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DISTRIBUTION AND TRENDS OF ENDEMIC HAWAIIAN WATERBIRDS, 1986–2023

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Abstract

This study updates the status assessment of four endemic endangered Hawaiian waterbird species—aeʻo (Hawaiian stilt, *Himantopus mexicanus knudseni*), ʻalae keʻokeʻo (Hawaiian coot, *Fulica alai*), ʻalae ʻula (Hawaiian gallinule, *Gallinula galeata sandvicensis*), and koloa maoli (Hawaiian duck, *Anas wyvilliana*)—from 1986 to 2016 by incorporating new data from 2017–2023. State-space models, which account for biological and sampling variation, were fitted to estimate population sizes and trends from both core and non-core wetland survey sites. Long-term trends (1986–2023) largely show increasing populations for all four species, but recent short-term trajectories (2013–2023) are to a greater degree than previous analyses, predominantly negative, indicating accentuated declines in some island populations. Summer counts have declined relative to winter counts over the 38-year period, indicating potential changes in habitat availability and breeding patterns due to shifting rainfall patterns. Although negative trends were apparent in some non-core wetlands, our study underscores the importance of both core and non-core wetlands for waterbird populations.

Introduction

The distribution and trends of four endemic Hawaiian species of wetland-dependent waterbirds —aeʻo (Hawaiian stilt, *Himantopus mexicanus knudseni*), ʻalae keʻokeʻo (Hawaiian coot, *Fulica alai*), ʻalae ʻula (Hawaiian gallinule, *Gallinula galeata sandvicensis*), koloa maoli (Hawaiian duck, *Anas wyvilliana*)—were evaluated by Paxton *et al.* (2021) for the 1986 to 2016 period of biannual surveys. In this report, we incorporated seven additional years (2017–2023) of survey data to update information on the status of the waterbirds for a 38-year (1986–2023) period. Hawaiian waterbirds are conservation-reliant species (i.e., requiring direct management of threats; Reed *et al.* 2012, Underwood *et al.* 2013), and up-to-date information on species status and trends are needed to guide habitat management and evaluate current federal and state-listing protection.

Waterbird ecology, conservation efforts, and analytical methodology are described in Paxton *et al.* (2021). We limited this report to a cursory description of the analytical methods (summarized from Paxton *et al.* 2021) and focus on the evaluation of population size and trends in abundance. We applied a state-space approach to produce estimates of population changes over time with associated estimates of uncertainty. State-space models account for both annual variation due to biological processes as well as count variation reflective of sampling error (Humbert *et al.* 2009), as such, state-space models impart biological realism in population size and improve detection of population trends.

Methods

Analysis

Waterbird surveys were organized by the State of Hawaii Division of Forestry and Wildlife (DOFAW), which collects survey data and archives survey results. The standardized State of Hawaii Biannual Waterbird Survey has been conducted on the third Wednesday of January and August each year on 6 of the 8 main Hawaiian Islands since 1986 and constitute the “winter” and “summer” periods, respectively, of the time series analyzed herein.

The biannual surveys are simple counts of all individual waterbirds, not corrected for imperfect detection, under- and over-counting, and other effects of sampling error, and as such do not

yield estimates of error associated with a population estimate. To estimate sampling error, we used a state-space analysis of the time series in the calculation of annual population size and trends. State-space analysis partitions the variation in a time series of counts into sampling error, which reflects variation due to non-biological changes (e.g., observer error, weather conditions), and process variation, which is reflective of biological (true) changes in bird abundance (Camp *et al.* 2016). We used the Stan Bayesian modeling language (Carpenter *et al.* 2017) run from an R environment (R Core Team 2024) with the *rstan* package (Stan Development Team 2018) and produced state-space estimates of abundance for the full 38-year (1986–2023) period of surveys and the most recent 11-year span (2013–2023). Log-linear regression of the state-space estimates of abundance were fitted to model population trends for these survey periods. State-space model fitting steps are detailed in Paxton *et al.* (2021).

State-space estimates of abundance were derived from annual counts from 1986–2023 for both "core" and "non-core" survey sites, where the former includes consistently sampled wetlands that support a relatively high number of birds and are important for the recovery of waterbirds, and the latter consist of sites that support relatively fewer birds and generally are more intermittently sampled (USFWS 2011). From the annual state-space estimates we calculated species population size for both core and non-core sites at the island-level and for all islands combined ("global"). For a snapshot of current species status, we present results for 2022, the most recent year with complete or near-complete data of surveys in core wetlands. We also present a five-year average of the 2019–2023 estimates. A five-year average was considered a balance between a shorter span that might be overly affected by inter-annual variability versus a longer span that would provide a less current estimate of population size. Koloa maoli on islands other than Kauaʻi are likely hybridized with mallards (*Anas platyrhynchos*; Fowler *et al.* 2008); therefore, we only considered counts of koloa maoli from Kauaʻi for our analysis.

To examine seasonal effects on population size, we compared state-space estimates of abundance between summer and winter surveys for both core and non-core sites combined. We calculated intra-annual differences in estimated abundance between summer and winter surveys and regressed this over the 38-year period. Following the approach used by Paxton *et al.* (2021), we also depicted waterbird distribution among islands based on counts averaged for the most recent three years of winter surveys (2021–2023) for each island moku (a traditional Hawaiian land division composed of several adjacent ahupuaʻa, or watersheds; Hawaii 2020). In addition, most waterbirds are supported by core wetlands (USFWS 2011), but the degree to which they reflect island-specific and global trends is not known. To assess this, we evaluated the correlation of species counts from core wetlands to that core and non-core wetlands combined for both winter and summer surveys.

We applied an equivalency testing approach to assess the statistical significance of a trend using the posterior probabilities derived from the state-space model (Camp *et al.* 2016). We chose biologically meaningful thresholds for the overall population trend, defined as a 25% change in the population over a 25-year period (annual rate of change equal to -0.0119 and 0.0089 on the log-scale), to delimit the equivalence region (Camp *et al.* 2010). Applied in a Bayesian framework, a biologically meaningful trend occurs when the posterior probability distribution of the slope lies outside the equivalence region, whereas a "negligible" trend occurs when the slope estimate lies within the equivalence region (and from which the population can be inferred to be stable). The posterior distribution of the slope was apportioned among each of three trend categories (upward, downward, or stable population trend). We evaluated the strength of evidence for a trend based on the weight of the posterior probabilities (Pr) among each category, where the evidence was weak if $0.5 \le Pr < 0.7$, strong if $0.7 \le Pr < 0.9$, and very strong if $Pr \ge 0.9$. In cases where small sample size and high variation in estimates results in the

posterior distribution of the slope having weak evidence among all three trend categories, we interpreted the trend to be "indeterminate." We present the state-space modeled trend for the full 38-year (1986–2023) period of surveys and the most recent 11-year period (2013–2023). For brevity and comparability to Paxton *et al.* (2021) only the state-space estimates of population size and trend derived from winter counts are presented in the body of the text (annual statewide population size counts and estimates for both summer and winter surveys are available in Appendix II, and island-specific counts and estimates for winter surveys are available in Appendix IV).

RESULTS

Population Estimates

State-space models for both core and non-core wetland surveys conducted in winter of 2022 estimated that Kauaʻi supported the most endemic waterbirds (2,207 [95% credible intervals {CI}: 1,365–3,387]), followed by Oʻahu (1,311 [547–2,761]), Maui (751 [568–1,019]), and the rest of the Hawaiian Islands (402 [176–824]; Table 1). Only Kauaʻi supported all four endemic waterbird species, followed by Oʻahu (three species, excluding highly hybridized koloa maoli), reflecting historical patterns of species distribution and possibly the greater amount of habitat available to waterbirds. The most numerous species based on the global (statewide) five-year average population estimate was the ʻalae keʻokeʻo (1,564 [1,306–1,858]), followed by aeʻo (1,511 [1,317–1,718]), both of which occurred on all six main Hawaiian Islands (Table 1, Figure 1, Appendix I). The global five-year average population estimate for the ʻalae ʻula was 712 (573–876), and on Kauaʻi, the estimate for the koloa maoli was 673 (516–854).

State-space models for surveys conducted only in core wetlands yielded global five-year average population estimates of 918 ʻalae keʻokeʻo (661–1,259), 977 aeʻo (765–1,210), 396 ʻalae ʻula (275–565), and 586 koloa maoli (406–786; Table 1). Relative to both core and non-core survey sites, the estimates of abundance for only core wetlands represented on average 65% of aeʻo, 59% of ʻalae keʻokeʻo, 56% of ʻalae ʻula, and 87% of koloa maoli global population sizes. Global annual counts at core-only sites were highly correlated to the combined (core and non-core) counts in both winter and summer surveys for all four waterbird species, and this relationship was also largely evident at the island-level (Table 2). The exceptions include low correlations observed for both summer and winter counts of aeʻo on the Island of Hawaiʻi (and to a lesser extent, summer counts on Molokaʻi), and for ʻalae keʻokeʻo on Molokaʻi (and to a lesser extent, summer counts on the Island of Hawaiʻi).

State-space estimates of abundance from combined core and non-core wetland sites were relatively similar between summer and winter surveys for ʻalae ʻula and koloa maoli, with the difference between seasonal counts being only 41 (95% CI: 26–57) and 59 (95% CI: 29–90) fewer birds during summer, respectively, as averaged over the 38-year survey period (Figure 2). In contrast, abundance estimates were on average higher in summer for aeʻo and ʻalae keʻokeʻo by 180 (95% CI: 114–246) and 269 (95% CI: 122–417) birds, respectively. However, summer abundances declined significantly relative to winter abundances for all four waterbird species over the 38-year survey period (Figure 3, Appendix II). For aeʻo and ʻalae keʻokeʻo, summer abundances were initially higher than winter abundances but became progressively more similar in successive years (aeʻo: slope = -15.1, $F(1,36) = 66.5$, $P < 0.001$; ʻalae keʻokeʻo: slope = -34.1, $F(1,36) = 72.5$, $P < 0.001$). By 2014, estimated annual summer abundances for ʻalae keʻokeʻo

Table 1. Counts and state-space estimates of abundance (SS mean and 95% credible intervals [CI]) for Hawaiian waterbird winter surveys in 2022, the most recent year of count data, and a five-year average (5-yr avg 2019–2023) at only core and both core and non-core survey sites. Proportion (prop) is the fraction of the five-year average of state-space estimates at core-only wetlands relative to the combined estimate for both core and non-core wetlands. Surveys do not correct for imperfect detectability and represent a minimum population size estimate. Lānaʻi has no core wetland survey sites and Molokaʻi was not surveyed at core wetland sites in 2022; entries for these cells are NA. Hawaiʻi = Island of Hawaiʻi; global = statewide.

