COMPARATIVE ANALYSES OF HAWAIIAN PETREL *PTERODROMA SANDWICHENSIS* MORPHOMETRICS

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SUMMARY

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Morphometric data of the Hawaiian Petrel (*Pterodroma sandwichensis*) from breeding colonies on the islands of Hawai'i, Kaua'i and Maui were analyzed. Significant differences were found in wing chord, culmen and tarsus measurements. Adult and fledgling petrels from Maui were larger than those from Hawai'i and Kaua'i. Differences may be evidence of ecological segregation at sea and reproductive isolation of island populations, as well as the random effects of genetic drift. The longer wings of Maui birds may allow those populations to travel to more distant foraging areas in the North Pacific. Differentiation may affect conservation decisions, as each colony may need to be considered a separate genetic management unit.

Keywords: Hawaiian Petrel, *Pterodroma sandwichensis*, morphometrics, dispersal, management

INTRODUCTION

Hawaiian Petrels *Pterodroma sandwichensis* nest on the main Hawaiian Islands. Island colonies are small in geographic area relative to the foraging range of this long-distance flier (Adams and Flora 2009). The species belongs to the order Procellariiformes and is characterized among the "gadfly" petrels because of the birds' erratic flight behavior. Like many other seabirds, Hawaiian Petrels are regarded as highly philopatric to natal breeding sites (Harris 1984, Warham 1990, Hamer 2001). Philopatry and the resulting reduced dispersal can contribute to population differentiation of seabirds (Greenwood 1980, Shields 1982, Clobert *et al.* 2001). Thus, philopatry may lead to the genetic isolation of island colonies. Evidence of subsequent differentiation may be apparent in behavior, breeding phenology and morphology.

Hawaiian Petrel nesting habitat, population status and management strategies are unique to each island. In addition, breeding cycles of petrels on Maui are temporally segregated relative to those of the other islands (Judge 2011). Recent molecular and feather isotope analyses suggest there is little to no recruitment of individuals to non-natal breeding sites (Wiley *et al.* 2010). Thus, unique selection pressures may be operating on island colonies. Phenotypic variation in characters may be expected in behaviorally and geographically isolated colonies.

Each island population of Hawaiian Petrel has experienced a drastic decline because of hunting pressures by early Hawaiians, habitat degradation and the introduction of predators (*see* Simons & Hodges 1998). The species is federally endangered, but its status in Hawai'i is difficult to determine because reproductive success appears variable among islands. Evidence of character differentiation may further confound discussion of the species' status. Significant differences in size may be caused by reproductive isolation, genetic drift or ecological segregation of Hawaiian Petrels at sea. Geographic variation of Hawai'i's avifauna, especially among passerines, is well known among evolutionary biologists. However, there is no evidence of variation in highly mobile species of Hawaiian seabirds. Here, we present the first comparison of morphometric data of Hawaiian Petrels from Kaua'i, Hawai'i Island and Maui. In particular, we examine differences in wing chord, tarsus length, culmen length and body mass.

STUDY AREA AND METHODS

Information on Hawaiian Petrel biology is difficult to collect because of the species' cryptic and nocturnal behavior. Nests are positioned deep inside underground burrows on steep vegetated slopes or on massive volcanoes. Numerous predation events in Hawai'i Volcanoes National Park (HAVO) have resulted in sizeable collections of Hawaiian Petrel specimens. Banding efforts provided measurement data on live birds at nest sites within Haleakalā National Park (HALE). Fallout, or the grounding of fledgling Hawaiian Petrels, occurs when fledglings depart the nest for the first time and become disoriented and confused by urban lighting (Imber 1975, Telfer *et al.* 1987). Grounded birds are found, measured, weighed, often fed and released by experienced personnel on Maui and Kaua'i.

Hawai'i Island

The only known nests of Hawaiian Petrels on Hawai'i Island are located on the sub-alpine and alpine slopes of Mauna Loa within HAVO. Measurements were made of 41 dead adults collected in the field near nest sites over a 25-year period. Hawaiian Petrels are very vulnerable to predation by feral cats when adults are incubating eggs, feeding nestlings or resting. Depredated Hawaiian Petrels are found outside of nest entrances, and carcasses are mostly consumed except for wings, feathers, legs and most of the head. Hawaiian Petrels first breed after an estimated six years (Simons 1984); thus, adults were fully grown when predation events occurred. Only wing and tarsus measurements were possible on most of the desiccated carcasses, and some carcasses were too old to measure because of decay. Specimens were stored in large Zip-loc bags at room temperature in collection storages within HAVO. We conducted all measurements in a laboratory in 2009 and 2013.

