Habitat Suitability Modeling for the Newell’s Shearwater on Kauai

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Abstract

The Newell’s shearwater, or ‘A’o Puffinus newelli, is endemic to the main islands of the Hawaiian Archipelago and is listed as endangered on the International Union for Conservation of Nature Red List and as threatened under the U.S. Endangered Species Act. Using abiotic and biotic environmental variables, we developed a terrestrial habitat suitability model for this species on Kauai to predict habitat that could be suitable in the absence of anthropogenic threats. In addition, we developed a habitat/threat-isolation index incorporating information from our suitability model to identify regions of structurally suitable habitat with less exposure to certain anthropogenic threats (relative to other portions of the island). The habitat suitability model suggests that slope, density of rock fragments within the soil, and native vegetation cover are important factors associated with the current known distribution of the Newell’s shearwater on Kauai, and that a moderate portion of the sloped interior terrain of Kauai could potentially be suitable nesting habitat for this species. The habitat/threat-isolation index identified the mountains on the north-central portion of the island as structurally suitable habitat most isolated from a combination of major anthropogenic disturbances (relative to other portions of the island). Much of this region, however, is privately owned and not designated as an official reserve, which could indicate a need for increased conservation action in this region in the future. This information is important for conservation biologists and private landowners because expanding efforts to control nonnative predators, as well as management of additional lands as reserves, may be necessary for the protection and preservation of the Newell’s shearwater.

Keywords: anthropogenic threats; Hawaiian Islands; Puffinus newelli; seabird conservation

Introduction

Large-scale habitat alteration, hunting pressure, and release of nonnative predators contributed to widespread avian extinction and extirpation in the Hawaiian Archipelago during the past 1,500 y (Olson and James 1982; Duffy 2010). Persisting endemic taxa, including the Newell’s shearwater Puffinus newelli, or ‘A’o, are now confined to breeding in remnant patches of high-elevation habitat. This seabird, considered by some to
be a subspecies of Townsend’s shearwater *Puffinus auricularis newelli*, is listed as endangered on the International Union for Conservation of Nature Red List (IUCN 2014) and considered threatened under the U.S. Endangered Species Act (ESA 1973, as amended). Ornithological radar surveys have revealed that the number of Newell’s shearwaters has declined sharply during the past 2 decades (Day et al. 2003; Griesemer and Holmes 2011) on Kauai, where ≈90% of the global population breeds (Ainley et al. 1997). Breeding sites of Newell’s shearwaters are characterized by steep slopes, a thick understory of native ferns, and an open canopy of scattered native trees (Ainley et al. 1997). Little more is known of this species’ habitat associations, and inaccessible terrain and expensive on-ground surveys can make wide-ranging search efforts difficult. Predictive habitat suitability modeling is therefore a practical approach to investigating environmental factors hypothesized to be important for the nesting activities of the Newell’s shearwater. Modeling may also allow the extent of remaining suitable habitat to be estimated to aid conservation efforts for this species.

In this study, we developed a terrestrial habitat suitability model for the Newell’s shearwater on Kauai derived from abiotic and biotic environmental variables. We then overlaid maps representing major anthropogenic threats to the species onto the habitat suitability model to develop a habitat/threat-isolation index identifying regions of structurally suitable habitat with less exposure to these threats (relative to other portions of the island). Our main objectives were 1) to describe relationships between environmental variables and known Newell’s shearwater distribution on Kauai, 2) to narrow future searches for breeding sites by identifying unsearched areas with habitat predicted to be suitable for the species (in terms of both structural suitability and isolation from major threats), and 3) to estimate the quantity of predicted suitable habitat available in major

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**Figure 1.** The island of Kauai, Hawaii, in five categories of land designation, based on information for property ownership (updated in 2009) and habitat reserves (updated in 2011). In the figure legend, PR = ‘private reserve,’ PNR = ‘private nonreserve,’ GR = ‘government reserve,’ GNR = ‘government nonreserve,’ and O = ‘other land.’ Several geographic locations are displayed as a visual guide for features and sites mentioned in the text. For simplicity, the approximate paths of Wainiha and Hanalei rivers are represented by a series of arrows representing water flow toward the Pacific Ocean.
categories of land designation and ownership (see Figure 1).

Methods

Modeling overview

Using a series of logistic regressions, we tested whether Newell’s shearwater activity sites could be distinguished from randomly selected background sites based on a suite of environmental variables. Our final model was used to predict the potential distribution of the Newell’s shearwater on Kauai (analyses described in subsequent subsections). Random pseudo-absence sites \((n = 5,000)\) were compared with known activity sites \((n = 35)\) because true absence locations (e.g., areas known conclusively to not contain the species) could not be identified with complete certainty. Therefore, our survey design was essentially a presence/available design (as opposed to presence–absence) in that the pseudo-absence sites were taken as a random sample of all available sites (Manly et al. 2002), with the exception that we did not allow any of the random pseudo-absence sites to overlap the known activity sites or overlap with one another. In this type of study design, some random locations can unknowingly contain the species of interest, but recent simulation studies have demonstrated that models perform well when known presence sites are compared with a large number (i.e., thousands) of random pseudo-absence locations (Wisz and Guisan 2009; Barbet-Massin et al. 2012). A recent empirical example of ecological modeling using random pseudo-absence locations to replace true absences was outlined by Jensen et al. (2008). All geographic information system (GIS)–based analyses described below were conducted using ArcGIS 9.3.1 (ESRI, Redlands, CA).

Shearwater activity sites, random sites, and environmental variables

A GIS shapefile containing polygons delineating sites of Newell’s shearwater terrestrial activity (observed during the breeding season from 2007 to 2010) was provided by the Kauai Endangered Seabird Recovery Project (KESRP; State of Hawaii/Pacific Co-operative Studies Unit). These sites were defined as areas where breeding birds have been observed or where presence of breeding individuals is strongly suspected based on acoustic surveys documenting consistent localized calling activity accompanied by other evidence of bird presence (i.e., ground calling and/or sounds associated with landing or takeoff through vegetation). Boundaries of polygons representing these sites were estimated based on the best judgment of observers collecting data in the field and the two-dimensional surface area of these polygons was highly variable (mean = 28,376.9 m², SD = 36,956.2 m², minimum = 537.0 m², maximum = 172,068.6 m²). To reduce the risk of pseudo-replication (i.e., falsely treating one occupied site as two), polygons within 175 m of one another (based on two-dimensional surface area) were combined into one site such that the original polygons remained geographically separated from one another, but were treated as one observational unit consisting of ≥2 polygons. Single polygons >175 m from any other polygon, as well as groups of polygons <175 m from one another, were termed Newell’s shearwater activity sites and used as presence sites (observational units) in this study. This resulted in a sample size of 35 Newell’s shearwater activity sites (i.e., presence sites). We chose a value of 175 m because this distance resulted in activity sites with a much greater degree of separation from other sites than would exist if all individual polygons were treated as unique observations. To assess the effect of clustering at this distance, we also constructed models based on larger activity sites (i.e., polygons within watersheds and polygons ≤1 km from one another within a watershed; \(n = 17\) activity sites). Results from this modeling procedure were very similar to those produced using the 175-m-clustering method, indicating that the models were not overly sensitive to clustering distance. We only present results for modeling based on the 175-m-clustering procedure.