	Core wetlands				Core and non-core wetlands combined				
	2022 season only		5-yr avg (2019-2023)		2022 season only		5-yr avg (2019-2023)		
	count	SS mean (95% CI)	count	SS mean (95% CI)	count	SS mean (95% CI)	count	SS mean (95% CI)	prop
Aeʻo, Hawaiian stilt (*Himantopus mexicanus knudseni*)									
Kauaʻi	185	341 (97-805)	228	330 (102-761)	269	454 (180-792)	330	336 (229-483)	0.98
Oʻahu	247	277 (192-385)	273	292 (205-399)	345	414 (290-563)	411	412 (313-535)	0.71
Maui	402	436 (304-616)	414	402 (258-586)	497	529 (421-673)	503	499 (350-669)	0.81
Molokaʻi	NA	347 (7-1,315)	100	NA	128	156 (65-320)	144	142 (114-176)	NA
Lānaʻi	NA	NA	NA	NA	41	41 (30-56)	44	43 (35-52)	NA
Hawaiʻi	8	3 (1-7)	3	3 (1-6)	91	81 (19-221)	77	73 (15-209)	0.04
Global	842	973 (762-1,210)	939	977 (765-1,210)	1,371	1,532 (1,259-1,847)	1,510	1,511 (1,317-1,718)	0.65
ʻAlae keʻokeʻo, Hawaiian coot (*Fulica alai*)									
Kauaʻi	339	369 (116-906)	290	350 (109-843)	590	627 (296-1,156)	555	552 (400-735)	0.63
Oʻahu	238	280 (75-698)	311	305 (89-762)	438	616 (171-1,537)	597	585 (313-998)	0.52
Maui	191	211 (118-373)	298	298 (162-508)	203	222 (147-346)	326	320 (204-468)	0.93
Molokaʻi	NA	3 (0-10)	0	NA	22	29 (18-46)	29	30 (22-41)	NA
Lānaʻi	NA	NA	NA	NA	14	16 (5-37)	14	14 (7-24)	NA
Hawaiʻi	37	30 (16-53)	33	29 (16-50)	76	79 (39-144)	77	76 (54-104)	0.38
Global	805	821 (590-1,129)	932	918 (661-1,259)	1,343	1,600 (1,093-2,208)	1,597	1,564 (1,306-1,858)	0.59
ʻAlae ʻula, Hawaiian gallinule (*Gallinula galeata sandvicensis*)									
Kauaʻi	248	265 (150-455)	277	295 (165-506)	413	428 (349-543)	471	485 (383-611)	0.61
Oʻahu	99	135 (39-315)	104	131 (41-303)	163	281 (86-661)	222	230 (108-437)	0.57
Global	347	356 (248-505)	381	396 (275-565)	576	737 (486-1,069)	693	712 (573-876)	0.56
Koloa maoli, Hawaiian duck (*Anas wyvilliana*)									
Kauaʻi	597	620 (433-838)	530	586 (406-786)	680	698 (540-896)	661	673 (516-854)	0.87

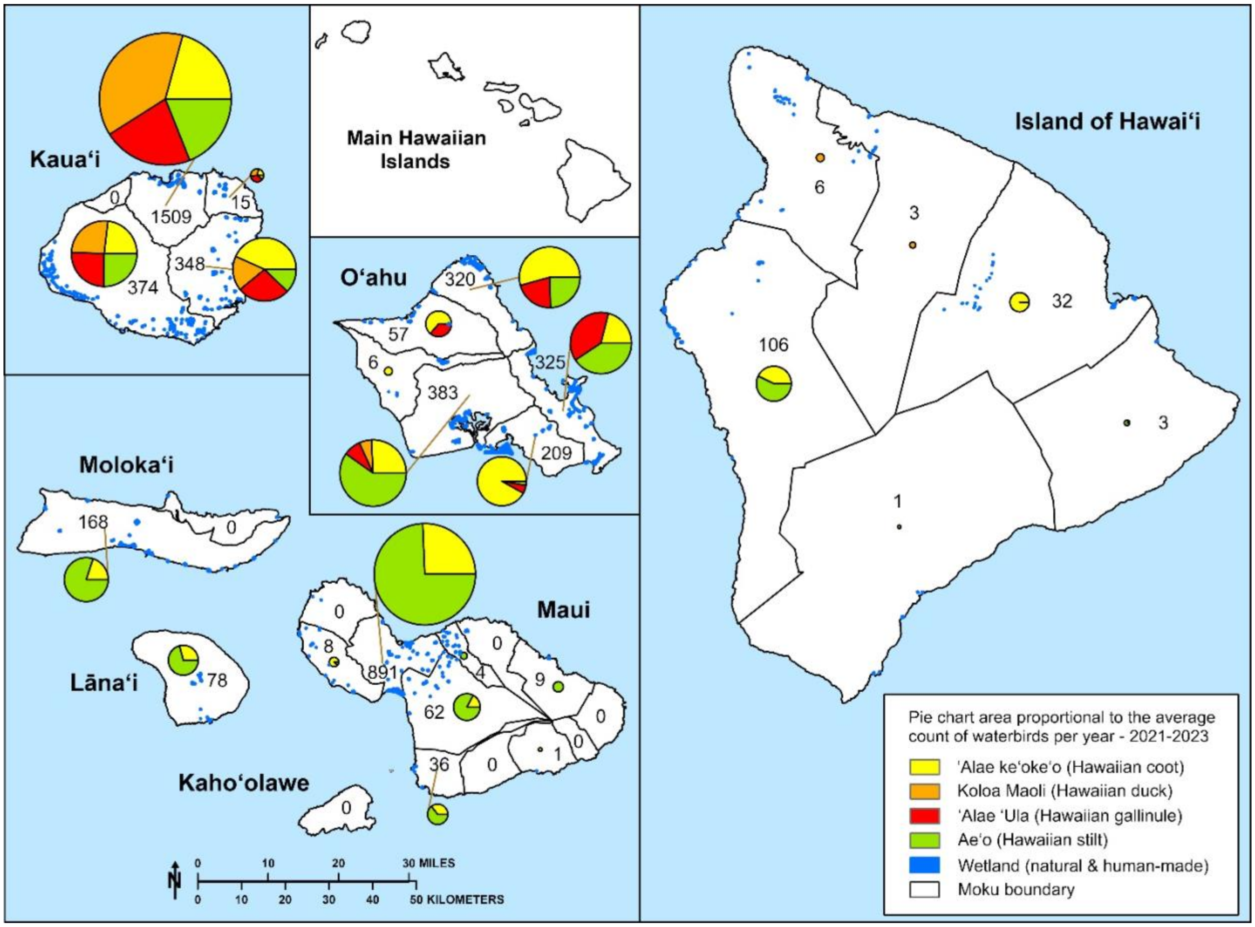

Figure 1. Distribution and abundance of Hawaiian waterbirds as averaged from the winter survey counts for the 2021–2023 period by island and moku (traditional Hawaiian land divisions). Pie charts show the relative proportion that each species contributes to the number of total waterbirds detected per moku (total number shown as number in each moku). Counts by species and island moku are tabulated in Appendix I.

were on average less than that of winter abundances. Estimated summer abundances for ‘alae ‘ula and koloa maoli were initially similar but became increasingly less than winter abundances (‘alae ‘ula: slope = -2.3, $F(1,36) = 14.0$, $P < 0.001$; koloa maoli: slope = -5.8, $F(1,36) = 30.1$, $P < 0.001$).

Trends

Global long-term (1986–2023) trends for both core and non-core wetlands combined indicated increasing population sizes for all four endemic waterbird species, with weak to strong support for positive annual increases ranging from an average of 1.3 to 5.0% (Table 3, Figure 4). Island by island trends were variable, with most species increasing over the 38-year period (Appendix III). An exception to this was ‘alae ke‘oke‘o, which had weak negative trends on the Island of Hawai‘i. Ae‘o and ‘alae ke‘oke‘o had indeterminant (but possibly negative) long-term trends on O‘ahu and Moloka‘i, respectively.

Table 2. Correlation of waterbird counts at core survey sites relative to the combined counts from both core and non-core sites in summer and winter from 1986 to 2023. Hawaiʻi = Island of Hawaiʻi; global = statewide.

	Summer		Winter	
	r	*P*-value	*r*	*P*-value
Aeʻo, Hawaiian stilt (*Himantopus mexicanus knudseni*)				
Kauaʻi	0.84	<0.001	0.95	<0.001
Oʻahu	0.83	<0.001	0.90	<0.001
Maui	0.98	<0.001	0.97	<0.001
Molokaʻi	0.37	0.023	0.68	<0.001
Hawaiʻi	0.06	0.740	0.12	0.460
Global	0.84	<0.001	0.90	<0.001
ʻAlae keʻokeʻo, Hawaiian coot (*Fulica alai*)				
Kauaʻi	0.77	<0.001	0.77	<0.001
Oʻahu	0.71	<0.001	0.88	<0.001
Maui	0.93	<0.001	0.97	<0.001
Molokaʻi	0.27	0.107	0.41	0.010
Hawaiʻi	0.42	0.008	0.59	<0.001
Global	0.59	<0.001	0.81	<0.001
ʻAlae ʻula, Hawaiian gallinule (*Gallinula galeata sandvicensis*)				
Kauaʻi	0.97	<0.001	0.99	<0.001
Oʻahu	0.92	<0.001	0.86	<0.001
Global	0.97	<0.001	0.98	<0.001
Koloa maoli, Hawaiian duck (*Anas wyvilliana*)				
Kauaʻi	0.95	<0.001	0.93	<0.001

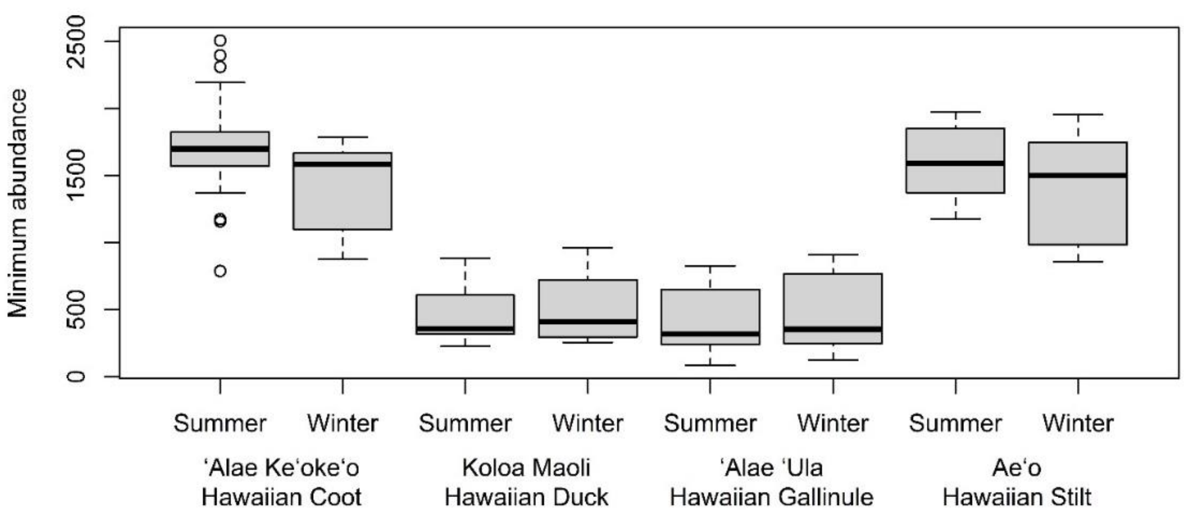

Figure 2. State-space estimates of abundance for the four Hawaiian waterbirds based on the intra-annual summer and winter bird surveys at all islands ("global") at both core and non-core survey sites from 1986–2023. Box plots show the median value (dark bar) within the interquartile range (box), 1.5 times the interquartile range (whiskers), and outliers (open circles). Surveys do not correct for imperfect detectability, and the estimates represent minimum population sizes.

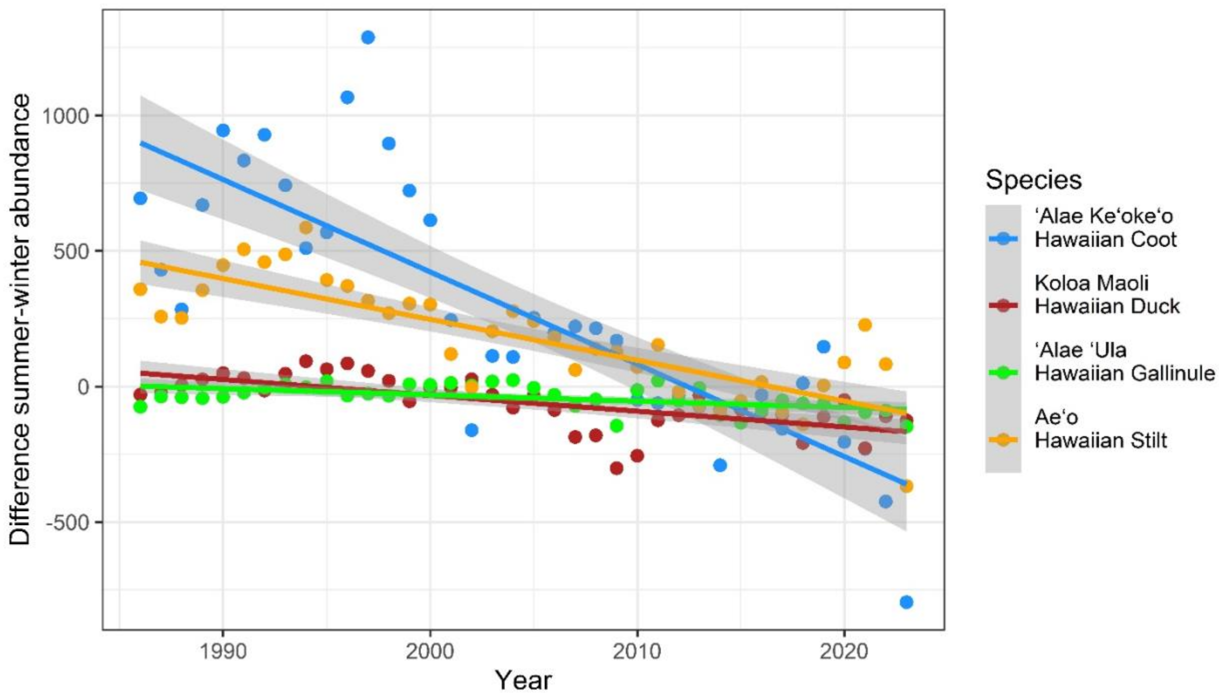

Figure 3. Difference between state-space estimates of abundance from summer and winter surveys for all islands ("global") at both core and non-core wetlands from 1986–2023. Positive values indicate higher estimated summer abundances. Linear models depict the overall trend for each of the four Hawaiian waterbirds. Intra-annual differences in summer and winter survey estimates are tabulated in Appendix II.

