The Wilson Journal of Ornithology 120(2):311–319, 2008

WETLAND FEATURES THAT INFLUENCE OCCUPANCY BY THE ENDANGERED HAWAIIAN DUCK

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ABSTRACT.—Habitat loss, introduced predators, and hybridization with feral Mallards (*Anas platyrhynchos*) continue to threaten the existence of the endangered Hawaiian Duck or Koloa maoli (*A. wyvilliana*). Protection and management of core breeding areas is a recovery objective, but lack of quantitative information on the species' habitat needs hinders recovery efforts. We conducted bi-monthly surveys of 48 wetlands on private lands on the Island of Hawai'i from March 2002 to June 2003. We compared Koloa use between seasons, wetland types, and study regions and modeled how use varied with 14 site and landscape variables. Koloa occupied 54% of the surveyed wetlands; use was higher on wetlands enhanced or created for Koloa primarily through the USDA's Wetlands Reserve Program (WRP) than on ponds created for agriculture (81 vs. 41%) and on wetlands in the Kohala than in the Mauna Kea region (93 vs. 38%). Koloa were more likely to use wetlands farther (>600 m) from houses, larger (>0.23 ha) wetlands, and those surrounded by more wetlands area (>1 ha). Our results (1) indicate WRP wetlands provide suitable habitat and (2) support wetlands enhancement or creation far from human disturbance. Habitat improvements combined with feral Mallard control may reduce extinction threats to Koloa. *Received 11 December 2006. Accepted 16 July 2007.*

The Hawaiian Duck or Koloa maoli (*Anas wyvilliana*), hereafter referred to as Koloa, is a monochromatic, non-migratory, endangered species allied with the North American Mallard (*A. platyrhynchos*) complex (Browne et al. 1993). With an approximate population of 2,200 birds (Engilis and Pratt 1993, Engilis et al. 2002), the Koloa is the only endemic duck species to remain in the main Hawaiian Islands of more than 11 members of Anatidae reported in the fossil record (Olson and James 1991, Burney et al. 2001). The breeding season is year-round with peaks in December to May on Kaua'i (Swedberg 1967) and April to June on Hawai'i (Giffin 1983). Koloa use diverse habitats from sea level to 3,000 m including palustrine emergent and riverine (Swedberg 1967, Giffin 1983, Engilis and Pratt 1993), but rarely estuarine (Engilis et al. 2002). Threats to Koloa persistence include depredation by introduced predators, habitat loss, and hybridization with feral Mallards (USDI 2005). Genetically-pure Koloa populations were believed to occur on the islands of Kaua'i (Browne et al. 1993, Rhymer 2001), Ni'ihau, and highlands of Hawai'i with hybrid swarms on O'ahu and Maui (Engilis and Pratt 1993), but there is now evidence of hybridization within pure populations (Engilis et al. 2002).

Habitat management of core breeding areas is a primary recovery objective for Koloa (USDI 2005). However, little is known about the basic ecology and habitat requirements of Koloa (Rhymer 2001, Engilis et al. 2002); thus, little specific information is available to guide habitat restoration. Wetlands were enhanced or created between 1999 and 2002 to improve habitat conditions on agricultural lands on the Island of Hawai'i through the USDA Natural Resources Conservation Service's Wetland Reserve Program (WRP) and other incentive programs (Ducks Unlimited's private lands initiative, North American Wetlands Conservation Act, and Partners for Fish and Wildlife). Wetland designs were based on limited field observations and earlier studies that indicated Koloa use should be higher in wetlands: (1) adjacent to other wetlands used by Koloa, (2) distant from human disturbance, (3) adjacent to streams, (4) containing an approximately 50:50 ratio of emergent plants to open water, (5) with an irregular shoreline, (6) free of introduced aquatic vertebrates, and (7) with controlled livestock grazing (Schwartz and Schwartz 1953; Swedberg 1967; Giffin 1983; K. A. Goebel, pers. comm.). These features are also considered important for North

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American dabbling ducks (Fredrickson and Dugger 1993, Weller 1999). No previous work has attempted to test the relative importance of these criteria on Koloa use or identify other criteria that might influence habitat suitability. This study was designed to: (1) characterize patterns of wetland use by Koloa, (2) compare characteristics of used and unused wetlands, and (3) examine how site and landscape characteristics influence wetland use by Koloa to guide future habitat enhancement projects.