Random circular pseudo-absence sites (50 m in diameter; two-dimensional surface area = 1,963.5 m²; \(n = 5,000\)) were generated above 200 m in elevation and in a manner such that they did not overlap with one another or with the 35 known Newell’s shearwater activity sites described above. The 50-m-diameter plots were large enough to encompass some of the smaller individual Newell’s shearwater activity site polygons, which were approximately circular in shape. Therefore, the size of these random sites allowed Newell’s shearwater activity sites to be compared with a wide scattering of background sites thought to be large enough to allow for the breeding activities of Newell’s shearwaters and to capture meaningful variation in the environmental variables used in our comparisons. The 200-m-elevation lower limit for random sites corresponds approximately to the lowest elevation of all known former breeding sites suspected to have been abandoned due to anthropogenic threats (though a small active breeding colony at Kilauea Point National Wildlife Refuge, formed through human efforts, and one small site of suspected ground activity [part of a larger Newell’s shearwater activity site used in our model validation procedure] are below 200 m). The presence of anthropogenic threats at low elevations might prevent otherwise structurally suitable habitat from being occupied by Newell’s shearwaters, which could potentially bias estimates of the effects of some habitat variables if low-elevation random sites were compared with currently active Newell’s shearwater sites. Therefore, random sites were only generated above 200 m in elevation. However, because areas below 200 m might indeed contain habitat structurally suitable for the species in the absence of anthropogenic threats, the final habitat suitability model was extrapolated to the entire island (including regions below 200 m).

We consulted studies of burrowing procellariiforms and other burrowing animals to develop a list of environmental variables to investigate in our modeling procedure (hypothesized effects are outlined in Table 1). Most of these variables could presumably provide structure appropriate for nesting or facilitate flight
Table 1. Potential effects of 11 abiotic and biotic environmental variables on Newell’s shearwater Puffinus newelli terrestrial habitat suitability.

<table>
<thead>
<tr>
<th>Environmental variable</th>
<th>Potential effects on terrestrial habitat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation (m)</td>
<td>Newell’s shearwaters were likely historically uncommon at lower elevations (Olson and James 1982; introduced predators are likely more abundant at lower elevations (Olson and James 1982; Harrison 1990; Rayner et al. 2007)</td>
</tr>
<tr>
<td>Slope (°)</td>
<td>Steeper slopes could facilitate access to (and departure from) breeding sites and provide  drainage during precipitation events (Schramm 1986; Stokes and Boersma 1991; Brandt et al. 1995; Catry et al. 2003; Rayner et al. 2007)</td>
</tr>
<tr>
<td>Northness and eastness (linear variables related to aspect; scale ranging from –1 to 1)</td>
<td>Direction of breeding-site slope may be associated with prevailing wind direction (which may facilitate taking flight [Schulz et al. 2005]) or thermal conditions appropriate for nesting</td>
</tr>
<tr>
<td>Distance to nearest ridge and distance to nearest drainage (m; based on three-dimensional surface area)</td>
<td>Habitat on or near ridges may facilitate accessibility to breeding sites (Schulz et al. 2005; Rayner et al. 2007) and habitat farther from drainages may be less likely to accumulate water during precipitation and more accessible to birds</td>
</tr>
<tr>
<td>Wind speed at 30-m altitude (m/s)</td>
<td>Particular wind speeds aloft may facilitate access to and departure from breeding sites (Bourgeois et al. 2008)</td>
</tr>
<tr>
<td>Proportion of native vegetation cover</td>
<td>Native vegetation may provide appropriate vegetative structure to facilitate access to breeding sites (Asner et al. 2008; Duffy 2010), and particular structural root components may provide burrow stability (Gillham 1961; Brandt et al. 1995; Ainley et al. 1997; Underwood and Bunce 2004; Bancroft et al. 2005)</td>
</tr>
<tr>
<td>Percent woody vegetation canopy cover (ordinal scale ranging from 0 to 10)</td>
<td>Lower shrub and tree cover may be associated with breeding site access (as this species is found in open forest [Ainley et al. 1997] and in Waimea Canyon on slopes with little vegetation [Wood et al. 2002]) and burrows may be located at the base of woody vegetation for burrow stability (Gillham 1961; Brandt et al. 1995; Ainley et al. 1997; Underwood and Bunce 2004; Bancroft et al. 2005)</td>
</tr>
<tr>
<td>Vegetation height (ordinal scale ranging from 0 to 3)</td>
<td>Greater vegetation height may be associated with trees suitable for climbing and launching to achieve flight (Ainley et al. 1997; Sullivan and Wilson 2001)</td>
</tr>
<tr>
<td>Percent rock fragment composition from 0 to 76.2 cm soil depth (or from 0 cm to covered bedrock &lt;76.2 cm in depth)</td>
<td>Larger rock fragments (Wingate 1964; Brandt et al. 1995) and greater rock fragment composition in soil (Stokes and Boersma 1991; Brandt et al. 1995; Bourgeois et al. 2008; Le Roux et al. 2011) may provide stability to burrows; birds may also nest in crevices in exposed bedrock (Brandt et al. 1995), but low availability of such features might cause habitat suitability to peak at intermediate rock density</td>
</tr>
</tbody>
</table>

Table 1. Potential effects of 11 abiotic and biotic environmental variables on Newell’s shearwater Puffinus newelli terrestrial habitat suitability.

Environmental variables included elevation, slope, northness and eastness (linear variables related to aspect; Roberts 1986; Guisan et al. 1999), distance to nearest ridge and distance to nearest drainage (both based on three-dimensional surface area), wind speed at 30 m in altitude, proportion of native vegetation cover, percent woody vegetation canopy cover, vegetation height, and percent rock fragment composition from 0 to 76.2 cm in soil depth (or from 0 cm to covered bedrock <76.2 cm in depth) including bedrock exposed at the surface (see Text S1 [Supplemental Material] for further explanation of this rock composition variable). Methods for the treatment and development of GIS layers depicting these environmental variables are discussed in Text S1 (see Supplemental Material).