Analyses restricted to surveys in only core wetlands demonstrated a similar pattern of positive long-term trends, except for ae'o on the Island of Hawai'i and 'alae ke'oke'o on the Island of Hawai'i and Moloka'i, which showed strong negative trends (Table 4). The difference between estimates for ae'o on the Island of Hawai'i in core and non-core versus core-only wetlands indicates that counts at non-core survey sites contribute markedly to the observed positive trend.

In contrast to the long-term pattern, short-term (2013–2023) recent trends for combined core and non-core wetland counts were almost entirely negative across all species and islands, with 10 of the 18 trend estimates showing strong evidence of declines (Table 3). The sole exceptions were for ae'o on Maui, which demonstrated weak evidence of a positive trend, and 'alae 'ula on O'ahu, which had an indeterminant (but possibly positive) trend.

Short-term (2013–2023) trends in only core wetlands also demonstrated declines in estimated population size (Table 4). Exceptions were for 'alae ke'oke'o on the Island of Hawai'i and koloa maoli on Kaua'i, both of which showed weak evidence of increasing abundance. The difference relative to the trends observed in the combined core and non-core wetlands indicated that much of the declines for both species had occurred in the non-core wetlands.

Table 3. State-space average annual population trends of Hawaiian waterbirds for 11-year (2013–2023) and 38-year (1986–2023) periods based on winter surveys at both core and non-core wetlands. Tabulated for each species and island are the average population change for each period, the 95% credible interval (CI) of that slope, and an equivalency test to determine support for change in population abundance of 25% over 25 years. Global estimates are for all islands combined; Hawai‘i is Island of Hawai‘i. The posterior distribution for an equivalency test of > 0.5 is weak evidence (single arrow), > 0.7 is strong evidence (two arrows), and > 0.9 is very strong evidence (three arrows) for a decreasing (dec), stable (stbl), or increasing (inc) population. If all values are < 0.5, then the results are indeterminate (ind).

	11-yr slope (95% CI)		Equivalency test				38-yr slope (95% CI)		Equivalency test			
			dec	stbl	inc	trend			dec	stbl	inc	trend
Ae‘o, Hawaiian stilt (*Himantopus mexicanus knudseni*)												
Kaua‘i	-0.049	(-0.323–0.190)	0.64	0.08	0.28	↓	0.065	(-0.035–0.161)	0.04	0.03	0.92	↑↑↑
O‘ahu	-0.034	(-0.166–0.122)	0.72	0.10	0.18	↓↓	-0.007	(-0.062–0.048)	0.41	0.36	0.23	ind
Maui	0.008	(-0.228–0.232)	0.41	0.08	0.51	↑	0.026	(-0.057–0.109)	0.17	0.16	0.68	↑
Moloka‘i	-0.041	(-0.171–0.088)	0.75	0.10	0.14	↓↓	0.071	(-0.117–0.239)	0.13	0.05	0.82	↑↑
Lāna‘i	-0.081	(-0.212–0.051)	0.89	0.04	0.07	↓↓	0.077	(-0.073–0.218)	0.11	0.06	0.83	↑↑
Hawai‘i	-0.083	(-0.811–0.712)	0.63	0.03	0.34	↓	0.031	(-0.224–0.295)	0.32	0.08	0.60	↑
Global	-0.025	(-0.099–0.064)	0.68	0.15	0.17	↓	0.016	(-0.022–0.054)	0.07	0.28	0.66	↑
‘Alae ke‘oke‘o, Hawaiian coot (*Fulica alai*)												
Kaua‘i	-0.031	(-0.212–0.141)	0.62	0.11	0.27	↓	0.031	(-0.059–0.118)	0.11	0.11	0.78	↑↑
O‘ahu	-0.026	(-0.387–0.320)	0.52	0.06	0.41	↓	0.008	(-0.174–0.181)	0.34	0.13	0.53	↑
Maui	-0.086	(-0.389–0.187)	0.72	0.05	0.23	↓↓	0.016	(-0.139–0.163)	0.34	0.10	0.55	↑
Moloka‘i	-0.107	(-0.290–0.102)	0.87	0.03	0.10	↓↓	-0.006	(-0.102–0.096)	0.46	0.18	0.36	ind
Lāna‘i	-0.017	(-0.457–0.410)	0.51	0.05	0.45	↓	0.047	(-0.193–0.294)	0.28	0.08	0.64	↑
Hawai‘i	-0.043	(-0.236–0.156)	0.71	0.07	0.22	↓↓	-0.014	(-0.173–0.148)	0.51	0.15	0.34	↓
Global	-0.040	(-0.147–0.058)	0.76	0.12	0.12	↓↓	0.013	(-0.044–0.063)	0.14	0.24	0.62	↑
‘Alae ‘ula, Hawaiian gallinule (*Gallinula galeata sandvicensis*)												
Kaua‘i	-0.049	(-0.190–0.098)	0.76	0.09	0.16	↓↓	0.056	(-0.057–0.170)	0.10	0.08	0.82	↑↑
O‘ahu	0.004	(-0.390–0.398)	0.44	0.07	0.49	ind	0.053	(-0.057–0.160)	0.07	0.05	0.88	↑↑
Global	-0.038	(-0.152–0.090)	0.76	0.10	0.15	↓↓	0.043	(-0.030–0.108)	0.06	0.08	0.87	↑↑
Koloa maoli, Hawaiian duck (*Anas wyvilliana*)												
Kaua‘i	-0.043	(-0.169–0.108)	0.75	0.09	0.17	↓↓	0.050	(-0.038–0.133)	0.07	0.08	0.84	↑↑

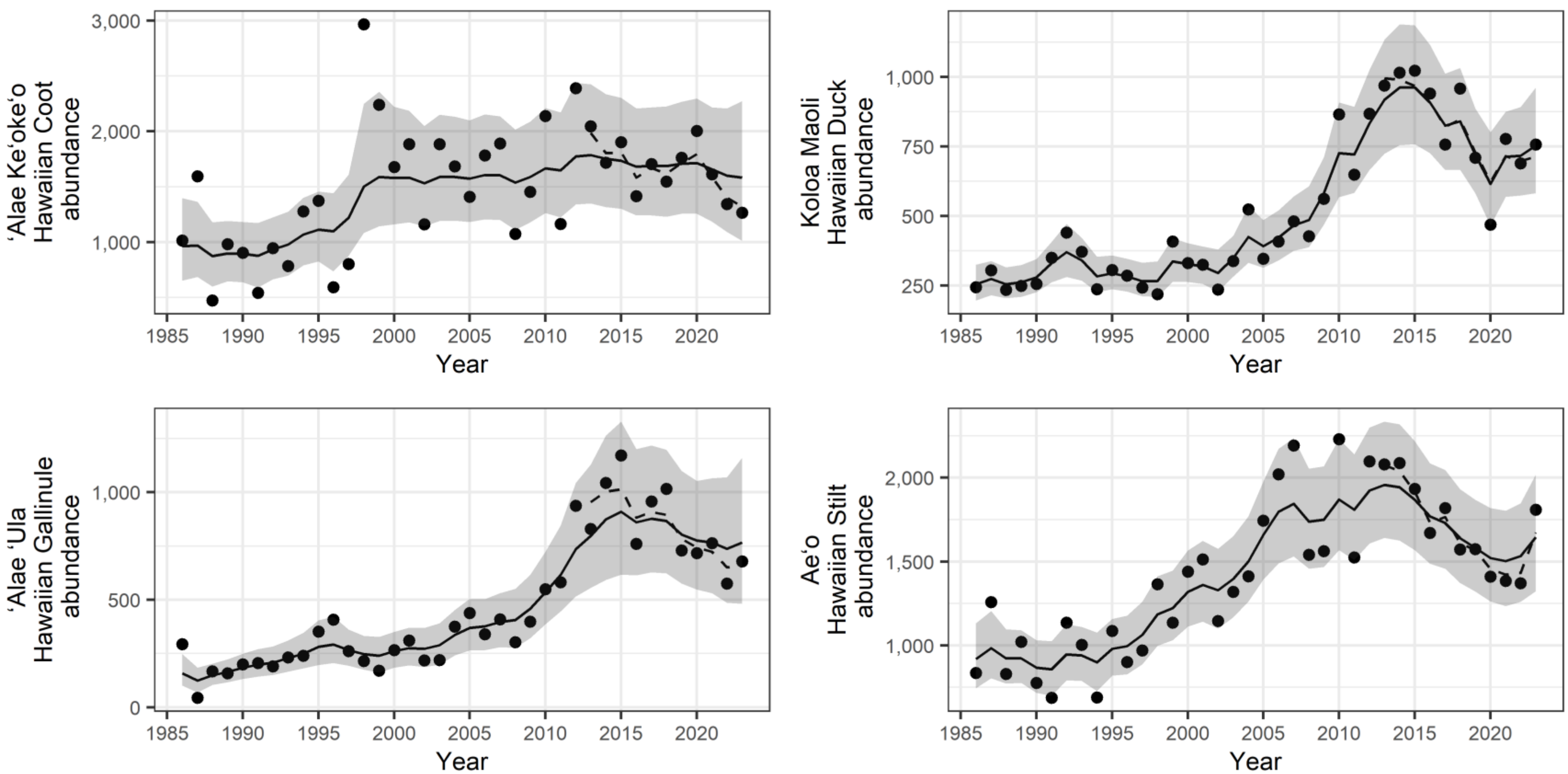

Figure 4. Annual counts (points) and state-space estimates of minimum population size (black line) and 95% credible intervals (shaded area) for four Hawaiian waterbird species based on winter surveys at all islands ("global") at both core and non-core wetlands from 1986–2023. Dotted lines represent the state-space average estimates for the short-term 11-year (2013–2023) trends. Surveys do not correct for imperfect detectability and represent a minimum population size estimate. Winter survey counts and estimates are tabulated in Appendix II.

Table 4. State-space average annual population trends of Hawaiian waterbirds for 11-year (2013–2023) and 38-year (1986–2023) periods based on winter surveys at only core wetlands. Tabulated for each species and island are the average population change for each period, the 95% credible interval (CI) of that slope, and an equivalency test to determine support for change in population abundance of 25% over 25 years. Global estimates are for all islands combined; Hawai‘i is Island of Hawai‘i. The posterior distribution for an equivalency test of > 0.5 is weak evidence (single arrow), > 0.7 is strong evidence (two arrows), and > 0.9 is very strong evidence (three arrows) for a decreasing (dec), stable (stbl), or increasing (inc) population. If all values are < 0.5, then the results are indeterminate (ind). Note that Lāna‘i is excluded because it does not have core wetlands.

