does not account for any natural mortality, the calculated increment for 2005 is based on an underestimated total population in 2004 and may therefore underestimate the number of removals necessary to prevent further population increase. The doubling time, i.e., the number time steps required for a population to double given these observed rates of increase, is on the order of 2.42 years at maximum biological potential without any removals, to 3.62 years with the typical number of historic removals. Because mouflon at Kahuku appear to follow a discrete birth-pulse pattern (births occur during a short period of the year) rather than a birth-flow pattern (births occur more or less continuously throughout the year), the population will increment at whole-year time steps. This implies that the population will actually require 3–4 years to reach levels in excess of doubling. The Kahuku mouflon population has sustained high levels of hunting pressure and emigration throughout its 36-year existence and yet has apparently demonstrated a nearly uninterrupted increase in abundance while simultaneously increasing its distributional range throughout many areas of southern Hawai`i Island.

Acknowledgments

We thank H. Hoshide and J. T. Tunison of HAVO NPS Resources Management, and the USGS Invasive Species Program for supporting our survey efforts. We thank J. Faford for flight following during aerial surveys, J. Faford, and D. Pacheco for assisting in ground surveys of lambs, T. Laqua for providing access to historical documents, and the K. Ross Toole Archives at The University of Montana for providing a copy of O'Gara's report, and K. Shimabukuro for permission to use Damon Estate documents. We also thank two anonymous reviewers for their suggestions to improve this report. Any use of trade, product, or firm names in this report is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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Appendix I. Kahuku Ranch Monthly Report for June & July 1968.

Hal. HC Copy to Each T

Kahuku Ranch

TELEPHONE 693-813

POST OFFICE BOX 174
NAALEHU, HAWAII 96772

MONTHLY REPORT FOR JUNE & JULY 1968

OPERATIONS

CATTLE

We finished the branding except for late calves that will be picked up in September when we take the bulls out.

Dry cows were culled. A few that we were not sure of will be picked up when we take the bulls out.

We shipped 80 fat cows to Hawaii Meat in June and 60 in July.

The cowboys, when the cattle work was completed for the week, joined with the two poison men and worked on fence repair. The bars on the ranch pen had to be replaced. We are having to redesign the chute at the ranch pen to facilitate handling of wean calves. We found that giving them pre-feed yard vaccinations and worming is best done at weaning.

PASTURE

Pakani -45 acres- was top dressed by air.

The Ranch Paddocks are being mowed. Desmodium entordum, a vine like legume, was planted in the kipukas around the main camp in an attempt to raise the carrying capacity in these conveniently located areas.

DEVELOPMENT

Planting continued in Akihi.

The D9 was sent to Theo. H. Davies in Hilo for replacement of the track group and a checkup on other parts. No major repairs were required on the engine. The track frame had to be removed and sent to Honiron to be pressed back in line. The D9 is at this time back working on the ranch. Clearing will go much faster now that Lui can maneuver with good traction . If we stay with clearing as versus digging reservoirs and making roads, the track group will last a long time because of the less abrasive effect of the forest clearing.

WILDLIFE

The Mouflon have arrived and in excellent condition. They are in Number III Kona Paddock. They seem to be doing very well there. They are a really beautiful animal resembling deer more than sheep.

The pheasants are doing well. We are going to raise them this year to maturity. We are using the pens behind my house. We are starting to feed them on the ground to train them to scratch for feed. We suffered some loss from pecking until we discovered canned

AUG 13 1968 COPIES TO TRUSTEES/FOR MEETING 8/13

-2-

MONTHLY REPORT FOR JUNE & JULY 1968

dog food is a favorite food and effectively eliminates the pecking. 50 pheasants eat four cans of dog food a day.

RESERVOIRS are full.

RAIN READINGS

HOUSE	1.59
KAMAOA	1.87
FIRST	3.80
SECOND	2.26
THIRD	2.86
KEALAKOA	4.48✓
GEORGE BECK	1.67
GLOVER	2.85
KAPUA	6.00
MANAWAI NUI	4.00

Respectfully submitted,

Harold F. Rice, Jr.
Manager

August 12, 1968

HFR/sr

AUG 13 '68

Appendix II. Excerpt from Kahuku Ranch Annual Summary of Operations 1968.

