Interpreting Feral Goat (*Capra hircus*) Movement to Guide Management in a Mesic Watershed on O'ahu, Hawai'i

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ABSTRACT: Endemic Hawaiian ecosystems evolved without ungulate herbivores. Feral goats, a common nonnative ungulate on Pacific Islands, browse and trample vegetation which can denude watersheds and expose them to soil erosion. Since 1993, the Hawaiʻi Division of Forestry and Wildlife has actively suppressed feral goat populations to protect critical watersheds in a 1600-ha management area on Mount Kaʻala in the leeward Waiʻanae mountain range of Oʻahu. Despite these ongoing efforts, total eradication has not been achieved to date. This study examined the movement patterns of one male and one female feral goat in this management area over one year in 2015-16 with GPS collars. The primary objective was to determine if feral goat movements are related to seasonality, moon phase and precipitation to inform future management efforts. The male goat exhibited a large range, extending out 2.5 km from its starting point and over an 800m elevation range within the year, traveling to lower elevations during the summer months. The female goat, in turn, had a much smaller range and stayed relatively close to its initial starting point. The male goat exhibited greater movement at night than during the day, and this was particularly evident during full moon phases; animals also exhibited aversion to movement during precipitation events. Hot spot analyses showed that the female was largely confined to one location throughout the course of the study, while the male moved to multiple locations but displayed a strong affinity to the eastern portion of the management area in the Fall season. These initial findings help build knowledge on local patterns of feral goat movement within this managed area that can be used for control efforts. GPS collars provided useful high-resolution data to support further adoption of this technology to better inform management decisions. Future management strategies should incorporate longer-term movement data sets from multiple individuals to better understand habituation (e.g., return to favored locations), patterns of sexual segregation and rutting. This would allow a more demographic approach for maintaining populations below levels that are considered detrimental to this critical habitat.

KEY WORDS: *Capra hircus*, eradication, feral goat, GPS collar, Hawaii, judas goats, movement ecology

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INTRODUCTION

Hawaiian ecosystems have high rates of endemism as a result of geographical isolation, with many species now threatened and endangered by extinction. The largest driver of extinction globally is habitat modification and loss (Brooks et al. 2002), with nonnative mammal introductions also playing an important role (Blackburn et al. 2004). Introduced ungulates (hard-hooved browsing mammals), in particular, are universal ecosystem transformers (Chynoweth et al. 2013, Hess 2016), with typically negative impacts on native species and ecosystems. No ungulates are native to Hawaiʻi, which resulted in plants losing at least some defenses against large herbivores (Hess 2016). Domestic goats (*Capra hircus*) were introduced to Hawaiʻi by Captain Cook, in the late eighteenth century, quickly becoming feral (Tomich 1986). Feral goats lack natural predators in Hawaiʻi, intrinsically growing into large herds that browse and trample vegetation, denuding native ecosystems resulting in severe soil erosion and coastal sedimentation (Chynoweth 2013, Hess 2016). Feral goat removal is prerequisite to the protection of diverse endemic Hawaiian ecosystems (Burt and Jokiel, 2011, Cabin et al. 2000, Hess 2016). With that, there is a need understand feral goat behavior and movement ecology across these diverse landscapes (Chynoweth et al. 2015), that could tailor management strategies to specific locations.

Goats are considered a diurnal species (Piccione et al. 2008, Shi et al. 2006). However, local hunting communities in Hawaiʻi have observed feral goats to be active at night during full moon phases. The lunar cycle does alter night-time visibility influencing predatory success but with varying, species-dependent prey responses (Palmer et al. 2017). However, in general, increased luminosity of the moon force prey to be less active and conversely show greater movements during the darkest periods (i.e., new moon) (Clarke 1983, Kotler et al. 2010, Penteriani et al. 2013). White-tailed deer (*Odocoileus virginianus*) in South Carolina and Oklahoma have shown predominant and routine crepuscular activities, with moon phase having only slight to no effect (Webb et al. 2010, Sullivan et al. 2016). In Hawaii, dog packs (*Canis lupus familiaris*) are used in pig (*Sus scrofa*) hunts and may become lost and feral. Otherwise, there are no other known top predators of ungulate prey in Hawaiʻi. Thus, in Hawaiʻi, it is unknown how active feral goats are at night and how they may respond to moon phases.