Logistic regression

For each activity site and random site, we calculated the mean value of each environmental variable (i.e., the mean of all pixel values within the boundary of a site) using the ‘Zonal Statistics +’ Tool (Beyer 2004). Because the GIS layer for native vegetation cover was categorical (nonnative vegetation pixels = 0; native vegetation pixels = 1), the mean for each site represented the proportion of pixels with a value of one.

We compared environmental variables at activity sites with those at random sites using a series of logistic regressions (i.e., generalized linear models with a binomial error distribution and a logit link function). Species presence was coded as the binary dependent variable (random site = 0; activity site = 1). Because of the disparity in sample size between activity sites (n = 35) and random pseudo-absence sites (n = 5,000), random sites were case-weighted to reduce the effective sample size, simulating an equal number of presence and random sites (Wisz and Guisan 2009; Barbet-Massin et al. 2012). Our intention was to develop a model that might be easily generalized and applied to other islands by requiring only a few important predictor variables. Therefore, we sought a priori to reduce our set of 11 environmental variables to a smaller number (e.g., Palma et al. 1999). We applied a logistic regression separately to each environmental variable to determine which of the 11 variables appeared to distinguish Newell’s shearwater activity sites from random sites. We sought to retain variables that potentially exhibit somewhat weak, but potentially important, relationships with Newell’s shear-
water occurrence on Kauai. Therefore, we retained variables with individual regression coefficients significant at $P < 0.15$ (based on z-statistic values). This initial analysis yielded three variables (slope, proportion of native vegetation cover, and percent rock composition within the soil; Table 2). We tested for multicollinearity among these three remaining variables by calculating variance inflation factor values for each (Quinn and Keough 2002). Variance inflation factor values for all three variables (calculated using case-weighted sites as described above) were <1.9, suggesting that they could be safely included together as independent variables in subsequent modeling procedures.

In very rocky environments, relatives of the Newell’s shearwater can nest in lava tubes and crevices when available (Brandt et al. 1995), and five Newell’s shearwater activity sites were characterized by rock composition in the soil >98% according to values extracted from a GIS layer of rock composition (see Data S1, Supplemental Material). However, many more Newell’s shearwater sites had percent rock composition values ranging from the low 30s to low 50s. Therefore, we investigated a possible quadratic effect of percent rock composition on habitat suitability for the Newell’s shearwater. Specifically, we hypothesized that suitability would be higher at intermediate values of rock density and decrease in cases of very high rock coverage. We examined the quadratic effect of percent rock composition within the soil in the final habitat suitability model more fully by calculating the value of percent rock composition at which habitat suitability is predicted to peak using the formula $(-b/2a)$, where $b =$ the regression coefficient for percent rock composition within the soil from the habitat suitability model and $a =$ the coefficient for the squared term for rock composition from the same model.

Table 2. Means, standard deviations (SD), and ranges (minimum and maximum values) for mean values of 11 GIS-based abiotic and biotic environmental variables calculated for 35 Newell’s shearwater Puffinus newelli activity sites (observed during breeding seasons from 2007 through 2010) and 5,000 computer-generated random sites on Kauai, Hawaii. The variables ‘ridge’ and ‘drainage’ = distance (m) to nearest ridge or drainage (based on three-dimensional surface area), respectively, ‘wind’ = wind speed (m/s) at 30 m in altitude, ‘native veg’ = proportion of native vegetation cover, ‘woody veg’ = percent woody vegetation canopy cover on an ordinal scale, ‘veg height’ = vegetation height on an ordinal scale, and ‘rock comp’ = percent rock fragment composition from 0 to 76.2 cm in soil depth (or from 0 cm to covered bedrock ~76.2 cm in depth).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Newell’s shearwater sites ($n = 35$)</th>
<th>Random sites ($n = 5,000$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Elevation</td>
<td>711.47</td>
<td>200.10</td>
</tr>
<tr>
<td>Drainage</td>
<td>71.74</td>
<td>28.96</td>
</tr>
<tr>
<td>Wind</td>
<td>3.85</td>
<td>1.91</td>
</tr>
<tr>
<td>Native veg</td>
<td>0.85</td>
<td>0.26</td>
</tr>
<tr>
<td>Woody veg</td>
<td>6.53</td>
<td>1.17</td>
</tr>
<tr>
<td>Veg height</td>
<td>1.70</td>
<td>0.51</td>
</tr>
<tr>
<td>Rock comp$^a$</td>
<td>49.24</td>
<td>26.16</td>
</tr>
</tbody>
</table>

$^a$ Regression coefficient for independent variable in single variable logistic regression model was significant at $P < 0.05$ (based on z-statistic value); regression coefficients for all other independent variables in single variable models were not considered significant ($P > 0.15$).
regression coefficients from models with ΔAICc values of <2 to produce a final habitat suitability model. Model weights for the averaged model were based on Akaike weights calculated for the 11 candidate logistic regression models, recalculated so that the weights for this subset of models summed to one. We calculated regression coefficients for the averaged model such that coefficients for variables not present in a particular model were treated as zero for that model (Burnham and Anderson 2002). To account for model selection uncertainty in variance estimates, we used the unconditional variance and standard errors for model-averaged coefficients (eq. 4.9 in Burnham and Anderson [2002]). These standard errors were used to calculate 95% confidence intervals for each averaged coefficient estimate. Ranges and standard deviations of mean values for each environmental variable were calculated to further describe activity sites and random sites in terms of original variables (Table 2). We conducted analyses using Program R version 2.15.1 (R Development Core Team 2012).

### Habitat suitability model development

We used digital raster layers representing independent variables contributing to the final logistic regression model (i.e., the final habitat suitability model) to produce the habitat suitability model in a GIS framework (i.e., a map of suitability values represented as probability values). Digital layers for model variables were inserted into the final habitat suitability model regression equation as the appropriate independent variable using the ‘Raster Calculator’ Tool. This produced the final habitat suitability model displayed as a map of Kauai (Figure 2A and Figure S1 [Supplemental Material]). The output of this model is the predicted probability that each pixel supports (or could support) the nesting activities of Newell’s shearwaters based on the environmental conditions of the pixel.

