

AN ABSTRACT OF THE THESIS OF

Roberta Swift for the degree of Master of Science in Wildlife Science presented on December 7, 2004.

Title: Potential Effects of Ungulate Exclusion Fencing on Displaying Hawaiian Petrels (*Pterodroma sandwichensis*) at Hawai'i Volcanoes National Park.

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Recently the National Park Service has proposed raising fence heights to exclude mouflon sheep (*Ovis montanus*) from conservation areas at Hawai'i Volcanoes National Park. Concern over previous mortality of Hawaiian Petrels (*Pterodroma sandwichensis*) due to collision with fences prompted this study to quantify the potential effects of raising fence heights on this critically endangered seabird. Avian perception and navigation capabilities were researched, and vision was judged to be the dominant sense that Hawaiian Petrels may use to detect and avoid fences. Previous studies and the techniques they used to assess the risk of bird collision with obstructions were also reviewed. In the current study, we used behavior to quantify the ability of Hawaiian Petrels to detect and avoid fences, and the relative collision risk of three different fence designs. We observed night-time flight behavior of Hawaiian Petrels using night vision goggles in a breeding colony display area for seven weeks during the summer of 2003. We recorded petrel behavior around three simulated fence designs: (1) a 1.2-m hogwire fence, (2) a 1.8-m hogwire fence, and (3) a 1.8-m hogwire fence with white flagging added for visibility. We also recorded behaviors during a control observation period, when no fence was present, to represent the natural flight behavior of the birds. Fences used during the trials were made of surrogate materials to mimic hogwire fencing, including 13-cm square fabric netting and padded bamboo poles that would not harm the birds, should they collide with them. Because collisions with fences

were rare, we quantified the risk of petrels colliding with each simulated fence by counting the number of passes attempted below fence height, as evidenced by late avoidance behaviors and collisions. We compared the proportions of late avoidance behaviors and collisions among fence types to investigate the effects of fence type on fence strike risk. Counts during the control period were a measure of the proportion of passes when birds were at risk of colliding with fences of different heights during unobstructed flight. Hawaiian Petrels were significantly more likely to attempt to pass at heights above ground level below fence height when no fence was present (during the control period) than when the 1.2-m fence or 1.8-m simulated fences were present. This result indicates that although petrels flew below fence height when no fence was present, they were able to detect and avoid 1.2-m and 1.8-m fences in their flight path. However, one petrel did collide with the simulated 1.2-m fence on a foggy night, suggesting that Hawaiian Petrels may have more difficulty avoiding fences during poor visibility conditions. There was no significant difference in the likelihood of Hawaiian Petrels to exhibit late avoidance behaviors and collisions between the two fence heights. Therefore, the 1.2-m and 1.8-m simulated fences apparently posed similar fence strike risk to birds. There was a suggestive difference in the likelihood of petrels to exhibit avoidance behaviors and collisions between flagged and unflagged fences. This suggests that Hawaiian Petrels were able to detect and avoid flagged fences at greater distances, possibly reducing fence strike risk. We also investigated the effect of fence orientation relative to slope on petrel avoidance behavior. Fence orientation had no detectable effect on the proportion of late avoidance behaviors and collisions exhibited by displaying Hawaiian Petrels. However, investigations into the effect of fence orientation may be more appropriate when studying behavior of petrels commuting to or from breeding colonies rather than that of displaying birds following circuitous flight paths. In conclusion, fences help to protect essential habitats of native species and pose little risk to displaying Hawaiian Petrels. Fence strike risk for this critically endangered species may be

further minimized by adding visible materials, such as white flagging, during construction. The methods developed in this study could be used to test fence designs proposed for future construction, particularly designs that would exclude both introduced predators and feral ungulates from Hawaiian Petrel breeding habitat.

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Potential Effects of Ungulate Exclusion Fencing on Displaying Hawaiian
Petrels (*Pterodroma sandwichensis*) at Hawai'i Volcanoes National Park

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TABLE OF CONTENTS

	<u>Page</u>
CHAPTER 1. INTRODUCTION	1
1.1. BACKGROUND.....	1
1.2. LITERATURE CITED	12
CHAPTER 2. POTENTIAL EFFECTS OF UNGULATE EXCLUSION FENCING ON DISPLAYING HAWAIIAN PETRELS (<i>Pterodroma sandwichensis</i>) AT HAWAI'I VOLCANOES NATIONAL PARK	18
2.1. ABSTRACT	18
2.2. INTRODUCTION	19
2.3. MATERIALS AND METHODS	23
2.3.1. Study Site	23
2.3.2. Site selection and pilot study	24
2.3.3. Field Methods: fence trials	25
2.3.4. Statistical methods	32
2.4. RESULTS	37
2.4.1. Hawaiian Petrel display behavior and reactions to fences...	37
2.4.2. Ability to detect and avoid 1.2-m fences	44
2.4.3. Ability to detect and avoid 1.8-m fences	45
2.4.4. Effect of fence type	46
2.4.5. Effect of orientation	48
2.4.6. Flagging color visibility	49
2.5. DISCUSSION	49
2.5.1. Hawaiian Petrel display behavior	49
2.5.2. Study limitations	54
2.5.3. Conservation implications	56
2.6. LITERATURE CITED	58

TABLE OF CONTENTS (Continued)

	<u>Page</u>
CHAPTER 3. CONCLUSIONS AND SYNOPSIS	60
3.1. ABILITY OF HAWAIIAN PETRELS TO AVOID FENCES	60
3.2. CONSERVATION AND MANAGEMENT IMPLICATIONS	61
3.3. SUGGESTIONS FOR FUTURE RESEARCH	61
BIBLIOGRAPHY	63
APPENDIX. Weather data	70

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
2.1. Map of the study site on Mauna Loa, Hawai'i Island, Hawai'i	24
2.2. Illustration depicting design of experimental zones during 1.2-meter simulated fence treatment and control nights	30
2.3. Illustration depicting design of experimental zones during 1.8-meter simulated fence treatment and control nights	31
2.4. Graph of maximum, minimum and mean total passes by displaying Hawaiian Petrels observed during each four-night sampling block.....	33
2.5. Scatter plot of the time after sunset of first Hawaiian Petrel detections at the study site between May 26 and July 31, 2003.....	38
2.6. Figure 2.6. Line graph depicting the proportion of avoidances and collisions relative to total passes by displaying Hawaiian Petrels for three simulated fence types, May 26 - July 31, 2003. Data points are labeled according to the order treatments were presented. 1.8mF denotes the flagged 1.8-m fence.....	40
2.7. Graphic summarizing the proportion of passes at each simulated fence height during control nights, no fence in place (<i>n</i> =443 passes)	43

LIST OF FIGURES (Continued)

<u>Figure</u>	<u>Page</u>
2.8 Box plot of the sample logits of the proportions (P) of Hawaiian Petrels attempting to pass below 1.2 m during the control period and the 1.2-m simulated fence treatment	44
2.9. Box plot of the logits of the proportions (P) of Hawaiian Petrels attempting to pass below 1.8-m during the control period and the 1.8-m simulated fence treatment	46
2.10. Box plots of the logits of the proportions (P) of Hawaiian Petrels attempting to pass below fence height for the three simulated fence designs.....	48
2.11. Box plots of the logits of the proportions (P) of Hawaiian Petrels attempting to pass below fence height as a function of orientation of simulated fences	49

LIST OF TABLES

<u>Table</u>	<u>Page</u>
2.1. Observed behaviors of displaying Hawaiian Petrels near three simulated fence types. % of avoidances is a percentage of total passes during that treatment	39
2.2. Passes of displaying Hawaiian Petrels observed passing through two heights above ground level during the control period , when no simulated fence was present	42
2.3. Results of two pairwise comparisons between the control and each of the 1.2-m and 1.8-m simulated fences, including estimates of the fixed effect of fence presence, standard errors, p-values, likelihood ratios and 95% confidence intervals.....	45
2.4. Results of two pairwise comparisons between three simulated fence types, including parameter estimates for the fixed effect of fence type on Hawaiian Petrel behavior, standard errors, 1-tailed p-values, likelihood ratios, and 95% confidence intervals.....	47

LIST OF APPENDIX TABLES

<u>Table</u>	<u>Page</u>
Appendix Table 1. Precipitation codes	71
Appendix Table 2. Nightly summary of weather data	72

Potential Effects of Ungulate Exclusion Fencing on Displaying Hawaiian Petrels (*Pterodroma sandwichensis*) at Hawai'i Volcanoes National Park

CHAPTER 1. INTRODUCTION

1.1. BACKGROUND

The Hawaiian Petrel or 'Ua'u (*Pterodroma sandwichensis*; formerly Dark-rumped Petrel, *Pterodroma phaeopygia sandwichensis*; AOU, 2001), a seabird species listed as endangered under the U.S. Endangered Species Act, has suffered a drastic decline in numbers as a result of human influence. Hawaiian Petrels were prehistorically common in Hawai'i (Olson and James 1982b), but were thought to be extirpated from Hawai'i Island until they were recently rediscovered on Mauna Loa (Conant, 1980). The largest population of Hawaiian Petrels persists on Mau'i at Haleakala National Park (Hodges and Nagata, 2001; Simons, 1985), but even this population is at risk because of anthropogenic threats. The decline of Hawaiian Petrel populations likely began before Europeans arrived in Hawai'i. These ground nesting seabirds were a delicacy to Hawaiians (Athens *et al.*, 1991) and were also preyed upon by Polynesian rats (*Rattus exulans*), dogs (*Canis familiaris*), and Polynesian pigs (*Sus scrofa*), which were brought to the islands by Polynesians (Simons and Hodges, 1998). Polynesians also may have altered some nesting habitat due to agriculture (Olson and James, 1982a; Cuddihy and Stone, 1990). Modern threats to Hawaiian Petrels include predation by introduced predators such as mongooses (*Herpestes auropunctatus*), rats (*Rattus* spp.), and feral cats (*Felis domesticus*; Hodges, 1994; Hodges and Nagata, 2001; Hu *et al.*, 2001). In addition, attraction to bright lights may lure fledglings off course, causing them to be stunned and fall prey to predators, or to collide with buildings, wires, tall vegetation and vehicles (Reed *et al.*, 1985; Telfer *et al.*, 1987).

Because Hawaiian plants and animals evolved in geographic isolation, they often lack defenses against introduced mammals and compete poorly with

introduced flora. Therefore, many conservation activities in Hawai'i focus on the removal or exclusion of harmful introduced species for the benefit of native organisms. Although most conservation goals benefit a variety of native species, management actions can be at odds if they have the potential to harm one species while protecting another.

Existing fences encircling subalpine habitat on Mauna Loa were originally built to exclude feral goats (*Capra hircus*) and pigs (*Sus scrofa*) and thus preserve native plant communities. Mouflon sheep (*Ovis musimon*), which were introduced to Hawai'i as a game animal, can easily clear existing 1.2-m park boundary fences, putting endangered plants at risk of intensive browsing. With the introduction and proliferation of mouflon in lands adjacent to Hawai'i Volcanoes National Park (HVNP), augmentation of existing fences became necessary to protect endangered plants. According to recent tests of fence designs, successful exclusion of mouflon requires raising fence heights to a minimum of 1.8 meters (Dan Goltz, Hawai'i Division of Land and Natural Resources [DLNR], pers. comm.; Howard Hoshide, HVNP, pers. comm.). Proposed fence construction to exclude mouflon sheep from high elevation conservation areas at HVNP has the potential to negatively affect the Hawaiian Petrel. Mortality of Hawaiian Petrels due to collision with fences 1.2 meters high has been documented (HVNP, unpubl. data), and it is unknown what effect raising fences to 1.8 m in order to exclude mouflon will have on these endangered seabirds.

Mortality of critically endangered Hawaiian Petrels due to collision with fences, although infrequent, has been documented in both Hawai'i Volcanoes National Park and Haleakala National Park (HNP) (C. Bailey, HNP, pers. comm.; HVNP, unpubl. data). Five Hawaiian Petrels have been found dead along fences at HVNP since the late 1980s; two were found during annual fence inspections and three were found opportunistically by biologists visiting subalpine areas. This count represents a minimum number because fence lines were not searched

regularly and systematically for carcasses, and scavengers may have removed some carcasses before they were discovered.

Hawaiian Petrel mortality due to fence collision is relatively minor compared with the number of petrels killed each year by feral cats in HVNP (Hu *et al.*, 2001; HVNP, unpubl. data). Since monitoring of Mauna Loa Hawaiian Petrel colonies began in 1993, 106 of the 145 Hawaiian Petrel carcasses (73%) found were attributed to feral cat predation (HVNP, unpubl. data). However, even seemingly minor sources of mortality such as collisions with fences could have serious effects on this already rare species if the population is unable to compensate for the losses (Bevanger, 1998). Because of their low reproductive rate and long lifespan, mortality of adult Hawaiian Petrels has the greatest potential to affect the population (Simons, 1984; Simons and Hodges, 1998). Although fence collision may not be a major limiting factor, it is a potential additive source of mortality for this critically endangered species that requires the attention of managers.

Construction of fences to exclude mouflon from conservation areas on Mauna Loa is necessary to protect endangered plant populations. However, it is not likely that installation of typical ungulate exclusion fences would directly benefit Hawaiian Petrels. Feral ungulates have been blamed for trampling burrows of ground nesting seabirds in Madeira (Zino, 2001) and at Haleakala National Park (Cathleen Bailey, HNP, pers. comm.), where Hawaiian Petrels excavate nest burrows mainly along steep crater walls among boulders and in erosional debris associated with bedrock (Simons 1983). In contrast, most petrel nests on Mauna Loa have been found in lava tubes in hard pahoe-hoe lava fields and are unaffected by trampling (Hu *et al.*, 2001; HVNP unpubl. data). Because ungulates do not typically destroy Mauna Loa petrel burrows, a fence that excludes mouflon will not directly benefit Hawaiian Petrels and may have a detrimental effect if birds collide with it.

