

Mortality in the endangered Laysan Teal *Anas laysanensis*: conservation implications

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The Laysan Teal *Anas laysanensis* is an endangered anatid of the Hawaiian Islands, currently restricted to an emergent atoll, Laysan Island. Laysan Island lacks terrestrial mammalian predators, which permits the examination of mortality rates and causes without the anthropogenic effects of introduced predators. Mass and morphometrics were measured during the colour-marking of 297 Laysan Teal between 1998 and 2001. Intensive mark-resighting and recovery methods were used to estimate adult and juvenile mortality. One hundred and nineteen carcasses were collected on Laysan between 1998 and 2003, and systematic gross and microscopic examinations were undertaken on 63 of these. Causes of mortality were categorised as trauma, emaciation, miscellaneous or undetermined. Annual adult mortality rates were low, 0.05–0.10 (s.e. < 0.01), but duckling mortality was much higher, varying from approximately 0.7–0.9 during 1998–2000 and 2003. Body condition of both sexes deteriorates during the breeding season, and most adult mortality (88%) occurred during or post-breeding (May–October). Cause of mortality was determined via necropsy in 22 ducks. Of three adults, one died from bacterial infections, one was egg bound, and one died from botulism concomitant with nematode infestation. Fourteen ducklings died from acute trauma, four from emaciation sometimes associated with nematode infection, and one from bacterial pneumonia. Trauma is a significant factor in Laysan duckling mortalities, and elucidating the cause of and preventing such trauma may allow for management measures to enhance duckling survivability. High duckling mortality rates and emaciation also indicate that habitat on Laysan Island may have limited capacity to support broods.

Key Words: Laysan Teal, *Anas laysanensis*, Laysan Island, mortality

The Laysan Teal *Anas laysanensis*, also known as the Laysan Duck (AOU 1998), is restricted to a single population on Laysan Island, a remote atoll of the Hawaiian archipelago with a hypersaline lake surrounded by brackish and freshwater seeps. Sub-fossil evidence indicates that the Laysan Teal was previously widespread on the Hawaiian archipelago, and its range contraction occurred between 1200 and 1500 years ago during the period of colonisation by humans and rats (Burney et al. 2001; Cooper et al. 1996; Olson & James 1991). The Laysan Teal feeds on seeds and invertebrates and depends on seeps around the lake for rearing ducklings. Because of its extremely restricted geographic range and the limited carrying capacity of Laysan Island, the Laysan Teal is vulnerable to extinction from chance events. Threats to the viability of the species include severe weather, disease, introduction of invasive species, and catastrophic limitations of food or fresh water. Indeed, in 1993, an unusually high level of mortality in ducks was attributed to a combination of emaciation and heavy parasite infections (Work et al. 2004). The Laysan Teal is presently listed as endangered by the U.S. Fish and Wildlife Service (USFWS) and critically endangered by the International Union for the Conservation of Nature and Natural Resources (IUCN) (Butchart & Hughes 2003).

The Laysan Teal is a relatively long-lived species (maximum known lifespan 12 years in the wild and 18 years in captivity) with a low reproductive rate (Moulton & Weller 1984; Reynolds & Kozar 2000). Having evolved with avian predators instead of mammalian ground

predators, the teal are more likely to walk than fly, and when startled they tend to freeze rather than flush. These behaviours make them vulnerable to introduced mammalian predators and exploitation by humans, and may partially explain their extirpation from the main Hawaiian Islands since humans settled there.

An understanding of mortality factors is essential to managing threatened or endangered species. Estimates of mortality are beneficial to understanding the ecological basis of population status, and age-specific mortality factors are beneficial for identifying vulnerable sex or age classes. Identifying causes for mortality permits the exploration of management options to mitigate these factors and enhance recovery of the species. Population losses due to emigration are difficult to observe and distinguish from losses due to mortality in most studies. However, because Laysan Teal do not leave the island, this bias is removed. The absence of mammalian predators and lack of immigration and emigration by Laysan Teal on Laysan permit the examination of survival and mortality factors without these effects. The objective of the present study was to estimate annual mortality rates of adult Laysan Teal during 1998–2000, estimate seasonal duckling mortality from 1998–2001 and 2003, and identify causes of mortality in both age groups during 1998–2003.