Goats have very low hydration requirements making them highly adaptable to xeric-mesic environments (Chynoweth et al. 2013, 2015). It's been further observed by local hunting communities in Hawaiʻi that feral goats seek shelter during heavy rain events and sun themselves on exposed ridges and high points afterwards. Rainfall has been found to affect animal movement across species, including white-tailed deer (Webb et al. 2010), wildebeest (*Connochaetes taurinus*) (Boone et al. 2006 and Holdo et al. 2009), elephants (*Loxodonta africana*) (Birket et al. 2012), and lions (*Panthera leo*) (Elliot et al. 2014).

However, Shi et al. (2006) found no effect on feral goat activity due to rain events on the Isle of Rum, Scotland.

On the island of O‘ahu, goats were unintentionally introduced to Mount Ka‘ala, in the Wai‘anae Mountain range. Mount Ka‘ala provides critical habitat for several threatened and endangered species. Due to the high levels of browse damage being observed on the native forest community, the Hawai‘i Division of Forestry and Wildlife (DOFAW) initiated a culling program in the mid-1990’s to reduce this feral goat population. Today, a small remnant population still resides in this relatively large management unit (>1600 hectares), where steep terrain and thick vegetation make it difficult for resource managers to monitor and completely eradicate the herd.

This feral goat management program has deployed a judas technique (Taylor and Katahira 1988), fitting a GPS/radiotelemetry collar on a single male and female goat to monitor the location of the herd for scheduled hunts and in the process have recorded several months of time-stamped geolocation data. With access to historical GPS data from 2015-16, we aimed to understand diel and seasonal movement patterns and how movements were affected by moon phase and precipitation in a mesic microsite of Mount Ka‘ala . We hypothesized according to hunter observations that i) goats would be more active during the day, ii) full moon phase would stimulate greater activity, iii) male and female goats would have distinct seasonal movement patterns, and iv) goats would prefer to move during periods with no precipitation.

METHODS

Study Area

This study was conducted in the north ridges of Mount Ka‘ala, consisting the Mokulē‘ia Forest Reserve (FR) and the Ka‘ala Natural Area Reserve (NAR). This area is managed by the Hawai‘i Division of Forestry and Wildlife (DOFAW), and encompasses ~1600 ha of the Wai‘anae Mountain range in northwestern O‘ahu Island, Hawai‘i (Figure 1). The area has a steep elevation gradient from 180 -1200 m a.s.l. with several drainage basins offering broad variations in slope and aspect. Within this microsite, mean annual rainfall ranges from 1023-1937 mm yr^{-1}, while the mean annual daily temperatures decrease from 22.7 to 15.8°C with increasing elevation (Giambelluca et al. 2013, Giambelluca et al. 2014). The study area is dominated by non-native vegetation at lower elevations and transitions into more intact native vegetation communities at higher elevations that serve as critical habitat for threatened and endangered native species.