A need clearly existed to better understand Hawaiian Petrel flight behavior and the species' interactions with fences. In the absence of these data, land managers could not proceed with urgently needed fencing projects because of the uncertain risk to petrels. This study examined petrel reactions to fences in order to investigate Hawaiian Petrel flight behavior and to determine whether raising park boundary fence heights would adversely affect petrels. The goal of this research was to better understand the ability of Hawaiian Petrels to detect and avoid fence structures in their flight path. To achieve this goal, we established three objectives. Our first objective was to determine if Hawaiian Petrels were able to detect and avoid 1.2-m and 1.8-m simulated fences. Secondly, we wanted to determine whether Hawaiian Petrels were better able to detect and avoid certain fence designs and materials. Our third objective was to determine if fence orientation affected the ability of Hawaiian Petrels to detect and avoid fences.

The ability of birds to avoid collision with man-made obstacles depends on their agility, morphology, experience, and ability to detect obstacles in low light conditions. Hawaiian Petrels are quite agile, as one of the gadfly petrels (genus *Pterodroma*), a group that has lower wing loading and therefore a more aerial mode of life than other procellariiform seabirds (Warham, 1977). However, compared to other birds they have narrow wings that are relatively small for their body size, and are therefore moderately susceptible to collision with structures in their path (Bevanger, 1998). Hawaiian Petrels on Kaua'i were better able to avoid power lines than Newell's Shearwaters (*Puffinus auricularis newelli*), perhaps because they moved during the crepuscular period when light was still available. The flight of Hawaiian Petrels was more "buoyant" than that of Newell's Shearwaters, allowing them to avoid wires, in one case nearly stopping in mid-air to avoid a collision (Cooper and Day, 1998).

All age classes of Hawaiian Petrels may be susceptible to fence collision although young birds may have a higher risk of colliding with obstacles because they have not yet learned to avoid them (Henderson *et al.*, 1996; Savereno *et al.*,

1996). Fledgling petrels may be at greater risk of collision with fences on their first flight seaward from mountain breeding colonies because they are not practiced flyers and may not yet be familiar with the landscape.

It is not fully understood how Hawaiian Petrels navigate at night or how they perceive obstacles in their path. Many birds can detect infrared (Martin, 1990) and ultraviolet wavelengths (Dalton, 2004) but sensitivity to ultraviolet and infrared wavelengths has not been documented for Hawaiian Petrels. Nocturnally active birds, such as Hawaiian Petrels, probably rely on a variety of sensory cues (Martin, 1990). Procellariiform seabirds may navigate using a combination of olfaction, vision, and knowledge of local topography (Brooke, 1988). Vision is used in burrow location by some shearwaters (Brooke, 1978; James, 1986). Most Hawaiian Petrel movements to and from breeding colonies occur during the crepuscular period, when some light is available (Cooper and Day, 1998). Light is also more available in the open habitats that Hawaiian Petrels frequent, even at night, because there is no dense canopy to obscure natural light from the moon and stars (Martin, 1990). The fact that Hawaiian Petrels are active during the crepuscular period, and fly over open and sparsely vegetated lava fields to find their nests, suggests that they may use vision to navigate.

The visual capabilities of Hawaiian Petrels have not been specifically assessed, but in general, procellariiforms have lower visual acuity than granivorous birds such as pigeons (Martin and Brooke, 1991; Hayes and Brooke, 1990). It is unknown whether Hawaiian Petrels possess any of the adaptations associated with activity at lower light levels, such as large pupil and eye size, large accommodative ability, a flat cornea, and a thick retina packed with visual cells or oil droplets (Day *et al.*, 2003). Procellariiform seabirds lack the long tube-shaped eyes that evolved in owls to maximize image brightness and image size at low light levels (Martin, 1990), but some procellariiform seabirds may possess other adaptations that allow them to see at night. Martin and Brooke (1991) found that the eyes of the Manx Shearwater (*Puffinus puffinus*), another seabird that returns to

its nest after dark, possess adaptations in eye structure and image brightness that facilitate vision at night. These adaptations, however, do not proffer night vision capabilities as advanced as those in other nocturnal animal species. Image brightness in the eyes of Manx Shearwaters is more similar to diurnal animals such as starlings (*Sturnus vulgaris*), pigeons (*Columba livia*), and humans than it is to nocturnal animals such as mice (*Mus musculus*), rats (*Rattus* spp.), cats (*Felis domesticus*), and owls (Order *Strigiformes*). Focal length and image brightness in Manx Shearwaters are only 1.5 times that of a pigeon at the same aperture (Hughes, 1977). Therefore, image brightness of Manx Shearwaters is not maximized, evolutionarily, for night time conditions (Martin and Brooke, 1991). However, the optical structure of Manx Shearwaters is similar to nocturnal species with respect to the ratio of anterior focal length to axial length (Pettigrew *et al.*, 1998) and the ratio of lens to corneal power. These adaptations would allow for some visually guided behaviors at night, especially in open conditions (Martin, 1991). Hayes and Brooke (1990) discovered a concentric area of high ganglion density in the Kerguelen Petrel (*Pterodroma brevirostris*), a gadfly petrel, similar to an elongated area in other procellariiforms studied. These areas probably have little to do with night vision, but may be motion sensitive, alerting birds to presence and movement of prey on or below the surface of the water, or maintaining visual control in birds following a low and fast flight path over the sea surface (Hayes *et al.*, 1991). Manx Shearwaters, which are active in open habitats where there are higher light levels and fewer obstacles to avoid, may not need to be as highly adapted as strictly nocturnal species that occur in closed habitats, such as beneath a forest canopy (Martin, 1991; Martin, 1990). Like Manx Shearwaters, Hawaiian Petrels are active at night in open habitats, and may similarly be moderately adapted to low light conditions.

Procellariiform seabirds probably do not navigate using vision alone (Billings, 1968). Olfaction is a highly developed sense (Bang and Cobb, 1968; Clark *et al.*, 1993; Cunningham *et al.*, 2003) and procellariiforms may use odors to

locate prey, to navigate (Cunningham *et al.*, 2003; Hutchinson and Wenzel, 1980; Nevitt, 2000; Nevitt and Haberman, 2003) and to find their individual nest burrows (Grubb, 1974; Bonadonna *et al.*, 2001; Bonadonna and Bretagnolle, 2002; Bonadonna *et al.*, 2003). As a member of the family Procellariidae, Hawaiian Petrels may use a similar combination of senses to locate breeding colonies and their individual burrows, while avoiding collisions with trees, rocks, and other obstacles.

In addition to vision and olfaction, seabirds may use echolocation to navigate to nest burrows (Grubb, 1974). It has been hypothesized that shearwaters use echolocation to locate nesting burrows (Wink *et al.*, 1980; in Martin, 1990; Lockley, 1969; cited in Brooke, 1978), although no supporting evidence is generally lacking (D. Ristow, pers. comm.). Ranft & Slater (1987) found that ultrasonic calls were absent from night-flying Storm Petrels (*Hydrobates pelagicus*), but lack of ultrasonic calls does not indicate that these birds are incapable of echolocation. Oilbirds (*Steatornis caripensis*) and some swiftlets (*Collocalia* spp. and *Aerodramus* spp.) have been documented as capable of echolocation using low frequency calls within the range of human hearing (Cranbrook & Medway, 1965; Fullard, 2003; Griffin, 1953; 1974; Medway, 1959; Novick, 1959; Price *et al.*, 2004) rather than the high-frequency ultrasound used by bats (Lee *et al.*, 1992). Griffin (1969) surmised that migrating birds may use ground echoes of low frequency flight calls to facilitate orientation. It is possible that Hawaiian Petrels do the same.

The frequency of the sound emitted determines the scale at which items can be detected by echolocation; the higher the frequency of the vocalization, the more detail can be detected. Using high frequencies of 10 to 160 kHz, bats can detect and avoid very small objects. The Pallid Bat (*Antrozous pallidus*) can avoid vertical wires 0.3 mm in diameter using frequencies from 30 to 60 kHz (Barber *et al.*, 2003). The Trident Leaf-nosed Bat (*Asellia tridens*), capable of call

frequencies over 100 kHz, can avoid wires as thin as 0.065 mm (Gustafson & Shnitzler, 1979; Obrist *et al.*, 1993).

In contrast, birds use low frequencies to echolocate and therefore can not discern fine spatial detail through echolocation. Swiftlets use low frequencies mainly between 2 and 10 kHz (Coles *et al.*, 1987; Cranbrook and Medway, 1965; Medway, 1959; Fullard *et al.*, 1993). Swiftlets have been documented as capable of detecting objects between 6 and 20 mm in diameter. The Grey Swiftlet (*Aerodramus spodiopygius*) was able to avoid 20 mm diameter aluminum rods (Smyth and Roberts, 1983). The Mountain Swiftlet (*Collocalia hirundinacea*) consistently avoided 10-mm diameter rods using 2 to 7.5 kHz vocalizations that included some components above 10 kHz (Fenton 1975). The Uniform Swiftlet (*Aerodramus* [formerly *Collocalia*] *vanikorensis*) regularly detected iron rods as thin as 6.3 mm in diameter using vocalizations that were most intense between 4.5 and 7.5 kHz but that ranged from 2 to 16 kHz (Griffin and Suthers, 1970). The frequency range of Oilbird vocalizations is even lower than that of swiftlets. Frequencies range from 1 to 15 kHz, but dominate in the 1.5 to 2.5 kHz range while echolocating. Oilbirds have the ability to avoid disks between 10 and 20 cm in diameter (Konishi and Knudsen, 1979). Because Oilbirds and swiftlets use low frequencies in echolocation, they can only detect relatively large objects.

Visual inspection of sonograms shows that the frequency range of Hawaiian Petrel vocalization is similar to Oilbirds and is limited to between 1 and 5 kHz (Simons & Hodges, 1998). Therefore Hawaiian Petrels should have comparable acuity to Oilbirds, in their ability to detect objects through echolocation, if echolocation is used. If Hawaiian Petrels were able to echolocate, they might be able to detect items as small as 10 cm, similar to Oilbirds. Metal fence posts of the kind used in fence construction in Hawai'i Volcanoes National Park are approximately 4.5 cm wide and are therefore probably too small to be detected through low-frequency echolocation. If Hawaiian Petrels do echolocate in order to avoid obstacles, it is unlikely that they would be able to detect fence

posts and mesh using this sense. Even birds that use echolocation may supplement it with other senses. Both swiftlets and Oilbirds orient visually in good light, using echolocation only when light is not available (Griffin, 1974; Novick, 1959). It is possible that Hawaiian Petrels use a similar combination, augmenting vision with echolocation to detect large objects during low light conditions. Hawaiian Petrels usually fly silently to their nests (Simons and Hodges, 1998) calling only occasionally on their way to breeding colonies (pers. obs.). Therefore, vision and olfaction are probably more dominant senses than echolocation during transit to and from breeding colonies.

No previous studies have attempted to quantify the reaction of Hawaiian Petrels to fences, probably because certain aspects of their biology make them difficult to observe. Hawaiian Petrels are pelagic seabirds and come to land only for breeding activities. From February to October, breeding petrels return to the colony between foraging bouts at sea to find mates, incubate eggs, and feed young (Simons and Hodges, 1998). Petrels are difficult to detect in flight because of high flight speeds in excess of 50 km/hour, and because they move onshore after sunset and commute to and from their breeding colonies during the crepuscular period and throughout the night (Day and Cooper, 1995). Non-breeding or pre-breeding birds also visit the colony in early to mid-summer to conduct nocturnal aerial flight displays in a central location for the purpose of courtship and pair bonding. Displays are characterized by raucous vocalizations and circuitous high-speed flights by single, paired, or small groups of birds (pers. obs.; Simons and Hodges, 1998). Actively breeding Hawaiian Petrels, in contrast, do not participate in aerial displays, but fly directly and silently to their nests, only occasionally calling from their burrows (Simons, 1985).

Hawaiian Petrels are also difficult to observe because they are sparsely distributed across the landscape outside of high-activity display areas. On other islands, petrels commuting to and from nesting colonies may concentrate along topographical features such as valleys and mountain ridges, which they appear to

follow to the nesting colonies (Day and Cooper, 1995). Pigeons have been documented following roads and highways back to their roosts (Davies, 2004) and it is possible that Hawaiian Petrels use similar landmarks. On one occasion, Hawaiian Petrels were seen flying overhead along the Mauna Loa Strip Road that climbs the southeast flank of Mauna Loa (HVNP, unpubl. data). In recent surveys on Mauna Loa, Hawaiian Petrels and Band-rumped Storm-Petrels (*Oceanodroma castro*) have been documented flying along lava flows and volcanic rift zones (HVNP, unpubl. data). However, concentrated and distinct flight corridors are not known on Mauna Loa. Therefore, we chose to observe petrel behavior where they congregate in a known display area. Although this restricts our scope of inference to displaying petrels, knowledge of petrel display behavior around fences is valuable. Fences passing near or through display areas would present an elevated risk of fence strikes relative to fences built outside display areas because of the increased petrel activity in these areas.

In addition to the cryptic nature of Hawaiian Petrels, an additional study design challenge was the need to quantify fence strike risk without harming these critically endangered birds. Previous research examining the effect of fences on birds assessed collision risk by counting carcasses along fence lines (Baines and Andrew, 2003; Baines and Summers, 1997; Summers, 1998). Carcass searching is also a common and accepted technique used to examine collision hazard at power lines (Bevanger, 2000; Henderson *et al.*, 1996; Rusz *et al.*, 1986; Morkill and Anderson, 1991). Carcass retrieval is not a practical way to quantify Hawaiian Petrel fence strikes at Hawai'i Volcanoes National Park because of the long fence lengths involved (~35 km), the remoteness of the area, and the rarity of the focal study species. Previous studies have combined carcass searching with behavioral observations to assess bird strike risk at power lines (Henderson *et al.*, 1996; Morkill and Anderson, 1991; Savereno *et al.*, 1996). Cooper and Day (1998), for example, paired carcass searches with observations of passing Newell's Shearwaters and Hawaiian Petrels as they crossed power lines on Kaua'i. When

observing bird behavior around actual utility structures, however, birds may be injured or killed by collision with the structure.