METHODS

Study Area.—Our study was conducted in the Kohala-Mauna Kea region (20° 00′ N, 155° 25′ W) of Hawai‘i, the largest and youngest island of the Hawaiian archipelago. The area studied was on the windward or northeast slopes of the Kohala and Mauna Kea mountains where the majority of mid-elevation depressional wetlands, agricultural ponds, and perennial streams occur because older volcanic substrates prevent percolation. A population of ~200 Koloa was re-established here by the State of Hawai‘i captive propagation and release program (1958–80) after near extirpation of Koloa in the 1950s (Schwartz and Schwartz 1953, Giffin 1983, Engilis and Pratt 1993).

Field Methods.—We surveyed all known wetlands on two properties each in the Kohala and Mauna Kea regions consisting of 14 and 34 wetlands, respectively (n = 48) between 305 and 1,219 m in elevation (Fig. 1). The study sites included 16 WRP wetlands (6 in Kohala and 10 in Mauna Kea) and 32 agricultural ponds (8 in Kohala and 24 in Mauna Kea) which were stock ponds and small reservoirs constructed between 1900 and 2001. Wetland vegetation consisted primarily of *Schoenoplectus* spp. and *Myriophyllum aquaticum*. Upland vegetation consisted of livestock forage grasses (e.g., *Urochloa mutica*, *Pennisetum clandestinum*) and small patches or stands of trees (e.g., *Psidium* spp., *Metrosideros polymorpha*). Land uses included cattle ranching and macadamia nut, coffee, and koa (*Acacia koa*) farming.

We measured 14 characteristics for each wetland (42 sites characterized in Mar–Apr 2002; 6 in Sep 2002; Table 1). We used a Global Positioning System or digital U.S. Geological Survey topographic quadrangles to calculate wetland size, shoreline development (Lind 1974), distance to house, distance to stream, surrounding wetlands, stream length, and building density. We quantified emergent and aquatic plant cover using the point-intercept method (Higgins et al. 1996) with points taken on a 5 × 1 m, 5 × 5 m, or 10 × 10 m grid for wetlands <0.10, 0.10–0.30, or >0.30 ha, respectively. Data on the presence or absence of non-native waterfowl, fishes, bullfrogs (*Rana catesbeiana*), and livestock grazing were gathered during initial wetland characterization visits and subsequent bird surveys. We classified livestock grazing by the length of the grazing period: continuous (livestock were free ranging and had year-round access to wetlands), seasonal (wetlands were fenced and livestock had access during part of the year; e.g., non-breeding season), or no grazing.

We surveyed each wetland for Koloa at least twice per month from 1 March 2002 to 25 June 2003 (6 wetlands were added in Sep 2002), which included two peak nesting periods (Apr–Jun; Giffin 1983). Surveys were conducted during mornings (sunrise until 4 hrs after sunrise) and afternoons (4 hrs before sunset to sunset). We established 1–2 survey points at each wetland at spots that minimized disturbance and maximized visibility of water birds. We observed wetlands for 5–10 min with 10 × 42 binoculars and a 25–56 × spotting scope from each point. We recorded the number of Koloa present on each wetland for each survey. We recorded direction of movement to minimize duplicate counts if birds flew from an occupied wetland. We walked the wetland shoreline if no Koloa were observed from our survey points. We assumed all ducks matching morphological and behavioral descriptions in Engilis et al. (2002) were Koloa. Mallard × Koloa hybrid phenotypes have been recorded on the Island of Hawai‘i (Engilis et al. 2002), but none was recorded at our study sites (1 Mallard male and 1 hybrid-like female observed in May 2003 in lowlands outside our survey area; KJU, pers. obs.). There were no field methods to distinguish Koloa from hybrids and few data on the prevalence of hybrids.