	11-yr slope (95% CI)		Equivalency test dec	stbl	inc	trend	38-yr slope (95% CI)		Equivalency test dec	stbl	inc	trend
Ae‘o, Hawaiian stilt (*Himantopus mexicanus knudseni*)												
Kaua‘i	-0.025	(-0.318–0.267)	0.55	0.07	0.38	↓	0.104	(-0.026–0.237)	0.03	0.02	0.95	↑↑↑
O‘ahu	-0.058	(-0.209–0.122)	0.80	0.06	0.14	↓↓	-0.011	(-0.078–0.057)	0.47	0.31	0.22	ind
Maui	0.016	(-0.285–0.306)	0.42	0.07	0.51	↑	0.023	(-0.091–0.141)	0.23	0.14	0.63	↑
Moloka‘i	-0.043	(-1.794–1.606)	0.51	0.02	0.47	↓	0.095	(-0.138–0.302)	0.11	0.03	0.86	↑↑
Hawai‘i	-0.006	(-0.824–0.778)	0.47	0.04	0.50	ind	-0.062	(-0.189–0.075)	0.85	0.05	0.10	↓↓
Global	-0.025	(-0.163–0.123)	0.62	0.12	0.27	↓	0.011	(-0.027–0.050)	0.09	0.34	0.58	↑
‘Alae ke‘oke‘o, Hawaiian coot (*Fulica alai*)												
Kaua‘i	-0.039	(-0.253–0.136)	0.65	0.08	0.27	↓	0.075	(-0.119–0.266)	0.14	0.05	0.81	↑↑
O‘ahu	-0.084	(-0.598–0.410)	0.67	0.04	0.29	↓	-0.007	(-0.200–0.163)	0.43	0.13	0.44	ind
Maui	-0.099	(-0.427–0.215)	0.75	0.04	0.21	↓↓	0.014	(-0.180–0.200)	0.37	0.09	0.54	↑
Moloka‘i	-0.427	(-2.498–1.796)	0.77	0.01	0.22	↓↓	-0.085	(-0.279–0.084)	0.86	0.04	0.09	↓↓
Hawai‘i	0.035	(-0.377–0.417)	0.33	0.06	0.61	↑	-0.035	(-0.121–0.051)	0.78	0.11	0.11	↓↓
Global	-0.072	(-0.230–0.067)	0.85	0.06	0.09	↓↓	0.003	(-0.073–0.073)	0.30	0.25	0.45	ind
‘Alae ‘ula, Hawaiian gallinule (*Gallinula galeata sandvicensis*)												
Kaua‘i	-0.063	(-0.235–0.118)	0.77	0.07	0.16	↓↓	0.079	(-0.149–0.306)	0.20	0.06	0.74	↑↑
O‘ahu	-0.054	(-0.633–0.532)	0.59	0.04	0.37	↓	0.061	(-0.062–0.177)	0.07	0.05	0.88	↑↑
Global	-0.083	(-0.216–0.058)	0.88	0.04	0.08	↓↓	0.059	(-0.077–0.196)	0.15	0.07	0.78	↑↑
Koloa maoli, Hawaiian duck (*Anas wyvilliana*)												
Kaua‘i	0.014	(-0.157–0.185)	0.31	0.16	0.53	↑	0.065	(0.005–0.111)	0.01	0.01	0.97	↑↑↑

Discussion

This report incorporated seven additional years (2017–2023) of survey data to update information on the status of the waterbirds previously examined by Paxton *et al.* (2021) for the 1986–2016 period. Hawaiian waterbird population sizes have increased since the mid-1980s, and the direction and strength of trends over the 38-year (1986–2023) period of monitoring are largely unchanged with the addition of the 2017–2023 survey data. The exceptions include an apparent weakening of the positive trends of aeʻo observed on the Island of Hawaiʻi and globally. Similarly, ʻalae keʻokeʻo trends on Molokaʻi shifted from a positive trend to an indeterminate result and also weakened globally despite improving on Oʻahu. On the other hand, the positive long-term trends for ʻalae ʻula and koloa maoli remained unchanged with inclusion of the new survey data.

In contrast to long-term survey results, recent (2013–2023) short-term tends were almost entirely negative or indeterminate and represent a more pronounced decline in the population size estimates of the four species compared to the 2006–2016 analysis of Paxton *et al.* (2021). Despite the more recent reversal in estimated population sizes, the overall distribution and proportional abundance of waterbirds by island and moku in 2021–2023 (Figure 1) showed little to no change from that reported for 2014–2016 by Paxton *et al.* (2021). Global counts at core survey sites were also highly correlated to that of all sites (i.e., core and non-core combined) and, as noted in Paxton *et al.* (2021), indicate that statewide population estimates and trends obtained from sampling core sites were generally representative of all available waterbird habitat. However, the exceptions noted for aeʻo and ʻalae keʻokeʻo indicate that habitats at non-core sites may benefit from enhanced survey effort on the Island of Hawaiʻi and Molokaʻi for both species.

Wetland habitat availability and ecosystem function reflect factors such as substrate age and climate (Delgado-Baquerizo *et al.* 2020) and the effects of historical land use (Cuddihy and Stone 1990, Lee and Lincoln 2023). Wetland habitat, particularly in coastal areas, is limited on Molokaʻi, Lānaʻi, and the Island of Hawaiʻi compared to Kauaʻi, Oʻahu, and Maui (e.g., coastal wetland: 40 km^2, 0 km^2, 6 km^2, 86 km^2, 44 km^2, 36 km^2, respectively; van Rees and Reed 2014). The relatively large wetland base on Kauaʻi, Oʻahu, and Maui support almost the entire global population of aeʻo (2023 state-space mean = 1,646), with abundance on the other islands amounting to only about 300 birds. Short-term trends were mixed for counts on Kauaʻi, Oʻahu, and Maui, and are notable for the weak upward trend detected for aeʻo on Maui after an initial rapid decline during the 2013–2023 period. The 600-bird difference between the global 2003 state-space estimate at the core and the estimate for the combined core and non-core count indicates that non-core sites harbored over one-third of the aeʻo population statewide. Likewise, the non-core wetland on the Island of Hawaiʻi, primarily consisting of human-made habitat, supported nearly the entirety of the island's population of aeʻo.

ʻAlae keʻokeʻo on Kauaʻi and Oʻahu together comprise about two-thirds of the global population (2022 state-space mean = 1,600), and core wetlands appear to support a little over one-half of the statewide population. Although recent short-term trends were weakly negative with variable inter-annual abundances, the pattern was in the context of a stable to positive long-term trend for the species over the past 25 years. In contrast, Maui supports a smaller number of individuals (2022 state-space mean = 222), and the population more than halved in the most recent five years of surveys with the species now almost entirely restricted to core wetlands. Populations on Molokaʻi and Lānaʻi together number about 45 birds and demonstrated marked declines in recent years relative to their peak abundance in the early 2010s. Although the population on the Island of Hawaiʻi has also undergone a decline over that period, this appears

to have occurred primarily in the non-core portion of the distribution, with the core wetlands showing weak evidence of an upward trend.

Recent ʻalae ʻula counts reflect a marked reversal to the steady increase in population size observed over the past 38 years of monitoring. Negative trends for the 2013–2023 period were particularly evident for Kauaʻi which had previously shown very strong evidence of a positive trend for the 2006–2016 period (Paxton *et al.* 2021). Core wetlands support about one-half of the global population (2022 state-space mean = 737), but recent downward trends in that habitat were more pronounced than that of the combined core and non-core sites, indicating that waterbird abundance in core habitat may be declining at a higher rate than at non-core sites. Moreover, ʻalae ʻula are behaviorally cryptic and limited survey coverage of lotic habitats such as upland streams, irrigation ditches, and drainage infrastructure may under-sample the species' distribution and abundance compared to open wetland habitat. The relatively wide credible intervals for population estimates derive in part from the difficulty of detecting secretive individuals during visual and aural surveys, and counts are known to underestimate true population size (DesRochers *et al.* 2008).

The 2022 state-space estimate for koloa maoli (mean = 698) represents a 30% decline in the population size relative to the 2016 estimate of 1,002 birds reported in Paxton *et al.* (2021). These numbers are considerably lower than that of the 2,500 birds estimated by Engilis and Pratt (1993). However, as noted in Paxton *et al.* (2021; citing Engilis and Pratt 1993), the species can breed in mountain streams, bogs, and ponds that are not readily surveyed. Although the population estimate at core survey sites comprised 89% of the estimate for all sample sites and counts over the 38-year period of monitoring were highly correlated, these results may simply indicate that the surveys at non-core sites are not sampling koloa maoli resident in less accessible montane habitats.

The observed long-term increase in Hawaiian waterbird populations reflect the results of past and on-going wetland restoration, protection, and management (USFWS 2011), as well as the variable contribution of human-made aquatic habitats such as aquaculture, drainage infrastructure, and wastewater treatment facilities (van Rees *et al.* 2018). But recent population declines indicate that several factors may be countering the accrued benefits of these habitat gains. The preponderance of historical wetland loss in the State of Hawaii has occurred along the coastal plains (van Rees and Reed 2014), and the correlation between waterbird abundance and the available extent of coastal wetlands implies that human population growth, urban development, and the demands on water resources may increasingly limit wetland habitat quantity, quality, and connectivity (e.g., for ʻalae ʻula; van Rees *et al.* 2018). Moreover, there has been a significant decline across the Hawaiian Islands from 1982 to 2019 in the normalized difference vegetation index (NDVI), a metric of plant health associated with precipitation (Madson *et al.* 2023) and groundwater flow to perennial wetland vegetation (e.g., White *et al.* 2016). The "browning" of vegetation cover as measured by NDVI occurred in almost all months, but especially during the wet season month of March through the summer months (Madson *et al.* 2023). Stream baseflow has also trended downward since the early 1940s (Oki 2004), consistent with a long-term decline in annual rainfall and increasing drought severity in much of the Hawaiian Islands (Frazier *et al.* 2022).

The observed long-term trend towards lower waterbird counts in the summer relative to winter surveys, particularly for ʻalae keʻokeʻo and aeʻo, is noteworthy as it indicates that changes in the timing and amount of rainfall and the ensuing effects on habitat availability and quality may be affecting the seasonal patterns of waterbird distribution. For example, given the capacity for year-round breeding by ʻalae keʻokeʻo (Shallenberger 1977, Engilis and Pratt 1993) and downward trends in rainfall, breeding activity may shift to some extent from drier summer periods to relatively wetter winter months. Areas that serve as supplemental habitat to birds

displaced during dry periods by limited wetland resources may also contribute to the trend towards lower summer counts. For example, satellite tracking of aeʻo reveals extensive use of non-wetland habitats at upland locations such as sports, agricultural, and aquaculture fields (Kawasaki *et al.* 2020), and these atypical habitats may be omitted during surveys. While atypical habitats (inclusive of human-made aquatic habitats) may support an important and substantial fraction of waterbird populations, long-term management to restore and enhance core wetland habitat for endangered waterbirds remains a key conservation priority (USFWS 2011, VanderWerf 2024).

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APPENDIX I

Appendix I, Table. Average of Hawaiian waterbird counts surveyed annually during the winter from 2021–2023 by island and moku (traditional Hawaiian land divisions). Values are graphically presented in Figure 1.

Island	Moku	Aeʻo, Hawaiian stilt	ʻAlae keʻokeʻo, Hawaiian coot	ʻAlae ʻula, Hawaiian gallinule	Koloa maoli, Hawaiian duck	Total
Hawaiʻi	Hāmākua	0.0	0.0	0.0	3.2	3.2
Hawaiʻi	Hilo	0.0	31.6	0.0	0.4	32.0
Hawaiʻi	Kaʻū	0.0	0.0	0.0	1.0	1.0
Hawaiʻi	Kohala	0.0	0.0	0.0	5.6	5.6
Hawaiʻi	Kona	60.8	45.4	0.0	0.2	106.4
Hawaiʻi	Puna	2.4	0.2	0.0	0.0	2.6
Kahoʻolawe	Honuaʻula	0.0	0.0	0.0	0.0	0.0
Kauaʻi	Haleleʻa	285.8	312.8	333.0	577.0	1,508.6
Kauaʻi	Kona	94.0	86.6	95.2	97.8	373.6
Kauaʻi	Koʻolau	1.6	3.2	5.6	4.4	14.8
Kauaʻi	Nāpali	0.0	0.0	0.0	0.0	0.0
Kauaʻi	Puna	42.6	150.6	93.4	61.6	348.2
Lānaʻi	Lānaʻi	55.0	22.6	0.0	0.0	77.6
Maui	Hāmākualoa	0.0	0.0	0.0	0.0	0.0
Maui	Hāmākuapoko	4.0	0.0	0.0	0.0	4.0
Maui	Hāna	0.0	0.0	0.0	0.0	0.0
Maui	Honuaʻula	23.2	12.8	0.0	0.0	36.0
Maui	Kāʻanapali	0.0	0.0	0.0	0.0	0.0
Maui	Kahikinui	0.0	0.0	0.0	0.0	0.0
Maui	Kaupō	0.0	1.2	0.0	0.0	1.2
Maui	Kīpahulu	0.0	0.0	0.0	0.0	0.0
Maui	Koʻolau	9.2	0.0	0.0	0.0	9.2
Maui	Kula	51.4	10.6	0.0	0.0	62.0
Maui	Lāhainā	1.0	6.8	0.0	0.0	7.8
Maui	Pūʻali	662.6	228.8	0.0	0.0	891.4
Molokaʻi	Kona	134.2	33.4	0.0	0.0	167.6
Molokaʻi	Koʻolau	0.0	0.0	0.0	0.0	0.0
Niʻihau	Kona	0.0	0.0	0.0	0.0	0.0
Oʻahu	ʻEwa	229.2	98.8	32.2	23.0	383.2
Oʻahu	Kona	5.6	191.6	11.4	0.0	208.6
Oʻahu	Koʻolauloa	78.6	174.0	67.6	0.2	320.4
Oʻahu	Koʻolaupoko	132.2	68.4	124.4	0.0	325.0
Oʻahu	Waialua	0.2	36.6	20.6	0.0	57.4
Oʻahu	Waiʻanae	0.0	5.6	0.0	0.0	5.6

APPENDIX II

Appendix II, Tables 1–4. Biannual Hawaiian waterbird survey counts and state-space estimates of abundance (SS mean and 95% credible intervals [lower, upper]) for summer and winter global (statewide) surveys at core and non-core wetlands from 1986 to 2023. Column "Diff" is the within-year difference in the SS mean values between summer and winter surveys. Positive values indicate higher estimated summer abundances. Values for winter surveys are graphically presented in Figure 4.