In order to minimize risk to Hawaiian Petrels, we chose to observe their behavior around simulated ungulate fences constructed of surrogate materials that would not harm the birds should they collide with them. Many of the techniques used in previous observational studies could then be applied to examine the reactions of Hawaiian Petrels to these test fences. The most direct way to quantify the risk of petrel fence strikes for petrels would have been to count the number of Hawaiian Petrels colliding with fences. However, based upon a pilot study conducted in 2002, we knew that collision with observed structures would be a rare event and would provide very few data (HVNP, unpubl. data). Similar to previous studies at power lines, we instead recorded the reactions of Hawaiian Petrels to fences in order to assess their ability to detect and avoid them (Henderson *et al.*, 1996; Morkill and Anderson, 1991; Saverno *et al.*, 1996). We counted late avoidance behaviors following Henderson *et al.* (1996) and used the proportion of late avoidances relative to the total number of passes by petrels to assess the ability of petrels to detect and avoid fences. Presumably, fewer late avoidances should occur in response to a more detectable fence because birds would detect and avoid the fence at greater distances.

Our goal for this study was to increase understanding of the flight behavior of Hawaiian Petrels around fences. Information on the ability of Hawaiian Petrels to detect and avoid fences will allow land managers to exclude mouflon sheep from conservation lands while minimizing negative impacts to a critically endangered seabird.

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CHAPTER 2. POTENTIAL EFFECTS OF UNGULATE EXCLUSION FENCING ON DISPLAYING HAWAIIAN PETRELS (*Pterodroma sandwichensis*) AT HAWAI'I VOLCANOES NATIONAL PARK

2.1. ABSTRACT

Recently the National Park Service has proposed raising fence heights to exclude mouflon sheep (*Ovis montanus*) from conservation areas at Hawai'i Volcanoes National Park to determine potential impacts of such fencing upon endangered Hawaiian Petrels (*Pterodroma sandwichensis*). We observed night-time flight behavior of petrels using night vision goggles in a breeding colony display area for seven weeks during the summer of 2003. We recorded petrel behavior around three simulated fence designs: (1) a 1.2-m hogwire fence, (2) a 1.8-m hogwire fence, and (3) a 1.8-m hogwire fence with white flagging added for visibility. We also recorded behaviors during a control observation period, when no fence was present, to represent the natural flight behavior of the birds. Because collisions with fences are rare, we quantified the risk of petrels colliding with each simulated fence by counting the number of passes attempted below fence height, as evidenced by late avoidance behaviors and collisions. Hawaiian Petrels were more likely to attempt to pass at heights above ground level below fence height when no fence was present (during the control period) than when the 1.2-m fence or 1.8-m simulated fences were present. This result indicates that although petrels flew below fence height when no fence was present, they were able to detect and avoid 1.2-m and 1.8-m fences in their flight path. However, one petrel did collide with the simulated 1.2-m fence on a foggy night, suggesting that fences may be more difficult to detect and avoid during low visibility conditions. There were no significant differences in the likelihood of Hawaiian Petrels to exhibit late avoidance behaviors and collisions between the two fence heights. Therefore, the 1.2-m and 1.8-m simulated fences apparently posed similar fence strike risk to birds. There was a suggestive difference in the likelihood of petrels to exhibit avoidance behaviors and collisions between flagged and unflagged fences. This

suggests that Hawaiian Petrels were able to detect and avoid flagged fences at greater distances, possibly reducing fence strike risk. Fence orientation had no detectable effect on the proportion of late avoidance behaviors and collisions exhibited by displaying Hawaiian Petrels. In conclusion, fences help to protect essential habitats of native species and pose little risk to displaying Hawaiian Petrels. Fence strike risk for this critically endangered species may be further minimized by adding visible materials, such as white flagging, during construction.

2.2. INTRODUCTION

This study was undertaken to determine if Hawaiian Petrels (*Pterodroma sandwichensis*) are able to detect and avoid fences of varying heights and designs. This subject was of particular interest because Hawaiian Petrels have been found dead along existing 1.2-m high ungulate exclusion fences in national parks in Hawai'i (Hawai'i Volcanoes National Park [HVNPN], unpubl. data; Cathleen Bailey, Haleakala National Park, pers. comm.). Although the number of documented fence strikes is low, mortality of this critically endangered species concerns National Park Service (NPS) and U.S. Fish and Wildlife Service (USFWS) biologists because populations have been decimated in Hawai'i (Hu *et al.*, 2001). Ungulate exclusion fences are a necessary management tool in Hawai'i to protect native plants from feral ungulates, and park boundary fence heights must be raised from 1.2-m to 1.8-m in order to exclude high-jumping mouflon sheep (*Ovis musimon*) from conservation areas. Information about the ability of displaying Hawaiian Petrels to detect and avoid fences would inform land managers about whether raising fence heights confers additional risks to Hawaiian Petrels.

Previous studies have monitored mortality and assessed behavior to quantify the risk of bird collisions with man-made structures. Some studies conducted carcasses searches along fence lines to assess the risk of bird strike at

fences (Baines and Andrew, 2003; Baines and Summers, 1997; Summers, 1998). Likewise, carcass searching has been used to examine collision hazard of power lines for birds (Bevanger and Broseth, 2001; Rusz *et al.*, 1986) although some have noted the limitations of this approach (Savereno *et al.*, 1996). Some authors have augmented carcass searches with behavioral observations of birds at power lines to assess powerline strike risk (Cooper and Day, 1998; Henderson *et al.*, 1996; Morkill and Anderson, 1991; Savereno *et al.*, 1996). Carcass searches were not a practical way to assess fence strike risk for Hawaiian Petrels in HVNP because of long fence lengths (~35 km), the rarity of collisions, the remoteness of the area, and the critically endangered status of the focal species of this study.

In the current study, we chose to use late avoidance behaviors as a measure of the ability of Hawaiian Petrels to detect and avoid fences. Cooper and Day (1998) similarly classified the behavior of Hawaiian Petrels and Newell's Shearwaters (*Puffinus auricularis newelli*) passing over power lines. They discovered that the number of these seabirds reacting to power lines was low, but that it increased for birds passing closer to the lines. Henderson *et al.* (1996) used "late avoidance actions" to assess the risk of striking a power line for Common Terns (*Sterna hirundo*), and as a measure of a tern's need for last minute avoidance behavior. In order to quantify responses of birds to power lines, Savereno *et al.* (1996) recorded the behaviors and heights of birds traversing power lines. Morkill and Anderson (1991) quantified Sandhill Crane (*Grus canadensis*) reactions to power lines in order to estimate the effectiveness of marking power lines to reduce bird strike.

Similarly, we quantified the behavioral responses of Hawaiian Petrels to fences to assess the relative strike risk associated with different fence designs. This approach assumes that a bird that detects an obstruction farther away will begin to avoid it at a greater distance, resulting in gradual change of course to avoid the obstruction rather than drastic, last-second avoidance. Birds are likely to resort to a late avoidance in close proximity to an obstruction, when detection does

not occur until close range. This is a reasonable assumption based upon the observations of Morkill and Anderson (1991) who observed that Sandhill Cranes were more likely to gradually increase flight altitude at a distance from marked power lines than unmarked spans. Late avoidance actions in response to a fence, therefore, can be used to represent the potential risk of collision with a particular fence design. We also counted actual collisions as a measure of realized strike risk. In this study, the number of late avoidances and collisions with a fence represented the proportion of birds at risk of colliding with fences, out of the total number of passes. Those birds that altered their course near the fence by pronounced evasive maneuvers were likely those that did not detect the fence sufficiently in advance to avoid it using gradual avoidance. Gradual avoidances of fences could not be recorded because if they occurred they were outside the visual range of the observers and were considered not at risk of collision.

This study addressed three research objectives. The first objective was to determine whether Hawaiian Petrels avoided 1.2-m and 1.8-m fences in their path. It was unknown if petrels rarely collided with fences because they flew too high to encounter fences or because they were actively avoiding them. We tested two research hypotheses: 1) Did the proportion of passes attempted by displaying Hawaiian Petrels below 1.2-m above ground level differ when the 1.2-m fence was in place compared to the control period? (2) Did the proportion of passes attempted by displaying petrels below 1.8-m above ground level differ when the 1.8-m fence was in place compared to the control period? Attempts to pass below experimental height included late avoidance actions and collisions with the fence during treatments, as well as passes made by petrels below fence height during control periods.

The second research objective investigated whether petrel response differed between the three types of simulated fences. We sought to answer the following research question: Does the proportion of passes made by displaying Hawaiian Petrels at risk of collision with test fences differ among 1.2-m fencing,

1.8-m fencing, and 1.8-m fencing with flagging? We predicted that Hawaiian Petrels would be less likely to exhibit late avoidances or collision with 1.2-m fences than 1.8-m fences because they are lower and constitute less of an obstruction. We also predicted that Hawaiian Petrels would exhibit fewer late avoidance behaviors when encountering the 1.8-m simulated fence with flagging because the fence would be detectable at a greater distance than the unflagged 1.8-m fence. This hypothesis would be supported if the proportion of birds exhibiting late avoidance behaviors or collisions when encountering the 1.8-m fence was higher than for the other two fences. The simulated fence that caused the lowest proportion of avoidance and collision events would be the fence design that posed the least risk. Petrel behavioral data collected near the flagged 1.8-m fence could help managers assess whether adding high visibility materials to fences enables petrels to better avoid them. If so, managers could reduce the risk of fence strike by adding high visibility materials, especially in high risk areas.

The third objective of this study was to determine whether the response of Hawaiian Petrels differed between fences oriented parallel versus perpendicular to the slope. This objective sought to answer the following research question: Does the relative proportion of passes made by displaying Hawaiian Petrels below fence height differ between fences oriented perpendicular to slope contours and fences orientated parallel to slope contours? We predicted that the proportion of late avoidance behavior and collision events would differ between simulated fences built parallel to slope contours compared to those built perpendicular to slope contours. Prevailing wind direction and other local conditions at the study area might affect petrel flight behavior depending on the bird's direction of travel. The results of this comparison between fence orientations could inform land managers how orientation of fences with respect to slope affects fence strike risk.

2.3. MATERIALS AND METHODS

2.3.1. Study Site

This study was conducted at a Hawaiian Petrel courtship display area on the northeastern flank of Mauna Loa at 2530 meters elevation within HVNP (Figure 2.1). A display area is a central location where non-breeding or pre-breeding birds congregate to conduct nocturnal aerial flight displays for the purpose of courtship and pair bonding. Displays are characterized by raucous vocalizations and circuitous high-speed flights by single, paired, or small groups of birds (pers. obs.; Simons and Hodges, 1998). We chose to conduct the study at this site because Hawaiian Petrels are sparsely distributed on Mauna Loa, flight corridors are not known, and the concentrated activity of birds at display areas offered the opportunity for larger sample sizes. A maximum of 11 petrels were seen displaying at one time during the pilot study in 2002 but the actual number of birds using the display area was unknown. At Haleakala National Park (HNP) on Maui, displaying petrels often congregate along steep cliffs to take advantage of updrafts (Simons and Hodges, 1998), but at our site on Mauna Loa, there were no obvious topographical features that characterized the display location. The substrate typical of the study site is gently sloping weathered pahoehoe lava over 2,000 years old with sparse sub-alpine vegetation consisting of native shrubs and grasses (Hu *et al.*, 2001). The study site is over 5 km from the nearest road and can be reached only by foot and helicopter.

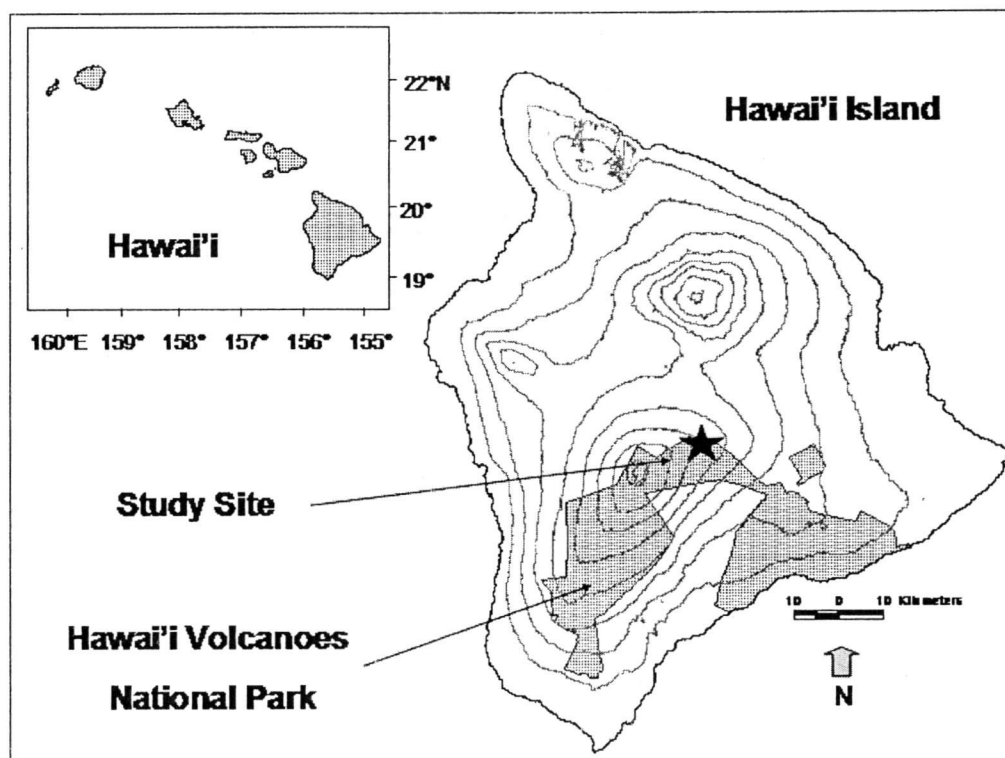


Figure 2.1. Map of the study site on Mauna Loa, Hawai'i Island, Hawai'i. Contour intervals 500 m.

2.3.2. Site selection and pilot study

In 2002, we gathered preliminary observations of Hawaiian Petrel behavior and their reactions to obstructions. During 12 nights, we observed displaying petrels using night vision goggles. We changed locations nightly until the approximate center of the display area was located. Once the area with greatest activity was found, a 15-m length of black fabric mesh was strung between black bamboo poles and the responses of birds to this simulated fence were observed during six nights. Support poles and mesh were loosely anchored so as to give way if a petrel collided with the structure. During four evenings when observations were made in the core of the display area, observers recorded a total of 345 total events when petrels passed over or reacted to the simulated fence. During the hundreds of observed passes, no birds were observed colliding with the

structure. Information from this pilot study, such as the location of the display area and the range of reactions by petrels to this structure, was used to develop the protocol for the main study.