Methods

Study area

Laysan Island (hereafter Laysan) [25°46' N, 171°44' W] has the largest continuous land area of the Northwestern Hawaiian Islands (**Figure 1**). Laysan lies 1,463 km northwest of Honolulu, and is accessible only by boat. The island is dominated by low herbaceous vegetation, and contains an interior hypersaline lake with mudflats and freshwater seeps (Ely & Clapp 1973). Laysan is part of the Hawaiian and Pacific Islands National Wildlife Refuge Complex under the jurisdiction of the USFWS and the Coral Reef Ecosystem Reserve (National Oceanic and Atmospheric Administration 2001; U.S. Fish and Wildlife Service 1982).

Capture and marking

Laysan Teal were captured during moonless nights and predawn periods using a flexible handheld net and headlamps. Birds were caught at the lake, in the vegetation, during March–May 1998, October 1998–March 1999, May–June 1999, March–July 2000 and October 2001. U.S. Geological Survey (USGS) numbered aluminium rings were placed on one leg, and plastic colour-rings, some with alpha or numeric codes, were applied to the other leg. All birds were weighed, measured, sexed and aged by plumage characteristics (Moulton & Marshall 1996), and released within 10–30 minutes near their capture site. Morphometric measurements included tarsus, wing chord and bill length. A keel palpitation (0–4) was included as

an indicator of body condition.