### Habitat/threat-isolation index development

Two major threats to Newell’s shearwaters are fledgling attraction to artificial light (Reed et al. 1985; Telfer et al. 1987; Ainley et al. 2001; Troy et al. 2013) and predation by introduced predators. Feral cats *Felis catus* (Medina et al. 2011) and rodents (Jones et al. 2008) are known nonnative predators of seabirds on Kauai. However, direct measures of their abundance in different habitats on Kauai do not exist. Because higher concentrations of nonnative terrestrial predators might exist closer to human disturbance (i.e., trails, roads [references within May and Norton (1996); Delgado et al. 2001], development, and agriculture [Chalfoun et al. 2002; Shake et al. 2011]), we used distance from these disturbances as an index to describe the potential for introduced predator presence. Though individual cats have been sighted in remote mountain locations on Kauai (KESRP, unpublished data), we consider this a potentially useful measure for cats (one of the major predators of seabirds on Kauai) on a landscape scale. It should be noted that this measure might not be appropriate for introduced barn owls *Tyto alba* or feral pigs *Sus scrofa*, which also prey upon seabirds (Byrd and Telfer 1980; KESRP, unpublished data) and are present in upper montane areas of Kauai (Griesemer and Holmes 2011).

We combined GIS layers representing these threats to the species with the original habitat suitability model. Our intention was to develop a habitat/threat-isolation index that, when mapped (Figure 2D and Figure S2 [Supplemental Material]), identified regions predicted to contain structurally suitable habitat where Newell’s shearwaters would be less likely to experience predator-related threats associated with human disturbance and where fledglings would also be less susceptible to attraction to artificial light (Troy et al. 2011), relative to other portions of the island. Maps of Kauai representing the degree of isolation from each of these threats are displayed in Figures 2B and 2C, respectively. In this step, both threats were equally weighted (see Text S1 [Supplemental Material] for GIS-based details of the development of this habitat/threat-isolation index). Some authors previously estimated that nonnative predators may be more threatening to this species than fledgling attraction to artificial light (Ainley et al. 2001; Griesemer and Holmes 2011). To assess the effect of equal weighting versus nonequal weighting of the two anthropogenic threats, an alternate version of the habitat/threat-isolation index was developed in which the proxy measure for the threat of introduced terrestrial predator presence (described above) was weighted at three times greater than the threat of fledgling attraction to artificial light (details of the alternate index are provided in Text S1, Supplemental Material). The map representing this alternate habitat/threat-isolation index (Figure S3, Supplemental Material) was very similar to that produced by the index in which both threats were equally weighted (Figure 2D and Figure S2 [Supplemental Material]), as was the summary of proportion of land within categories of predicted index values in categories of land designation between the index with equal threat weights and the alternate version (Table S1, Supplemental Material). Values of the habitat/threat-isolation in which both threats were equally weighted are on a scale ranging from 0 to 0.9. Unlike predicted values from the habitat suitability model, these index values represent the combination of predicted structural habitat suitability and degree of isolation from threats (relative to all other portions of the island). Therefore, this index does not represent actual values of predicted probability of occurrence of suitable shearwater habitat. High values represent habitat predicted to be structurally suitable and most isolated from threats (relative to other areas of the island), though known activity sites could potentially be found in regions characterized by low numerical values when located in areas of suitable habitat not predicted to be as isolated from threats. Power lines are also a known source of mortality for Newell’s shearwaters (Podolsky et al. 1998; KESRP, unpublished data). Power lines overlap with artificial lights around coastal regions of Kauai, so we expect that outcomes here will also provide some guidance for the risk of collision with
power lines that birds may encounter along their flight paths. However, our analyses do not account for potential collisions in darkened locations on Kauai.

**Habitat suitability model and habitat/threat-isolation index processing**

To make the suitability model and index layers more interpretable for this large-scale study, we resampled layers representing the habitat suitability model and habitat/threat-isolation index (using nearest-neighbor assignment) to 50 × 50 m pixel resolution (2,500 m²). This allowed one pixel to fully encompass many of the smallest Newell’s shearwater activity-site polygons. We then reclassified both layers into intervals of 0.1. This resulted in categorical values of the habitat suitability model ranging from 0–0.1 to >0.9–1.0 and categorical
values of the habitat/threat-isolation index ranging from 0–0.1 to >0.8–9.0.

Model validation

We examined the validity of the habitat suitability model by calculating the percentage of activity sites from a testing data set that were correctly classified by our model (based on five different threshold values). To develop this testing data set, polygons delineating locations known or highly suspected to contain breeding Newell’s shearwaters during the 2011 and 2012 breeding seasons were clustered into activity sites based on the same stipulations described for the development of the 35 Newell’s activity sites used to develop the habitat suitability model. In addition, we deleted polygons <175 m from any of the 35 activity sites used to develop the model. This resulted in a testing data set consisting of 29 Newell’s shearwater activity sites equivalent to the 35 activity sites used to develop the model and, thus, are well-suited as a model-validation data set. Boundaries of polygons representing these sites were estimated in the same manner as those of the activity sites used to develop the habitat suitability model, and the two-dimensional surface area of these polygons was highly variable (mean = 57,509.3 m², SD = 73,577.3 m², minimum = 101.0 m², maximum = 353,012.3 m²). We did not include one breeding site located at Kilauea Point National Wildlife Refuge in the testing data set, because this site was established through human efforts. For model validation, we calculated the mean of each environmental variable in the final habitat suitability model for each activity site, and inserted these into the logistic regression equation for the habitat suitability model to calculate an overall predicted suitability value. Values of these environmental variables, as well as predicted values for these 29 activity sites, are available in Data S2 (see Supplemental Material). We assessed the percentage of activity sites from the testing data set that were correctly classified by our model at threshold levels of predicted suitability ranging from >0.5 to >0.9 (in increments of 0.1).

Land ownership and reserve designation

A shapefile of property ownership (containing all private lands ≥404.7 ha in size and all public lands) on an individual Hawaiian island (based on 2009 update for Kauai) and a shapefile of habitat reserves (based on 2011 update) were obtained from the Hawaii Statewide GIS Program (http://hawaii.gov/dbedt/gis/). We used these layers to develop a GIS layer (Figure 1) with five land ownership and designation categories (government reserves [49,719.2 ha; 35% of Kauai], government non-reserves [14,879.3 ha; 10% of Kauai], private reserves [3,266.6 ha; 2% of Kauai], private nonreserves [33,861.5 ha; 37% of Kauai], and other land [i.e., nonreserve lands owned by those with <404.7 ha; 22,016.1 ha; 15% of Kauai]; see Text S1, Supplemental Material). For each land type, we calculated the proportion of area covered by categories of probability (from 0–0.1 to >0.9–1.0) estimated from the habitat suitability model and in categories of index values (from 0–0.1 to >0.8–0.9) from the habitat/threat-isolation index. Portions of some land-type polygons were smaller than the 50 × 50 m resolution of our models. Because of the manner in which raster summary software calculates pixel overlap with polygons, portions of larger pixels that overlap with smaller polygons can be incorrectly excluded from overlap analyses. Therefore, we resampled layers to 10 × 10 m resolution (which still retained the 50 × 50 m data resolution) only to facilitate more appropriate pixel overlap summaries.

