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SUPPLEMENTARY INFORMATION

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Rapid morphological change of a top predator with the invasion of a novel prey

Christopher E. Cattau[1], Robert J. Fletcher Jr[1*], Rebecca T. Kimball[2], Christine W. Miller[3] and Wiley M. Kitchens[4]

[1]Department of Wildlife Ecology and Conservation, University of Florida, Gainesville, FL 32611, USA. [2]Department of Biology, University of Florida, Gainesville, FL 32611, USA. [3]Department of Entomology and Nematology, University of Florida, Gainesville, FL 32611, USA. [4]US Geological Survey, Florida Cooperative Fish and Wildlife Research Unit, University of Florida, Gainesville, FL 32611, USA. *e-mail: robert.fletcher@ufl.edu

Supplementary Table 1. Model selection results explaining variation in morphology of fledging-age snail kites in Florida, USA, since the invasion of their range by an exotic apple snail (*Pomacea maculata*), 2005-2012. We modeled size traits using GLMs (Gaussian error, identity link). Covariates included sex, year (as a linear trend), and exotic apple snail presence in the natal wetland. Models for measured bill length also included age effects. For linear size traits, we also considered models including standardized body mass (SBM) (within sex) as a covariate. We compared models using Akaike's Information Criterion corrected for small sample size (AIC_c) and AIC_c weights (w_i). We report model differences (ΔAIC_c) as a measure of comparison.

Trait	Model structure	K[a]	AIC_c	ΔAIC_c	w_i
Body mass	Sex + Exotic	4	5275.10	0.00	0.61
	Sex + Exotic + Year	5	5276.00	0.91	0.39
	Sex + Year	4	5288.00	12.92	0.00
	Sex	3	5293.40	18.31	0.00
	Exotic	3	5369.90	94.85	0.00
	Exotic + Year	4	5371.60	96.53	0.00
	Year	3	5384.40	109.31	0.00
	Null	2	5387.50	112.40	0.00
Tarsus length	Sex + SBM + Year	5	2632.00	0.00	0.86
	Sex + Exotic + Year	5	2635.70	3.76	0.13
	SBM + Year	4	2641.60	9.60	0.01
	Exotic + Year	4	2643.90	11.93	0.00
	Sex + Exotic	4	2653.20	21.21	0.00
	Sex + Year	4	2656.70	24.74	0.00
	Exotic	3	2660.00	28.00	0.00
	Year	3	2665.90	33.88	0.00
	Sex + SBM	4	2668.40	36.45	0.00
	SBM	3	2676.30	44.32	0.00
	Sex	3	2698.80	66.81	0.00
	Null	2	2706.10	74.12	0.00
Bill length[b]	Exotic + Year	4	1397.20	0.00	0.53
	Sex + Exotic + Year	5	1397.60	0.35	0.44
	Sex + Year	4	1405.40	8.19	0.01
	Year	3	1405.40	8.20	0.01
	SBM + Year	4	1406.00	8.77	0.01
	Sex + SBM + Year	5	1406.00	8.77	0.01
	Exotic	3	1428.60	31.36	0.00
	Sex + Exotic	4	1429.50	32.33	0.00
	SBM	3	1457.60	60.35	0.00
	Sex + SBM	4	1458.20	60.98	0.00
	Null	2	1459.40	62.18	0.00
	Sex	3	1460.00	62.82	0.00

Bill length[c]	Age + Exotic + Year	5	1399.00	0.00	0.53
	Age + Sex + Exotic + Year	6	1399.30	0.36	0.44
	Age + Sex + Year	5	1407.10	8.15	0.01
	Age + Year	4	1407.10	8.15	0.01
	Age + SBM + Year	5	1407.70	8.76	0.01
	Age + Sex + SBM + Year	6	1407.70	8.76	0.01
	Age + Exotic	4	1430.20	31.22	0.00
	Age + Sex + Exotic	5	1431.10	32.19	0.00
	Age + SBM	4	1458.50	59.56	0.00
	Age + Sex + SBM	5	1459.10	60.18	0.00
	Age (Null)	3	1460.30	61.38	0.00
	Age + Sex	4	1461.00	62.01	0.00

[a] Number of parameters
[b] Age-corrected bill length
[c] Bill length as measured

Supplementary Table 2. Estimates from top models (Supplementary Table 1) and full models explaining trends in morphology.