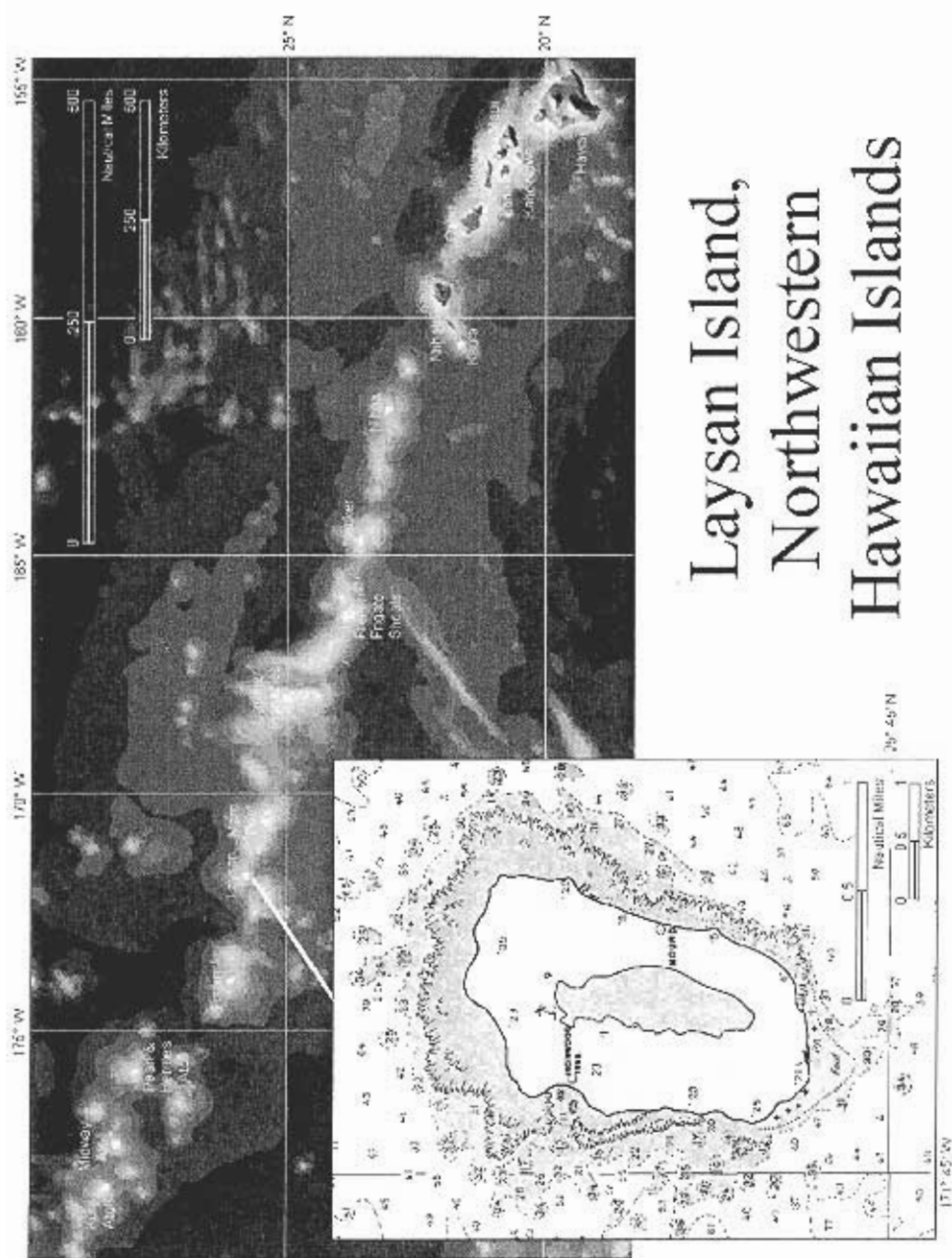
Population monitoring

Colour-rings were read weekly prior to sunset around the lake from March 1998 – October 2001, and twice per month at flocking areas on the coast from March 1998 – October 1999 and March–July 2000. During October–February 2000 and from July–September 2001, and November 2001– March 2004, resighting efforts were reduced to twice per month around the lake. Resighting efforts were increased to twice weekly during October 2001 and from April–July 2003 and 2004. Observers noted the sex, age and ring combination of each bird (Moulton & Marshall 1996). Ring combinations observed incidentally were also recorded between 1998 and 2004.

During the breeding season (typically April–July) in 1998, 2000 and 2003 broods were checked daily around the lake using a spotting scope (40–60x zoom) and binoculars (10 x 40). In 1999, brood sightings were recorded incidentally, approximately four times per week. Breeding was not monitored in 2001–2002. Female parents were identified and all broods and ducklings were counted and assigned to an age class based on plumage characteristics (Gollop & Marshall 1954; Marshall 1989; Moulton & Weller 1984).

Laysan Teal carcasses were collected incidentally during population monitoring. Intact carcasses were weighed with a spring balance, and sexed and aged by plumage characteristics. Bill and tarsus lengths of ducklings were measured. Carcasses

Figure 1. Map of Hawaiian Islands, with detail of Laysan Island.



were preserved by freezing or by placing the entire carcass in 10% neutral buffered formalin for necropsy as described (Work *et al.* 2004). Preserved carcasses were weighed with a spring balance, and systematically examined externally and internally. Tissues including brain, kidney, lung, liver, spleen, oesophagus, proventriculus, intestines, pancreas and gonad were fixed in 10% neutral buffered formalin, embedded in paraffin, sectioned at 5 μm , stained with haematoxylin and eosin and examined with a microscope. Gram stains (Prophet *et al.* 1992) were used to characterise bacteria in tissue sections. Hearts were stored frozen and blood assayed for presence of botulism type C using the mouse cross-protection test. Causes of death were categorised as Trauma, Emaciation, or Miscellaneous. 'Trauma' included animals with evidence of broken bones, bruising, or frank haemorrhage in musculature and internal organs and absence of other lesions. 'Emaciation' included animals with lack of body fat and atrophy of the liver with or without evidence of nematode infection. 'Miscellaneous' were all other causes of mortality.

Analysis

The estimate of mortality was not influenced by individuals leaving the study area because Laysan Teal do not emigrate from the island. During capture, age was classified as hatch year (HY), after hatch year (AHY), or after fourth year (AFY, birds ringed prior to this study) enabling estimation of mortality for three age classes. Capture of HY birds took

place after fledging, thus the period of high mortality experienced by downy ducklings had already passed (see duckling mortality below). Mortality of adults was assessed by intensive monitoring of the marked individuals. Annual adult mortality was estimated as the ratio of known live birds (based on recaptures, resightings and carcass recoveries) to the total number ringed during the previous year (Johnson 1996), with 95% binomial confidence limits:

$$\chi^2 = \frac{\nu s^2}{\sigma^2} \quad (1)$$

where χ^2 is the statistical distribution with ν degrees of freedom, s^2 is the sample variance and σ^2 is the population variance (Zar 1999). Although the annual mortality rate was estimated for only the first year after a cohort of birds were marked, long-term resighting data (1998–2004) provided several years of data to confirm individual survivorship. For individuals not resighted, recaptured or collected as carcasses, mortality was assumed if there were no sightings of an individual one year after it had been ringed, and during the subsequent 3–5 years of systematic surveys and incidental resightings. Survival estimates were not reported after the first year post-capture, as colour-ring fading and variable resighting efforts were likely to bias estimates. Models using detection probabilities for the 6-year study are in progress for a future manuscript.