Statistical Analyses.—Birds on a wetland were unlikely to be undetected during a survey given the small size (0.01–1.3 ha) and

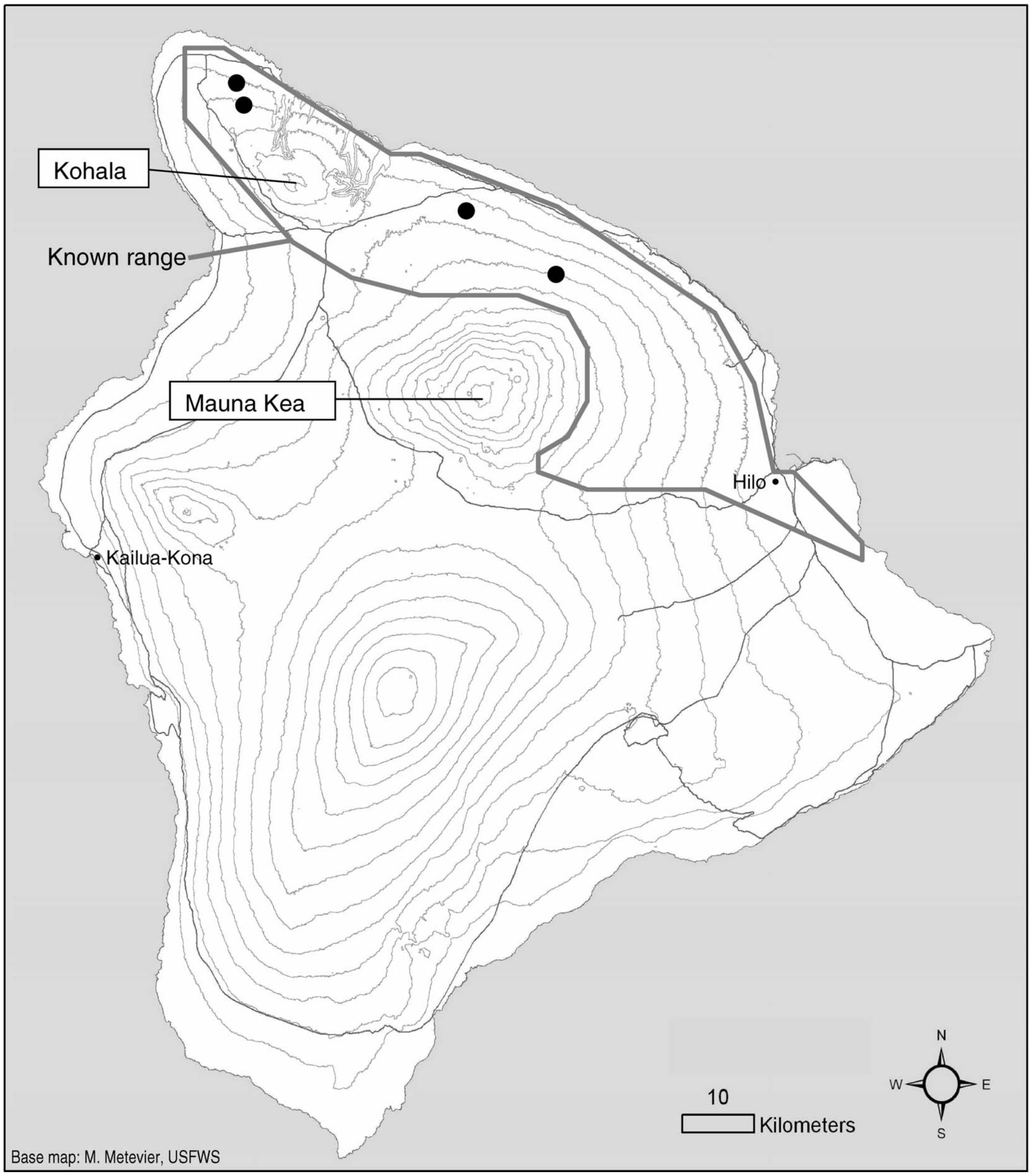

FIG. 1. Study sites (black dots) in the Kohala-Mauna Kea region of Hawai'i where wetlands were surveyed for presence of Koloa relative to the known range of Koloa on Hawai'i (gray line).