Kahuku Ranch

TELEPHONE 693-813

POST OFFICE BOX 174
NAALEHU, HAWAII 96772

ANNUAL SUMMARY OF OPERATIONS 1968

Harold F. Rice, Jr.
Manager
February 6, 1969

Copy for each Trustee
agenda 2/13.

FEB 10

COPIES TO TRUSTEES FOR MEETING 2/13

after all the disturbance have evidently decided to let the matter drop concerning all the problems we were supposed to have. The difficulties seem to come more from a political struggle as to jurisdiction rather than from actual disease danger to the cattle in the state.

Eight Mouflon were released on the ranch and have made their home in the pastures around the 3500 feet elevation.

50 Mongolian pheasants were raised and released and have taken to the transition area between the improved and unimproved pastures.

Feeder cattle were shipped by air to the feed yard saving an average of 30 pounds per head. Shipping cost amounted to $3 per head more than by Young Bros barge. Figuring a cost per pound gain in the feed yard of 24¢ per pound, we saved $7.20 per head or a net of $4.20. However, the disadvantage is the small numbers that can be shipped at a time and hence the time taken away from the ranch as versis the shipping of large numbers by Young Bros. barge. There is considerable discussion of an airstrip at South Point to service new development in the Kau area. If and when this access to air shipment occurs so that we save the trucking to Hilo as well as the 30 pounds shrink, flying feeders wil be a great saving.

A much needed new cattle truck was purchased and put into use.

The Department of Wildlife built a cabin on our Maunaloa section. Their release of nene has been very successful. We have pairs of nene at Kapua, Number IV, Keokeo, Number II , and occasionally at the ranch in addition to those that have remained on Maunaloa.

The sale of beach property put the ranch in a better light but took no productive land out of the operation.

A windbreak of Norfolk Island pine and ironwood was planted for the office, main ranch camp, and Kamaoa holding pens.

Appendix III. Kahuku Ranch Monthly Report for August 1974.

Kahuku Ranch

TELEPHONE 929-7413

POST OFFICE BOX 174
NAALEHU, HAWAII 96772

COPIES TO TRUSTEES FOR MEETING 9-19-1974

MEMORANDUM TO: Trustees, Estate of Samuel Mills Damon

FROM: Thomas M Waddoups, Jr

SUBJECT: MONTHLY REPORT - AUGUST, 1974

DATE: September 9, 1974

Rainfall: 1974 August - Ranch average at 8 stations - 2.00"
1973 August - Ranch average at 9 stations - 1.09"

Water Storage: Mauka reservoir; down 2 feet
Makai reservoir; full

Pastures: All pasture conditions remain good.

Livestock: August 1, 1974, 15 cows were shipped to Kulana Foods. August 8, 1974, one (1) bull was slaughtered at Kona Meat Company. August 15, 1974, 15 cows were shipped to Kulana Foods.

A total of 10 Angus bull, 16 Hereford bulls, and 6 work horses were purchased in California in August. These animals will arrive in Hilo on September 17, 1974.

Our stallion, Peppy Dart, has been sent to stud at Kukaiau Ranch for a monthly rental of $400.00 per month.

Building and Construction:

Two ranch homes (recently remodeled) were tented for termite control on August 27, 1974.

Game Management:

We received a beautiful two-year Mouflon ram and two yearling Mouflon ewes from the Honolulu Zoo. These animals are presently in the release pen in KeoKeo Paddock, and will be released in about two weeks.

Thomas M Waddoups, Jr
Manager

TMW:11

Appendix IV. Memo to Trustees of Damon Estate dated 17 August 1993.

COPIES TO TRUSTEES FOR MEETING 8/18/93✓

August 17, 1993

To: Trustees, Estate of S. M. Damon

Subject: Meeting with Charles Wakida, Hawaii District Manager
Division of Forestry and Wildlife
Kahuku Ranch, August 13, 1993

On Friday, August 13, 1993, Jim Whitman, Soot Bredhoff, Charles Wakida and one of his staff members met for an inspection of the higher elevations of Kahuku Ranch lands by helicopter with Bill Lacy Jr. piloting. The flight path, under windy conditions, followed the HOVE boundary up to 5,000 feet, over the reservoirs, and generally followed the Ka'u Forest Reserve/Kahuku boundary, which is surprisingly well defined, to Kilohana and into Kapapala beyond. The return was over the State forest makai of the ranch boundary, with the added bonus to Wakida in that a substantial patch of pakalolo was located for future eradication.