Fledging success

The number of ducklings and new broods with marked and unmarked female parents was monitored during

the 1998–2000 and 2003 breeding seasons. Surveys to determine fledging success were conducted within two months of the peak of fledging in September or October of 1998–2001. Fledging success or survival to post-fledging (\hat{SPF}) was estimated as the ratio of HY birds shortly after fledging

$$\hat{SPF}_x = \frac{n_{tx+1}}{n_{tx}} \quad (2)$$

to the total number of ducklings produced within a breeding season or cohort (x); where \hat{SPF} is the proportion of individuals (n) surviving to t+1 or fledging (Krebs 1999) with 95% binomial confidence limits (Zar 1999). It was assumed that the ducklings and fledglings from a cohort were equally observable in the brood-rearing areas at the lake. This assumption may have been violated, especially during the first two days after hatching, when some females with broods are secretive, and loss of ducklings would be undetected before they reached brood-rearing areas. If fledglings were more easily detected than ducklings, the consequence of this violation is a positive bias in estimated fledging success, however results suggest a lack of this bias in the present study (low fledging success).

Body condition

The body condition index (BCI) of captured birds was calculated using the ratio of body mass to bill length (Harder & Kirkpatrick 1996). Birds were also assigned a subjective condition score based on degree of pectoral muscle atrophy ranging from 0 (severely atrophied) to 4 (no atrophy).

Results

Fledgling and adult mortality

Two hundred and forty eight adult ducks (AHY) and 45 fledged juveniles (HY) were marked with numbered metal and/or coloured leg rings from 1998 to 2001. Fifteen previously marked birds (AFY ringed in 1993 and 1994) were recaptured or resighted during the study. Only one of 45 HY birds marked during 1998–2001 was recovered as a second year (SY) carcass, and 41 were resighted the year after being tagged. Annual mortality of birds marked as HY during 1998–2001 was 0.09 (95% confidence interval [0.07, 0.10]; **Table 1**).

The survival of each 'cohort' of newly ringed adults is followed for one year after capture and their annual mortality rate is reported (**Table 1**). During 1998, 138 adult birds (AHY) were marked, 130 were resighted or recaptured at least 12 months later, and three were recovered as carcasses. Estimated annual adult mortality in 1998 was 0.06 (95%; confidence interval [0.09, 0.05]). In 1999, 74 of 78 marked adults were resighted or captured in the following year(s). Two were recovered as carcasses. Adult mortality was 0.05 (95%; confidence interval [0.12, 0.02]) in 1999. In 2000, 44 of 49 marked birds were resighted or recaptured a year later, and two were recovered as carcasses, with mortality estimated at 0.10 (95%; confidence interval [0.22, 0.04]). For all periods, pooled annual adult mortality is estimated at 0.06 (95%; confidence interval [0.04, 0.10]); n = 265 birds; 1998–2001).

Two of 15 (AFY birds detected in

Table 1. Laysan Teal mortality estimates with 95% confidence intervals.

Year	Age class ¹	Laysan Teal <i>Anas laysanensis</i> marked	Annual mortality estimate	95% confidence interval	
				Lower	Upper
1998	AHY	138	0.06	0.90	0.05
	Duckling	--	0.90	0.89	0.91
1999	AHY	78	0.05	0.12	0.02
	Duckling	--	0.71	0.66	0.75
2000	AHY	49	0.10	0.22	0.04
	Duckling	--	0.70	0.66	0.75
1998–2001	HY	45	0.09 [†]	0.07	0.10
1998–2001	AFY	15	0.13 [†]	0.10	0.14

¹AHY = After Hatch Year or Adult, HY = Hatch Year or fledged juvenile, AFY = after fourth year or bird whose age is 5 years or older.

[†] Pooled data from these age classes.

1998, first ringed in 1993 and 1994) were recovered as carcasses in June 2001. Six of the 14 have been resighted as recently as 2003, and the remaining seven birds have not been seen since at least 2001. AFY mortality was 0.13 [95%; confidence interval (0.10, 0.14)] for all periods combined during 1998–2001.