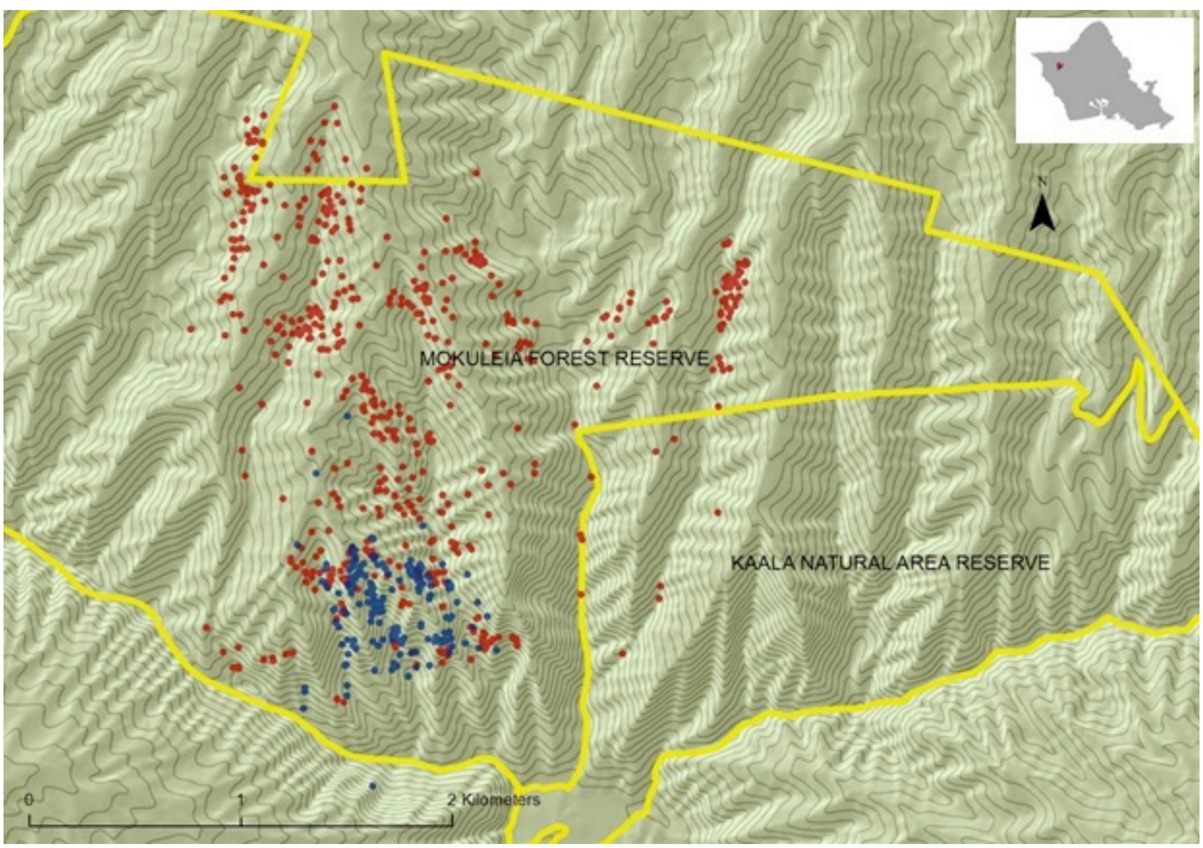

Figure 1. Map of study site, Makaleha Valley comprises both Mokulē‘ia Forest Reserve and Ka‘ala Natural Area Reserve (yellow boundaries) on the island of Oahu. Male (red) and female (blue) GPS points recorded for 12- and 6-month periods, respectively, during 2015-2016.

GPS Collaring Goats

Two feral goats were live-captured following DOFAW standard operating procedures to install Wildlife GPS/radiotelemetry collars (Lotek Wireless Inc. Newmarket, ON), same day. The first feral goat, a male, was collared on February 20, 2015, and the second, a female, on June 15, 2015. Each collar was programmed to take location points at 0400H, 1000H, 1600H, and 2200H daily. The male goat location data spanned a full year (February 20, 2015-February 20, 2016) before the battery in the collar died. The female goat location data spanned from June 15, 2015 through November 27, 2015, at which point the female goat died for unknown reasons. Due to the limited dataset for the female goat, we only analyzed the movement data from the male collar data. Capture and handling methods were not administered by the authors and thus an exemption to access and analyze this management data was granted by the by the University of Hawai'i at Mānoa Institutional Animal Care and Use Committee.

Environmental Variables

Elevation data were extracted from a digital elevation model (DEM) of O'ahu (NOAA 2007; 10 m resolution). Local precipitation data was downloaded from a nearby weather station (Intelesense Technologies Fremont, CA; 21.54603N, 158.195W). The weather station recorded 340 days within the 12-month period of this study in 2015-2016. Total precipitation was 1494 mm, accumulated in 123 days which was 15% higher than average annual precipitation of that pixel location and within the range of the management area of interest. There were 217 days of no precipitation recorded. Average annual rainfall was extracted from isohyet polyline shapefiles for O'ahu (Giambelluca et al. 2013). Average annual rainfall from the raster was extracted with ArcGIS (v. 10.2.2, ESRI Company Redlands, CA).

Moon phase data was obtained from the Hawaiian moon calendar (Kamehameha Publishing, 2016), and was categorized into trimesters based on light availability from the moon and designated as: new moon, full moon, and transitioning stages. The new moon trimester consisted of the phases four days before and after the new moon, with the full moon consisting of four days before and after the full moon. The transitioning trimester combined the waxing and waning moon phases between new and full moon phases.