Additional preliminary surveys were conducted during the first two visits to the study site in 2003 (May 6-8 and May 19-22). During the first visit, intended as a training and preliminary observation period, we observed petrel behavior informally for three evenings to pinpoint the area of highest display activity so that subsequent tests could be located there. We erected a simulated fence of black bamboo poles and mesh on the second and third survey nights in order to gain familiarity with petrel flight behavior and reactions to obstructions. This structure was dissimilar from the design used in the main simulated fence trials because materials used in that study were not yet available. Detailed data on the frequency of avoidance behaviors and the number of passes through the study area were not collected. During the second period of preliminary observations (May 19-22), we built test fences to resemble ungulate fences and observed petrel flight behavior around them in order to hone observation skills and develop data recording protocols.

2.3.3. Field methods: fence trials

Collection of data used in subsequent analyses began during the third visit to the study area (May 26-29, 2003). Ten-meter segments of 1.2-m and 1.8-m simulated fence were placed in the high activity center of the display area, and the behavior of displaying Hawaiian Petrels near the structures was recorded. Behavior near three treatment fences was recorded: a 1.2-m fence, a 1.8-m fence, and a 1.8-m fence with three horizontal strips of white flagging. The first two fence designs were selected in order to answer specific questions posed by the USFWS and the NPS regarding the potential effects of raising ungulate fence heights from 1.2-m to 1.8-m. The 1.8-m fence with flagging was selected in order to test a potential design that might make fences more detectable to petrels and

which could be used by NPS to mitigate the risk of collision with new 1.8-m fences. In addition to the three simulated fence treatments, petrel behavior was recorded during control periods, when no simulated fence structure was in place.

Each treatment fence was constructed of surrogate materials that mimicked ungulate fencing, but would not likely harm the petrels in the event of a collision. Bamboo poles, instead of metal fence posts, supported a 10-m length of black 13-cm square nylon knotted mesh (twine size #27, West Coast Netting, Kingman, Arizona). The nylon mesh had been painted gray, the color of ungulate fencing and pulled taut between the bamboo poles to minimize movement. Twine size and mesh size of the netting were similar to hogwire fencing, the current standard used for ungulate fencing. Strips of grey closed-cell foam were used to cover the six bamboo poles that supported the simulated fencing to mimic weathered grey metal t-posts used in ungulate fences, and to cushion petrels from potential injury in the event of a collision. Poles were supported by two-gallon plastic buckets filled with concrete and painted to match the lava substrate. An additional bucket at each end of the fence anchored lengths of twine tied to the top of each end pole for support. Twine tied between buckets and rocky protuberances along the sides of the fences provided further stability on windy nights. Simulated fences were erected at two orientations with respect to terrain slope contours at the study site: parallel and perpendicular. Orientation was alternated for each four-night block. Each test fence segment was deconstructed at the end of each evening to avoid potential entanglement of birds while observers were not present. Control periods consisted of observations of petrel flight passes through a vertical area 10 meters wide and 1.8 meters high bounded on its sides by two reference poles without intervening mesh. Reference poles were wrapped with white flagging tape to enhance their visibility.

We evaluated flagging color to assess the relative detectability of different colors of flagging during evening fog to assess which color could be best seen by petrels in poor visibility conditions, and hypothesized that dark blue would be

visible at the greatest distance because it would contrast most with fog. We tested white, dark blue, blue-and-white striped, yellow, and dayglo pink flagging tape (Forestry Suppliers, Inc., Jackson, Mississippi) by recording the maximum distance from which we could see each strip of flagging. Because we could not see flagging after dark with the naked eye, we chose to conduct this test during foggy twilight conditions

We observed reactions of Hawaiian Petrels to test fences placed in a location used for aerial courtship displays. We monitored the reactions of birds to three fence designs: a 1.2-m hogwire fence, formerly the standard for ungulate exclusion in HVNP; a 1.8-m hogwire fence, the new standard; and a 1.8-m hogwire fence with three equally-spaced (approximately 0.75 m apart) horizontal strips of white flagging placed along its length. Counts during these treatments were compared to counts of passes below experimental height during a control period, when no fence was present.

Bird behavior was observed near a single treatment fence per night during seven blocks of four consecutive nights. Within each block of nights, the test fences were presented in a random order to reduce bias, but the control night always preceded the three treatment nights so that the control would represent the most natural behavior of the birds. Each block of observation nights was separated by at least three nights when no observations were recorded in order to reduce habituation. Two blocks of four nights were scheduled during two consecutive work weeks, with the third consecutive week off from field sampling.

The same two observers concurrently observed and recorded behavior beginning one hour after sunset (approximately 20:00 HST) and continuing for two hours (until approximately 22:00 HST) between May 26 and July 29, 2003. We chose this time interval because previous observations at HVNP and HNP indicated that Hawaiian Petrels displayed from May to August (NPS, unpubl. data; Simons and Hodges, 1998) during the first few hours of the night (HVNP, unpubl. data). Simons (1985) noted that, whereas Galapagos Petrels (*Pterodroma*

phaeopygia) experience a second early morning peak of activity (Cruz and Cruz, 1990), calling by Hawaiian Petrels at HNP began one hour after sunset, peaking two to three hours later, and usually ended by 01:00. Radar surveys have documented a second early morning peak in movements by transiting Hawaiian Petrels (Day and Cooper, 1995). However, opportunistic listening throughout the night at our study site revealed no corresponding peak in display activity.

Each observer sat at an established position approximately 20 m perpendicular from the center of the test fence and counted birds flying toward her using 1x third generation night vision goggles (model AN/PVS-7; Ranger Joe's, Columbus, Georgia). All collisions and avoidance behaviors were recorded by one observer, regardless of direction of travel, because they were so rare. Observers alternated sides for each occurrence of a fence design, training their goggles on the fence and recording birds entering their field of view. Each observer placed the fence at the bottom of their field of view in order to maintain a uniform frame of vision. Observers counted the number of individual passes of Hawaiian Petrels that were attempted within the plane defined by the ground, the fence end poles, and the upper limit of the field of view of the night vision goggles. Observers recorded height and behavior of passing birds.

Flight behavior of birds was watched continuously for 25-minute periods separated by 5-minute breaks (Day and Cooper, 1995) and observations were recorded on hand-held microcassette recorders. During three weeks, recording equipment of one observer malfunctioned and observations were recorded by hand. Time was recorded in response to an interval alarm set at 5-min. intervals.

During treatment nights we recorded petrels passing above experimental height (fence height) and passes attempted below experimental height, which represented birds at risk of colliding with the fence. Passes attempted below fence height included collisions and late avoidance actions below fence level. Collisions were defined as any event when a bird physically collided with the mesh or support poles of a simulated fence. "Late avoidances" were drastic evasive

maneuvers made by petrels in close proximity (≤ 2 m) of the fence after approaching the fence below or near fence height. Because we counted only late avoidance behaviors within close proximity of the fence, we assumed that all behavioral responses were caused by the fence as did Day and Cooper (1995). We were unable to measure the actual distance at which birds initiated late avoidances, but we estimated that late avoidances occurred within two meters of the fence.

Because we did not observe petrels actually colliding with structures during the 2002 pilot study, we chose to count late avoidances as an indicator of the risk of petrel collision with each fence. Late avoidances included such behaviors as banking, fluttering, flaring, or turning abruptly before flying over or around the fence, or reversing flight direction after turning abruptly. We were conservative about which behaviors we counted as late avoidances in response to the fence and counted only avoidances within approximately two meters of the fence, because we did not want to count avoidances of rocks, bushes or other birds.

During treatment nights, we classified each pass by a petrel into one of two height categories: 1) attempts to pass at or below fence height as evidenced by late avoidance actions and collisions ($Area_b [A_b]$, Figures 2.2 and 2.3), and 2) passes above fence height up to the upper limits of our field of view approximately 8 m above ground level (A_a). An additional height class was used during field data collection and included birds passing within one fence height above each test fence, but these were lumped into A_a for analysis. For late avoidance behaviors, we also recorded the nature of each late avoidance and the height at which each bird approached the fence. The actual height of approaches and collisions below fence height were estimated to the nearest 15 cm.

During control nights, observers recorded the behavior and number of passes through an area corresponding to the exact location of the treatments presented during that block of nights. The control area was defined by two poles placed where fence end poles would have been. Passes through the area between

the poles below fence height represented birds at risk of colliding with fences, had a test fence been in place. Passes were assigned to four height categories: (1) passes below 1.2 m (A_f), (2) passes between 1.2 m and 1.8 m (A_e), (3) passes from 1.8 m to 3.6 m (A_d), and (4) passes from 3.6 m up to the upper limit of our field of view (A_c). The 1.8 to 3.6 m category and 3.6 to 8 m height category were used to describe petrel flight behavior during descriptive data summaries, but were pooled to represent passes above fence height for statistical analyses. The actual height above ground level of passes below fence height was also estimated and recorded. On a few occasions, petrels exhibited late avoidance reactions to the reference poles used during the control treatment. Late avoidance reactions to reference poles were counted as pass attempts below fence height during the control, and were classified according to their height above ground level. For statistical analyses, passes were lumped into two categories to reflect passes attempted below fence height and passes above fence height.

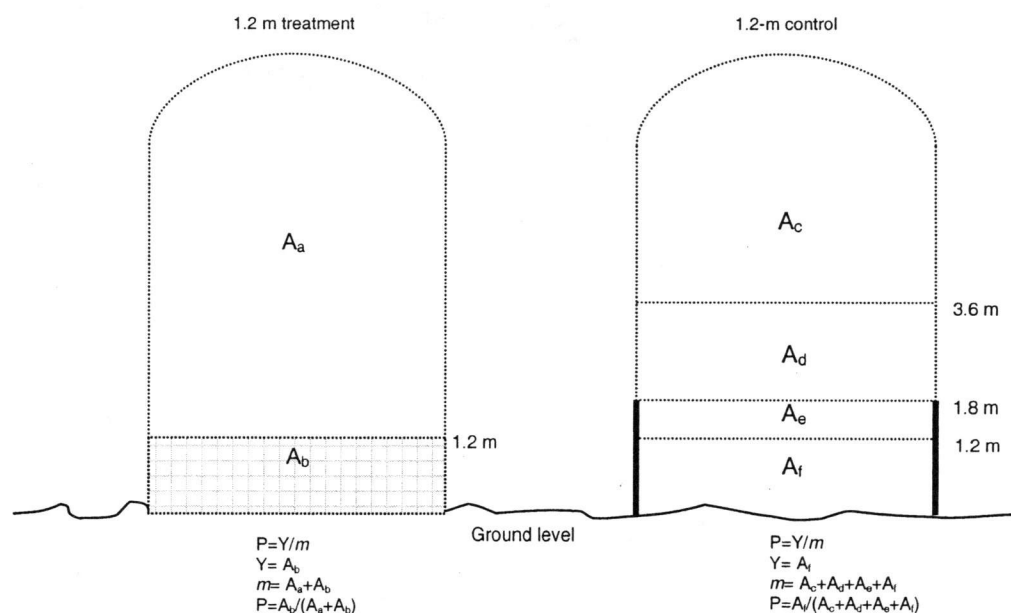


Figure 2.2. Illustration depicting design of experimental zones during 1.2-meter simulated fence treatment and control nights.

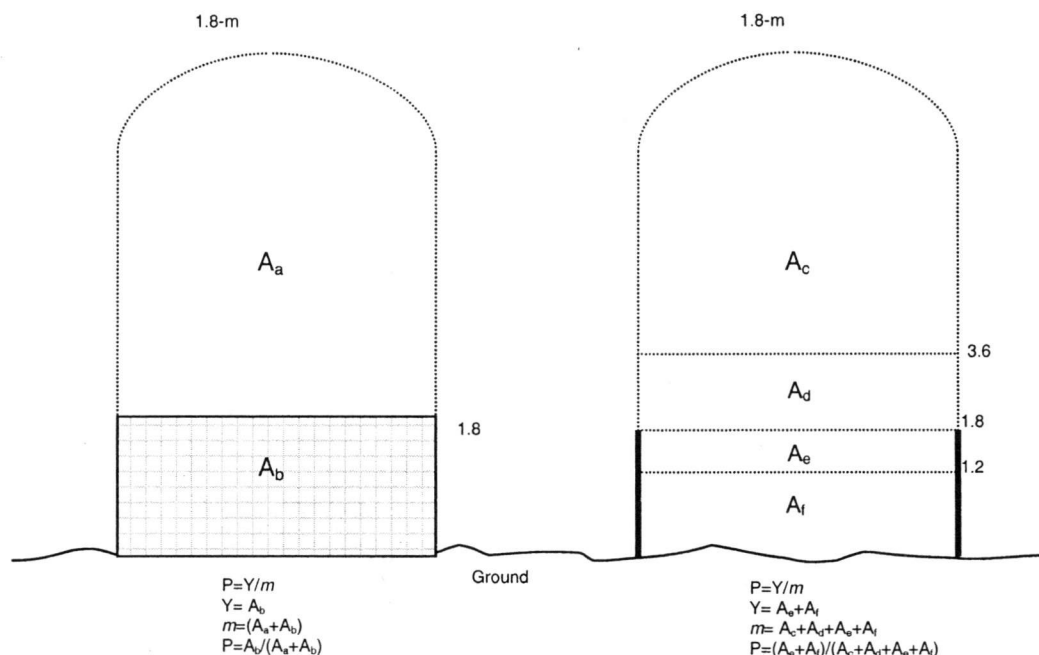


Figure 2.3 Illustration depicting design of experimental zones during 1.8-meter simulated fence treatment and control nights.

Weather was recorded during five-minute breaks at 30-minute intervals, at the beginning and end of each night time observation period, and whenever conditions changed considerably (Appendix A). Observers estimated percent cloud cover, measured wind speed using a hand-held anemometer, and estimated wind direction. Precipitation was documented on an eight-point scale ranging from no precipitation (1) to heavy downpour (8). Official sunset, moon phase and the time of moon rising or setting were also recorded.

All data were double checked at each stage of data transfer: from tape recorder (or field notes) to data sheet, and from data sheet to database. I could not, however, double-check three nights of one observer's recorded data because field recordings were accidentally taped over after initial transcription to data sheets.