Duckling survival

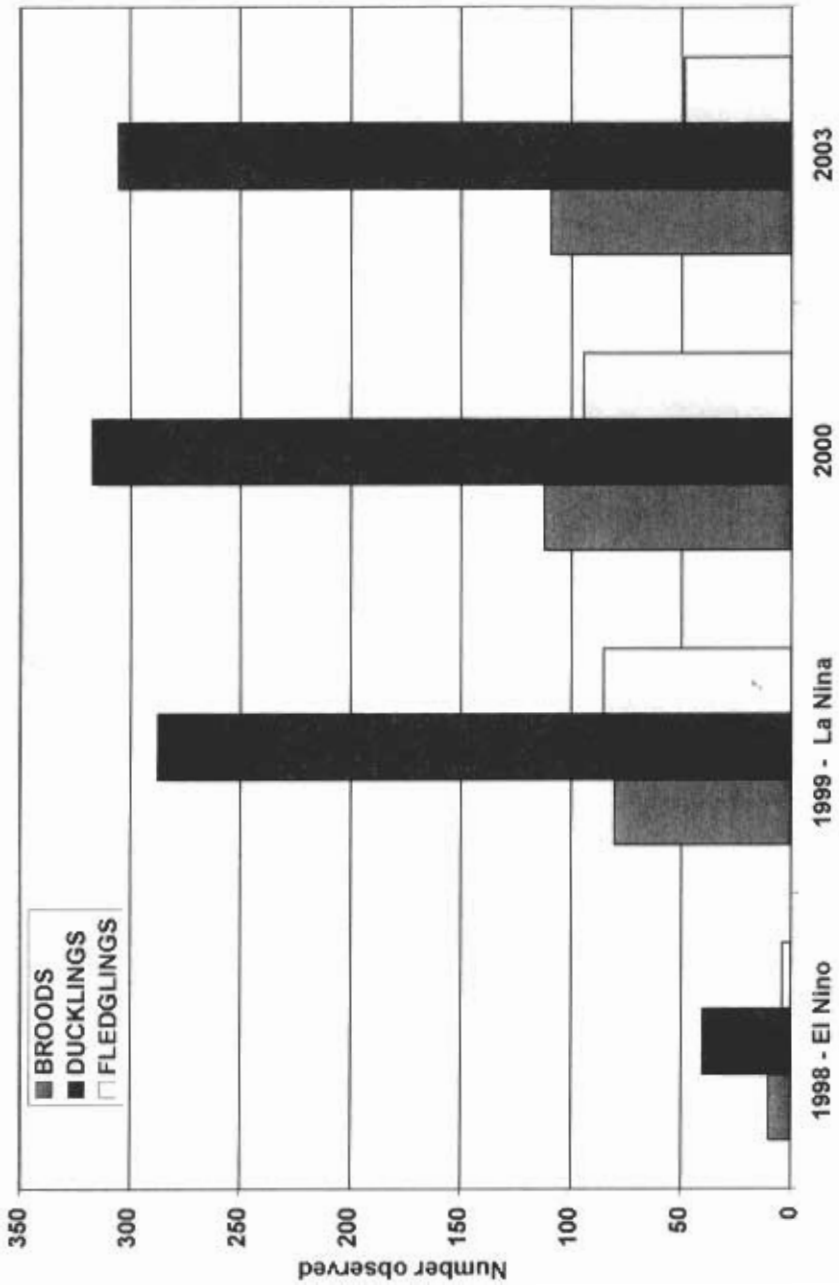
Survival of ducklings to post-fledging ($\hat{S}PF$) was 0.10 [95% confidence interval (0.03, 0.28)] in 1998, 0.29 [95% confidence interval (0.25, 0.34)] in 1999, and 0.29 in 2000 [95% confidence interval (0.25, 0.34)]. The mean ratio $\hat{S}PF$ for 1998–2000 was 0.28 [95% confidence interval (0.21, 0.36)]. Limited observations suggest that fledging success for 2003 was low (0.16; 95% confidence interval (0.21, 0.36)) based on maximum juvenile counts in

October [USFWS, unpublished data]. $\hat{S}PF$ is not dependent on tracking individual broods, and is supported by the population estimates derived from mark-resighting methods. Duckling mortality is reported as 1- $\hat{S}PF$ (**Table 1**). Numbers of ducklings, broods and fledglings from sighting data 1998–2000 and 2003 are given in **Figure 2**.