Trait	Parameter	Estimate	SE	95% CI	*P*
Top models					
Body mass	Exotic	20.5	3.1	14.4–26.6	<0.0001
	Sex (male)	-26.7	2.5	-31.7– -21.7	<0.0001
Tarsus length	Sex (male)	-0.73	0.22	-1.17– -0.30	0.0009
	SBM[d]	0.56	0.11	0.34–0.79	<0.0001
	Year	0.21	0.04	0.13–0.30	<0.0001
Bill length[a]	Exotic	0.36	0.11	0.14–0.58	0.0015
	Year	0.11	0.02	0.07–0.14	<0.0001
Bill length[b]	Age	0.22	0.02	0.18–0.26	<0.0001
	Exotic	0.36	0.12	0.14–0.58	0.0013
	Year	0.10	0.02	0.07–0.14	<0.0001
Full models					
Body mass	Year	1.03	0.63	-0.20–2.26	0.102
	Exotic	16.55	3.95	8.79–24.29	<0.0001
	Sex (male)	-26.85	2.54	-31.83– -21.86	<0.0001
Tarsus length	Year	0.12	0.05	0.01–0.23	0.0282
	Exotic	1.00	0.35	0.32–1.68	0.0041
	Sex (male)	-0.71	0.22	-1.14– -0.27	0.0015
	SBM[d]	0.51	0.11	0.28–0.73	<0.0001
Bill length[a,c]	Year	0.11	0.02	0.07–0.14	<0.0001
	Exotic	0.34	0.11	0.11–0.56	0.0032
	Sex (male)	-0.10	0.07	-0.23–0.04	0.1800
	SBM[d]	0.02	0.04	-0.05–0.10	0.5478
Bill length[b,c]	Year	0.10	0.02	0.07–0.14	<0.0001
	Exotic	0.34	0.11	0.12–0.57	0.0026
	Sex (male)	-0.10	0.07	-0.24–0.04	0.1526
	SBM[d]	0.02	0.04	-0.05–0.09	0.5694
	Age	0.22	0.02	0.18–0.26	<0.0001

[a]Age-corrected bill length; [b] Bill length as measured; [d]SBM = standardized body mass (within sex). [c]We also analyzed bill length data with log transformations, including a cub-root transformation of bill length, but obtained similar results.

Supplementary Table 3. Directional (S, β) and quadratic (c, γ) selection parameters (differentials, gradients) for morphology of fledging-age snail kites from 9 pooled cohorts (2004-2012) in Florida, USA. Selection parameters were estimated using numerical approximations of first and second partial derivatives of relative fitness averaged over the distribution of observed phenotype based on generalized additive model functions fit to standardized trait values (zero mean, unit variance). Standard errors and significance based on bootstrapping (n = 2000 samples).

Sex (survivors/N[a])	Trait[b]	$S \pm$ SE	$\beta \pm$ SE	$c \pm$ SE	$\gamma \pm$ SE
Both sexes	Tarsus length	0.077 ± 0.043 °	0.009 ± 0.044	-0.163 ± 0.043 **	-0.147 ± 0.040 **
(274/561)	Bill length[b]	0.131 ± 0.043 ***	0.102 ± 0.044 **	-0.010 ± 0.008	-0.000 ± 0.001
	Body mass	0.175 ± 0.043 ***	0.181 ± 0.044 ***	-0.113 ± 0.043 *	-0.054 ± 0.027
Females	Tarsus length	0.094 ± 0.054 °	0.021 ± 0.060	-0.215 ± 0.053 **	-0.205 ± 0.053 **
(145/286)	Bill length	0.169 ± 0.058 **	0.141 ± 0.059 **	0.000 ± 0.004	-0.001 ± 0.003
	Body mass	0.149 ± 0.060 **	0.140 ± 0.060 **	-0.063 ± 0.273	-0.013 ± 0.012
Males	Tarsus length	0.035 ± 0.063	-0.021 ± 0.063	-0.059 ± 0.048	-0.040 ± 0.030
(129/275)	Bill length	0.092 ± 0.064	0.081 ± 0.063	0.001 ± 0.002	0.000 ± 0.002
	Body mass	0.190 ± 0.064 ***	0.192 ± 0.065 ***	-0.137 ± 0.072	-0.140 ± 0.071