The inspection, at approximately 9:30 A.M., revealed only small isolated groups of Mouflon at the higher elevations with a pair observed at the Kapapala boundary. While no Mouflon were observed in the forest, 5 Hereford cows were seen.

Wakida has been on and flown over the ranch on a number of occasions and makes the following comments: he estimates that he has seen upwards of 2,000 sheep on the ranch on a given day, with groups of as many as 50 on Kapapala lands. A Mouflon has recently been shot in the Volcanoes National Park. Mouflon were observed 2 miles deep into the forest reserve during the recent bird habitat study. He further states that his study of the Mouflon's characteristics in the Mediterranean contradicts Yap's claim that they shun the forest habitat.

My own observations of the forest reserve lands from the air reveals that this is not a typical forest in the upper areas. The forest, while dense in some areas, has considerable areas of scrub ohia and tree fern which provides open grazing which would be attractive to the Mouflon as well as cattle. Wakida estimates that they have killed 300 head of cattle in the forest to date.

Wakida advises that pressure from conservations groups, including the Sierra Defense League, is such that the question is no longer "if" the State will take action but "when" it will be necessary to do so. The pressure is being exacerbated by people like our friend Dr. Lockwood who is flying over the ranch quite regularly and urging the conservationists to take action, possibly out of spite.

While none of the options available to the Estate are attractive, nor can they be the complete answer to the problem, Wakida sees them as follows:

a) Fence the Ka'u Forest Reserve and Kapapala boundaries with hog wire (approx. 20 miles @ $5,000 per mile not including cost of clearing and flying fence material in). This does not solve the problem of sheep already in the forest.

b) Charter a helicopter for the control program at $600 per hour. This would not be effective for forest control unless several sheep were first captured and fitted with electronic transmitters so that movement in the forest could be tracked. The State would be willing to provide this service.

c) In terms of control of sheep in the forest and to pacify the conservationists, Wakida feels that a cooperative hunting program with his department would be most effective. In accordance with the wishes of the Estate, the State would issue hunting permits, enforce hunting seasons and designated hunting areas, be responsible for cleanup and would fight any fires on ranch lands at the State's cost. (An example would be five hunting groups of not more than five hunters each at any one time with a hunting area limited to makai of the ranch road and into the forest reserve).

To further promote hunting in the forest reserve, the State has undertaken the task of grading a jeep road following the old Ainapo trail through Kapapala and to within 2 miles of Kahuku ranch. The Kahuku/Kapapala boundary is designated by fence posts, most of which are down. The State would also like to cut a new road through the forest reserve parallel to the Kahuku boundary to encourage hunting in the forest reserve. They have still to convince the environmentalists of the advantages of such a road.

Lastly, Wakida feels it is only a matter of time before the portion of the old Ainapo trail which runs across the ranch at the 6,000 to 7,000 foot elevation will be reopened to the public.

Appendix V. Letter enclosed with O'Gara's (1994) Report to Trustees of the Damon Estate concerning mouflon on the Kahuku Ranch.

COPIES TO TRUSTEES SEP 1 1994 INFORMATION

DATE SENT

215 Red Fox Rd.
Lolo, MT 59847
(406) 273-6827

Bart O'Gara, Ph.D.
Wildlife Consultant
Research Biologist (retired) U.S. Fish and Wildlife Service
Wildlife Professor Emeritus, University of Montana

09 September 1994

Mr. Jim Whitman
Estate of S. M. Damon
First Hawaiian Tower
1132 Bishop Street
Suite 1507
Honolulu, Hawaii 96813

Dear Mr. Whitman:

Enclosed is my report concerning mouflon on the Kahuku Ranch. I am sorry it has been somewhat delayed, but I received the pathology report only 2 weeks ago and the tooth growth-ring data 3 days ago.

Obviously, the mouflon population has outgrown its habitat, and parasites are reducing reproduction. If these were Rocky Mountain bighorns, a population crash would be inevitable. However, mouflon are more resistant, and culling now may reduce numbers without a catastrophic crash that would seriously impact trophy hunting.

If I can be of further service to you, please let me know. I believe another collection in December would answer several questions and provide a better basis for management of the mouflon population.

Respectfully,

Bart O'Gara

Bart O'Gara
Professor Emeritus

BO/vb

Enclosure

SEP 12 1994