Results

The three candidate models with the lowest AICc values had Akaike weights that were substantially greater than all other candidate models and ΔAICc values of <2 (Table 3). Slope, proportion of native vegetation cover, and the quadratic effect of percent rock fragment composition within the soil (i.e., both the term for percent rock composition and its squared term) were included as independent variables collectively among these top three models. Therefore, the final habitat suitability model contained averaged regression coefficients for all four of these variables (Table 4).

Positive regression coefficients from the habitat suitability model (Table 4) suggest that the probability that a site on Kauai could be a Newell’s shearwater activity site increases with steeper slopes and greater native vegetation cover. The positive coefficient for percent rock fragment composition within the soil was accompanied by a small negative coefficient for the squared term for percent rock composition. Further exploration of this quadratic relationship revealed that suitability is predicted to increase as rock coverage within the soil increases below ~60% coverage, peak when rock coverage is ~60%, and begin to decrease as rock coverage increases beyond ~60%. The 95% confidence intervals for model-averaged regression coefficients did not overlap zero for any variables (Table 4).

The habitat suitability model (the averaged model) had a good fit to the original data (i.e., good discrimination ability; the top three models had AUC values ranging from 0.84 to 0.88; Table 3) and validation of the model using an independent testing data set revealed that several recently observed Newell’s shearwater activity sites (not used to develop the model) were predicted by the model to be moderately to highly suitable for the species. For example, 19 of the 29 sites (approx. 66%) had a model-predicted suitability value >0.5 and 11 (approx. 38%) had a model-predicted suitability >0.7 (Table 5). Furthermore, when these same 29 activity sites were plotted on the GIS map displaying the habitat suitability model (shown in Figure 2A and Figure S1 [Supplemental Material]), 25 of the sites (86%) still contained areas (pixels) predicted to be highly suitable (i.e., values of >0.7) within their boundaries (data not shown).

The habitat suitability model suggests that a moderate portion of the sloped interior of Kauai is potentially suitable habitat for the Newell’s shearwater (with predicted suitability values >0.7; Figure 2A and Figure
Table 3. Information for comparison of candidate Newell's shearwater *Puffinus newelli* habitat suitability models for Kauai, Hawaii, developed using GIS-based abiotic and biotic environmental variables, 35 Newell's shearwater activity sites (observed during breeding seasons from 2007 through 2010), and 5,000 computer-generated random sites. The variable ‘native veg’ = proportion of native vegetation cover and ‘rock comp’ = percent rock fragment composition within 76.2-cm soil depth (or to bedrock <76.2 cm). Number of model parameters (K), −2×log-likelihood (−2×LL), Akaike's Information Criterion (corrected for small sample size [AICc]), change in AICc (ΔAICc), Akaike weight (AICc weight) and area under the receiver operating characteristic curve (AUC) are reported for each candidate model.

<table>
<thead>
<tr>
<th>Model</th>
<th>K</th>
<th>−2×LL</th>
<th>AICc</th>
<th>ΔAICc</th>
<th>AICc weight</th>
<th>AUC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope + rock comp + rock comp²</td>
<td>4</td>
<td>24.03</td>
<td>32.65</td>
<td>0.00</td>
<td>0.37</td>
<td>0.86</td>
</tr>
<tr>
<td>Slope + native veg</td>
<td>3</td>
<td>27.16</td>
<td>33.52</td>
<td>0.87</td>
<td>0.24</td>
<td>0.84</td>
</tr>
<tr>
<td>Slope + native veg + rock comp + rock comp²</td>
<td>5</td>
<td>23.10</td>
<td>34.03</td>
<td>1.39</td>
<td>0.19</td>
<td>0.88</td>
</tr>
<tr>
<td>Slope + native veg + rock comp</td>
<td>4</td>
<td>27.12</td>
<td>35.74</td>
<td>3.09</td>
<td>0.08</td>
<td>0.84</td>
</tr>
<tr>
<td>Rock comp + rock comp²</td>
<td>3</td>
<td>30.24</td>
<td>36.60</td>
<td>3.95</td>
<td>0.05</td>
<td>0.80</td>
</tr>
<tr>
<td>Native veg + rock comp + rock comp²</td>
<td>4</td>
<td>28.44</td>
<td>37.06</td>
<td>4.41</td>
<td>0.04</td>
<td>0.83</td>
</tr>
<tr>
<td>Native veg + rock comp</td>
<td>3</td>
<td>33.09</td>
<td>39.46</td>
<td>6.81</td>
<td>0.01</td>
<td>0.76</td>
</tr>
<tr>
<td>Slope</td>
<td>2</td>
<td>35.84</td>
<td>40.02</td>
<td>7.37</td>
<td>0.01</td>
<td>0.78</td>
</tr>
<tr>
<td>Slope + rock comp</td>
<td>3</td>
<td>35.09</td>
<td>41.46</td>
<td>8.81</td>
<td>0.00</td>
<td>0.78</td>
</tr>
<tr>
<td>Native veg</td>
<td>2</td>
<td>37.85</td>
<td>42.03</td>
<td>9.38</td>
<td>0.00</td>
<td>0.69</td>
</tr>
<tr>
<td>Rock comp</td>
<td>2</td>
<td>45.64</td>
<td>49.82</td>
<td>17.18</td>
<td>0.00</td>
<td>0.69</td>
</tr>
</tbody>
</table>

S1 [Supplemental Material]). However, the habitat/threat-isolation index (habitat suitability model combined with threats) identifies a much more restricted portion of the island as structurally suitable habitat that is most isolated from the anthropogenic threats examined in this study (Figure 2D and Figure S2 [Supplemental Material]). In addition, the majority of the island predicted to contain suitable habitat and to be most isolated from the combination of the two anthropogenic threats occurs within privately owned land not designated as official reserve land (Table 6).