°$P < 0.1$, *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$

[a] N = combined number of survivors and non-survivors

[b] Bill length = age-corrected bill length

Supplementary Table 4. Estimates (SE) of phenotypic variance components, heritability (h^2), and coefficient of additive genetic variance (CV_A) of morphological traits in fledging-age snail kites in Florida, USA. Estimates were obtained using individuals from all wetlands across the kite's range and from only wetlands either invaded or uninvaded by an exotic snail (*Pomacea maculata*). Total phenotypic variance (V_P) is partitioned into additive genetic (V_A), environmental (V_E), and residual (V_R) components. Environmental variance is further partitioned into components attributable to effects of common nest environment (V_{En}) and, at a larger-scale, common wetland (V_{Ew}) and year (V_{Ey}) environment. Variance components were estimated using Bayesian inference with MCMC. Fixed effects included sex and, in models for bill length, also age.

Trait	Source	All N=590	Invaded N=466	Uninvaded N=124	Invaded - Uninvaded (95% CI)[b]
Bill length[a]	V_A	0.322 (0.076)	0.409 (0.120)	0.086 (0.141)	**0.16 (0.03 -0.47)**
	V_{En}	0.305 (0.054)	0.307 (0.069)	0.266 (0.125)	0.02 (-0.08 -0.25)
	V_{Ew}	0.069 (0.068)	0.048 (0.102)	0.070 (0.143)	-0.05 (-0.14 -0.16)
	V_{Ey}	0.168 (0.148)	0.062 (0.094)	0.178 (0.223)	-0.12 (-0.25 -0.16)
	V_R	0.061 (0.063)	0.082 (0.101)	0.100 (0.141)	-0.14 (-0.34 -0.32)
	V_P	0.993 (0.166)	0.996 (0.152)	1.103 (0.275)	-0.07 (-0.2 -0.27)
	h^2	0.302 (0.080)	0.397 (0.118)	0.082 (0.121)	**0.18 (0.06 -0.47)**
	CV_A	2.70% (0.352)	3.04% (0.501)	2.05% (0.721)	**0.66 (0.05 -2.23)**
Tarsus length	V_A	2.760 (0.962)	2.878 (1.183)	1.773 (1.069)	1.05 (-0.02 -4.01)
	V_{En}	2.120 (0.469)	2.0187 (0.527)	0.938 (0.916)	0.71 (-0.06 -2.42)
	V_{Ew}	0.479 (0.451)	0.446 (0.669)	0.338 (0.500)	0.13 (-0.21 -1.99)
	V_{Ey}	1.164 (1.101)	1.164 (1.519)	1.041 (1.391)	-0.01 (-0.86 -3.68)

	V_R	1.944 (0.894)	1.740 (1.039)	0.416 (1.076)	**2.1 (0.92 -6.58)**
	V_P	8.618 (1.270)	8.902 (1.771)	6.404 (1.587)	0.33 (-0.68 -3.1)
	h^2	0.367 (0.109)	0.282 (0.130)	0.060 (0.156)	0.06 (-0.08 -0.43)
	CV_A	3.34% (0.553)	3.36% (0.671)	2.44% (0.759)	0.57 (-0.1 -2.5)
Body mass	V_A	429.345 (117.989)	272.265 (121.028)	171.026 (227.181)	67.84 (-273.17 -342.67)
	V_{En}	325.928 (63.061)	305.820 (66.368)	131.71 (121.576)	157.98 (62.02 -362.92)
	V_{Ew}	194.742 (139.336)	42.604 (77.422)	211.00 (214.761)	-185.77 (-315.06 -79.22)
	V_{Ey}	55.677 (55.683)	57.377 (91.964)	77.015 (132.591)	-20.32 (-91.24 -246.36)
	V_R	175.394 (112.354)	168.617 (110.995)	86.188 (221.185)	-349.69 (-540.78 -115.97)
	V_P	1117.941 (156.782)	1039.001 (132.772)	1246.092 (283.984)	-153.35 (-332.61 -258.36)
	h^2	0.340 (0.100)	0.292 (0.116)	0.075 (0.159)	0.02 (-0.13 -0.35)
	CV_A	5.21% (0.874)	4.99% (0.929)	6.05% (1.587)	-0.74 (-2.08 -2.65)

[a]Bill length as measured. Note that variance components for measured bill length obtained from models that included age as a fixed effect (above) were similar to those obtained from models that simply included age-corrected bill length as the response variable. [b]Test for changes in variance components taken from differences in posterior distributions from invaded and uninvaded wetlands. Changes with 95% credible intervals not overlapping zero shown in bold.