Cause of mortality

One hundred and seventeen Laysan Teal carcasses were recovered during 1998–2003, and 63 were examined post mortem. Cause of mortality was determined in 3 adults and 19 ducklings. Of the 53 birds with undetermined cause of death, 29 birds were too decomposed to assess. The three adults died from miscellaneous causes: one died from bacterial infections exemplified by multiple foci of necrosis in the brain associated with

Figure 2. Reproductive success of Laysan Teal from brood surveys during 1998–2000 and 2003.



gram negative bacteria, one died from severe haemorrhage in the oviduct associated with an unpassed egg (egg bound) concomitant with nematode infestation, and one adult died from botulism concomitant with nematode infestation. Fourteen ducklings died from acute trauma. Trauma often affected multiple regions, however, instances of trauma to the thoracic region were seen most often ($n = 9$) followed by abdominal region ($n = 6$) and head ($n = 4$). Trauma to the head was characterised by puncture of the skull, frank bleeding in the brain or decapitation. Trauma to the thoracic regions was characterised by severe bleeding of the lungs or heart. Trauma to the abdominal region was characterised by severe bruising of the abdomen or ruptured liver with frank bleeding into the coelomic cavity. Four ducklings died from emaciation, two cases of which were complicated by nematode infection in the proventriculus associated with inflammation (See also Work *et al.* 2004). One duckling died from severe necrosis and inflammation of the lungs associated with bacterial infection. No lesions indicative of cause of death were seen in 19 duckling carcasses suitable for examination. All ducklings had lipid-rich livers and an undetermined number had yolk sac remnants in the coelomic cavity. This suggests that nutritional stress was not a cause of mortality. The majority of carcasses collected were downy ducklings. The age could be determined for 113 carcasses during 1998–2003, revealing that the first six days after hatching are very critical. Most carcasses found were ducklings in the downy plumage stages less than

18 days old (78%), with most carcasses less than six days old (60%, $n = 113$) (**Figure 3**). Most duckling carcasses from 1998–2003 were found in the spring and summer after the peaks of hatching. Adults comprised 17% (19 of 113) of the specimens recovered, and of those in good condition for determination of sex, 81% (13 of 16) were females. Most adult carcasses were found in mid to late summer after the peak of breeding. Body mass, BCI and keel palpitations indicated poor body condition during the breeding season compared with pre-breeding and post-moult for both sexes (**Table 2** and **Figure 4**). Females with ducklings were not disturbed for weighing, but males were weighed throughout the breeding period.

Figure 3. Known age classes of Laysan Teal carcasses recovered 1998–2003 (n = 104).