**Discussion**

In this study, we present information valuable for defining habitat characteristics for the Newell's shearwa-
We defined the extent and location of habitat predicted to be suitable for the species, including regions predicted to be most isolated from two major anthropogenic threats, and estimated the proportion of suitable habitat within major categories of land differing in ownership type and reserve status. The results of this study will be useful in aiding future conservation efforts for the Newell’s shearwater on Kauai, as well as other Hawaiian Islands on which the species persists.

Newell’s shearwaters have been observed breeding in rocky volcanic soil on steep slopes (Ainley et al. 1997; KESRP, unpublished data), similar to our findings based on large-scale GIS-based data. Steep slopes may facilitate access to (and departure from) breeding sites, provide suitable drainage during precipitation events to prevent burrow flooding (Schramm 1986; Stokes and Boersma 1991; Brandt et al. 1995; Catry et al. 2003; Raymer et al. 2007), and/or represent locations difficult for nonnative predators to access. Steep slopes may also be linked to burrow stability. Typical soil profiles of Kauai soil map units suggest that many soils of the mountainous interior are composed of at least a moderate amount of fine soil particles, which is positively related to burrow stability in other species (Stokes and Boersma 1991; Carter 1997; Holmes et al. 2003; Kintigh and Andersen 2005). In this study, percent rock composition in the soil exhibited a positive correlation with slope (Spearman’s rho = 0.60) and soils within activity sites generally contained a greater density of rock fragments and areas of exposed bedrock than did those of random sites. When associated with Newell’s shearwater burrows, rocks within the soil likely provide additional benefits to these seabirds, increasing the sturdiness of burrow walls (Stokes and Boersma 1991) and supplying roofs to burrows (Wingate 1964; Brandt et al. 1995; Bourgeois et al. 2008; Le Roux et al. 2011) as in other burrowing species. Burrowing procuellariforms can nest in locations with very high rock composition when suitable topographic features (e.g., lava tubes or crevices) are available (Brandt et al. 1995), and five Newell’s shearwater activity sites in this study were characterized by rock composition values of >98% (as measured using GIS output). Our results suggest that suitability for Newell’s shearwaters increases with increasing rock fragment density in the soil, peaks at moderate rock coverage (specifically at ≈60% coverage), and decreases as percent rock coverage approaches 100%. Therefore, locations with more soil (and a moderate amount of rocks within the soil) might provide

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### Table 5. Percent correct classification of Newell’s shearwater *Puffinus newelli* activity sites from a testing data set (observed on Kauai, Hawaii, during the 2011 and 2012 breeding seasons; *n = 29*) based on habitat suitability (probability) predicted from a habitat suitability model developed using GIS-based abiotic and biotic environmental variables, 35 Newell’s shearwater activity sites (observed during breeding seasons from 2007 through 2010), and 5,000 computer-generated random sites. ‘Suitability threshold’ refers to the level of suitability predicted for known activity sites (actual suitability = 1) from the testing data set.

<table>
<thead>
<tr>
<th>Suitability threshold</th>
<th>% Correct classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;0.9</td>
<td>65.5</td>
</tr>
<tr>
<td>&gt;0.6</td>
<td>51.7</td>
</tr>
<tr>
<td>&gt;0.7</td>
<td>37.9</td>
</tr>
<tr>
<td>&gt;0.8</td>
<td>17.2</td>
</tr>
<tr>
<td>&gt;0.9</td>
<td>10.3</td>
</tr>
</tbody>
</table>

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### Table 6. Proportion of land within categories of predicted suitability from a Newell’s shearwater *Puffinus newelli* habitat suitability model and predicted values from a habitat/threat-isolation index in five categories of land designation on Kauai, Hawaii. The habitat suitability model was developed using GIS-based abiotic and biotic environmental variables, 35 Newell’s shearwater activity sites (observed during breeding seasons from 2007 through 2010), and 5,000 computer-generated random sites, and the index was developed by combining the habitat suitability model with GIS layers spatially representing two major anthropogenic threats to the species (risk of introduced terrestrial predator presence and risk of fledgling attraction to artificial light, relative to other portions of the island). Values from the habitat/threat-isolation index represent predicted suitability (from the habitat suitability model) combined with the degree of isolation from the two major threats (relative to all other portions of the island) and are on the same numerical scale as the values of predicted suitability from the habitat suitability model. PR = ‘private reserve,’ PNR = ‘private nonreserve,’ GR = ‘government reserve,’ GNR = ‘government nonreserve,’ and O = ‘other land.’ Proportions in some categories of habitat suitability do not sum exactly to one due to rounding.

<table>
<thead>
<tr>
<th>Habitat suitability model</th>
<th>Habitat/threat-isolation index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suitability</td>
<td>PR</td>
</tr>
<tr>
<td>0.0–0.1</td>
<td>0.01</td>
</tr>
<tr>
<td>0.1–0.2</td>
<td>0.02</td>
</tr>
<tr>
<td>0.2–0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>0.3–0.4</td>
<td>0.04</td>
</tr>
<tr>
<td>0.4–0.5</td>
<td>0.05</td>
</tr>
<tr>
<td>0.5–0.6</td>
<td>0.06</td>
</tr>
<tr>
<td>0.6–0.7</td>
<td>0.08</td>
</tr>
<tr>
<td>0.7–0.8</td>
<td>0.10</td>
</tr>
<tr>
<td>0.8–0.9</td>
<td>0.12</td>
</tr>
<tr>
<td>0.9–1.0</td>
<td>0.19</td>
</tr>
</tbody>
</table>
more opportunities for nesting (i.e., excavating a burrow) because topographical features that can serve as suitable burrows in extremely rocky environments might not be available in large quantities.

Previous research found that many Newell’s shearwaters breeding sites contain a thick understory of uluhe fern *Dicranopteris linearis* and an open canopy of scattered ohia *Metrosideros polymorpha* trees (Ainley et al. 1997; KESRP, unpublished data). In our study, Newell’s shearwater activity sites and random sites were generally characterized by similar values of mean vegetation height (ranging from >0–5 to 5–10 m) and woody vegetation canopy cover (60–70%; Table 2). These values suggest a widespread coverage of woody vegetation with openings in the canopy, similar to that previously observed. Although Newell’s shearwaters may indeed benefit from this structural arrangement of woody shrubs and trees (Ainley et al. 1997), our analyses suggest that it does not influence the clustered distribution of these birds on Kauai. Activity sites, however, were covered by more native vegetation than were random sites, suggesting that nonnative vegetation might provide less suitable habitat. Invasive plants alter the three-dimensional structure of Hawaiian forests (Asner et al. 2008), which can affect seabird habitat use. For example, young strawberry guava *Psidium cattleianum* plants can form nearly impenetrable stands of vegetation, limiting opportunities for seabirds to physically access the ground and to burrow (Duffy 2010; VanZandt et al. 2014); this invasive plant is associated with at least one abandoned Newell’s shearwater colony on Kauai (KESRP, unpublished data).