Data Analysis

GPS data were compiled and analyzed using ArcGIS (v. 10.2.2, ESRI, Redlands, CA), Microsoft Excel (Microsoft, Redmond, WA) and XLSTAT add-in (v. 19.5, Addinsoft, New York, NY). Elevation, moon phase and mean annual rainfall attributes were added to the corresponding GPS locations and timestamps, respectively. Data were also categorized into diurnal and nocturnal time periods. Horizontal and absolute vertical velocities were derived from the Euclidian distance between points over time (e.g., 6 hrs), independent of terrain contours. Local precipitation was calculated as the average precipitation rate (mm hr^{-1}) between points (e.g., 6-hr time interval). Position and velocity data were plotted against time, date, moon phase and precipitation. Precipitation rates were binomially categorized as precipitation > 0.0 mm hr^{-1} "no precipitation." A Wilcoxon signed-rank test was used to analyze daily pairwise comparisons of nocturnal versus diurnal periods. This non-parametric test was used due to the excess kurtosis in the data distribution. A one-way analysis of variance (ANOVA) was used to assess the effects of seasonality, precipitation and moon phase. Although the data

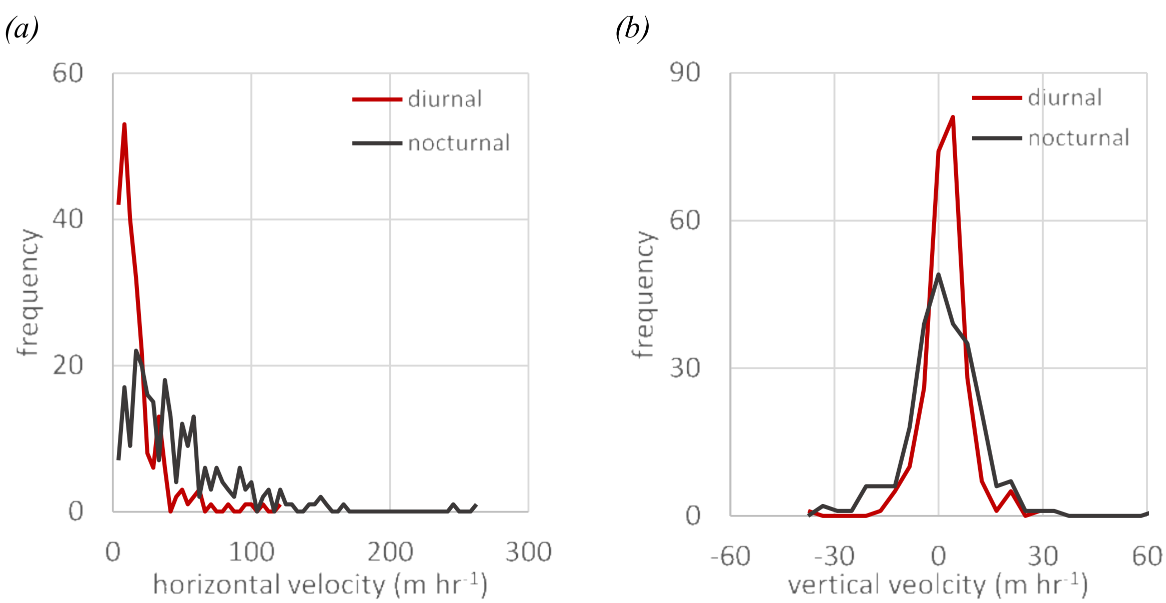

Figure 2. Male horizontal (a) and vertical (b) velocity histograms comparing diurnal and nocturnal frequency distributions.