2.3.4. Statistical methods

We summarized the percentage of petrels passing within the each height class during the control period in order to better understand unobstructed Hawaiian Petrel display behavior. In order to compare the frequency of flights between height classes, we divided the number of passes observed within each height class by the area represented by that height class and the total number of hours that observations were conducted during control periods. The resulting frequency of passes within each height class was then compared between height classes in order to understand at what height petrels most frequently flew.

We tested for differences between treatments and controls by comparing the proportion of passes at risk of colliding with fences relative to the total number of passes observed through the experimental area on each survey night. The resulting proportion was the response variable used to estimate the risk of bird strike for each treatment. The proportion was based on a sum of binary counts: avoidances, collisions, and passes below fence level were classified as passes attempted below fence height and therefore at risk of colliding with the fence; these passes were scored as a “1” for each occurrence. All other passes through the experimental area were scored as zeros. The counts of passes at risk of colliding with simulated fences (Y) were expressed as a proportion of the total number of passes (m) observed through the study area for each night. The response variable, P , therefore was the proportion of the total number of passes that were attempted through the plane of each fence (Y/m) (Figures 2.2 and 2.3). Seven replications of each treatment resulted in a sample size of seven proportions (P) for each treatment – one for each night that a particular treatment was presented.

It was important to express counts as proportions because of the high variability among nights in display activity at the study site. The total number of passes observed varied widely among nights, ranging from 10 to 166 passes per night (mean = 70.8, s.d. = 38.3; see Figure 2.4). In addition, on some nights, no

collisions or late avoidance actions were observed, yielding a response of zero over the total number of passes for that night. The sum of binary data resulting from the counts described above adequately follows a binomial distribution. Therefore, these data were modeled using logistic regression for binomial counts using the logit link (Ramsey and Schafer, 2002). In order to fit the data to the binomial model, raw data were transformed by taking the logit $[\pi=e^n/(1+e^n)]$ of each proportion.

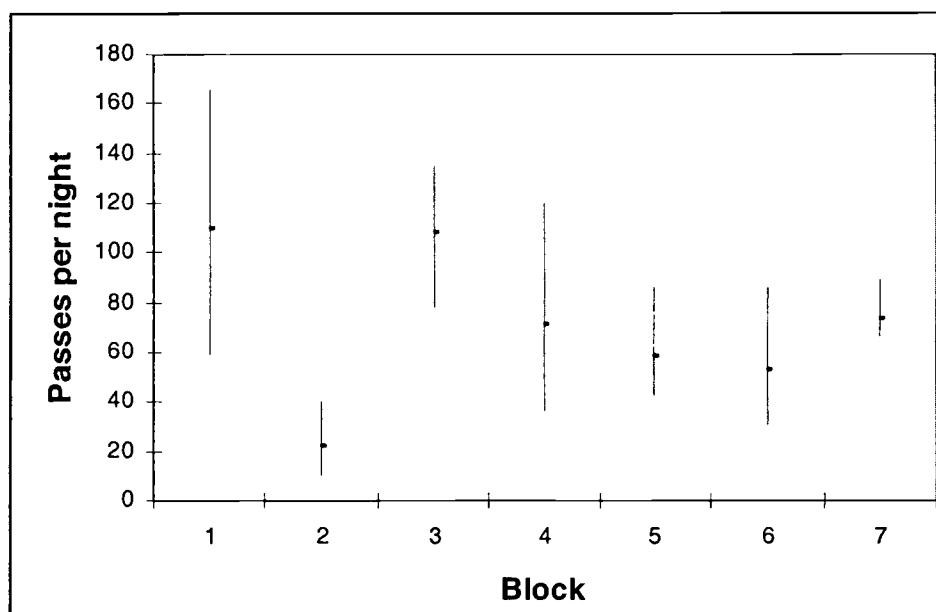


Figure 2.4. Graph of maximum, minimum and mean total passes by displaying Hawaiian Petrels observed during each four-night sampling block.

We conducted a secondary analysis of the data using a Fisher's exact test, which is based upon contingency tables, but chose not to use this statistical method. In calculating estimates of differences between treatments, Fisher's Exact test (SAS, Proc Freq) was unable to use zeros, which frequently occurred in our

data, allowing less confidence in the estimates generated. For this reason, we chose to model our data using logistic regression.

Three research questions were addressed by using separate comparisons among treatments (1.2-m, 1.8-m and flagged 1.8-m fence) and between two of the treatments (1.2-m and 1.8-m) and their respective controls (Figures 2.2 and 2.3). The first research question asked whether Hawaiian Petrels actively avoid fences or if the rarity of collision with fences is due to their generally flying above fence level. If Hawaiian Petrels were not avoiding fences, but were simply flying too high to encounter fences, the proportion of birds attempting to fly below fence height should be small, and should be similar between nights when a fence is present relative to nights when no fence is present. By comparing each of the 1.2-m and 1.8-m fence nights independently to the control, we attempted to assess whether the scarcity of collisions with fences was because petrels were actively avoiding fences. If the proportion of passes attempted below fence height is greater during controls than treatments, the difference represents those passes when birds gradually avoided the fence well in advance, and outside the observers' range of view, without resorting to late avoidance actions. If petrels regularly fly below fence height and therefore must actively avoid fences in their path, a larger proportion should fly below fence height during control nights relative to treatment nights.

Statistical analyses were conducted to answer each of the three research questions using similar techniques. We used logistic regression through the GENMOD procedure in SAS Version 8 (LR, SAS Proc Genmod; SAS Institute Inc., Cary, NC) and the drop-in-deviance F-test to determine whether a difference existed among groups. Estimates of the effects of the parameters were back transformed and reported as log odds ratios. The dataset was fit to the following binomial model for each comparison: $Logit(P) = \beta_0 + \beta_k F_k$ where $Logit(P) = \log(P/1-P)$; $P = Y/m$, a mean of the proportion of the number of attempted passes below fence level, Y , among m total passes; the distribution of Y is approximately

binomial (m, P); β_0 is the intercept; β_k is the fixed effect of treatment for $k = 1, 2$; and F_k is the indicator variable for fence treatment type $k = 1, 2$ ($F_k = 0$ for the control, $F_k = 1$ for the treatment fence). The Bonferroni correction was used to account for multiple comparisons. Using Bonferroni-corrected α -values, α'' , differences between groups were considered significant if $p \leq \alpha''$ where $\alpha'' = \alpha/k$, and k equaled the number of unplanned comparisons. If $p > \alpha''$ we failed to reject the null hypothesis that there was no difference between groups (R. Camp, pers. comm., 2004; Sokol and Rohlf, 1995). In the third comparison, where we investigated the difference between fence orientations relative to terrain slope contours, two-tailed p -values were considered significant based upon guidelines by Ramsey and Schafer (2002), where $p \leq 0.05$ was considered significant.

The first set of comparisons used a two-tailed test to determine whether a difference existed between controls and treatments. The statistical null hypotheses for the first comparison $H_{0(1)}$ states that there is no difference in the proportion of passes attempted at or below fence height between the 1.2-m simulated fence treatment and the control. The second null hypothesis ($H_{0(2)}$) states that there is no difference in the proportion of the passes attempted at or below fence height between the 1.8-m simulated fence treatment and the control. The null hypothesis of no difference between fence treatments and controls can also be stated in terms of the model $Logit(P) = \beta_0 + \beta_k F_k$ as follows:

$$Logit(P) = \beta_0,$$

where $\beta_k = 0$ if there is no effect of fence type on the proportion of petrels displaying late avoidance actions.

The second set of comparisons sought to answer the second research question which asked whether fence type affected the reactions of birds to fences. This comparison involved two statistical null hypotheses, the first of which, ($H_{0(3)}$) states that there is no difference in the proportion of passes attempted below fence height (relative to the total number of passes) between the 1.2-m fence and the 1.8-m fence treatments. If data supported rejection of this null hypothesis, we would

accept the alternative hypothesis that the 1.8-m fence increased fence strike risk compared to the 1.2-m fence. The second null hypothesis ($H_{0(4)}$) states that there is no difference in the proportion of passes of birds attempting to pass below fence height between the 1.8-m fence and flagged 1.8-m fence treatments. We predicted that adding flagging to fences would increase visibility to petrels and decrease fence strike risk. Therefore, if forced to reject the null hypothesis, we would accept the alternative hypothesis that adding flagging to a fence decreased the proportion of passes attempted below fence height. Similar statistical methods were used as in the previous analyses. Two pairwise comparisons were conducted (LR, SAS Proc Genmod) to determine whether a difference existed between the proportion of passes attempted below fence height for the 1.8-m fence, and the other two treatments (1.2-m fence and flagged 1.8-m fence). Estimates of these effects were back transformed and reported as log odds ratios relative to the 1.8-m fence treatment which was set as the reference. We reported results as one-tailed and used the Bonferroni adjustment for multiple pairwise comparisons. The dataset was fit to the same binomial model as used for the first comparison (LR, SAS Proc Genmod) where F_k is the indicator variable for fence treatment type $k=1, 2$; $F_k=0$ for the 1.8-m treatment fence and $F_k=1$ for either the 1.2-m fence, or the flagged 1.8-m fence.

The null hypothesis of no difference between fences types can also be stated in terms of the model $Logit(P) = \beta_0 + \beta_k F_k$:

$$Logit(P) = \beta_0,$$

where $\beta_k = 0$ if there is no effect of fence type on the proportion of late avoidances. If the data do not indicate a difference in the likelihood of Hawaiian Petrels exhibiting late avoidance behaviors when encountering each type of fence, the fence strike risk does not differ among fence types.

The third research question investigated whether the proportion of passes at risk of colliding with test fences was different between fences built parallel to slope contours and versus fences built perpendicular to slope contours. The

statistical null hypotheses ($H_{0(5)}$) states that there is no difference in the proportion of passes attempted at or below fence height between fences constructed parallel and fences constructed perpendicular to slope contours. If data supported rejection of the null hypothesis, fence orientation affected the ability of displaying Hawaiian Petrels to avoid fences. Results of this two-tailed test were reported as a likelihood ratios. The data were fit to the following binomial model (LR, SAS Proc Genmod):

$$\text{Logit}(P) = \beta_0 + \beta_k O_k,$$

β_k is the fixed effect of treatment (parallel or perpendicular) for $k=1, 2$; O_k is the indicator variable for fence orientation $k=1, 2$, $O_k=1$ for parallel to contours, $O_k=0$ for perpendicular.

The null hypothesis of no difference between fences orientations can also be stated in terms of the model, $\text{Logit}(P) = \beta_0 + \beta_k O_k$:

$$\text{Logit}(P) = \beta_0,$$

where $\beta_k=0$ if there is no effect of fence orientation.

2.4. RESULTS

2.4.1. *Hawaiian Petrel display behavior and reactions to fences*

From 26 May through 31 July, 2003 we witnessed 1,982 total passes of Hawaiian Petrels during 49 hours of observation ($\bar{x} = 40$ passes/hour). Late avoidance behaviors and collisions in response to test fences were rare; most birds passed over fences without exhibiting detectable avoidance behaviors or collisions. Birds were first detected at the study site as early as 43 minutes after sunset and as late as 2 hours and 18 minutes after sunset (Figure 2.5). The first birds to arrive at the study site each evening arrived an average of 68 minutes after sunset (s.d. = 20 minutes). The time of sunset at Hilo, the nearest town, ranged from 18:52 to 19:03 hours during the study (Edwards, 2001).

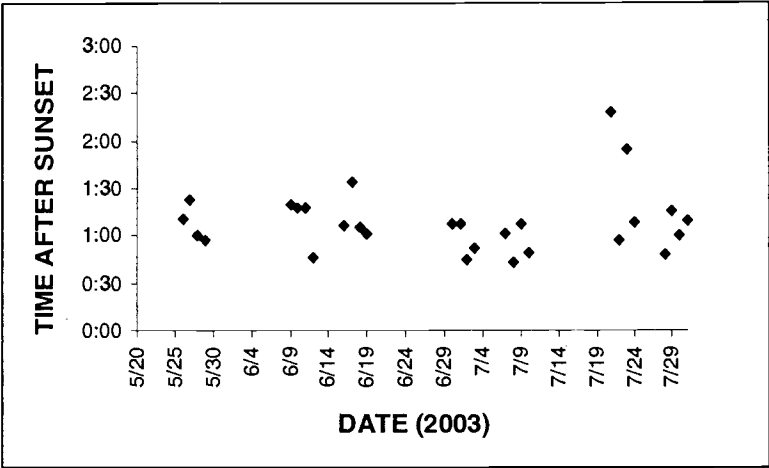


Figure 2.5. Scatter plot of the time after sunset of first Hawaiian Petrel detections at the study site between May 26 and July 31, 2003.

During treatment nights we witnessed 1,539 total passes, including only 16 avoidances and one collision in 36.9 hours of observation (17/36.9; $\bar{x} = 0.46$ passes/hour). The 16 avoidances, 1.0% of observed total passes, were birds that were at potential risk of colliding with fences because they resorted to drastic behaviors within 2 m of the fence in order to avoid it (Table 2.1). The single collision we witnessed was with a 1.2-m test fence, indicating that the risk of collision was real but represented only 0.06% of all passes (1/1539).

The number of passes witnessed during each fence treatment was similar. We recorded 526 passes near the simulated 1.2-m fence in 12.25 hours of observation (42.9 passes/hour), 562 passes during the simulated 1.8-m fence in 12.41 hours of observation ($\bar{x} = 45.3$ passes/hour), and 451 passes near the flagged 1.8-m fence during 12.25 hours of observation ($\bar{x} = 36.8$ passes/hour).

Table 2.1. Observed behaviors of displaying Hawaiian Petrels near three simulated fence types. % of avoidances is a percentage of total passes during that treatment.