Supplementary Table 5. Pearson correlation coefficients (*r* ± 95% confidence interval) for pairs of morphological traits measured in male (n = 274) and female (n = 293) fledging-age snail kites in Florida, USA, 2004-2012.

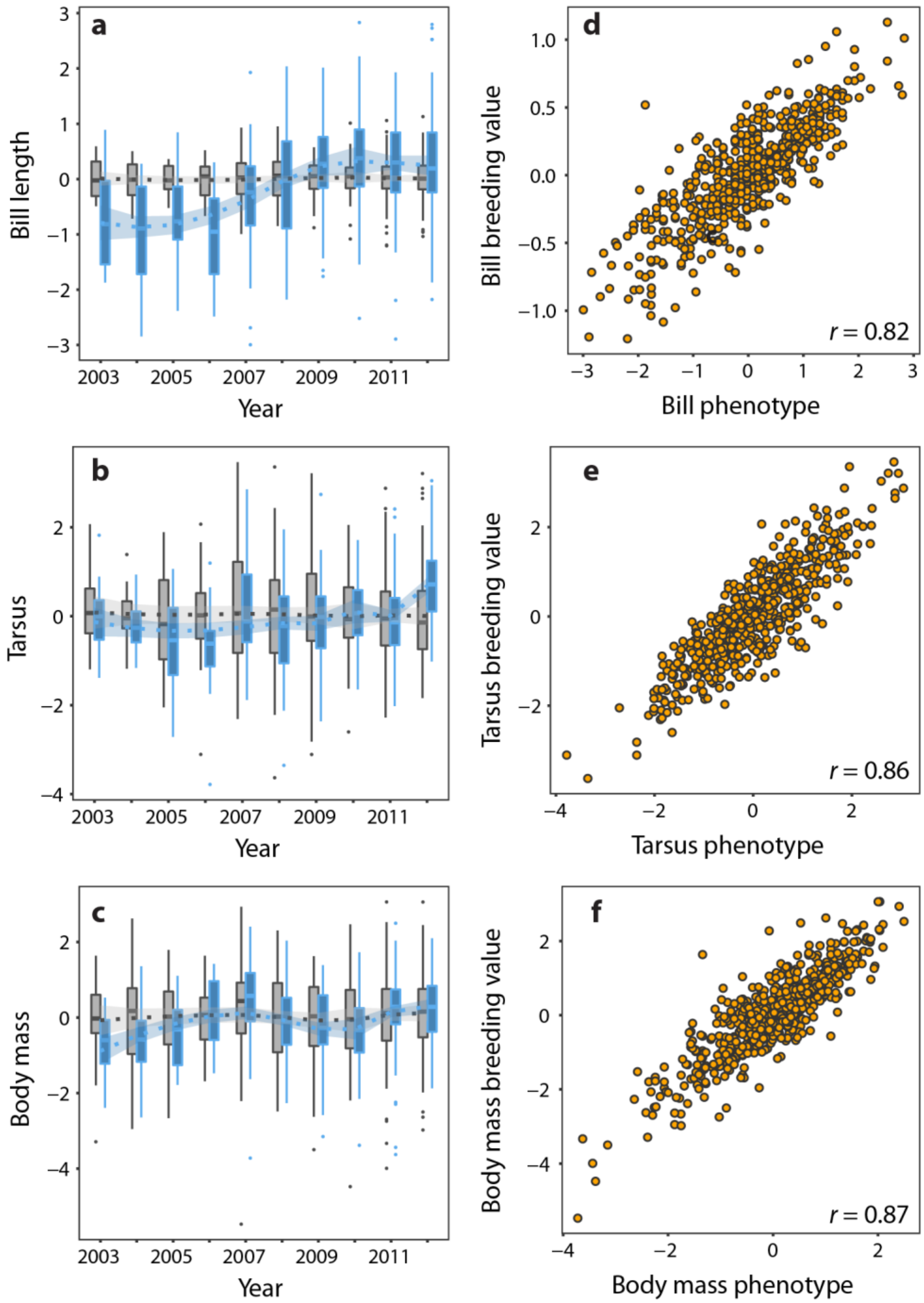
Sex	Traits[a]	*r*	95 % CI	*P*
Males	Tarsus length – Bill length	0.26	0.15−0.37	<0.001
	Body mass – Bill length	0.17	0.05−0.28	0.005
	Tarsus length – Body mass	0.26	0.14−0.36	<0.001
Females	Tarsus length – Bill length	0.13	0.02−0.24	0.024
	Body mass – Bill length	0.05	-0.07−0.16	0.437
	Tarsus length – Body mass	0.22	0.11−0.33	<0.001