Appendix II, Table 1. ʻAlae keʻokeʻo (Hawaiian coot, *Fulica alai*)

Year	Season	Count	SS mean	Lower	Upper	Season	Count	SS mean	Lower	Upper	Diff
1986	Summer	1,799	1,660	1,215	2,119	Winter	1,014	965	653	1,398	695
1987	Summer	1,369	1,403	1,088	1,816	Winter	1,594	972	688	1,365	431
1988	Summer	836	1,159	807	1,703	Winter	474	875	600	1,179	284
1989	Summer	1,660	1,569	1,222	1,949	Winter	982	900	648	1,191	670
1990	Summer	2,082	1,841	1,384	2,309	Winter	905	896	639	1,183	945
1991	Summer	1,607	1,711	1,357	2,155	Winter	543	877	592	1,173	834
1992	Summer	2,024	1,864	1,434	2,314	Winter	946	935	667	1,226	929
1993	Summer	1,708	1,723	1,357	2,150	Winter	784	981	699	1,277	742
1994	Summer	1,401	1,580	1,232	2,072	Winter	1,279	1,069	791	1,402	511
1995	Summer	1,483	1,683	1,316	2,191	Winter	1,375	1,114	827	1,457	569
1996	Summer	2,305	2,166	1,668	2,706	Winter	593	1,099	739	1,442	1,067
1997	Summer	2,851	2,509	1,803	3,207	Winter	804	1,221	878	1,610	1,288
1998	Summer	2,475	2,399	1,804	3,027	Winter	2,967	1,502	1,084	2,249	896
1999	Summer	2,383	2,313	1,762	2,916	Winter	2,241	1,590	1,143	2,358	723
2000	Summer	2,385	2,195	1,678	2,754	Winter	1,680	1,581	1,161	2,223	614
2001	Summer	1,883	1,828	1,442	2,272	Winter	1,886	1,582	1,179	2,187	246
2002	Summer	997	1,370	973	1,952	Winter	1,163	1,532	1,144	2,050	-161
2003	Summer	1,835	1,701	1,326	2,106	Winter	1,884	1,589	1,192	2,150	113
2004	Summer	1,629	1,697	1,344	2,127	Winter	1,684	1,589	1,193	2,134	109
2005	Summer	1,906	1,828	1,436	2,276	Winter	1,409	1,575	1,183	2,101	253
2006	Summer	1,800	1,806	1,428	2,253	Winter	1,782	1,607	1,205	2,152	199
2007	Summer	1,872	1,826	1,432	2,281	Winter	1,891	1,604	1,202	2,135	222
2008	Summer	1,720	1,753	1,395	2,191	Winter	1,076	1,538	1,111	2,017	215
2009	Summer	1,818	1,758	1,381	2,197	Winter	1,456	1,589	1,180	2,089	169
2010	Summer	1,544	1,618	1,283	2,043	Winter	2,140	1,668	1,263	2,212	-50

Year	Season	Count	SS mean	Lower	Upper	Season	Count	SS mean	Lower	Upper	Diff
2011	Summer	1,483	1,588	1,260	2,002	Winter	1,166	1,649	1,223	2,172	-62
2012	Summer	1,848	1,744	1,353	2,171	Winter	2,391	1,775	1,341	2,439	-31
2013	Summer	1,827	1,711	1,327	2,132	Winter	2,045	1,785	1,349	2,427	-74
2014	Summer	1,265	1,461	1,145	1,890	Winter	1,718	1,752	1,317	2,337	-291
2015	Summer	1,646	1,605	1,267	1,992	Winter	1,904	1,735	1,303	2,304	-129
2016	Summer	1,724	1,650	1,290	2,055	Winter	1,415	1,682	1,244	2,207	-32
2017	Summer	1,399	1,533	1,218	1,946	Winter	1,706	1,689	1,241	2,217	-156
2018	Summer	1,748	1,699	1,319	2,123	Winter	1,546	1,687	1,231	2,226	12
2019	Summer	2,188	1,855	1,333	2,377	Winter	1,762	1,708	1,258	2,268	147
2020	Summer	1,446	1,511	1,182	1,912	Winter	2,003	1,715	1,258	2,296	-205
2021	Summer	1,541	1,427	1,091	1,786	Winter	1,612	1,658	1,185	2,215	-230
2022	Summer	1,271	1,176	900	1,484	Winter	1,343	1,600	1,093	2,208	-424
2023	Summer	575	788	538	1,299	Winter	1,266	1,584	1,014	2,275	-796

Appendix II, Table 2. Koloa maoli (Hawaiian duck, *Anas wyvilliana*)

Year	Season	Count	SS	Lower	Upper	Season	Count	SS	Lower	Upper	Diff
1986	Summer	186	225	137	352	Winter	245	255	197	326	-30
1987	Summer	271	251	163	370	Winter	305	274	216	338	-23
1988	Summer	230	261	172	379	Winter	235	256	206	316	5
1989	Summer	273	289	192	417	Winter	249	263	211	325	26
1990	Summer	346	329	221	481	Winter	257	280	227	345	49
1991	Summer	429	362	241	530	Winter	351	331	263	408	31
1992	Summer	313	356	241	516	Winter	441	371	282	471	-15
1993	Summer	454	387	258	565	Winter	372	341	269	421	47
1994	Summer	394	377	253	547	Winter	237	284	226	354	93
1995	Summer	320	358	243	514	Winter	307	294	238	359	63
1996	Summer	459	369	246	542	Winter	286	284	229	347	85
1997	Summer	315	323	218	463	Winter	244	266	213	332	57
1998	Summer	237	288	188	417	Winter	220	267	210	338	20
1999	Summer	216	282	183	408	Winter	409	337	264	421	-55
2000	Summer	387	322	214	461	Winter	332	328	264	402	-6
2001	Summer	290	315	211	453	Winter	326	319	257	391	-4
2002	Summer	329	322	215	465	Winter	236	296	228	380	27
2003	Summer	270	318	212	458	Winter	338	349	283	429	-31

Year	Season	Count	SS	Lower	Upper	Season	Count	SS	Lower	Upper	Diff
2004	Summer	373	348	232	500	Winter	524	426	333	536	-78
2005	Summer	408	358	237	520	Winter	347	392	315	486	-34
2006	Summer	387	336	225	482	Winter	409	423	341	521	-87
2007	Summer	177	281	174	428	Winter	481	467	376	570	-187
2008	Summer	354	305	195	451	Winter	428	486	388	608	-181
2009	Summer	99	280	136	468	Winter	562	582	469	711	-302
2010	Summer	685	470	315	682	Winter	866	726	568	908	-256
2011	Summer	653	597	401	867	Winter	649	722	584	893	-125
2012	Summer	766	728	474	1,079	Winter	868	834	665	1,025	-106
2013	Summer	1,202	884	534	1,363	Winter	969	918	724	1,133	-33
2014	Summer	924	877	552	1,314	Winter	1,016	962	755	1,189	-85
2015	Summer	1,006	877	560	1,302	Winter	1,023	962	758	1,186	-85
2016	Summer	894	816	536	1,201	Winter	940	908	726	1,115	-91
2017	Summer	724	722	481	1,045	Winter	757	825	665	1,012	-103
2018	Summer	542	632	423	912	Winter	958	841	667	1,033	-209
2019	Summer	616	608	409	876	Winter	710	720	582	886	-112
2020	Summer	601	566	373	826	Winter	469	616	466	801	-50
2021	Summer	260	486	286	751	Winter	777	713	570	875	-228
2022	Summer	770	608	396	889	Winter	689	717	574	891	-110
2023	Summer	619	629	384	963	Winter	757	754	583	961	-125

Appendix II, Table 3. ʻAlae ʻula (Hawaiian gallinule, *Gallinula galeata sandvicensis*)

Year	Season	Count	SS	Lower	Upper	Season	Count	SS	Lower	Upper	Diff
1986	Summer	81	83	64	109	Winter	294	158	101	248	-75
1987	Summer	77	87	69	113	Winter	44	124	69	185	-37
1988	Summer	115	109	86	135	Winter	168	148	104	203	-39
1989	Summer	115	121	97	152	Winter	158	165	117	224	-43
1990	Summer	145	146	117	181	Winter	200	184	132	250	-38
1991	Summer	177	175	138	218	Winter	206	198	142	271	-23
1992	Summer	209	205	162	254	Winter	190	208	150	283	-3
1993	Summer	251	236	184	294	Winter	232	228	166	311	8
1994	Summer	229	247	195	308	Winter	240	249	181	346	-3
1995	Summer	372	300	222	388	Winter	352	281	197	404	19
1996	Summer	250	258	206	323	Winter	407	292	205	422	-34

Year	Season	Count	SS	Lower	Upper	Season	Count	SS	Lower	Upper	Diff
1997	Summer	242	240	190	298	Winter	262	266	194	362	-26
1998	Summer	176	213	166	275	Winter	215	248	175	332	-34
1999	Summer	256	248	196	307	Winter	170	240	161	327	8
2000	Summer	265	267	212	332	Winter	266	261	185	351	6
2001	Summer	309	289	227	357	Winter	310	276	195	371	13
2002	Summer	249	276	220	347	Winter	218	273	188	369	4
2003	Summer	296	307	244	386	Winter	220	289	199	391	18
2004	Summer	395	360	279	451	Winter	375	337	241	452	24
2005	Summer	381	365	285	454	Winter	438	370	265	505	-5
2006	Summer	344	345	274	428	Winter	340	376	266	503	-31
2007	Summer	291	325	257	413	Winter	410	397	281	530	-72
2008	Summer	398	358	281	447	Winter	303	406	277	551	-48
2009	Summer	202	313	214	437	Winter	399	458	321	616	-145
2010	Summer	627	523	403	654	Winter	550	536	387	723	-13
2011	Summer	696	637	492	802	Winter	581	616	446	846	21
2012	Summer	661	683	535	849	Winter	938	736	516	1,043	-53
2013	Summer	886	792	605	989	Winter	829	797	556	1,129	-5
2014	Summer	758	769	609	959	Winter	1,044	875	592	1,264	-105
2015	Summer	777	775	613	967	Winter	1,171	909	618	1,329	-134
2016	Summer	744	773	612	960	Winter	761	860	614	1,200	-87
2017	Summer	873	826	644	1,027	Winter	958	877	628	1,218	-52
2018	Summer	835	804	634	997	Winter	1,016	867	623	1,198	-62
2019	Summer	762	740	585	916	Winter	729	804	575	1,099	-64
2020	Summer	571	645	510	817	Winter	718	776	548	1,053	-131
2021	Summer	688	670	532	832	Winter	764	766	532	1,065	-96
2022	Summer	646	649	512	820	Winter	576	737	486	1,069	-88
2023	Summer	565	619	472	828	Winter	678	767	481	1,161	-148