Treatment	Total Passes		Avoidances		
	Number	Passes/hour	Number	%	Avoidances/hour
1.2-m	526	42.9	5*	0.95%*	0.41*
1.8-m	562	45.3	10	1.8%	0.81
1.8-m F [#]	451	36.8	2	0.44%	0.16
Totals	1539	41.7	17	N.A.	0.46

*includes one collision

[#]1.8-m fence with flagging

Only one Hawaiian Petrel was observed to collide with a test fence during the 28 nights when data were collected. The collision occurred with the 1.2-m test fence on an evening when visibility of the fence was obscured by quickly-moving, dense fog. The bird attempted to slow its flight by flapping vigorously before colliding just below the top of the 1.2-m fence. Although the bird collided with enough force to move the support poles, it immediately recovered and proceeded to fly over the fence. This event occurred on one of six evenings when fog occurred at some point during an observation session.

The largest proportion of passes at risk of collision occurred during the 1.8-m fence treatment, when 1.7% (10/562) of the total passes involved avoidances. For the 1.2-m fence treatment, 0.95% (5/526) of passes were at risk of colliding with the fence, including four late avoidances (0.76%; 5/526) and one collision (0.19%; 1/526) with the 1.2 m fence. The smallest proportion of passes at risk of collision (0.44%) occurred during the 1.8-m flagged fence treatment (2/451).

The proportion of avoidances over time for each fence type is depicted in Figure 2.6. This graph shows a general decrease in the proportion of late avoidances and collisions over the season. One potential explanation for this trend is that fewer naïve birds may have visited the display area as the season progressed. It is possible that as the proportion of naïve birds present decreased,

the likelihood of reactions to simulated fences also decreased. Weeks when no data was collected occurred after the first week, third week and fifth week of observations. These breaks do not appear to systematically increase the proportion of responses to simulated fences on the first observation night of each week.

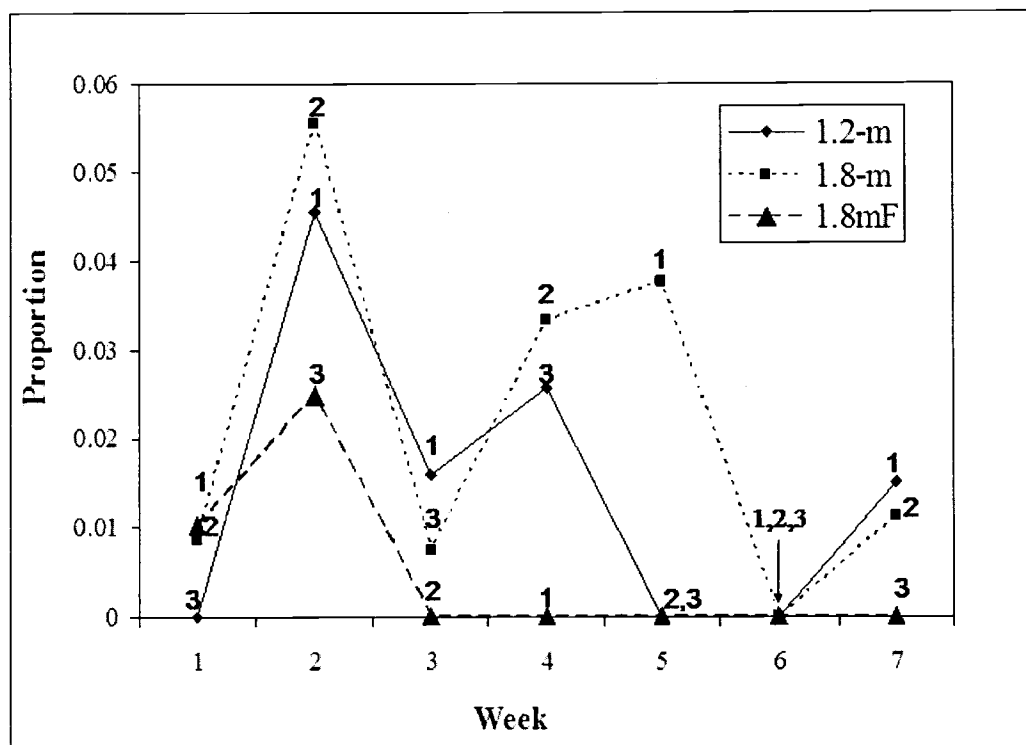


Figure 2.6. Line graph depicting the proportion of avoidances and collisions relative to total passes by displaying Hawaiian Petrels for three simulated fence types, May 26 - July 31, 2003. Data points are labeled according to the order treatments were presented. 1.8mF denotes the flagged 1.8-m fence.

In order to investigate the effect of habituation among observation nights within weeks, we labeled each proportion with the order in which the corresponding treatment was presented within each week (Figure 2.6). During three of seven weeks, the first treatment presented also showed the highest proportion of petrels exhibiting avoidances or collisions. This suggests that the

order in which treatments were presented did not strongly affect the response of petrels to simulated fences. We further investigated the effect of habituation by ranking each proportion according to its relative magnitude within each week. The greatest proportion from each week was scored as a 1, the middle value was scored as a 2, and the lowest was scored as a 3. These scores were then averaged over the season. If habituation affected the responses of Hawaiian Petrels within weeks, we would expect proportions to decrease with each consecutive night, and for treatments presented first to have the highest average rank. The average rank for treatments presented first was 1.86; the average rank for treatments presented second was 1.79; and the average rank of treatments presented third was 2.07. These average rankings were similar and did not fit the pattern one would expect if habituation caused the proportion of responses to decline over the span of each week.

In 12.2 hours of observation during control nights, we witnessed 443 total passes through the experimental zone of the control, bounded by the end poles and the upper limits of the night vision goggles ($\bar{x} = 36.3$ passes/hour). The number and rate of passes through each height class of the control zone are summarized in Table 2.2.

Table 2.2. Passes of displaying Hawaiian Petrels observed through two height classes above ground level during the control period, when no simulated fence was present.

Height Class	Passes		
	Number	% of total passes (443)	Passes/hour
Below 1.2 m	21	4.7	1.7
1.2 to 1.8 m	35	7.9	2.9
1.8 to 3.6 m	164	37	13.4
Above 3.6 m	222	50.1	18.2

Data from control nights were summarized to provide baseline information on display flight behavior (Figure 2.7). During control nights we witnessed 443 total passes. Six of these involved avoidance of the end poles, including four below 1.2 m and two between 1.2 and 1.8 m. These were considered as passes at risk of colliding with fences and were counted as passes through the height category at which they approached. Proportionally, 87% of passes were above the level of both 1.2 and 1.8-m fences. Within height classes, the highest proportion of passes (222/443 or 50.1%), occurred between 3.6 meters and the upper limit of the night vision goggles; 37% (164/443) occurred between 1.8 meters and 3.6 meters, 7.9% (35/443) occurred between 1.2 m and 1.8 m, and 4.7% (21/443) occurred below 1.2 m. Therefore, 56 bird passes (12.6%) were at direct risk of colliding with 1.8-m fences and 21 (4.7%) were at direct risk of colliding with 1.2-m fences.

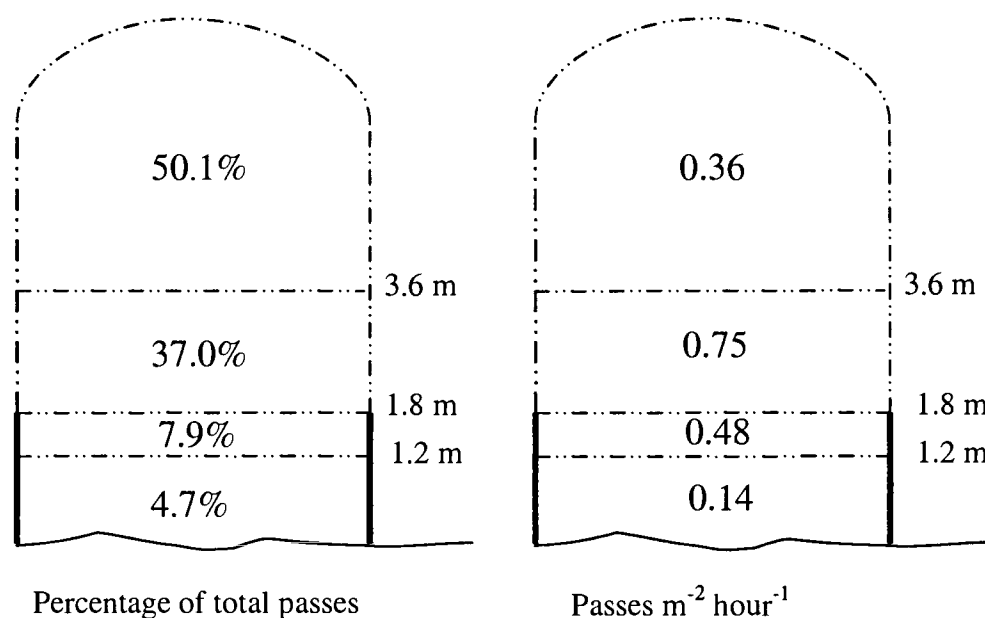


Figure 2.7. Graphic summarizing the proportion of passes at each fence height during control nights ($n=443$ passes).

After taking into account the area represented by each height class (Figure 2.7), petrels most commonly flew between 1.8 m and 3.6 m above ground level at a rate of $0.75 \text{ passes m}^{-2} \text{ hour}^{-1}$. The rate of passes between 1.2 m and 1.8 m was also relatively high at a rate of $0.48 \text{ passes m}^{-2} \text{ hour}^{-1}$. This was four times the relatively low rate of passes under 1.2 m of $0.14 \text{ m}^{-2} \text{ hour}^{-1}$, indicating that Hawaiian Petrels did frequently fly between 1.2 and 1.8 m during their natural behavior. Therefore, raising fence heights from 1.2 m to 1.8 m should result in an increase in collisions at a rate of $0.48 \text{ passes m}^{-2} \text{ hour}^{-1}$ or 7.9% of total passes, if Hawaiian Petrels could not detect and avoid fences. Passes through the upper height class occurred at a rate of $0.36 \text{ passes m}^{-2} \text{ hour}^{-1}$, the third highest rate of passage.

2.4.2. Ability to detect and avoid 1.2-m fences

There was suggestive but inconclusive evidence of a difference in the proportion of passes attempted below the 1.2-m level between the control and the 1.2-m fence treatments (LR, SAS Proc Genmod; $F_{1,12} = 6.23$, $p = 0.028 \sim$ equal to $\alpha'' = 0.025$; Sokol and Rolf, 1995). A graph of the logits of the response variable, P , shows that the logits of the proportion of birds attempting to pass below experimental height was slightly smaller for the 1.2-m treatment than for the control (Figure 2.8). According to the log odds ratio, birds were 5.4 times more likely to attempt to pass beneath 1.2 m above ground level during the control than when the 1.2-m fence was present (95% CI: 1.4 to 34.8; Table 2.3). Parameter estimates for the model, $\text{Logit}(P) = \beta_0 + \beta_k F_k$ were as follows:

$$\text{Logit}(P) = -2.9 - 1.7F_k,$$

where F_k is the indicator variable for control versus treatment.

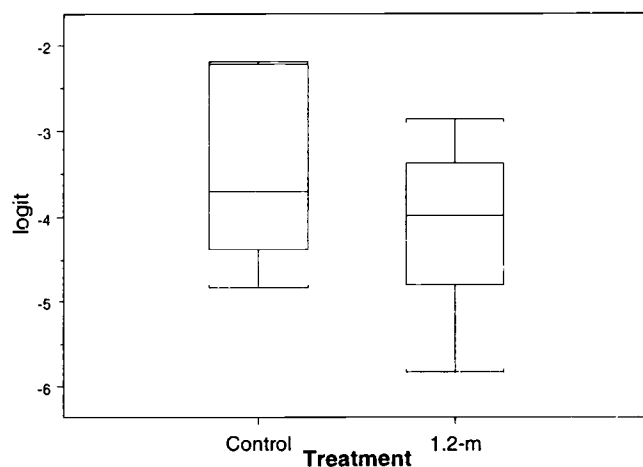


Figure 2.8. Box plot of the sample logits of the proportions (P) of Hawaiian Petrels attempting to pass below 1.2 m during the control period and the 1.2-m simulated fence treatment.

2.4.3. Ability to detect and avoid 1.8-m fences

Results of the logistic regression analysis indicated that the presence of the 1.8-m simulated fence had a significant effect on the proportion of passes attempted below the 1.8-m level ($F_{1,12} = 27.94$, $p = 0.0002$), even using the Bonferroni-corrected α'' value of 0.025 ($p < \alpha''$; Sokol and Rolf, 1995), which we employed because of multiple (2) pairwise comparisons using the same control data. In terms of the log odds ratio, petrels were eight times more likely to attempt to fly beneath 1.8 m above ground level during the control nights when the simulated fence was absent compared to the treatment night when the 1.8-m simulated fence was present (95% CI: 3.3, 23.1; Table 2.3). A graph of the logits of the response variable (P) versus the explanatory variable, fence type, indicates that the logits of the proportion of birds attempting to pass below the height of simulated fence were greater during the control than during the 1.8-m fence treatment (Figure 2.9). Parameter estimates for the model, $Logit(P) = \beta_0 + \beta_k F_k$ are as follows:

$$Logit(P) = -1.9 - 2.09F_k,$$

where F_k is the indicator variable for control versus treatment.

Table 2.3. Results of two pairwise comparisons between the control and each of the 1.2-m and 1.8-m simulated fences, including estimates of the fixed effect of fence presence, standard errors, p-values, likelihood ratios and 95% confidence intervals.

Comparison	Estimate (β_k)	S.E.	p- value	Log Likelihood	95% C.I.
Control vs. 1.8-m	-2.09	0.48	0.0002	8	3.3, 23
Control vs. 1.2-m	-1.7	0.78	0.028	5.4	1.4, 34.8

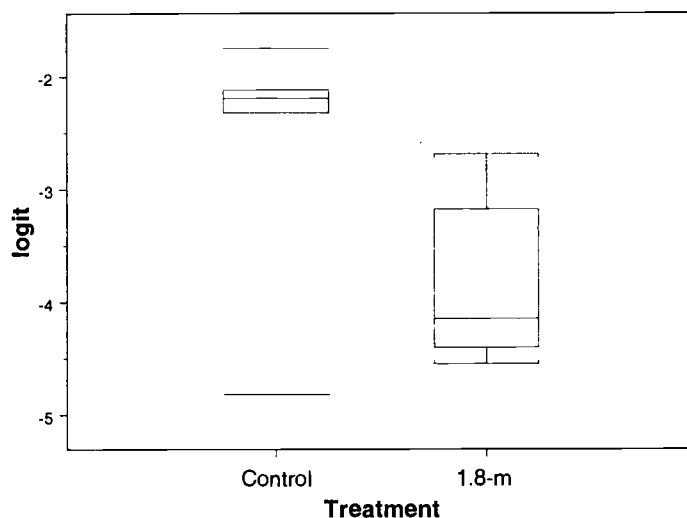


Figure 2.9. Box plot of the logits of the proportions (P) of Hawaiian Petrels attempting to pass below 1.8-m during the control period and the 1.8-m simulated fence treatment.