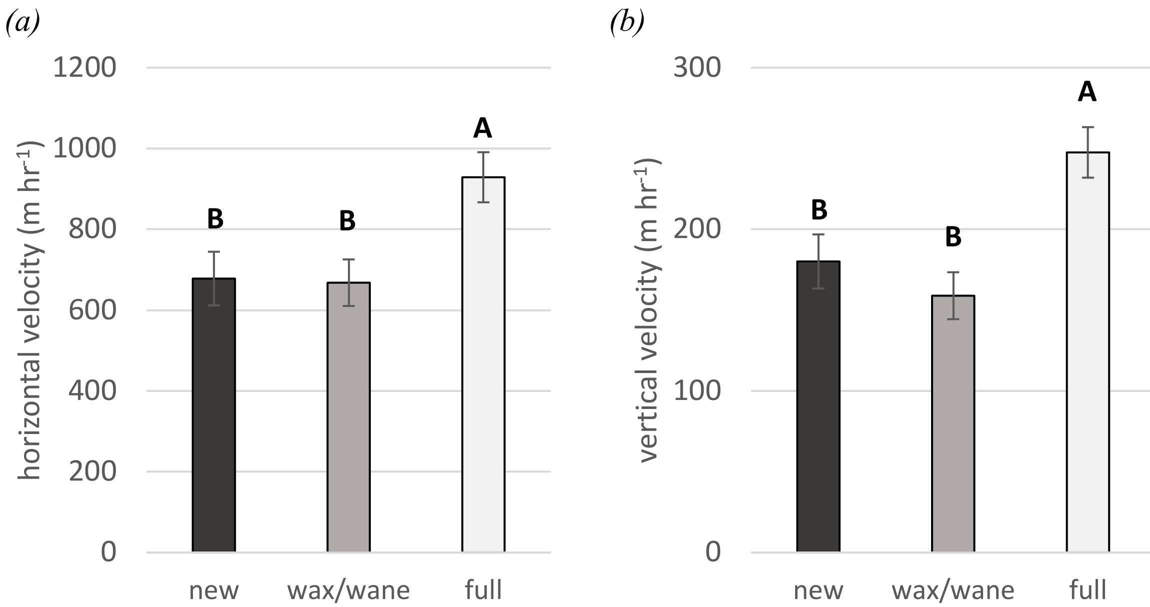

Figure 3. Male horizontal (a) and absolute vertical (b) mean velocities +/- SE plotted against moon phase. Bars with the different letters are significantly different (p < 0.05).

distribution was non-normal, the large dataset allowed for robust confidence of the one-way ANOVA. Post-hoc analyses were conducted with a Tukey HSD, when $p < 0.05$.

An optimized hot spot analysis was used to calculate the Gi* statistic, measuring the z-score of each point corresponding to other points as a relative clustering measure to indicate an affinity or habituation to a particular location (Getis and Ord, 1992, Love et al. 2015, Putra et al. 2016). Area utilized was estimated for the male and female by a minimum bounding convex hull around all GPS points.

RESULTS

Goat Locations

The male goat occupied a large area, spanning approximately 550 hectares and ranging in elevation from 223-985 m a.s.l. over a 12-month period (Figure 1). In contrast, the area occupied by the female goat was much smaller, spanning only ~75 hectares in a 6-month period.

Diel Movements

The male goat's frequency distributions of horizontal and vertical velocities showed kurtosis with strong sharp peaks around zero and fat tails for the highest velocities (i.e., max_h 260 m hr^{-1} and max_v 60 m hr^{-1}) (Figure 2). Moreover, frequency distributions of vertical velocities were relatively symmetrical with low skewness ($-1 < s_{k2} < 1$). Mean and median horizontal and vertical movements were 3-times and 2-times faster during nocturnal periods, respectively ($p < 0.0001$).

Moon Phase Movements

Male goat movement varied between moon phases (Figure 3). Mean horizontal ($p = 0.003$) and absolute vertical movements ($p < 0.0001$) were significantly faster during the full moon phase compared to new and waxing/waning moon phases. The differences observed between diurnal and nocturnal movements were consistent across moon phases with no observed accentuation of differences in any of the moon phases (e.g., full moon).

Seasonal Movements

The male started within the female home range in Feb. 2015 and segregated to lower elevations in the spring and throughout the summer, eventually returning to the original location in late fall within the female's home range during the winter (Figure 4). The male goat exhibited significantly higher mean horizontal velocities in the spring and summer than fall and winter ($p < 0.0001$), and significantly higher mean absolute vertical velocities in the spring compared to other seasons ($p < 0.0001$) (Figure 5).

Movements Influenced by Rainfall Events

The frequency distributions of horizontal and vertical velocities binned by precipitation showed similar excess kurtosis (Figure 6). Horizontal ($p = 0.0001$) and absolute vertical movements ($p < 0.0001$) were significantly faster with no precipitation. Points with horizontal velocity 0-5 m hr^{-1} were 2.6 times greater when precipitation was recorded, while points with vertical velocity 0-1 m hr^{-1} were 2.9 times greater when precipitation was recorded.