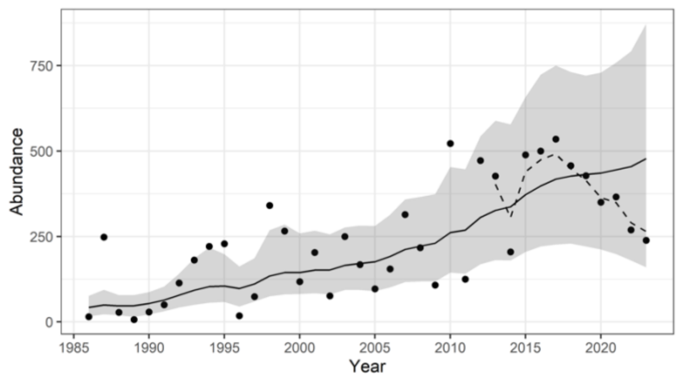
Appendix II, Table 4. Ae‘o (Hawaiian stilt, *Himantopus mexicanus knudseni*)

Year	Season	Count	SS	Lower	Upper	Season	Count	SS	Lower	Upper	Diff
1986	Summer	1,315	1,278	1,058	1,513	Winter	836	919	745	1,132	359
1987	Summer	1,249	1,242	1,055	1,448	Winter	1,259	984	803	1,206	258
1988	Summer	1,026	1,176	984	1,409	Winter	830	923	772	1,096	253
1989	Summer	1,311	1,278	1,097	1,474	Winter	1,022	923	775	1,089	355

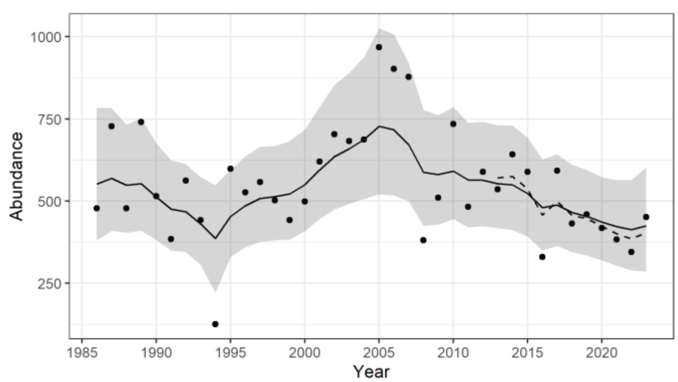
Year	Season	Count	SS	Lower	Upper	Season	Count	SS	Lower	Upper	Diff
1990	Summer	1,306	1,315	1,132	1,517	Winter	777	868	718	1,030	447
1991	Summer	1,380	1,364	1,175	1,575	Winter	687	858	700	1,025	506
1992	Summer	1,429	1,406	1,207	1,629	Winter	1,135	946	792	1,125	459
1993	Summer	1,425	1,428	1,225	1,658	Winter	1,004	940	788	1,109	488
1994	Summer	1,645	1,485	1,253	1,736	Winter	690	898	726	1,076	587
1995	Summer	1,285	1,372	1,181	1,598	Winter	1,086	979	819	1,158	393
1996	Summer	1,318	1,367	1,174	1,587	Winter	900	996	828	1,177	371
1997	Summer	1,302	1,379	1,181	1,606	Winter	970	1,063	887	1,261	317
1998	Summer	1,455	1,457	1,254	1,679	Winter	1,365	1,186	998	1,411	271
1999	Summer	1,550	1,529	1,311	1,765	Winter	1,136	1,223	1,031	1,445	306
2000	Summer	1,846	1,621	1,354	1,918	Winter	1,439	1,319	1,111	1,567	302
2001	Summer	1,473	1,481	1,267	1,717	Winter	1,512	1,361	1,141	1,623	120
2002	Summer	973	1,326	984	1,682	Winter	1,145	1,329	1,101	1,576	-3
2003	Summer	1,664	1,600	1,371	1,843	Winter	1,319	1,396	1,166	1,651	204
2004	Summer	1,873	1,778	1,514	2,069	Winter	1,413	1,500	1,261	1,770	278
2005	Summer	1,996	1,899	1,599	2,222	Winter	1,743	1,658	1,393	1,976	241
2006	Summer	2,154	1,977	1,642	2,335	Winter	2,020	1,797	1,489	2,173	180
2007	Summer	1,902	1,906	1,635	2,213	Winter	2,193	1,845	1,531	2,235	61
2008	Summer	1,851	1,876	1,618	2,175	Winter	1,540	1,737	1,457	2,053	139
2009	Summer	1,826	1,877	1,622	2,184	Winter	1,562	1,750	1,468	2,067	128
2010	Summer	1,997	1,942	1,662	2,246	Winter	2,230	1,870	1,567	2,231	72
2011	Summer	2,048	1,962	1,673	2,277	Winter	1,525	1,809	1,509	2,139	153
2012	Summer	1,889	1,904	1,638	2,207	Winter	2,098	1,923	1,607	2,298	-19
2013	Summer	1,918	1,887	1,619	2,190	Winter	2,079	1,957	1,641	2,335	-71
2014	Summer	1,871	1,853	1,592	2,144	Winter	2,088	1,943	1,626	2,319	-90
2015	Summer	1,828	1,814	1,562	2,090	Winter	1,933	1,867	1,568	2,217	-54
2016	Summer	1,904	1,786	1,525	2,072	Winter	1,670	1,769	1,487	2,085	16
2017	Summer	1,607	1,634	1,403	1,890	Winter	1,819	1,730	1,457	2,047	-96
2018	Summer	1,294	1,500	1,243	1,797	Winter	1,573	1,639	1,373	1,932	-139
2019	Summer	1,604	1,586	1,358	1,833	Winter	1,574	1,583	1,322	1,869	3
2020	Summer	1,558	1,609	1,384	1,866	Winter	1,410	1,520	1,261	1,818	89
2021	Summer	1,988	1,731	1,421	2,076	Winter	1,384	1,504	1,235	1,803	227
2022	Summer	1,843	1,615	1,340	1,902	Winter	1,371	1,532	1,259	1,847	82
2023	Summer	973	1,278	958	1,718	Winter	1,809	1,646	1,322	2,019	-368

APPENDIX III

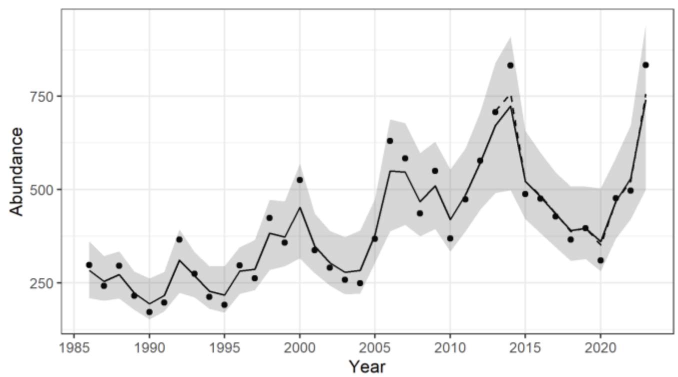
Appendix III, Figures. Annual counts (points) and estimates of mean population size (black line) and 95% credible interval (shaded area) from the 38-year state-space model for the winter period by island for four Hawaiian waterbird species from 1986–2023. Data include survey counts from both core and non-core wetlands. Dotted lines represent the state-space estimates for the short-term 11-year (2013–2023) trends. Survey counts and state-space estimates do not correct for imperfect detectability and represent a minimum population size estimate. Counts and estimates derived from the winter surveys for the 38-year state-space models that are presented in this appendix are tabulated in Appendix IV.



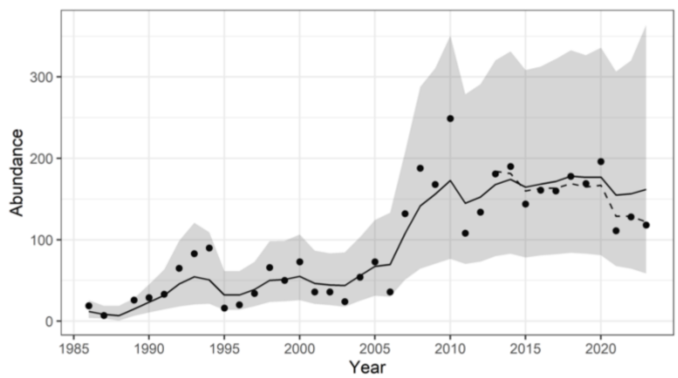
Ae‘o, Hawaiian stilt (*Himantopus mexicanus knudseni*) - Kaua‘i



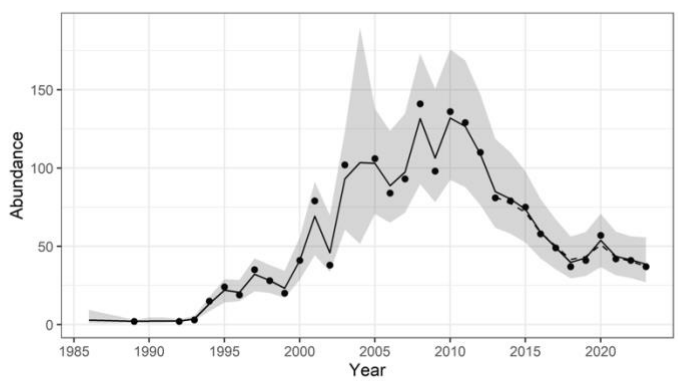
Ae‘o, Hawaiian stilt (*Himantopus mexicanus knudseni*) - O‘ahu



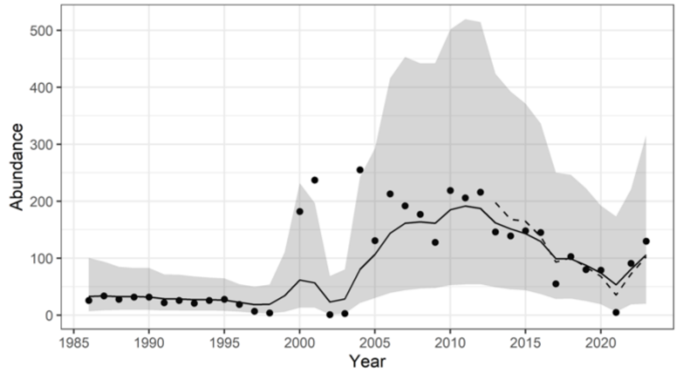
Ae‘o, Hawaiian stilt (*Himantopus mexicanus knudseni*) - Maui



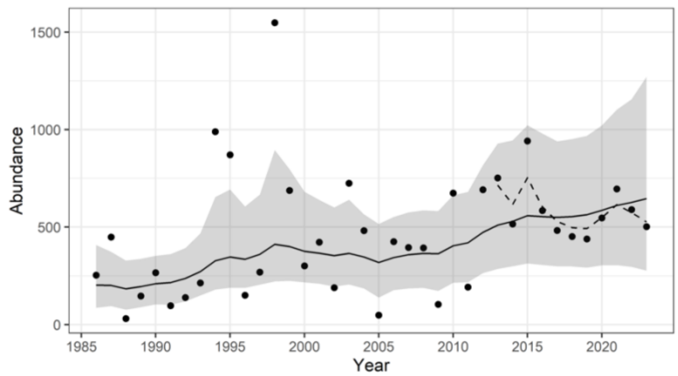
Ae‘o, Hawaiian stilt (*Himantopus mexicanus knudseni*) - Moloka‘i



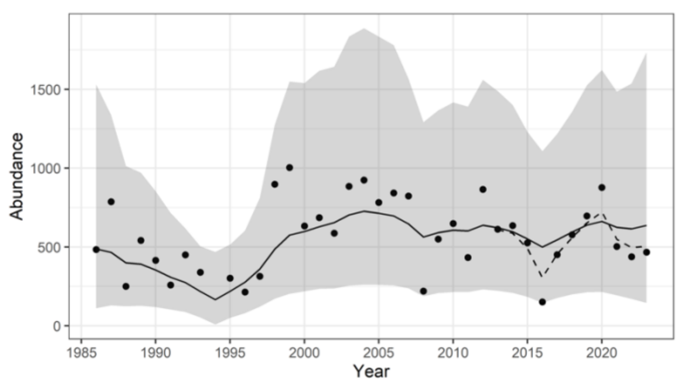
Ae‘o, Hawaiian stilt (*Himantopus mexicanus knudseni*) - Lāna‘i



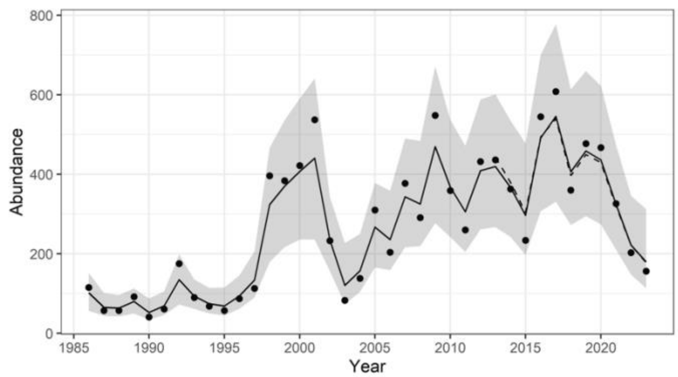
Ae‘o, Hawaiian stilt (*Himantopus mexicanus knudseni*) - Island of Hawai‘i