sparse vegetation of most wetlands, and we assumed a detection probability of 1.0. We assumed that birds were not concealed in vegetation or flushed without detection. A wetland was defined as ''occupied'' if Koloa were observed at least once during a survey. Multiple surveys (19–35 visits per wetland) were used to identify the status of a wetland and minimize assigning a wetland to the wrong category. Bias from undetected birds could result in conservative estimates of occupancy. However, we strived to identify wetlands with regular diurnal use and a wetland with an undetected bird would likely represent extremely low or nocturnal use, which was beyond the scope of our study. Data were untransformed.

TABLE 1. Site and landscape characteristics measured for 48 study wetlands surveyed for Koloa on the Island of Hawai'i during 2002.

Variable	Description
Site	
Wetland size	Estimated wetland area using GPS and GIS (ha)
Wetland vegetation structure (PCA of three variables)	
i. Open water	Percent area without vascular vegetation
ii. Emergent	Percent area with emergent vegetation (e.g., *Cyperus*, *Schoenoplectus*)
iii. Aquatic	Percent area with submergent or floating vegetation (e.g., *Myriophyllum*, *Nymphaea*)
Invasive species (presence of any one of the following)	
i. Non-native waterfowl	Ornamental or barnyard waterfowl in a domestic or semi-feral state (e.g., domestic Mallard breeds, such as Khaki Campbell, Pekin)
ii. Fishes	Cyprinids, poeciliids, or cichlids
iii. Bullfrogs	*Rana catesbeiana*
Grazing regime	Length of cattle or sheep grazing period (none, seasonal, continuous)
Shoreline development	Measurement of shoreline regularity; ratio of the shoreline length to the circumference of a circle with the same area as the wetland (1 = perfect circle)
Landscape	
Distance to house	Linear distance (m) from center of study wetland to nearest occupied house
Distance to stream	Linear distance (m) from center of study wetland to nearest intermittent or perennial stream
Surrounding wetlands	Percent wetland area within a 1-km radius from center of study wetland
Stream length	Intermittent or perennial stream km within a 1-km radius from center of study wetland (m/ha)
Building density	Number of houses and other structures within a 1-km radius from center of study wetland (n/ha)

We calculated occupancy rate as the proportion of wetlands occupied at least once by Koloa. We calculated percent occurrence as the number of surveys Koloa were present on a wetland divided by the total number of surveys. We assigned each survey to dry (May–Oct) or wet (Nov–Apr) and breeding (Jan–Jun) or nonbreeding (Jul–Dec) seasons. We used a likelihood ratio Chi-square test to compare occupancy rates and the Wilcoxon signed-rank test to compare percent occurrences between wetland categories (e.g., WRP vs. agricultural site).

We used logistic regression (Hosmer and Lemeshow 2000; SAS Institute 2001, 2005) in conjunction with an information-theoretic approach (Burnham and Anderson 2002) to examine habitat characteristics most closely associated with Koloa use. We examined bivariate relationships between explanatory variables using Spearman's rank correlation coefficient prior to modeling. Distance to house and building density ($r_s = -0.88$, $P < 0.0001$), distance to stream and stream length ($r_s = -0.74$, $P < 0.0001$), and surrounding wetlands and stream length ($r_s = 0.72$, $P < 0.0001$) were strongly correlated. Thus, we excluded one variable from each of the three pairs and retained distance to house, distance to stream, and surrounding wetlands. Measures of open water and emergent vegetation were correlated ($r_s = -0.82$, $P < 0.0001$); therefore, we used the first principal component (66% of total variance) from a PCA of these two variables and percent area with aquatic vegetation to represent vegetation structure in the wetland (eigenvectors = −0.71 for open water, 0.51 for emergent, and 0.48 for aquatic). We combined non-native waterfowl, fishes, and bullfrogs into one variable (invasive species) because introduced vertebrates may decrease habitat quality for

TABLE 2. Logistic regression identifying factors that influence occupancy of wetlands by Koloa on the Island of Hawai'i, 2002–2003, in order of increasing AIC_c value and decreasing Akaike weight (w_i). All models within 10 AIC values of the best model are presented.