2.4.4. Effect of fence type

Pairwise comparisons suggested a difference between the unflagged 1.8-m fence and the flagged 1.8-m fence, but not between the 1.2-m fence and the unflagged 1.8-m fence (LR, SAS Proc Genmod). There was not a significant difference in the proportion of petrels attempting to pass beneath fence height between the 1.2-m fence and 1.8-m fence treatments ($F_{1,12} = 1.20$; one-sided $p = 0.1475$). Because $p = 0.1475$ is greater than $\alpha'' = 0.025$, we fail to reject the null hypothesis that there was no difference in bird reactions between the 1.2-m fence and 1.8-m fence (Sokol and Rolf, 1995). Figure 2.10, a box plot of the logits of the response variable, P , versus the explanatory variable, fence type, depicts the relationship among fence types. Petrels were 1.9 times more likely to attempt to pass below fence level when the 1.8-m fence was present relative to when the 1.2-m fence was present, (95% C.I. 0.61, 6.77), although this difference was not statistically significant (one-tailed $p = 0.148$) in context with the Bonferroni-

corrected α'' value of 0.025 ($p > \alpha''$; Sokol and Rolf, 1995). Because we failed to reject the null hypothesis, fence type had no detectable effect for the comparison between the 1.2-m and 1.8-m fences, and $\beta_k = 0$. The resulting model, $Logit(P) = \beta_0 + \beta_k F_k$, with parameter estimates was:

$$Logit(P) = -4.01$$

Results of this analysis, including parameter estimates for the fixed effect of fence type on Hawaiian Petrel behavior, standard errors, 1-tailed p-values, likelihood ratios, and 95% confidence intervals, are listed in table 2.4.

There was suggestive, but inconclusive evidence of a difference in the proportion of passes attempted below fence height between the unflagged and flagged 1.8-m fences ($F_{1,12} = 4.08$; one-tailed $p = 0.033 \sim$ equal to $\alpha'' = 0.025$; Sokol and Rolf, 1995;). Because $p = 0.033$ was approximately equal to $\alpha'' = 0.025$, this test provides suggestive but inconclusive evidence to reject the null hypothesis that there was no difference in petrel reactions between the 1.8-m fence and the flagged 1.8-m fence (Sokol and Rolf, 1995). Petrels were about four times more likely to attempt to pass below 1.8 m above ground level when the 1.8-m fence was present relative to when the 1.8-m fence with flagging was present (95% CI 0.68, 27.9). Parameter estimates for the model, $Logit(P) = -4.01 + \beta_k F_k$, where F_k is the indicator variable for fence type, are listed in Table 2.4. The resulting model was:

$$Logit(P) = -4.01 + 1.4 F_k.$$

Table 2.4. Results of two pairwise comparisons between three simulated fence types, including parameter estimates for the fixed effect of fence type on Hawaiian Petrel behavior, standard errors, 1-tailed p-values, likelihood ratios, and 95% confidence intervals.

Comparison	Estimate (β_k)	S.E.	1-tailed p- value	Log Likelihood	95% C.I.
1.2m vs. 1.8-m	-0.64	.59	0.148	1.9	(0.61, 6.77)
1.8mF* vs. 1.8-m	-1.4	.79	0.033	4	(0.68, 27.9)

*1.8-mF indicates the 1.8-m flagged fence

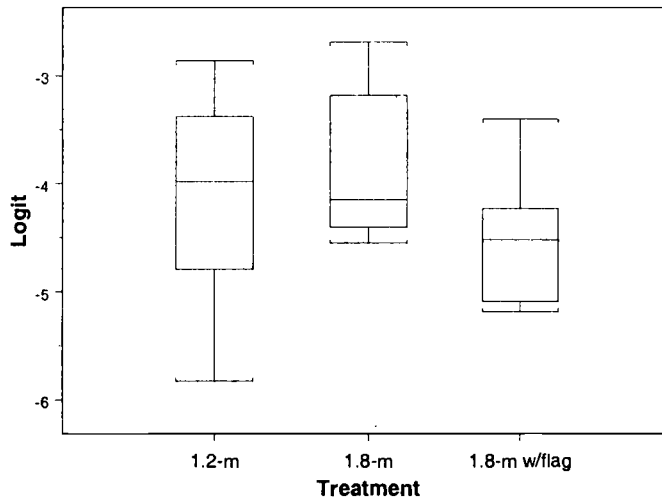


Figure 2.10. Box plots of the logits of the proportions (P) of Hawaiian Petrels attempting to pass below fence height for the three simulated fence designs.

2.4.5. Effect of orientation

The proportion of passes occurring below fence height relative to the total number of passes did not significantly differ between fences oriented parallel to slope contours and fences oriented perpendicular to slope contours. ($F_{1,19} = 2.49$; $p = 0.13$). Because we failed to reject the null hypothesis, the resulting model, $\text{Logit}(P) = \beta_0 + \beta_k O_k$, with parameter estimates was:

$$\text{Logit}(P) = -4.78,$$

where O_k is the indicator variable for fence orientation and $\beta_k = 0$ if there is no effect of fence orientation. A graph of the logit of the response variable, P , depicts the relationship between fence orientations. In terms of the log odds ratio, petrels were 2.2 times more likely to attempt to pass below the level of a fence perpendicular to slope contours versus a fence parallel to slope contours (95% CI 0.82, 5.7), but this difference was not significant.

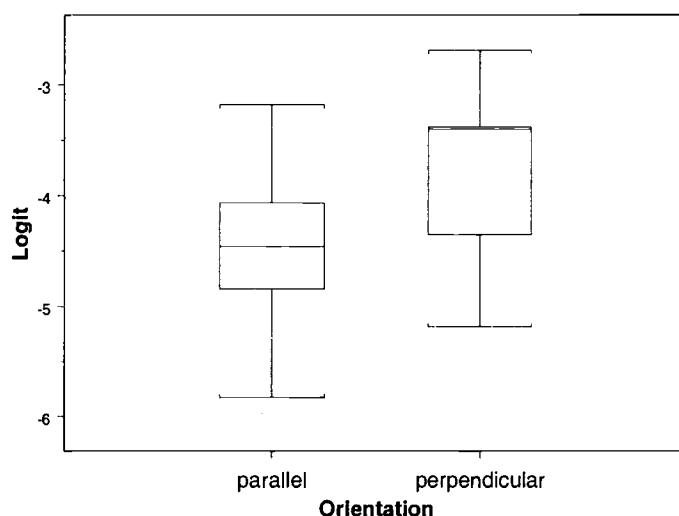


Figure 2.11. Box plots of the logits of the proportions (P) of Hawaiian Petrels attempting to pass below fence height as a function of orientation of simulated fences.

2.4.6. *Flagging color visibility*

Results of our flagging visibility trial showed that white was the most visible color among the colors tested. Contrary to our initial hypothesis, dark blue flagging disappeared first, and white flagging remained visible at the greatest distance. Dayglo pink remained visible for almost as long as white.

2.5. DISCUSSION

2.5.1. *Hawaiian Petrel display behavior*

Displaying Hawaiian Petrels attempted fewer passes at or below fence height for both 1.2-m and 1.8-m simulated fences compared to control nights when no fences were present, indicating that they were able to detect and avoid both fence types, because they altered their normal flight courses, rather than because

they typically flew above heights at which they would encounter fences. We witnessed petrels apparently investigating the fence, flying very close to the structure, implying that they readily detected the simulated fences. A summary of the height classes through which displaying petrels passed supports this view, indicating that displaying petrels regularly flew below fence height during normal display activity. Five percent of the total passes occurred below 1.2 m above ground level during control nights, but only 0.95% of total passes were events below 1.2 m when the 1.2-m simulated fence was present. Only 1.8% of passes were events below 1.8 m when the 1.8-m simulated fence was present, whereas 13% of events occurred below 1.8-m on control nights. If Hawaiian Petrels could not detect and avoid fences, we would expect collisions or late avoidances in response to test fences at the same rate as they pass below 1.2 m above ground level and below 1.8 m above ground level during control nights. Based on the heights at which petrels flew past on control nights, 8% more passes occurred below 1.8 m than below 1.2 m during natural behavior. This indicates that 8% more passes would be at risk of collision with a 1.8-m fence than with a 1.2-m fence if petrels did not detect and avoid fences. However, comparisons between the 1.2 m and 1.8 m fence treatments did not show a corresponding increase in reaction rates of passing petrels; no significant difference was found between these two groups. In addition, no birds collided with the fence between 1.2 m and 1.8 m during data collection. The difference in rates between controls and treatments may indicate the percentage of birds that were able to detect the fence at a distance and avoid it using a gradual alteration of their flight path that was not detectable by the observers. Birds gradually avoiding simulated fences were apparently not at risk of colliding with the fences because they detected and avoided the fence at a greater distance.

After establishing that displaying Hawaiian Petrels actively avoided fences, we investigated whether they could differentially detect and avoid different fence designs. Our test showed that petrels were marginally better able to detect and

avoid flagged 1.8-m fences than unflagged 1.8-m fences, as indicated by fewer late avoidances. Petrels were four times more likely to attempt to pass below 1.8 m above ground level when unflagged fences were present compared to when flagged fences were present. After accounting for multiple comparisons and despite a small sample size, our results suggested a difference, providing sufficient evidence that adding flagging to fences enhances detection and avoidance by petrels. Our inability to detect a significant difference between fence heights, and our ability to detect only a suggestive difference between flagged and unflagged fences may have been an artifact of the high variability in the data and small sample size. If managers were particularly interested in learning how the response of Hawaiian Petrels differs between fence heights, additional testing may be needed in order to increase sample size. The added visibility conferred by white flagging may contribute to petrels' ability to detect and avoid fences more significantly during inclement weather and low visibility conditions. The single collision that occurred with the 1.2 m fence on a night when fog quickly entered the study area suggests that low visibility conditions such as fog may increase fence strike risk. This could be tested in future studies.

There was no difference in the ability of petrels to detect and avoid fences built parallel to slope contours versus fences built perpendicular to slope contours. The uneven lava terrain may have had a confounding influence on the perceived effects of fence orientation. A slightly higher proportion of Hawaiian Petrels exhibited late avoidances around fences built perpendicular to slope contours compared to fences built parallel to contours. At our study site, the fence may have been hidden from birds approaching from the southwest by a high tumulus. Therefore, birds approaching from the southwest may not have been aware of the fence until they came into close proximity, increasing the likelihood of avoidance behaviors with the perpendicular fence.

While fence orientation apparently did not affect the ability of Hawaiian Petrels to avoid fences in the display area, fence orientation may have more

influence on birds commuting to and from breeding colonies. Because of the circuitous flight patterns of aerial displays, birds probably crossed the fence at equal frequencies in display areas, regardless of orientation. Transiting birds may cross fences parallel to slope contours more often because these fences are generally perpendicular to the birds' flight paths up or down slope. When a greater number of birds cross a fence, there is a higher incidence of collisions. Three of the five carcasses opportunistically found along HVNP fences in the past 16 years were not in the vicinity of known active colonies, and were probably mortalities of commuting birds on the way to or from breeding colonies. Cooper and Day (1998) studied Hawaiian Petrels and Newell's Shearwaters crossing power lines on their way to and from breeding areas and suggested that Hawaiian Petrels may have less risk of colliding with obstructions such as fences and power lines because they move during the crepuscular period when objects are still somewhat visible.

Fledgling petrels leaving the colony for the first time may be at highest risk of collision with fences. To test this idea, we attempted to determine the age of the two fence-killed carcasses that were available, but they were too weathered to judge age based upon feather wear. The side of the fence on which the birds were found was not recorded. These data may have revealed valuable information about what direction of each bird's flight path when it struck the fence. Improved data collection at the site of fence strikes in the future may reveal if petrels are colliding with fences while approaching or leaving colonies.

Hawaiian Petrels on Kaua'i fly inland between sunset and the point of complete darkness (~30 min after sunset) and fly at least 50 km/hour (Day and Cooper, 1995; Day *et al.*, 2003). The nearest coast to our study site is approximately 20 km to the southeast, and based upon patterns observed on Kaua'i, the first birds may arrive from the nearest coast to our study site as early as 25 minutes after sunset, if they fly over land at sunset. The average arrival time of birds at our study site was more than an hour after sunset (1:18), implying that

birds are either not flying from the nearest coast, or initiated their flight inland later than observed on Kaua'i. Based on Day *et al.* (2003), Hawaiian Petrels may have crossed the coastline to fly inland as far as 80 km away (Pololu Valley) and as close as 50 km (Kehena). In order to arrive at our study site between 42 minutes and 2:18 hours after sunset, Hawaiian Petrels may have come from as close as 35 km and as far as 131.5 km, if they crossed the coastline at sunset.

Before undertaking the study, I suspected that Hawaiian Petrels had some ability to avoid fences. Up to 192 passes over the simulated fence were observed per evening during the pilot study in 2002 and no collisions were witnessed. Unexpectedly, during preliminary field observations (May 6-8, 2003) that were part of our pilot study, three birds collided with a length of black nylon netting suspended on poles in the display area. These collisions occurred on the second night the structure was present. The first night the structure was present, birds could be seen inspecting it while flying past it but none collided with it. The first of the three birds that collided with the structure barely clipped it while flying past and over. The second bird hit the fence with full force, rolled to the ground, and fluttered into flight immediately. The third bird partially collapsed the structure by colliding with it, and was released uninjured from underneath the netting. After these three collisions, we notified the U.S. Fish and Wildlife Service and we were urged to continue our study. We believe that the petrels collided with the structure during our pilot study because it differed from the simulated fences built during the actual study, and was less visible to the birds. The mesh that the three birds struck was black and had a smaller mesh size than the grey mesh used in subsequent trials. In addition, thin black supporting posts used in the pilot study may have been more difficult to detect than the thicker grey posts used during the trials. It is likely that the simulated fence designs used in the actual study, built to resemble real fences, were more visible to the birds.