The habitat suitability model (based only on abiotic and biotic environmental variables and not including threats) suggests that a moderate portion of the steep-sloped interior of Kauai may be potential habitat for the Newell’s shearwater. This model exhibited a good fit to the original data used to develop the model (based on AUC values for the top three models contributing to the final averaged model) and was somewhat effective in predicting 29 recently documented Newell’s shearwater activity sites not used to develop the model (based on mean environmental variable values for the entire site; Table 5). Furthermore, when these same 29 activity sites were plotted on the GIS map displaying the habitat suitability model (shown in Figure 2A and Figure S1 [Supplemental Material]), 25 of the sites (86%) still contained areas (pixels) predicted to be highly suitable (i.e., values of >0.7). Therefore, it appears that the habitat suitability model may indeed be useful for predicting currently undocumented breeding locations and additional habitat potentially suitable for this species. Recent searches for this species conducted in mountains of the central and northwestern sections of Kauai (from which data for the present study were obtained) revealed that Newell’s shearwater activity sites are scattered through sloped regions characterized by high predicted suitability values. However, these regions characterized by high predicted suitability values do not appear to be fully saturated with Newell’s shearwaters because many locations exist in which sites of terrestrial activity were not documented (though true absences could not necessarily be confirmed). This result may therefore reflect other variables not related to structural components of the habitat that could affect distribution, including intrinsic factors (such as social attraction [Podolsky and Kress 1989] and site fidelity), as well as factors that negatively affect seabird populations (including terrestrial anthropogenic threats [e.g., Ainley et al. 2001; Keitt et al. 2002]).

The habitat/threat-isolation index incorporating structural suitability and two major terrestrial threats (the threat of fledgling attraction to artificial light and potential prevalence of introduced predators [particularly feral cats]) identified areas predicted to contain structurally suitable habitat that are most isolated from these specific threats relative to other areas of the island. According to this index, some current Newell’s shearwater activity sites are located in areas with predicted index values in the >0.2–0.3 range (e.g., sites in Upper Limahuli Preserve, an important location for the species because it is a reserve in which active predator control occurs). This suggests that other areas with similar predicted values could potentially harbor additional activity sites, despite their seemingly low values. However, these areas are predicted to be more degraded by human disturbance (despite containing breeding birds) and may require future active management to offset the threat of predation (as is currently undertaken in Upper Limahuli Preserve). Importantly, the habitat/threat-isolation index highlights a particular region with appropriate topographic and vegetation structure that is the most isolated from the combination of human disturbances considered in this study (with predicted index values ranging from >0.6 to 0.9). This suggests that this area might be a promising candidate for long-term persistence of breeding colonies, assuming that this region is indeed more isolated from introduced predators than other areas of the island (which requires confirmation). This area exists in the mountains of the north-central region of the island, north of Mount Waialeale, south of Hanalei, east of the Wainiha River, and west of the Hanalei River; this region only partially overlaps with Halelea and Wainiha reserves.

Habitat predicted as structurally suitable on the northwestern portion of Kauai (e.g., that along the Na Pali coast) is predicted to be the least affected by artificial light (Figure 2C) and a separate version of the habitat/threat-isolation index (in which light was considered the only threat) predicted this area to be the best region on the island for the species (unpublished data); this region is located within Na Pali Coast State Park (Department of Land and Natural Resources) along the Na Pali coast. This suggests that additional ground-based searches should be conducted in this area to confirm additional breeding locations, in concert with expanding efforts to control introduced predators (as in Upper Limahuli Preserve and Hono o Na Pali Natural Area Reserve) where necessary. Importantly, the large colonies of breeding Newell’s shearwaters along the Na Pali coast are found on high sea cliffs and, thus, may be relatively safe from feral cat predation; that is, this area may actually be more isolated from predators than is predicted by our index. Therefore,
the Na Pali coast colonies are likely important global breeding sites for this species in terms of both structural habitat suitability and isolation from major anthropogenic threats. Moreover, according to our habitat suitability model, much of the predicted structurally suitable habitat in the interior of Kauai can likely increase in overall suitability if efforts to control introduced predators become widely established and artificial light output is limited during the fledging season of this species. However, the potential for collision with power lines, which are prevalent at the mouths of many valleys on the island, is still a significant conservation concern.

Some private lands on Kauai are potentially being managed for the conservation of native species without being officially recognized as reserves. However, our summary of habitat suitability within land types was conducted using information concerning landownership (government vs. private) and official reserve status. Our habitat suitability model suggests that predicted probabilities in the >0.5–1.0 range are found in approximately equal high proportions in government reserves and private nonreserve land, with a much smaller amount being located within private reserves. In the habitat/threat-isolation index, however, the largest portion of land in all categories with predicted values above 0.2 (a range of values that characterizes 82% of known active Newell’s shearwater sites used to develop the habitat suitability model and to validate it) is located on privately owned land not designated as reserve land. Notably, the important breeding sites on sea cliffs of the Na Pali coast are found on land with official government reserve status and are protected. However, the large region of the island predicted to be both structurally suitable Newell’s shearwaters and most isolated from a combination of two major anthropogenic threats (Figure 2D and Figure S2 [Supplemental Material]) is not officially protected at this time (i.e., it is not a reserve). This information is critical for discussions between conservation biologists and private landowners concerning future searches for this species, possible induced formation of new breeding colonies, efforts to control nonnative predators, and management of additional lands as reserves (which may be necessary for protection and preservation of this species). Habitat suitability models for species of conservation concern may benefit greatly by accounting for isolation from anthropogenic disturbances to identify regions more likely to resist degradation induced by human activities.

Though some areas (e.g., sea cliffs of the Na Pali coast) may be inherently more conducive to long-term persistence of the species, the persistence of the Newell’s shearwater on Kauai and other islands in the Hawaiian Archipelago will likely require increased predator-control efforts, further reduction and elimination of artificial light use during the nocturnal fledging period, mitigation of collisions with power lines (potentially including elimination of above-ground power lines), and development of additional protected areas and reserves that will serve as current and future breeding sites for the species.