Optimized Hot Spot Analysis

The male goat displayed a large number of grids identified as hot spots on the eastern edge of its home

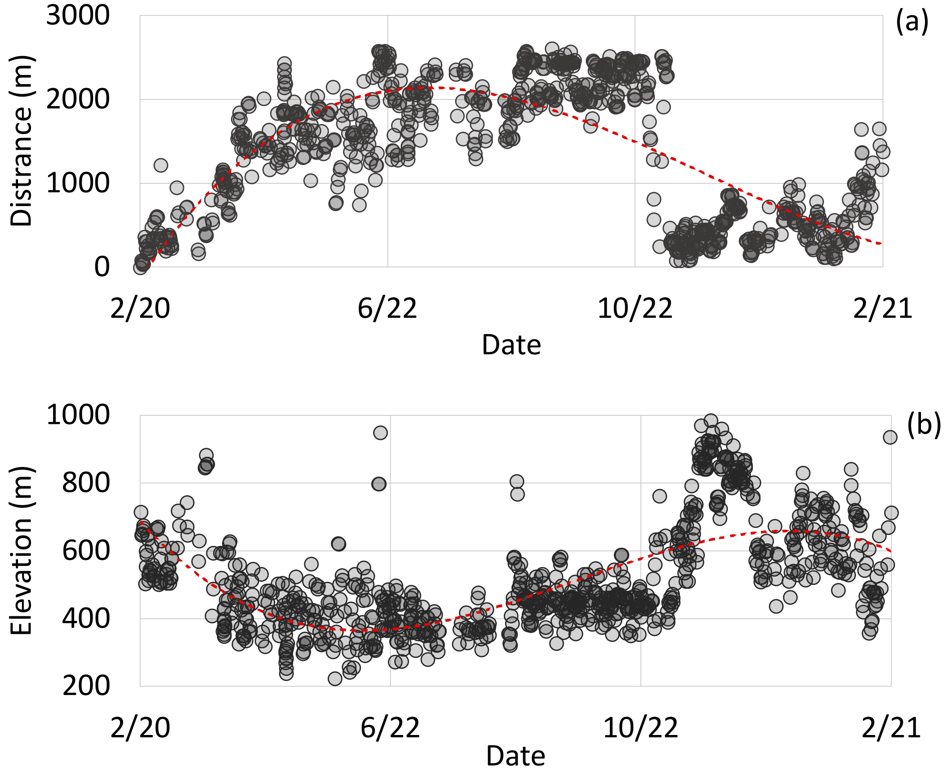

Figure 4. Male horizontal distance from initial collaring point (a) and elevation profile (b), displaying phenological trends. Second order polynomial displayed for visual purposes only.

range, during the fall months (Figure 7). The female range was much more confined and did not exhibit any hot spots or affinities to a particular location relative to its entire range, again within only a 6-month period.

DISCUSSION

This study supports utilizing GPS collar technologies to better inform control efforts protecting Hawaii's native ecosystems. Our basic GIS analyses brought novel, local insight to the spatial range and movement of feral goats influenced by day, moon phase, season, and precipitation. This tropical mesic island watershed exhibiting steep topography, isothermic ambient environment and likely ample food supply. Movement patterns described here were consistent or contrary to the behavior of goats and other prey species in other distinct habitat locations.

In this study both goats moved and rested/fed at all times of the diel period and probably did both within a typical 6-hr period regardless of the time of day. We hypothesized that feral goats would be more active during the day supported by other studies designating goats and other small ruminants as diurnal species (Piccione et al. 2008, O'Brien 1988, Shi et al. 2006). However, our data has showed greater activity at night, similar to nocturnal behavior of other animals, as described above (Clarke 1983, Kotler et al. 2010, Palmer et al. 2017, Penteriani et al. 2013). We speculate on the possibility that nocturnal movements could be due to pressures put on by feral dog packs known to roam this area.

The male goat also exhibited significantly greater activity during the full moon, which conflicts with other reports of prey activity during the darkest periods (e.g., new moon). Our data did not show the same crepuscular activities as reported by Sullivan et al (2016), which could be due to the comparatively coarse data frequency (data not shown). Many reports cited above suggest that moon phase is influential by its luminosity, exposing prey to predators (Clarke 1983, Kotler et al. 2010, Penteriani et al. 2013). Again, this could be further elucidated by the role of goats as prey if there are existing predatory pressures, yet to be determined.