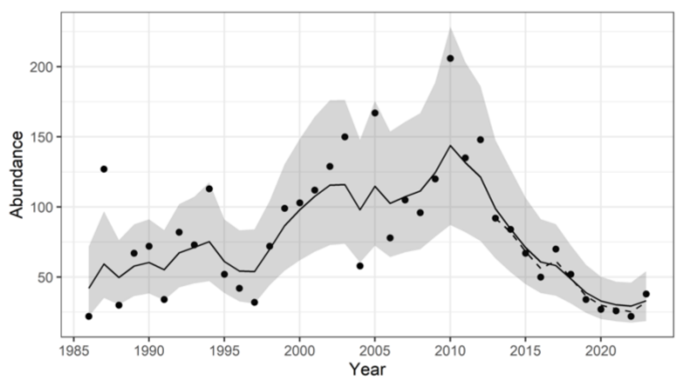
‘Alae ke‘oke‘o, Hawaiian coot (*Fulica alai*) - Kaua‘i



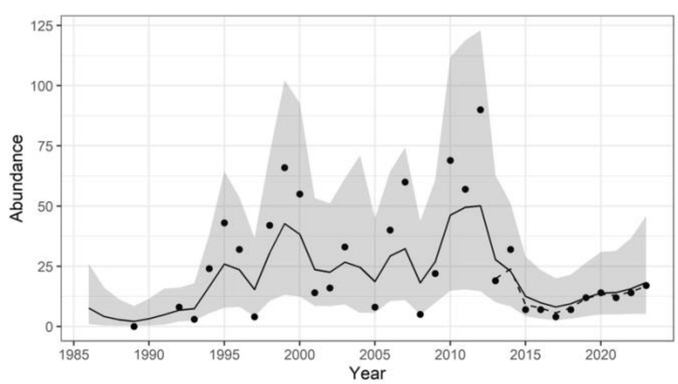
‘Alae ke‘oke‘o, Hawaiian coot (*Fulica alai*) - O‘ahu



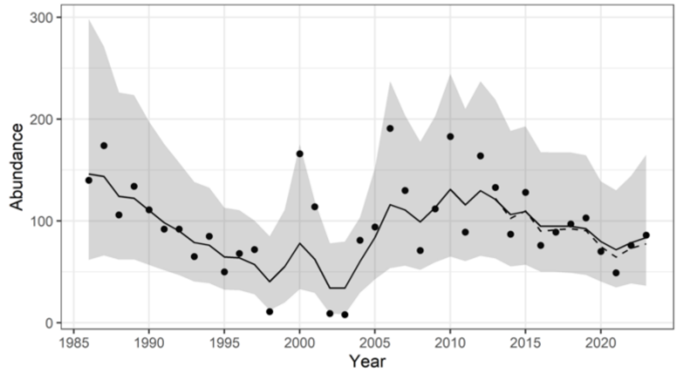
‘Alae ke‘oke‘o, Hawaiian coot (*Fulica alai*) - Maui



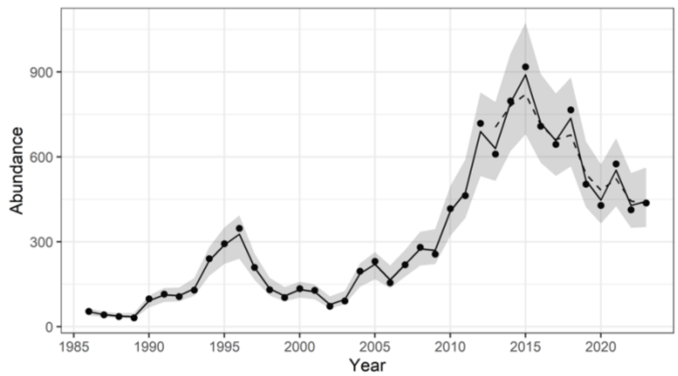
‘Alae ke‘oke‘o, Hawaiian coot (*Fulica alai*) - Moloka‘i



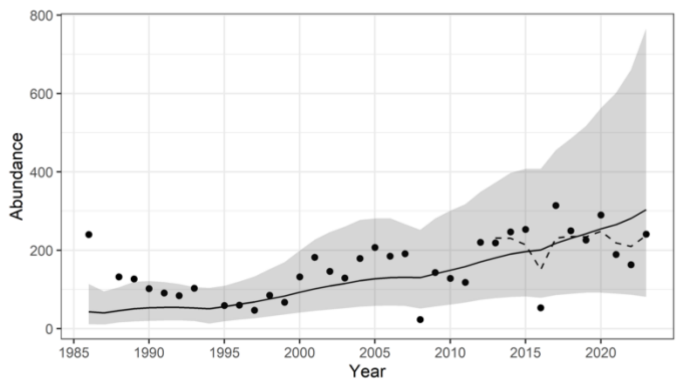
‘Alae ke‘oke‘o, Hawaiian coot (*Fulica alai*) - Lāna‘i



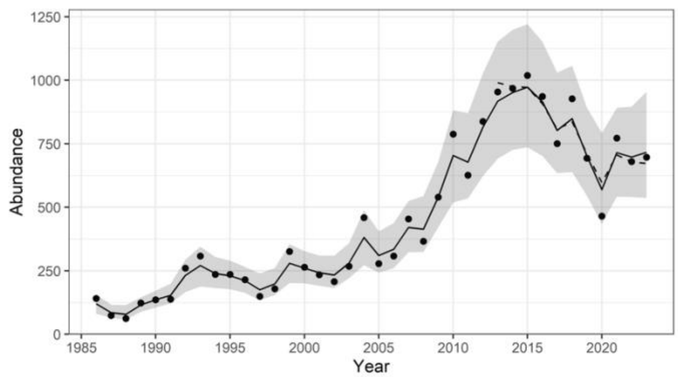
‘Alae ke‘oke‘o, Hawaiian coot (*Fulica alai*) - Island of Hawai‘i



‘Alae ‘ula, Hawaiian gallinule (*Gallinula galeata sandvicensis*) - Kaua‘i



‘Alae ‘ula, Hawaiian gallinule (*Gallinula galeata sandvicensis*) - O‘ahu



Koloa maoli, Hawaiian duck (*Anas wyvilliana*) - Kaua‘i

APPENDIX IV

Appendix IV, Tables. Annual counts and estimates of abundance for the 38-year state-space models (SS mean and 95% credible intervals [lower, upper]) for winter surveys at core and non-core wetlands (combined) from 1986 to 2023. Survey counts and state-space estimates do not correct for imperfect detectability and represent a minimum population size estimate. The island- and species-specific counts and estimates tabulated below are presented graphically in Appendix III.

Ae‘o, Hawaiian stilt (*Himantopus mexicanus knudseni*) - Kaua‘i

Year	Count	SS	Lower	Upper
1986	15	42	16	76
1987	248	50	22	94
1988	28	47	20	78
1989	7	47	15	78
1990	29	54	22	87
1991	50	64	31	104
1992	114	78	42	141
1993	181	93	50	186
1994	221	103	56	218
1995	229	105	59	199
1996	18	98	45	162
1997	74	111	60	187
1998	341	135	75	269
1999	266	144	81	285
2000	118	145	82	259
2001	203	152	84	267
2002	76	152	81	256
2003	250	166	93	277
2004	168	171	93	282
2005	97	176	90	281
2006	155	191	101	314
2007	314	212	117	359
2008	217	221	119	366
2009	108	230	118	374
2010	522	261	144	454
2011	125	268	141	447
2012	472	306	169	543
2013	427	326	181	589
2014	205	337	180	578
2015	489	372	205	658
2016	500	398	221	724
2017	535	418	227	750
2018	457	427	229	731
2019	428	431	221	720
2020	350	436	212	730
2021	366	445	199	759
2022	269	454	180	792
2023	239	478	160	872

Ae‘o, Hawaiian stilt (*Himantopus mexicanus knudseni*) - O‘ahu

Year	Count	SS	Lower	Upper
1986	478	552	381	784
1987	728	569	410	783
1988	478	548	404	733
1989	740	553	410	753
1990	515	513	382	676
1991	385	476	350	625
1992	562	467	345	612
1993	442	431	306	573
1994	126	387	221	549
1995	598	454	330	594
1996	527	486	360	636
1997	558	508	376	666
1998	502	514	381	667
1999	442	522	384	682
2000	499	550	409	717
2001	620	595	445	787
2002	703	635	475	854
2003	682	659	492	889
2004	687	687	507	938
2005	968	727	521	1,025
2006	902	717	517	1,007
2007	878	672	500	919
2008	381	588	425	777
2009	510	580	428	761
2010	735	592	446	786
2011	483	564	420	738
2012	589	563	424	742
2013	536	553	418	731
2014	642	549	412	730
2015	589	523	392	693
2016	330	480	350	627
2017	592	488	364	642
2018	432	466	345	610
2019	460	453	335	595
2020	418	436	320	573
2021	383	422	303	563
2022	345	414	290	563
2023	451	425	286	602

Ae‘o, Hawaiian stilt (*Himantopus mexicanus knudseni*) - Maui

Year	Count	SS	Lower	Upper
1986	298	284	209	361
1987	242	254	202	322
1988	296	272	208	334
1989	215	223	178	281
1990	172	194	153	262
1991	197	216	174	279
1992	366	311	223	393
1993	274	269	211	332
1994	212	227	181	295
1995	191	218	171	295
1996	297	281	221	345
1997	262	286	230	365
1998	424	383	285	473
1999	358	373	295	468
2000	526	452	316	569
2001	337	348	276	436
2002	291	304	243	390
2003	258	279	219	373
2004	249	284	222	390
2005	368	379	304	475
2006	630	550	388	689
2007	584	547	405	679
2008	436	468	375	598
2009	550	511	395	628
2010	369	420	334	554
2011	474	486	389	611
2012	577	572	446	707
2013	708	672	491	840
2014	833	724	498	910
2015	488	522	421	658
2016	476	481	383	599
2017	428	435	346	546
2018	366	390	309	508
2019	396	396	314	508
2020	310	361	282	504
2021	477	468	369	585
2022	497	529	421	673
2023	834	741	500	944

Ae‘o, Hawaiian stilt (*Himantopus mexicanus knudseni*) - Moloka‘i

Year	Count	SS	Lower	Upper
1986	19	12	4	26
1987	7	9	3	19
1988	1	7	1	19
1989	26	15	7	28
1990	29	23	11	45
1991	33	32	14	63
1992	65	46	18	99
1993	83	54	20	121
1994	90	51	21	109
1995	16	32	14	62
1996	20	32	14	61
1997	34	39	19	73
1998	66	50	24	98
1999	50	51	24	99
2000	73	55	26	106
2001	36	46	21	87
2002	36	44	20	83
2003	24	44	18	84
2004	54	56	25	103
2005	73	67	31	124
2006	36	70	30	133
2007	132	108	51	208
2008	188	142	64	288
2009	168	156	70	311
2010	249	173	77	351
2011	108	145	70	279
2012	134	153	73	291
2013	181	168	80	320
2014	190	174	83	331
2015	144	165	78	308
2016	161	168	81	313
2017	160	172	82	322
2018	178	178	84	333
2019	169	177	83	327
2020	196	177	81	336
2021	111	155	68	307
2022	128	156	65	320
2023	118	162	59	364

Ae‘o, Hawaiian stilt (*Himantopus mexicanus knudseni*) - Lāna‘i

Year	Count	SS	Lower	Upper
1986	1	3	1	9
1987	1	3	1	7
1988	1	2	1	5
1989	2	2	1	3
1990	1	2	1	5
1991	1	2	1	5
1992	2	2	2	3
1993	3	4	3	5
1994	15	13	9	18
1995	24	22	14	29
1996	19	21	15	29
1997	35	32	21	42
1998	28	28	20	38
1999	20	23	17	34
2000	41	41	29	56
2001	79	69	44	91
2002	38	46	34	70
2003	102	93	61	123
2004	1	103	51	190
2005	106	103	71	138
2006	84	89	65	124
2007	93	97	71	135
2008	141	132	90	173
2009	98	106	78	151
2010	136	132	92	176
2011	129	127	88	169
2012	110	109	76	147
2013	81	85	62	119
2014	79	80	58	110
2015	75	74	52	98
2016	58	59	42	80
2017	49	49	35	67
2018	37	40	29	56
2019	41	43	31	59
2020	57	54	37	71
2021	42	43	32	59
2022	41	41	30	56
2023	37	39	27	56