This paper does not address learning or habituation by birds to a fence which may occur for individual petrels at a given location that encounter a fence

repeatedly. Birds may return to sea to feed, or may remain in burrows during the day between display nights. It is unknown whether there is any interchange between the individuals present in the display area from night to night. Figure 2.9 suggests that Hawaiian Petrels may be able to adapt to the presence of fences, as the proportion of avoidances generally declined over the season. If Hawaiian Petrels do habituate to fences, novel fences on the landscape may pose the highest strike risk immediately after construction. Therefore, it is important to place visible materials, such as flagging, on fences immediately after construction to avoid fence strike during the crucial initial exposure period.

2.5.2. Study limitations

We would suggest some alterations in methodology before replication of this study. One of the major limits of this study was the small size of its dataset, though this was to be expected because of the critically endangered status of the study species. Additional data may have provided greater power to detect differences. Because of the statistical limits of such a small dataset, multiple parameters could not be added to the logistic regression model to assess the effects of covariates such as weather. In addition, the data showed high variability, which is probably due to variation in bird attendance, behavior, viewing conditions, and weather.

Some of the limitations of this study were imposed by survey methodology. Behavioral classification of bird passes by observers was often, by nature, subjective. Because the normal display behavior of Hawaiian Petrels includes circuitous flight behavior, we counted only obvious avoidances, to provide the truest measure of how many birds may have had difficulty avoiding the fences. In addition, the view through night vision goggles can make judging perspective difficult, hindering observers from accurately judging distance. Attempts to control these sources of variation will make data less subjective and improve future studies of this type.

This study required acceptance of one main assumption: that birds are acting independently on each pass over the fence test unit. Henderson *et al.* (1996) treated passes by terns as independent events even though birds flew repeatedly over power lines between nesting and foraging areas. Because of the circular flight patterns, birds at our study site pass over a given point on the landscape repeatedly each night. They are constantly distracted by other birds by chasing and being chased. It can be assumed that, once an individual has followed a circuitous path around the colony, it has been so distracted by its interaction with other birds, it must react to the fence independently with each new pass. Many of the passes recorded were groups of birds. Behavior with respect to fences often differed within group. Therefore, the route that each bird takes as part of a group may not be independent but its reaction or non-reaction to the fence can be considered an independent event.

In retrospect, statistical power of this study would have been greatly increased if a control night had been paired with each treatment, rather than combining the controls for two treatments. Placing a “wash-out” period of at least one week between each treatment may have also reduced effects of habituation. However, both of these techniques would have decreased sample size because of the limited time available to conduct this study.

This study was conducted at a breeding colony display area within HVNP on the island of Hawai'i where the activity of birds was concentrated and predictable. The necessity of choosing this site limits the scope of inference of the results to displaying birds on Mauna Loa. Assuming that display behavior and demographics are similar between Hawaiian Petrel populations, these results can be applied to Hawaiian Petrel colonies on other Hawaiian islands. Since this study was conducted on pre-breeding Hawaiian Petrels in a display area, the results do not technically extend to breeding birds not engaged in aerial display. Differences in behavior between pre-breeding and breeding adults may make their collision risk very different. While young pre-breeders engage in aerial displays near the

breeding colony, breeding adults are preoccupied with nesting and fly straight to their burrows to attend their eggs and young (Simons, 1985). However, the physiological ability of displaying Hawaiian Petrels to detect and avoid fences should be similar within the population.

2.5.3. Conservation implications

The Hawaiian Petrel was originally listed as an endangered subspecies of *Pterodroma phaeopygia* in 1967 and was reclassified in 2001 as a full species, *Pterodroma sandwichensis* (AOU, 2001). Because of its highly endangered status, any mortality of this species is a concern. The greatest modern threat to Hawaiian Petrels is predation by introduced predators. However, because of the species' low fecundity, death of even a few Hawaiian Petrels due to fence strike may have a negative effect on their populations (Simons, 1984). We undertook this study in order to assess the relative fence strike risk posed by different fence designs in response to a need to build taller fences to exclude feral ungulates from conservation areas, while reducing fence related mortality of Hawaiian Petrels.

The results of this study suggest that Hawaiian Petrels can detect and avoid fences, but that adding visible materials such as white flagging may help them to better avoid these structures. Because one Hawaiian Petrel collided with a fence on a foggy night, there is still concern that these seabirds may collide with fences mainly during inclement weather and fog. Other materials, such as white plastic tags that move in the wind, should be evaluated for their detectability in foul weather.

Hawaiian Petrel nesting occurs above 2500 meters, above the range of most predators, but feral cats (*Felis domesticus*), rats (*Rattus* spp.), and Barn Owls (*Tyto alba*) still persist at this elevation. Although eggs can be consumed by rats, most predation of adult and juvenile petrels has been attributed to feral cats (HVNP, unpubl. data). Feral cats may return to a nest year after year, depredating repeated nesting attempts and surviving adults. Since monitoring of Hawaiian

Petrel colonies began in 1993, 145 Hawaiian Petrel carcasses have been found in Mauna Loa breeding colonies (HVNP, unpubl. data). Most of these deaths, (73%; 106/145) can be attributed to feral cat predation. Mortality due to feral cat predation is probably higher as many of the carcasses with unknown cause of death (n=29) were too old to judge cause of death. Five petrels have been found dead along park fences, possibly due to collision with park boundary fences. This is a minimum number because some injured petrels may have landed far from fences and predators may have moved carcasses away from the fence corridor. Fence strikes are minimal compared to the number of petrels killed by feral predators at HVNP.

It is difficult to estimate the biological significance in terms of individual mortality that raising fence heights would have on Hawaiian Petrels. However, our data do not show that raising fence heights from 1.2 m to 1.8 m will have a significant effect on fence strike risk to Hawaiian Petrels. An unflagged 1.8-m fence poses quadruple the fence strike risk of a flagged 1.8-m fence. Therefore, adding flagging might reduce the number of fence strikes. If all fences in petrel habitat were outfitted with flagging or other visible materials, we could expect to see a reduction in the number of petrel deaths due to fence strike. With a critically endangered species that has such low fecundity, even this improvement may positively affect the population, especially if more fences are built. From our limited test comparing the visibility of different colors of flagging, it appeared that white flagging was a good choice of material to make fences more detectable to Hawaiian Petrels in foggy weather. Therefore, we suggest that white flagging be placed upon fences in areas where Hawaiian Petrels and other montane seabirds may be at risk of colliding with these barriers.

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3. CONCLUSIONS AND SYNOPSIS

3.1. ABILITY OF HAWAIIAN PETRELS TO AVOID FENCES

Observations of Hawaiian Petrels at an aerial display location indicated that displaying Hawaiian Petrels actively avoided fences in their path. Behavior was statistically different between controls and treatments. Only one collision out of 1539 flight passes was observed during treatment nights. During the control, which represented the most natural behavior of the birds, 12.6 % of passes were through the area between the 1.8-m tall poles. Since no birds collided with the 1.8-m treatment, this indicates that at least 12.6% of passes avoided this area on nights when 1.8-m fences were present. Results did not support the hypothesis that Hawaiian Petrels have significantly more difficulty avoiding a 1.2-m fence than a 1.8-m fence. However, there was suggestive evidence that displaying petrels more easily avoided the 1.8-m fence with flagging compared to the 1.8-m hogwire fence. There was no evidence that the orientation of fences with respect to slope contours affected the ability of displaying Hawaiian Petrels to avoid them.

3.2. CONSERVATION AND MANAGEMENT IMPLICATIONS

Results from this study will have a positive impact on the conservation of native ecosystems in Hawai'i Volcanoes National Park. The safe use of 1.8-m fences in areas where avian fence strike risk exists could give managers one more tool to fight the constant battle against introduced species in Hawai'i and other island ecosystems. There was no evidence that 1.8-m fences pose a greater fence strike risk than 1.2-m fences. Therefore, retrofitting 1.2-m park boundary fences with 1.8-m fences should not result in significantly more losses of Hawaiian Petrels than the 1.2-m fence would. However, even 1.2-m fences may adversely affect Hawaiian Petrel populations. Five Hawaiian Petrels have been found dead

along park fences in the past sixteen years. Results suggest that adding visible materials such as white flagging to fences may make it easier for Hawaiian Petrels to avoid fences and therefore may reduce the number of fence strikes.

3.3. SUGGESTIONS FOR FUTURE RESEARCH

The survey techniques developed in this study could be used to test other fence designs that might be considered for future construction. Since feral cat predation is a major source of mortality for Hawaiian Petrels in Hawai'i Volcanoes National Park (Hu, *et al.*, 2001), the greatest benefit for all subalpine species would be attained using a predator-proof fence to exclude both feral cats and mouflon sheep from crucial seabird breeding areas. Such a fence cannot be built, however, until its effect on montane seabirds is evaluated.

Collision risk is likely to be higher where birds are regularly crossing an obstacle (Henderson *et al.* 1996). Frequent crossings may be common along commuting corridors that birds use to fly between mountain breeding colonies and ocean feeding grounds. On other islands, many commuting petrels follow topographical features such as valleys and mountain ridges to reach breeding colonies (Day and Cooper, 1995). Where such flight corridors exist, surveys can be situated near these identifiable topographical features. However, no such commuting corridors have been identified at Hawai'i Volcanoes National Park. The terrain of Mauna Loa is typical of shield volcanoes: gently sloping and lacking large erosional features such as distinct valleys and ridges. It is possible that Hawaiian Petrels reach Mauna Loa breeding grounds by following the edges of lava flows or by simply taking the shortest course between ocean feeding grounds and mountain breeding colonies. Further research should be undertaken to discover seabird flyways on Mauna Loa and to monitor montane seabird interactions with fences in those areas. Increased knowledge of flight corridors could help managers further reduce fence strike risk in those high risk areas.

This study was not able to assess bird reactions during inclement weather because it did not occur frequently during surveys, and because we had too small a sample size to add another covariate to our regression equation. One bird did collide with fences during a bout of quickly approaching fog. There is concern that Hawaiian Petrels may collide with fences during low visibility conditions and inclement weather. Henderson *et al.* (1996) observed that terns flew lower in higher wind speeds, thus increasing their vulnerability to collisions. During preliminary observations, Hawaiian Petrels appeared less able to control their flight in high winds (pers. obs.). Future studies should attempt to assess the effects of weather on the ability of Hawaiian Petrels to avoid fences and confirm if any materials are more visible in inclement weather than other. Finally, any additional information on the movements, distribution and behavior of Hawaiian Petrels would enable managers to reduce the number of collisions with fences.

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APPENDIX

Weather Data

APPENDIX. Weather data

Data on weather were collected in the interest of relating bird behavior to weather conditions. However, because of our limited number of data points, our model could not support another parameter to account for the effects of weather on petrel behavior. Weather data presented in Appendix Table 2 were not used in analyses. Weather was recorded every half-hour during surveys and when conditions changed. Variables recorded included cloud cover (%), wind direction (bearing), wind speed (mph) and precipitation using increasing classes of intensity from no precipitation (1) to heavy downpour (8) (Appendix Table 1). Wind direction and speed were measured using a hand-held anemometer and compass.

Appendix Table 1. Precipitation codes

Code	Decription
1	No precipitation
2	Fog
3	Mist
4	Intermittent rain
5	Steady sprinkle
6	Light, steady rain
7	Heavy, steady rain
8	Downpour

Appendix Table 2. Nightly summary of weather data

Date	Precip. Code ¹	Wind (mph)	Wind Dir. ²	Clouds (%)	Sun- set ³	Lunar Day ⁴	Moon- rise ³	Moon- set ⁵
5/26	1	0-1	NE	0-5	18:52	26	3:02	15:00
5/27	1	1-2	W	0-5	18:53	27	3:34	15:48
5/28	1	0-2	SW	25-50	18:53	28	4:07	16:37
5/29	1	0-1	NW	15-40	18:53	29	4:42	17:28
6/9	1	6-13	NW	5	18:58	11	14:22	1:19
6/10	1	5-7	NW	5	18:58	12	15:23	1:59
6/11	1	0-3	N/NW	5-10	18:58	13	16:27	2:41
6/12	3, 2	3-5	NE	60-95	18:59	14	17:34	3:28
6/16	1	1-6	NW	0	19:00	18	21:48	7:26
6/17	1	7-12	NW	0	19:00	19	10:36	8:29
6/18	1	1	NW	0	19:00	20	23:18	9:29
6/19	1	2-6	NW	0	19:01	21	23:56	10:25
6/30	1	0-8	NW	5	19:03	2	6:32	19:48
7/1	1, 3	12-15	NW	10-40	19:03	3	7:29	20:36
7/2	1, 2	1-6	N, S ⁶	5-30	19:03	4	8:27	21:21
7/3	1, 2	0-4	SE	35-100	19:03	5	9:25	22:02
7/7	2, 1	7-15	N	15-90	19:03	9	13:13	23:57
7/8	1, 2	1-4	NW	35-95	19:03	10	14:14	0:37
7/9	3, 1	2-10	NW	5-100	19:03	11	15:17	1:21
7/10	1	1-4	W	5	19:03	12	16:23	2:09
7/21	1	1-4	NW	5	19:01	23	0:07	12:35
7/22	1	0-4	NW	10-60	19:01	24	0:40	13:15
7/23	1, 4, 5	3-9	SW	25-75	19:00	25	1:16	14:06
7/24	1, 2, 5, 6	0-5	SW	40-100	19:00	26	1:56	14:59
7/28	1	5-10	NW	5-15	18:59	1	5:20	18:31
7/29	1	0-3	NW	5	18:58	2	18:19	19:18
7/30	1	5-8	NW	5-15	18:58	3	19:19	20:02
7/31	1	0-5	NW	5	18:57	4	20:17	20:42

¹Precipitation codes as described in Appendix Table 1²Overall prevailing wind direction for each night³Times from www.sunrisesunset.com (Edwards, 2001)⁴New moon = day 1⁵Times from sunrisesunet.com (Edwards 2001) minus 32 minutes⁶Wind direction varied between north and south