Sexual segregation is the seasonal tendency of sexually dimorphic, polygynous ungulates to congregate in groups separated by sex, outside of the rutting period (Ahmad et al. 2017). The male goat in this study apparently showed sexual aggregation/segregation patterns with the female goat, suggestive of a winter rutting period. This data alone was inadequate to establish the reproductive cycles of female goats in this area. In Hawai'i, female breeding cycles may be year-round (Ohashi and Schemnitz 1987). Otherwise, they are known to be seasonally (i.e., short-day) polyestrous with breading cycles in the fall and winter (Fatet et al. 2011). This knowledge is critical to understanding the demographics and dynamics as it relates to managing populations below damaging thresholds. Furthermore, post-parturition if predictable, could be a vulnerability, exposing females trying to protect their kids, but unable to avert danger. This could be exploited in

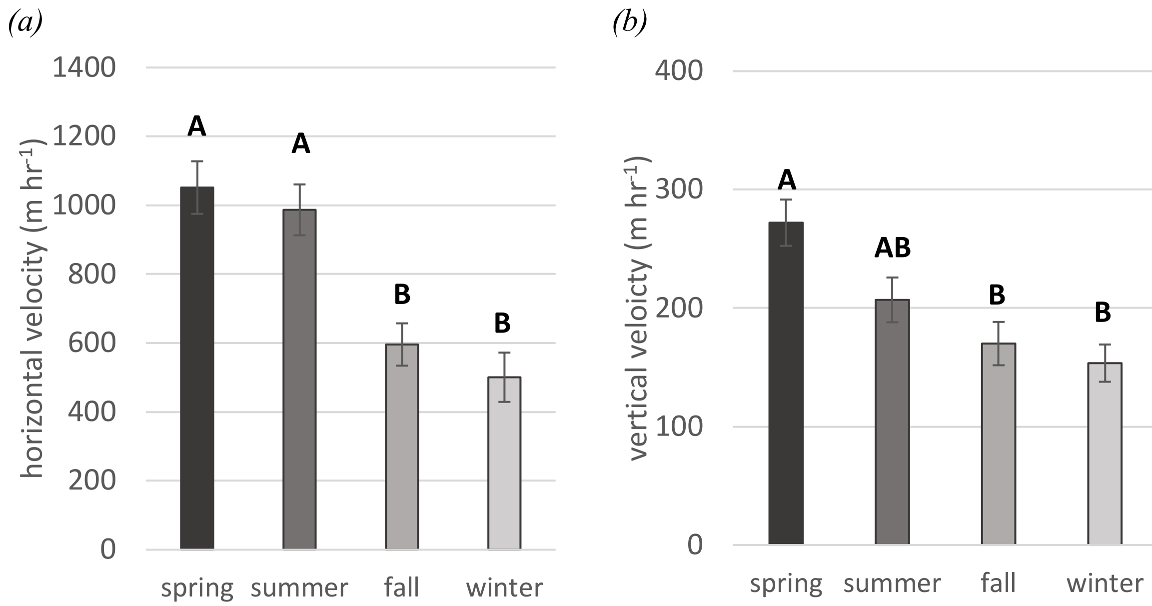

Figure 5. Male horizontal (a) and absolute vertical (b) mean velocities +/- SE plotted against season. Bars with the same letter are not significantly different (p <0.05).

culling efforts with evidence of seasonal aggregation, estrous cycles, and knowledge of breeding site habituation.

Goats in Hawai'i are adapted to the dry, mesic environments and less prevalent in wetter environments. There are anecdotes of goats' aversion to rainfall, which may be related to thermoregulation in preventing hypothermia (GISD 2018). This study supports this behavior evidenced by the reduced movements associated with any precipitation event. This may further explain reduced movements in the fall and winter months when cumulative precipitation is the greatest in this tropical Mediterranean climate.

Moving forward, management strategies to maintain this population below damaging thresholds would be well informed with a greater commitment to this long-term monitoring approach accumulating posteriori knowledge deciphering sexually distinct movement patterns, seasonal breeding cycles and possibly site habituation, over multiple generations. A single male and female is unlikely to be sufficient to broader interpretations in herd behavior. Many of the studies cited herein had 20-30 animals collared and split evenly between males and females. The coarse resolution of time (e.g., 6-hr intervals) was adequate for interpreting diel movements, but fine scale time resolution (e.g., 1-hr intervals) may be required for measuring crepuscular activities. This geographical approach in combination with better demographics will assist with better management decisions reducing goat impact to this important habitat.