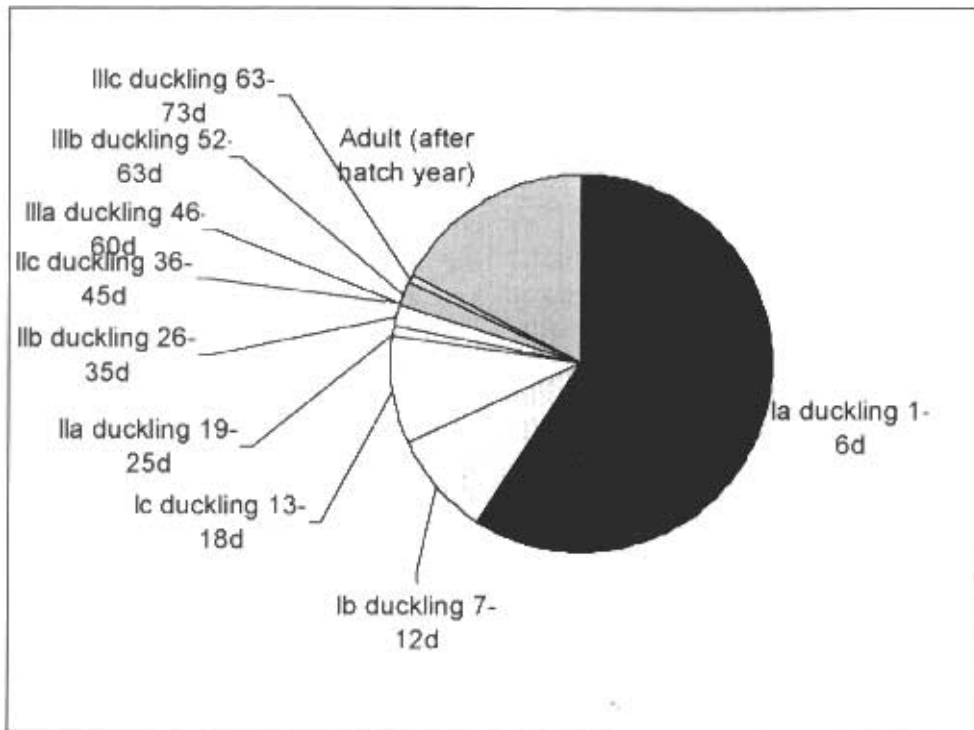


Table 2. Monthly mean mass (g), body condition indices¹ (BCI), and average keel index for Laysan Teal, 1998–2001.

Month/Yr	Mean mass (s.d.)		N		BCI		Keel ²	
	♀	♂	♀	♂	♀ N	♂ N	♀	♂
Mar 98	509.91 [52.63]	498.67 [27.83]	11	9	155.12 (15.47)	144.63 (14.14)	No data	
Apr 98	477.32 [51.76]	444.32 [31.58]	34	19	136.52 (16.51)	117.96 (8.14)	No data	
May 98	448.90 [52.16]	450.13 [33.98]	20	16	126.75 (16.21)	119.70 (7.92)	No data	
Oct 98	486.80 [20.87]	490.50 [72.13]	15	6	139.71 (5.56)	135.82 (27.80)	No data	
Nov 98	481.71 [39.53]	494.30 [45.19]	28	10	135.67 (10.16)	125.99 (10.54)	2.7	2.7
Dec 98	489.84 [34.74]	528.67 [42.47]	25	24	137.81 (9.01)	139.89 (11.52)	2.5	2.7
Jan 99	515.38 [33.58]	520.19 [45.32]	29	21	147.69 (6.02)	140.73 (8.47)	2.8	2.7
Feb 99	523.47 [46.32]	481.70 [36.21]	15	27	148.51 (13.44)	125.73 (10.31)	2.7	2.2
Mar 99	459.08 [47.12]	434.60 [33.01]	13	10	130.38 (12.79)	111.43 (7.66)	2.2	1.6
May/June 99	452.00 [55.18]	440.83 [24.08]	14	6	121.88 (11.27)	115.65 (5.54)	1.9	2
Mar/Apr 00	468.97 [40.78]	443.57 [26.08]	38	21	130.13 (11.02)	114.17 (7.33)	2.3	2
May 00	433.00 [55.19]	429.33 [33.36]	10	12	128.91 (10.88)	109.52 (10.65)	2.3	1.8
Oct 01	436.84 [33.88]	447.00 [25.27]	19	15	112.23 (26.05)	95.16 (47.62)	2.4	1.9
Total Adult	477.01 (50.23)	475.76 (49.11)	196	132	121.48 (25.90)	121.48 (25.90)		
Gravid	486.39 [63.65]		32		135.80 (18.61)	144		
HY Fledglings (both sexes)	407.05 [45.19]		44		111.16			
SY	474.04 [54.32]	440.00 [33.62]	22	11	131.29 (14.94)	113.60 (8.15)		

¹ BCI = body mass/bill length (Harder and Kirkpatrick 1996)² Keel = scale of 0–4; 0 = atrophy, no fat/muscle; 4 = plump

Figure 4. Seasonal body condition of Laysan Teal before breeding, during the breeding season, and post-moult on Laysan Island during 1998–2001. Females with ducklings were not captured for weighing, but males were weighed throughout the breeding season.