Model	$-log(L)$[a]	K[b]	AIC_c	ΔAIC_c	w_i
Distance to house, Surrounding wetlands	21.787	3	50.119	0.00	0.338
Distance to house, Wetland size	22.248	3	51.041	0.92	0.213
Distance to house	23.627	2	51.521	1.40	0.168
Distance to house, Grazing regime	22.968	3	52.481	2.36	0.104
Distance to house, Invasive species	23.323	3	53.191	3.07	0.073
Distance to house, Distance to stream	23.591	3	53.182	3.61	0.056
Wetland size, Invasive species	23.970	3	54.485	4.37	0.038
Surrounding wetlands, Invasive species	26.120	3	58.785	8.67	0.004
Intercept only	33.104	1	68.295	18.18	0.000

[a] −log-likelihood.
[b] Number of variables.

waterfowl through competition for resources (Weller 1999).

Our selection of explanatory variables was *a priori*, but we could not reasonably develop a subset of multivariable models to compare. Thus, we examined all combinations of two-variable models (*a posteriori*) using variables from the first analysis that performed as well or better than the null model. We evaluated the relative strength of one- and two-variable models using ΔAIC_c and model weights (w_i), and the predictive ability of the best approximating models using concordance values. We considered models within 2.0 AIC values of the best model as competitive (Burnham and Anderson 2002). We evaluated parameter estimates within each model by investigating if confidence limits around the mean included zero and summing model weights for all models containing that variable (i.e., variable importance weight; Burnham and Anderson 2002). We used regression for variables associated with occupancy status to compare percent occurrence against the explanatory variable and *t*-tests to evaluate how slope estimates differed from zero, restricting our analysis to wetlands occupied by Koloa. Means ± SE and 95% confidence intervals are reported.

RESULTS

The wetlands had an occupancy rate of 54% and a mean percent occurrence of 9 ± 12% (range 0–46%) for Koloa. WRP wetlands had a higher occupancy rate (81%, $n = 16$) than agricultural ponds (41%, $n = 32$; $\chi^2 = 6.21$, df = 1, $P = 0.01$) and a higher percent occurrence (13 ± 3%) than agricultural ponds (7 ± 2%; $Z = 2.23$, $P < 0.03$). Wetlands at Kohala had both a higher occupancy rate (93 vs. 38%; $\chi^2 = 13.77$, df = 1, $P < 0.001$) and percent occurrence (20 ± 3% vs. 4 ± 1%; $Z = 4.13$, $P < 0.001$) than wetlands at Mauna Kea. Occupancy rates did not differ between wet versus dry season ($P = 1.00$) or breeding versus nonbreeding season ($P = 0.09$). However, Koloa had a tendency to occupy more wetlands during the breeding (46%, $n = 22$) than the nonbreeding (29%, $n = 14$) season. We combined data for all seasons when modeling the influence of habitat features on wetland use, and used all surveys of each wetland when calculating occupancy status.

Six variables performed as well or better than the null model including distance to house, wetland size, surrounding wetlands, grazing regime, invasive species, and distance to stream. The best approximating model, using these six variables in the multivariate analysis, was distance to house and surrounding wetlands ($w_i = 0.338$; $c = 84.4$) which received 1.6 times more support than the next best model (Table 2). Distance to house occurred in all six models and received the highest variable importance weight (0.952), followed in decreasing order by surrounding wetlands (0.344), wetland size (0.254), invasive species (0.115), grazing regime (0.105), and distance to stream (0.056). Only two models ranked above the single-variable model of distance to house, and the confidence intervals for parameter estimates included zero for all explanatory variables except distance to house.