Ae‘o, Hawaiian stilt (*Himantopus mexicanus knudseni*) - Island of Hawai‘i

Year	Count	SS	Lower	Upper
1986	26	33	7	101
1987	34	34	9	94
1988	28	32	9	85
1989	32	33	9	83
1990	32	32	9	83
1991	22	29	8	72
1992	26	28	8	71
1993	21	27	8	68
1994	26	27	8	66
1995	28	26	8	65
1996	19	22	6	54
1997	7	19	4	50
1998	4	19	3	54
1999	1	34	6	111
2000	182	62	13	232
2001	237	57	13	197
2002	1	23	1	69
2003	3	29	3	80
2004	255	80	22	242
2005	131	107	30	293
2006	213	144	39	416
2007	192	162	44	453
2008	177	164	47	442
2009	128	161	48	442
2010	219	185	53	502
2011	206	192	54	519
2012	216	187	55	515
2013	146	162	49	424
2014	139	151	46	392
2015	148	143	44	371
2016	145	129	37	336
2017	55	99	28	250
2018	103	99	29	246
2019	80	88	25	223
2020	79	74	19	192
2021	5	54	6	174
2022	91	81	19	221
2023	130	106	20	316

‘Alae ke‘oke‘o, Hawaiian coot (*Fulica alai*) - Kaua‘i

Year	Count	SS	Lower	Upper
1986	253	203	86	408
1987	449	201	95	373
1988	31	183	77	328
1989	147	195	90	337
1990	266	209	103	352
1991	97	216	101	361
1992	139	237	119	392
1993	214	272	150	467
1994	989	327	180	654
1995	871	347	190	692
1996	150	335	188	605
1997	269	360	205	666
1998	1,548	412	222	895
1999	688	401	224	797
2000	301	376	217	681
2001	423	366	210	639
2002	189	353	195	600
2003	725	365	206	641
2004	482	347	185	566
2005	48	319	138	516
2006	426	344	177	552
2007	395	358	186	576
2008	393	365	188	586
2009	104	364	173	582
2010	674	405	215	664
2011	192	419	218	680
2012	692	474	264	817
2013	752	510	285	928
2014	516	530	299	945
2015	942	559	314	1,022
2016	585	554	306	980
2017	483	550	299	940
2018	452	554	298	951
2019	439	563	292	968
2020	547	586	304	1,021
2021	696	611	305	1,102
2022	590	627	296	1,156
2023	502	646	277	1,271

‘Alae ke‘oke‘o, Hawaiian coot (*Fulica alai*) - O‘ahu

Year	Count	SS	Lower	Upper
1986	484	487	113	1,530
1987	787	466	130	1,336
1988	250	399	124	1,013
1989	542	391	128	972
1990	415	354	119	854
1991	259	309	104	717
1992	450	275	88	618
1993	339	218	53	504
1994	1	166	9	468
1995	302	219	50	515
1996	214	278	80	604
1997	314	360	122	812
1998	898	487	172	1,275
1999	1,004	575	203	1,549
2000	633	598	219	1,540
2001	686	629	234	1,618
2002	587	655	237	1,643
2003	885	704	255	1,835
2004	925	727	262	1,887
2005	782	714	260	1,835
2006	843	697	257	1,781
2007	824	647	238	1,568
2008	220	564	187	1,291
2009	550	591	208	1,367
2010	649	607	215	1,417
2011	433	601	215	1,391
2012	865	638	232	1,560
2013	613	622	223	1,489
2014	636	597	209	1,401
2015	526	552	184	1,231
2016	152	499	146	1,108
2017	452	545	177	1,217
2018	578	595	200	1,358
2019	697	639	213	1,526
2020	878	662	215	1,623
2021	503	625	194	1,485
2022	438	616	171	1,537
2023	467	636	146	1,736

‘Alae ke‘oke‘o, Hawaiian coot (*Fulica alai*) - Maui

Year	Count	SS	Lower	Upper
1986	115	102	57	151
1987	57	65	44	101
1988	57	63	42	96
1989	92	80	50	113
1990	41	52	34	88
1991	61	69	46	105
1992	175	135	72	198
1993	90	93	61	135
1994	68	74	50	114
1995	57	69	45	115
1996	87	94	62	146
1997	113	134	90	206
1998	396	324	179	467
1999	384	370	217	536
2000	422	407	236	591
2001	537	441	236	641
2002	233	235	156	343
2003	83	120	73	227
2004	138	157	104	250
2005	310	267	166	378
2006	204	236	159	359
2007	377	343	217	490
2008	291	325	219	484
2009	548	470	277	672
2010	359	368	242	537
2011	260	306	205	472
2012	432	409	262	588
2013	436	420	267	601
2014	363	367	242	535
2015	234	297	197	478
2016	545	492	307	701
2017	608	546	331	778
2018	360	406	272	614
2019	477	459	295	660
2020	467	436	274	623
2021	326	324	210	474
2022	203	222	147	346
2023	156	179	113	312

‘Alae ke‘oke‘o, Hawaiian coot (*Fulica alai*) - Moloka‘i

Year	Count	SS	Lower	Upper
1986	22	42	22	72
1987	127	59	35	97
1988	30	50	30	76
1989	67	58	37	88
1990	72	60	38	91
1991	34	55	33	84
1992	82	67	43	102
1993	73	71	46	107
1994	113	75	47	118
1995	52	61	39	91
1996	42	54	33	83
1997	32	54	31	84
1998	72	70	44	104
1999	99	87	55	131
2000	103	98	62	149
2001	112	108	68	164
2002	129	116	73	176
2003	150	116	74	176
2004	58	98	60	148
2005	167	115	72	176
2006	78	103	64	154
2007	105	107	68	161
2008	96	111	70	167
2009	120	124	79	189
2010	206	144	87	229
2011	135	132	82	203
2012	148	121	76	186
2013	92	99	63	148
2014	84	84	54	127
2015	67	71	45	107
2016	50	61	39	91
2017	70	58	37	88
2018	52	49	31	73
2019	34	39	25	59
2020	27	33	20	50
2021	26	30	18	47
2022	22	29	18	46
2023	38	33	19	54

‘Alae ke‘oke‘o, Hawaiian coot (*Fulica alai*) - Lāna‘i

Year	Count	SS	Lower	Upper
1986	1	8	1	26
1987	1	4	0	16
1988	1	3	0	11
1989	1	2	0	8
1990	1	3	0	12
1991	1	5	1	16
1992	8	7	2	16
1993	3	7	2	18
1994	24	17	6	38
1995	43	26	8	64
1996	32	24	8	54
1997	4	15	4	37
1998	42	31	11	72
1999	66	43	13	102
2000	55	38	12	93
2001	14	24	9	53
2002	16	23	8	51
2003	33	27	9	62
2004	1	25	6	71
2005	8	19	6	45
2006	40	29	11	64
2007	60	32	11	74
2008	5	18	5	44
2009	22	27	10	61
2010	69	46	15	112
2011	57	49	15	119
2012	90	50	15	123
2013	19	28	10	63
2014	32	23	8	51
2015	7	13	4	29
2016	7	10	3	24
2017	4	8	2	20
2018	7	9	3	22
2019	12	12	4	26
2020	14	14	5	31
2021	12	14	5	31
2022	14	16	5	37
2023	17	18	5	46

‘Alae ke‘oke‘o, Hawaiian coot (*Fulica alai*) – Island of Hawai‘i

Year	Count	SS	Lower	Upper
1986	140	146	62	298
1987	174	144	66	271
1988	106	124	62	226
1989	134	122	62	224
1990	111	110	57	198
1991	92	98	52	176
1992	92	90	47	157
1993	65	79	41	138
1994	85	76	39	133
1995	50	65	33	113
1996	68	64	32	111
1997	72	57	28	100
1998	11	40	12	85
1999	1	55	20	111
2000	166	78	33	175
2001	114	62	29	120
2002	9	34	9	78
2003	8	34	8	80
2004	81	60	30	104
2005	94	84	43	152
2006	191	116	54	237
2007	130	111	56	204
2008	71	99	52	178
2009	112	113	59	203
2010	183	131	65	244
2011	89	116	61	210
2012	164	130	66	237
2013	133	121	63	219
2014	87	106	55	188
2015	128	109	57	193
2016	76	95	50	168
2017	89	95	50	167
2018	97	95	49	167
2019	103	92	47	164
2020	70	80	41	139
2021	49	72	35	130
2022	76	79	39	144
2023	86	84	36	165

‘Alae ‘ula, Hawaiian gallinule (*Gallinula galeata sandvicensis*) - Kaua‘i

Year	Count	SS	Lower	Upper
1986	54	53	40	65
1987	42	43	34	53
1988	36	37	30	47
1989	31	35	29	49
1990	98	92	68	109
1991	115	112	87	137
1992	106	110	89	138
1993	129	134	110	172
1994	240	233	180	281
1995	293	289	222	351
1996	347	326	240	393
1997	209	209	166	258
1998	130	134	110	172
1999	103	108	89	140
2000	134	131	103	159
2001	128	124	97	149
2002	72	78	64	107
2003	91	96	79	126
2004	196	187	141	223
2005	231	221	168	264
2006	155	165	136	216
2007	219	219	177	271
2008	280	275	216	335
2009	256	270	221	344
2010	417	408	321	496
2011	463	473	384	590
2012	718	689	532	827
2013	610	629	515	794
2014	797	792	621	966
2015	918	890	680	1,074
2016	708	720	580	893
2017	644	657	533	824
2018	766	736	566	880
2019	503	517	422	654
2020	428	447	365	574
2021	575	553	425	665
2022	413	428	349	543
2023	437	442	352	562

‘Alae ‘ula, Hawaiian gallinule (*Gallinula galeata sandvicensis*) - O‘ahu

Year	Count	SS	Lower	Upper
1986	240	43	12	114
1987	1	40	11	95
1988	132	46	16	106
1989	127	51	18	120
1990	102	53	20	122
1991	91	54	21	119
1992	84	54	21	114
1993	103	53	19	106
1994	1	51	13	104
1995	59	56	19	109
1996	60	62	23	121
1997	47	68	27	133
1998	85	76	32	152
1999	67	83	36	170
2000	132	93	41	200
2001	182	102	45	227
2002	146	109	49	246
2003	129	115	52	261
2004	179	122	56	277
2005	207	127	58	281
2006	185	130	59	282
2007	191	131	58	267
2008	23	130	51	252
2009	143	140	56	281
2010	128	149	61	301
2011	118	158	67	318
2012	220	171	74	349
2013	219	181	78	373
2014	247	190	81	398
2015	253	197	82	407
2016	53	201	79	408
2017	314	218	86	456
2018	250	230	89	485
2019	226	242	92	517
2020	290	255	92	563
2021	189	265	90	602
2022	163	281	86	661
2023	241	304	81	766

Koloa maoli, Hawaiian duck (*Anas wyvilliana*) - Kauaʻi

Year	Count	SS	Lower	Upper
1986	141	120	81	156
1987	74	85	65	116
1988	62	79	58	115
1989	123	116	89	145
1990	136	136	105	171
1991	138	154	122	199
1992	260	232	166	294
1993	308	271	188	345
1994	236	239	182	304
1995	236	230	178	290
1996	215	211	163	265
1997	149	175	135	239
1998	179	198	155	261
1999	326	279	202	355
2000	264	260	201	327
2001	234	242	191	310
2002	207	234	182	309
2003	268	281	221	359
2004	459	381	272	489
2005	278	311	243	406
2006	308	335	260	438
2007	454	421	323	525
2008	366	413	324	544
2009	540	540	421	679
2010	788	704	519	882
2011	626	678	535	870
2012	838	815	623	1,027
2013	954	918	692	1,152
2014	968	952	726	1,198
2015	1,019	973	737	1,221
2016	936	915	702	1,152
2017	751	803	635	1,030
2018	927	849	639	1,057
2019	693	702	545	892
2020	465	569	435	793
2021	772	715	542	892
2022	680	698	540	896
2023	697	716	537	955