[a] Bill length = age-corrected bill length

Supplementary Table 6. Tests for the trends in predicted breeding values. The linear model is based on a regression of breeding values with year, while the categorical trend model tests for changes from pre-invasion (2003-2004) to initial invasion (2005-2008), and post-invasion (2009-2012), by treating year as a categorical variable.

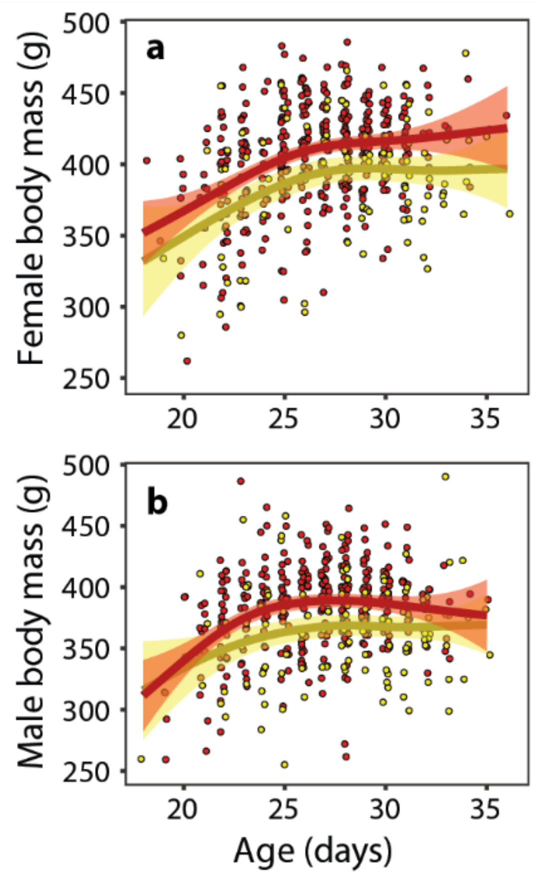
Trait	Model	Slope	LCL	UCL	*P*	P_{drift}
Body mass	Linear trend	0.033	-0.517	0.573	0.550	0.523
	Categorical: pre-initial	0.272	-4.526	5.089	0.548	0.523
	Categorical: pre-post	0.367	-4.349	5.189	0.565	0.545
Tarsus length	Linear trend	-0.005	-0.057	0.043	0.399	0.444
	Categorical: pre-initial	0.068	-0.349	0.521	0.630	0.565
	Categorical: pre-post	-0.022	-0.448	0.414	0.460	0.474
Bill length[a]	Linear trend	0.003	-0.014	0.020	0.628	0.579
	Categorical: pre-initial	0.028	-0.116	0.167	0.656	0.601
	Categorical: pre-post	0.050	-0.100	0.197	0.756	0.671
Bill length[b]	Linear trend	0.003	-0.013	0.020	0.641	0.591
	Categorical: pre-initial	0.032	-0.112	0.182	0.761	0.613
	Categorical: pre-post	0.054	-0.087	0.210	0.672	0.683

[a]Age-corrected bill length; [b]Bill length as measured. *P*-values based on posterior distributions of slope parameters and quantify the probability that there was an increase in breeding values over time. P_{drift} relates to the probability that increases occurred greater than would be expected from drift.