Maui

HALE personnel provided all measurements of Hawaiian Petrel on Maui. The largest known nesting colony is within HALE, where there are 3000–4000 breeding pairs (C. Bailey unpub. data). Nests are located on the steep slopes of Haleakalā Crater, where individuals excavate volcanic cinders to create a burrow. Measurements were taken from 96 breeding adults at nest sites there from 1994 to 2009. Fledgling measurements were recorded from 192 fallout victims, found in areas of the island where bright lights confuse birds.

Kaua'i

All data from Kaua'i were provided by the Save Our Shearwaters (SOS) program, funded by the Kaua'i Island Utility Cooperative and operated by the Kaua'i Humane Society program. SOS personnel collected measurements from fallout birds. The majority of fallouts are fledgling birds that have flown from the nest for the first time, so the age of individuals is nearly the same for this highly synchronous species. Adults are also vulnerable to fallout, but only five adult specimens were measured from Kaua'i.

Measurements

Unstraightened wing chord measurements were taken from carpal joint to tip of longest primary with a flexible tape measure. Caution was taken to not flatten wings during measurements. Culmen length was taken from the implantation of feathers to the tip of the curved bill, using a digital caliper. Bill depth was measured at the nostrils. Bill width was measured at the base of the culmen. Tarsus length was taken with digital calipers, from the middle of the midtarsal joint to the distal end of the tarsometatarus. Only petrels from Maui and Kaua'i were weighed. Intra-observer variability in measurements was expected (Barrett *et al*. 1987); thus, personnel from each island strictly followed measurement protocol to assure techniques were consistent.

Neither live nor dead petrels were sexed, but measurements were taken solely from breeding adults (in addition to fledglings). Both adult male and female Hawaiian Petrels attend to nest duties equally (Simons 1985), so it is assumed there was a near equal distribution of the sexes in the study. Variance was low for all measurements, which suggests that physical traits do not vary across sexes, but we cannot exclude the possibility of Hawaiian Petrel dimorphism. Furthermore, there are examples of dimorphism in three other species of gadfly petrels, the males being larger in each case (Warham 1990).

Statistical analysis

Raw morphometric data were available from Kaua'i and Hawai'i Island, and these were compared by a two-sample *t*-test. HALE personnel provided only summary statistics from Maui; thus, comparisons to Kaua'i and Hawai'i Island morphometrics were made by a one-sample *t*-test. A significance level of $P \leq 0.05$ was used for all statistical analyses. Data are presented as mean ± SD.

TABLE 1
Summary of measurements of adult and fledgling Hawaiian Petrels from the islands of Maui, Hawai'i and Kaua'i

Measurement	Mean ± SD, mm, (n) and relevant statistic				
	Adults			Fledglings	
	Maui	Hawai'i Island	Kaua'i	Maui	Kaua'i
Culmen length	33.04 ± 2.06 (96) $t = -8.32$, df = 9, $P < 0.01$	30.58 ± 0.92 (10)	31.79 ± 1.95 (5)	31.57±1.66 (192)	
Nares to tip	23.10 ± 0.55 (3)		23.35 ± 1.12 (5)		
Bill width	9.17 ± 0.78 (96)		7.98 ± 0.96 (5)	8.39 ± 0.83 (192)	
Bill depth	10.71 ± 0.78 (96)			9.76 ± 0.69 (192)	
Skull	80.20 ± 9.41 (96)		79.60 ± 3.38 (3)	79.63 ± 3.33 (192)	
Depth at gonys	10.80 ± 0.68 (4)		10.00 ±0.26 (3)		
Wing chord	305.29 ± 13.42 (96) $t = -8.69$, df = 33, $P < 0.01$	293.82 ± 7.50 (34)		297.33 ± 18.15 (192) $t = -6.38$, df = 18, $P < 0.01$	281.36 ± 10.90 (19)
Tarsus	38.85 ± 1.57 (96) $t = -22.36$, df = 40, $P < 0.01$	35.19 ± 1.28 (31)		38.85 ± 1.94 (192) $t = -6.45$, df = 8, $P < 0.01$	36.57 ± 1.05 (9)

RESULTS

Wing chord measurements of adult Hawaiian Petrels from Hawai'i Island were significantly shorter than those from Maui (Table 1; Fig. 1). Additionally, tarsus measurements from Hawai'i Island were significantly shorter than those of Maui (Fig. 2). Culmen length measurements from Hawai'i were also shorter than those from Maui (Table 1). Fledgling birds from Kaua'i had significantly shorter wing chord measurements than fledglings from Maui (t = -6.3773, df = 18, $P < 0.01$). Tarsus measurements of Kaua'i fledglings were also smaller than those of Maui fledglings (t = -6.4521, df = 8, P = 0.0002). Small sample sizes precluded statistical comparisons of most bill and skull measurements (Table 1).