Koloa used wetlands farther from houses (2,500 ± 261 m for occupied vs. 855 ± 209 m for unoccupied wetlands), larger wetlands (0.23 ± 0.06 ha for occupied vs. 0.06 ± 0.02 ha for unoccupied wetlands), and those surrounded by more wetland habitat (0.32 ± 0.04% occupied vs. 0.19 ± 0.03% for unoccupied). No wetland within 600 m of a house was used by Koloa suggesting human disturbance influenced use, but these wetlands (n = 12) also contained invasive species. All wetlands >600 m from houses that had invasive species (n = 8) were also used by Koloa. We discriminated between the influence of invasive species versus distance to house by controlling for distance to house, rerunning all six single-variable models using only wetlands >600 m from a house (n = 36). The only competitive model was wetland size (w_i = 0.952) and the confidence limits around the parameter estimate did not include zero. Percent occurrence for occupied wetlands (n = 26) was independent of surrounding wetlands (P = 0.23), increased with distance to house (t = 3.04, P < 0.006; Fig. 2), and was not linearly related to wetland size (P = 0.16). However, percent occurrence increased linearly with wetland size (t = 4.20, P < 0.0004; Fig. 2) when we restricted our analysis to wetlands <0.50 ha (n = 24) because the distribution of wetland size was inadequate to test for a relationship across the full range of sizes (only 2 of 26 wetlands were >0.50 ha and both were outliers being >10 SEs above the mean).

Wetland characteristics associated with Koloa use varied by wetland type and study region (Table 3). WRP wetlands were similar to agricultural ponds in size and the amount of surrounding wetlands, but averaged more than twice as far from houses. Wetlands at Kohala were on average almost three times farther from houses, larger, and in landscapes with more wetlands than those at Mauna Kea.

DISCUSSION

Koloa occupancy of WRP wetlands was high and our estimate of 81% is likely conservative since we also saw sign (feathers, tracks, droppings) at wetlands where birds were not observed. Koloa responded to new WRP wetlands within days of completion at Kohala and 3 months at Mauna Kea (KJU, pers. obs.). Higher Koloa use on WRP versus agricultural ponds indicates that WRP wetlands provided suitable Koloa habitat. Greater wetland remoteness and area contributed to higher Koloa use at Kohala than at Mauna Kea (Table 3). The low percent occurrence at study sites likely reflects the small Koloa population on Hawai‘i. Population size may be constrained by a lack of sufficient wetlands habitat, but also may be a consequence of other limiting factors.

Koloa have been described as sensitive to disturbance (Swedberg 1967, Giffin 1983, Chang 1990, Engilis et al. 2002), consistent with our characterization. Koloa did not use any wetland within 600 m of a house. Distance to houses beyond 600 m did not influence wetlands occupancy; however, percent occurrence increased as distance increased. Distance to house was associated with other anthropogenic factors that may have discouraged use by Koloa. However, when we controlled for distance to house, wetland occupancy was not associated with invasive species or grazing regime suggesting human disturbance was most important. Koloa in other areas (e.g., river valleys on Kaua‘i) may habituate to human activity. However, this is more common in landscapes characterized by larger wetland area intermixed with agriculture and dwellings (Engilis et al. 2002; KJU, pers. obs.). Our study wetlands were small (0.15 ± 0.04 ha, range 0.01–1.3 ha), kettle-shaped (shoreline development: 1.2 ± 0.02, range 1.0–1.7), and most were recently constructed or grazed and contained sparse emergent vegetation. This combination of features may make waterfowl more sensitive to disturbance than in larger wetlands, which generally provide greater escape cover that may buffer against human disturbance (Diefenbach and Owen 1989; KJU, pers. obs.) and have higher resource diversity (Brown and Dinsmore 1986, Weller 1999). Koloa occurred in wetlands as small as 141 m^2 indicating they will use small wetlands. However, both occupancy rate and percent occurrence increased with wetland size indicating larger wetlands up to 0.5 ha were used more consistently.