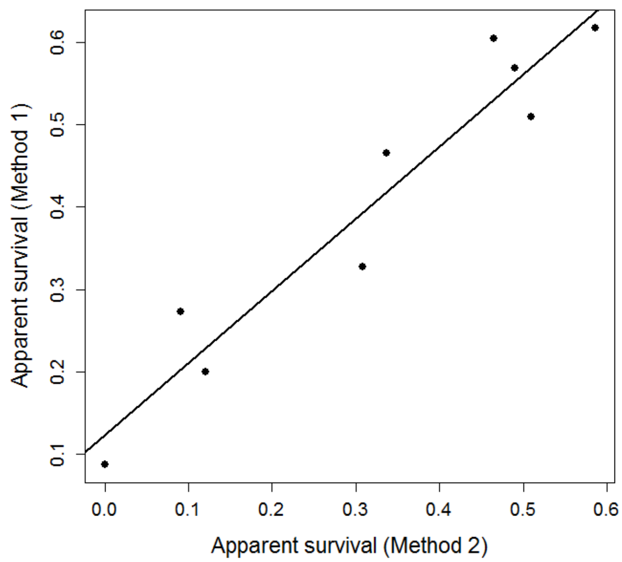
Supplementary Figure 1

Increases in bill and body mass, but not breeding values (a-c), occurred over time (Table S1), even though there were strong correlations between phenotypic traits and breeding values (d-f). (a-c) Shown are box plots for phenotypic traits (blue) and breeding values (grey), with a loess trend and associated SE overlaid. (d-f) Scatterplots of individual breeding values and phenotypic traits, with Pearson correlation shown. For c, f, body mass breeding values were scaled (divided by 10) to improve visualization.



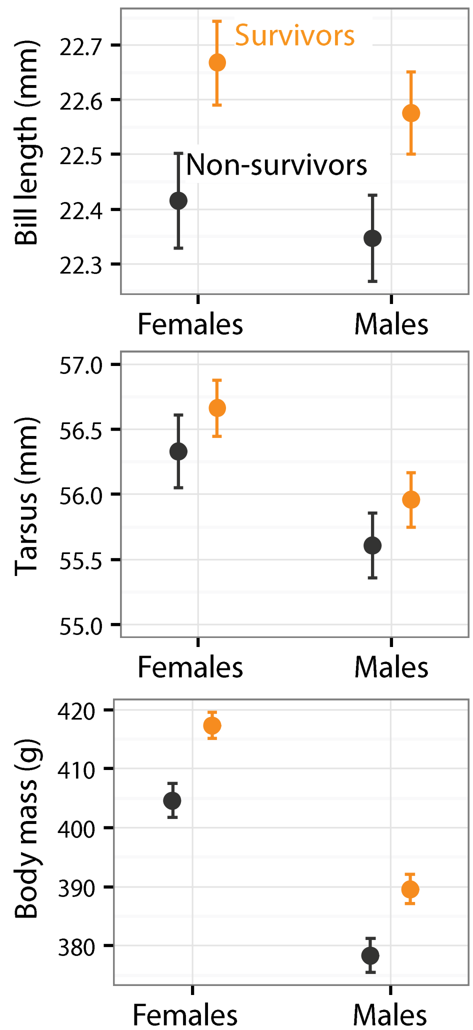
Supplementary Figure 2

Nestling growth rates were greater in invaded (red) and non-invaded (yellow) wetlands for (a) females and (b) males (Exotic effect: $F_{1,43}$, $P < 0.0001$). Predictions (+95% CIs) taken from generalized additive models (identity link function, with wetland and sex as grouping factors for splines). Data points jittered to facilitate visualization. Note that nestlings were only weighed >17 days old to limit disturbance to nests.



Supplementary Figure 3

Comparison of two methods used to generate estimates of apparent first-year survival for snail kite fledglings from 9 cohorts (2004–2012) in Florida, USA. Estimates were derived using band-resight data to classify individuals as survivors if they were observed at least once (1) during any post-fledging year throughout the study (y-axis), or (2) during only the 2 years following fledging for each respective cohort (x-axis). Line represents a linear regression ($r^2 = 0.92$, $F_{1,7} = 81.25$, $p < 0.001$). Note that residuals from this model were not significantly correlated with time ($r = -0.35$, $t = -0.99$, df = 7, $P = 0.36$).



Supplementary Figure 4

Bill length and body mass, but not tarsus length, of both male and female snail kites were greater for individuals that survived the first year of life to those that did not for ($t > 3.10$, $P < 0.005$).