### Supplemental Material

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**Data S1.** Data table containing mean values of 11 GIS-based abiotic and biotic environmental variables for 35 Newell’s shearwater *Puffinus newelli* activity sites (observed during breeding seasons from 2007 through 2010) and 5,000 computer-generated random sites. Also included are a nominal response variable (site) coded as ‘shearwater’ for activity sites and ‘random’ for random sites, a recoded response variable (‘siteasnumeric’) with values of one (for activity sites) and zero (for random sites), and a variable containing weights (‘caseweight’) used to simulate an equal number of Newell’s shearwater activity sites and random sites in regression analysis. These data were used to develop a habitat suitability model for the Newell’s shearwater on Kauai, Hawaii. Variables ‘ridge’ and ‘drainage’ = distance (m) to nearest ridge or drainage (based on three-dimensional surface area), respectively. The variable ‘wind’ = wind speed (m/s) at 30 m in altitude, ‘native veg’ = proportion of native vegetation cover, ‘woody veg’ = percent woody vegetation canopy cover on an ordinal scale, ‘veg height’ = vegetation height on an ordinal scale, and ‘rock comp’ = percent rock fragment composition from 0 to 76.2 cm in soil depth (or from 0 cm to covered bedrock <76.2 cm in depth).

Found at DOI: 10.3996/12013-JFWM-074.S1 (1198 KB XLS).

**Data S2.** Data table containing mean values of three GIS-based abiotic and biotic environmental variables within Newell’s shearwater *Puffinus newelli* activity sites from a testing data set (observed on Kauai, Hawaii, during the 2011 and 2012 breeding seasons; *n* = 29) used to validate a Newell’s shearwater habitat suitability model. The variable ‘native veg’ = proportion of native vegetation cover, ‘rock comp’ = percent rock fragment composition from 0 to 76.2 cm in soil depth (or from 0 cm to covered bedrock <76.2 cm in depth), and ‘rock comp’ = the squared term for percent rock fragment composition. The habitat suitability model was developed using GIS-based abiotic and biotic environmental variables, 35 Newell’s shearwater activity sites (observed during breeding seasons from 2007 through 2010), and 5,000 computer-generated random sites. Predicted suitability (probability) values for each of the 29 activity sites from the testing data set, calculated from the habitat suitability model, are also included in the data table.

Found at DOI: 10.3996/12013-JFWM-074.S2 (19 KB XLS).

**Text S1.** Detailed GIS-based methods used in the development of a habitat suitability model and habitat/threat-isolation index for the Newell’s shearwater *Puffinus newelli* on Kauai, Hawaii. Included are methods used for the acquisition and development of GIS layers for 11 abiotic and biotic environmental variables potentially available.
important to Newell’s shearwater distribution on Kauai, methods for combining habitat suitability model output with digital layers spatially representing two major anthropogenic threats to the species (risk of introduced terrestrial predator presence and risk of fledgling attraction to artificial light, relative to other portions of the island), and methods used for development of a land ownership and designation layer for Kauai.

Found at DOI: 10.3996/12013-JFWM-074.S3 (98 KB PDF).

**Table S1.** Proportion of land within categories of predicted values for a second version of the Newell’s shearwater *Puffinus newelli* habitat/threat-isolation index in five categories of land designation on Kauai, Hawaii. The habitat suitability model was developed using GIS-based abiotic and biotic environmental variables, 35 Newell’s shearwater activity sites (observed during breeding seasons from 2007 through 2010), and 5,000 computer-generated random sites, and this alternative index was developed by combining the habitat suitability model with GIS layers spatially representing two major anthropogenic threats to the species (risk of fledgling attraction to artificial light and risk of introduced terrestrial predator presence [weighted three times greater than risk of fledgling attraction to artificial light], relative to other portions of the island). Values from the habitat/threat-isolation index represent predicted suitability (from the habitat suitability model) combined with the degree of isolation from the two major threats (relative to all other portions of the island). PR = ‘private reserve,’ PNR = ‘private nonreserve,’ GR = ‘government reserve,’ GNR = ‘government nonreserve,’ and O = ‘other land.’ Proportions in some categories of habitat suitability do not sum exactly to one due to rounding. Note that this alternate habitat/threat-isolation index has 10 categories of values when comparing to the habitat/threat-isolation index developed in which both threats were weighted equally (presented in Figure 2D and Figure S2 [Supplemental Material]).

Found at DOI: 10.3996/12013-JFWM-074.S4 (61 KB PDF).

**Figure S1.** The island of Kauai, Hawaii, in 10 categories of predicted suitability (probability) from a Newell’s shearwater *Puffinus newelli* habitat suitability model developed using GIS-based abiotic and biotic environmental variables, 35 Newell’s shearwater activity sites (observed during breeding seasons from 2007 through 2010), and 5,000 computer-generated random sites. This figure is a larger version of Figure 2A representing the undistorted 50-m-pixel resolution of the habitat suitability model GIS layer.

Found at DOI: 10.3996/12013-JFWM-074.S5 (2.4 MB TIF).

**Figure S2.** The island of Kauai, Hawaii, in 9 categories of values from a habitat/threat-isolation index, developed by combining the habitat suitability model (displayed in Figure 2A and Figure S1 [Supplemental Material]) with GIS layers spatially representing two major anthropogenic threats to the species (displayed in Figures 2B and 2C). Values from the habitat/threat-isolation index represent predicted suitability (from the habitat suitability model) combined with the degree of isolation from the two major threats (relative to other portions of the island). This figure is a larger version of Figure 2D representing the undistorted 50-m-pixel resolution of the habitat/threat-isolation index GIS layer.

Found at DOI: 10.3996/12013-JFWM-074.S6 (1.0 MB TIF).

**Figure S3.** An alternate version of the habitat/threat-isolation index displayed in Figure 2D and Figure S2 [see Supplemental Material]. The island of Kauai, Hawaii, in 10 categories of values from a habitat/threat-isolation index, developed by combining the habitat suitability model (displayed in Figure 2A and Figure S1 [Supplemental Material]) with GIS layers spatially representing two major anthropogenic threats to the species (displayed in Figures 2B and 2C). In this alternate index, the proxy metric for the threat of introduced predator presence was weighted three times higher than the threat of fledgling attraction to artificial light. Values from the habitat/threat-isolation index represent predicted suitability (from the habitat suitability model) combined with the degree of isolation from the two major threats (relative to other portions of the island).

Found at DOI: 10.3996/12013-JFWM-074.S7 (1.6 MB TIF).


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