DISCUSSION

Geographic variation in morphometrics is not unusual among species of Procellariiformes (Spear & Ainley 1998). The Galápagos Petrel and Hawaiian Petrel were lumped together as the Dark-rumped Petrel *Pterodroma phaeopygia*, until the species were split by the American Ornithological Union in 2002 because of differences in behavior and morphology (Tomkins & Milne 1991, Browne *et al.* 1997). Simons (1985) summarized morphometric data of Hawaiian Petrels in Maui during his research there from 1979 to 1981, but little data were available from other Hawaiian Islands. Tomkins & Milne (1991) found significant differences in morphological characters of the Galápagos Petrel, which nests on separate islands in the small Galápagos archipelago. Differences are likely an adaptation to various selection pressures (James 1982). Wing size of birds may be affected by foraging behavior (Hertel & Ballance 1999), sexual selection and distance of migration (Gaston 1974). Wiley *et al*. (2010) reported evidence for ecological segregation of Hawaiian Petrel by analyzing carbon and nitrogen stable isotopes in flight feathers. The breeding chronology of those from Maui was 26–30 days earlier than each of the other island colonies. Temporal segregation may be additional evidence of differentiation in foraging habitat. Segregation of foraging habitat may also be representative of competition among Hawaiian Petrel or seasonal variation in prey abundance (Bull 2006).

Long wings are cost-efficient for long-distance fliers (Savile 1957), but there are constraints in wing size due to the energy and nutrients required to replace feathers (King 1974, King 1980). The longer wings of Maui birds could facilitate travel to highly productive feeding areas in the North Pacific Ocean. The random effects of genetic drift also could affect phenotypic traits (Abbott & Double 2003). However, recent molecular research on the Wedge-tailed Shearwater *Puffinus pacificus* by Peck *et al.* (2007) suggests that selection may be operating on morphological differences observed with the species, and it is unlikely that drift alone can explain differences. Regardless, there appears to be little gene flow among populations of Hawaiian Petrel in the Hawaiian Islands. Wiley *et al*. (2012) concluded that Hawaiian Petrels from Kaua'i and Hawai'i were genetically distinct populations (F_{ST} = 0.05). There is a strong likelihood that Maui birds are also genetically distinct, as evidenced by size differences and the isolation of neighboring island colonies. Differences in morphometric traits demonstrated here provide further support for the hypothesis that each island colony is distinct. Prioritizing management and conservation actions may need to consider status of each colony to preserve genetic diversity of the species.

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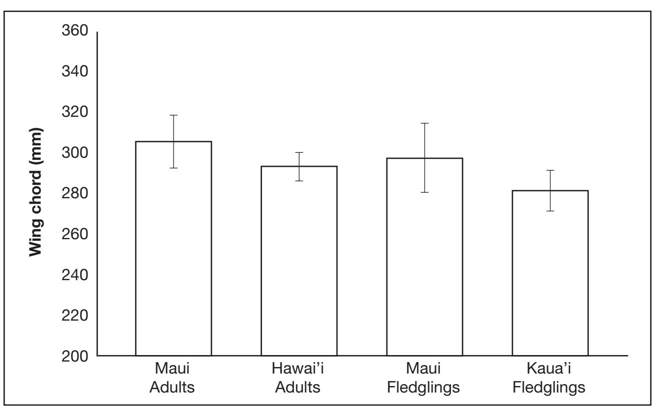

Fig. 1. Hawaiian Petrel wing chord measurements from Maui, Kaua'i and Hawai'i Islands. Mean wing chords of Maui adults are nearly 3 cm longer than those of Hawai'i Island adults. Maui fledglings have significantly longer wing chords than Kaua'i fledglings.

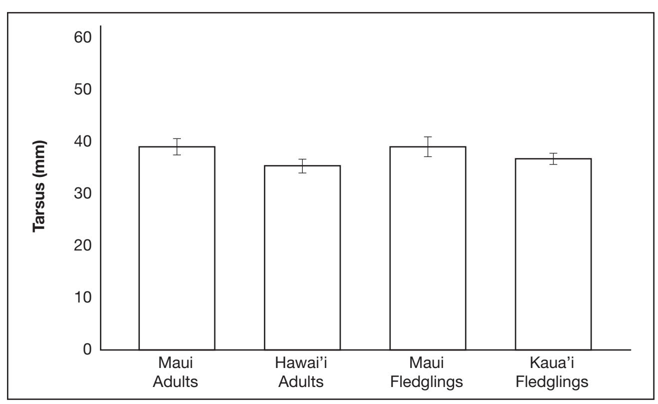

Fig. 2. Hawaiian Petrel tarsus measurements from Maui, Kaua'i and Hawai'i Islands. Tarsus measurements from Maui fledglings and adults are significantly longer than those from Hawai'i and Kaua'i.

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