WRP sites were constructed near agricultural ponds already used by Koloa under the principle that a wetland complex is more attractive and productive than a similar but iso-

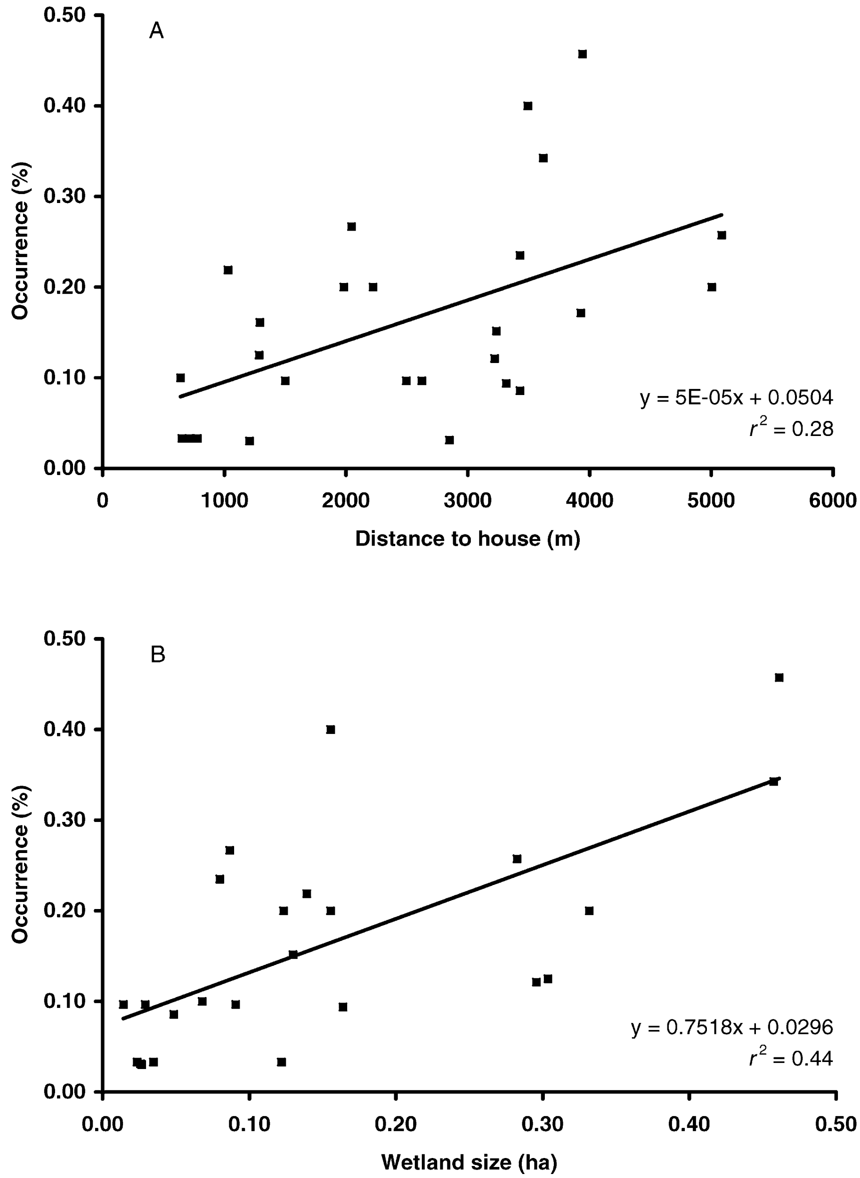

FIG. 2. Relationship between the percent occurrence of Koloa versus distance to house (A) and wetland size (B).

lated wetland (Forman 1995, Weller 1999). Koloa occupancy increased with wetland abundance supporting the concept of developing wetland complexes. This model received limited support, but Koloa did not abandon existing agricultural ponds following completion of WRP wetlands. Koloa were regularly observed moving among agricultural, stream, and new WRP habitats (KJU, pers. obs.).