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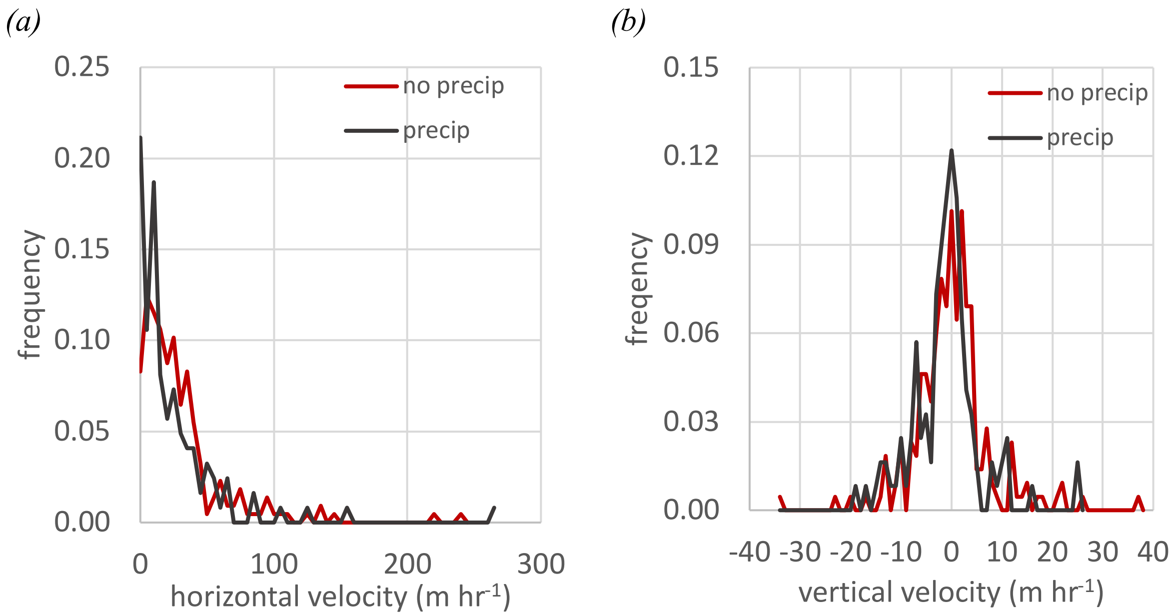

Figure 6. Male horizontal (a) and vertical (b) velocity histograms comparing periods of no precipitation against all other precipitation events (rates >0.0mm hr-1).

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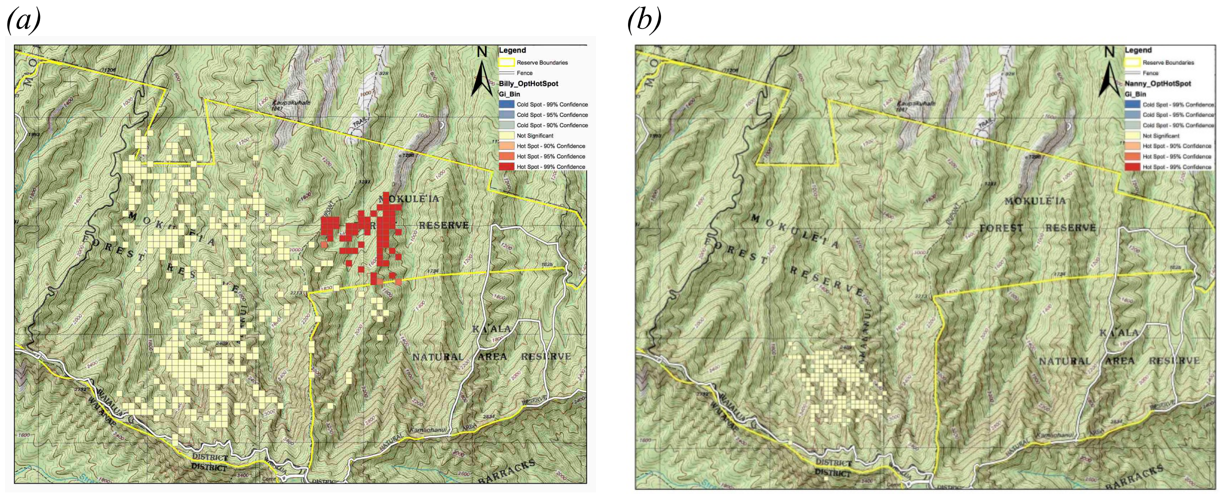

Figure 7. Hot Spot Analysis of male (a) and female distributions (b). Hot spots appear marked in red (p <0.05, confidence interval >90%).

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