Occupancy was not associated with shoreline development or vegetation structure as predicted because basin topography and vegetation communities of study sites were similar. Our measures for livestock grazing and invasive species were relatively crude, and a

TABLE 3. Wetland characteristics by wetland type (WRP vs. agricultural) and study area (Kohala vs. Mauna Kea) on the Island of Hawai'i, 2002–2003.

	Distance to house (m)	Surrounding wetlands (%)	Wetland size (ha)
Wetland type			
WRP (n = 16)	2,686 ± 309	0.23 ± 0.04	0.11 ± 0.02
Agricultural (n = 32)	1,276 ± 230	0.28 ± 0.03	0.18 ± 0.05
Study area			
Kohala (n = 14)	3,202 ± 1,317	0.48 ± 0.19	0.39 ± 0.36
Mauna Kea (n = 34)	1,147 ± 990	0.18 ± 0.09	0.05 ± 0.04

more focused study may reveal a stronger response by Koloa. Alternately, these variables may influence factors such as duckling survival instead of adult occupancy. We predicted juxtaposition of wetlands to streams may be important as, historically, high densities of Koloa were reported in streams (Schwartz and Schwartz 1953, Swedberg 1967, Giffin 1983). Koloa use did not vary by distance to stream, but our study sites were all within 1 km of a stream which was probably too small a scale to show variation in duck use. Thus, additional research is needed at a larger scale to evaluate if proximity to streams affects use.

Our models are descriptive, designed to provide baseline data about wetland characteristics that relate to Koloa use, and guide habitat restoration and management strategies for depressional wetlands on Hawai'i. Our findings indicate that managers should enhance or create wetlands >600 m from human dwellings, >0.23 ha in size, and in areas with >1 ha of surrounding wetland area within a 1-km radius. Beyond those minima, larger wetlands (up to 0.5 ha) and those farther from human disturbance received more frequent use (Fig. 2). These conditions, however, may be difficult to achieve in the relatively steep topography of mid-elevation Hawai'i; wetlands remote from human activity can present challenges for wetland managers.

Agricultural and small wetlands at Mauna Kea received less use by Koloa, but these wetlands may provide functional habitat, particularly when part of a wetland complex (Fredrickson and Dugger 1993, Semlitsch and Bodie 1998, Naugle et al. 2000, Engilis et al. 2002). Information on the daily and seasonal movements of Koloa is unknown, as is the optimal dispersion of wetlands. Tracking studies may be used to reveal use patterns and test detection probability assumptions. Studies that identify factors currently limiting Koloa population size are also needed; this information would allow for more effective conservation strategies and efficient use of conservation dollars. Private landowners, through WRP and other incentives, should be encouraged to enhance wetlands to increase habitat availability for Koloa. However, efforts to increase wetlands abundance will benefit not only Koloa, but feral Mallards and Mallard × Koloa hybrids, as evidenced by the rising population trends of Mallards and hybrids on some bird reserves on O'ahu and Maui, and recent sightings of hybrid phenotypes on Hawai'i (USDI 2005). Thus, it is essential that habitat improvements proceed in parallel with efforts to identify and remove Mallards and hybrids. Finally, occupancy is only one measure of habitat suitability. Information on how birds use wetlands would provide a better understanding of how wetlands are functioning to meeting life history needs of Koloa at Kohala and Mauna Kea.

ACKNOWLEDGMENTS

Financial and technical assistance was provided by Ducks Unlimited Inc., Delta Waterfowl Foundation, Bard College, USDA Natural Resources Conservation Service, USDI Fish and Wildlife Service, and the Hawai'i State Department of Land and Natural Resources. We are grateful to J. W. and M. T. Bailey, Bennett Dorrance Jr., Thuy Fujimoto, M. S. Gomes, E. L. and H. T. Gunther, and D. M. Matsuura for providing access to their land and logistical support. We thank K. M. Dugger, T. A. Erickson, K. A. Goebel, J. M. Higashino, Erik Kiviat, A. P. Marshall, and K. E. Moore for technical support and review of drafts of the manuscript. This publication was improved by the comments of M. H. Reynolds and an anonymous peer reviewer.

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