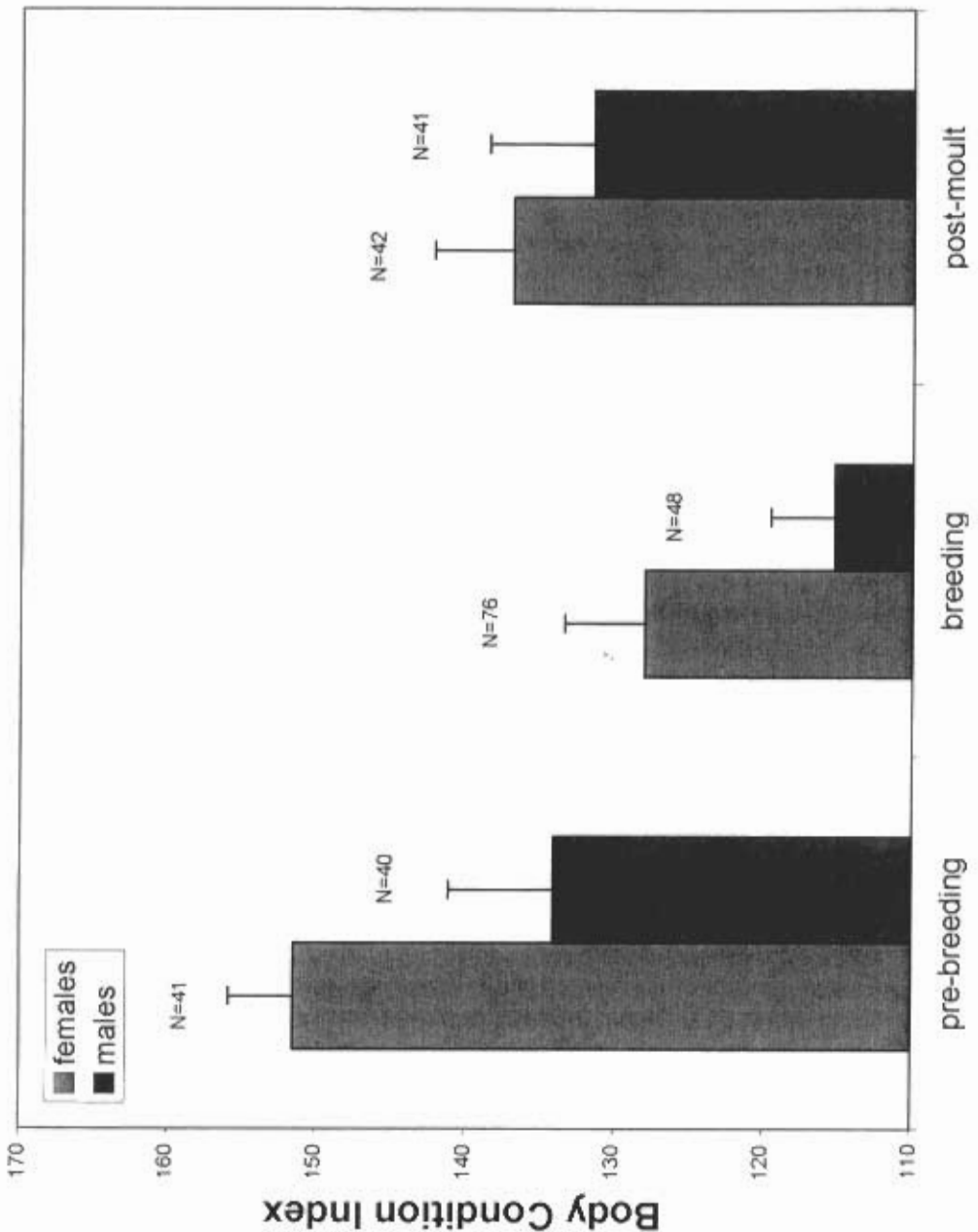


Table 3. Adult survivorship estimates from other waterfowl species.

Species	♀ mean. annual survival (s.e.)	Reference
Black Duck <i>Anas rubripes</i>	0.45(0.39)	(Krementz <i>et al.</i> 1987)
Brown Teal <i>A. chlorotis</i>	0.63 ¹	(Williams & Dumbell 1996)
Green-winged Teal <i>A. crecca</i>	0.51(0.06)	(Chu <i>et al.</i> 1995)
Campbell Island Teal <i>A. nesiotis</i> .	> 0.652	(McClland 2001)
Laysan Teal <i>A. laysanensis</i>	0.94 ² (0.10)	(Reynolds 2002)
Pacific Grey Duck <i>A. superciliosa</i>	0.55(0.12)	(Caithness <i>et al.</i> 1991)
Mallard <i>A. platyrhynchos</i>	0.54–0.59	(Drilling <i>et al.</i> 2002)
Nene Branta <i>sandvicensis</i>	0.87(0.04)	(Banko <i>et al.</i> 1999)

¹ All post-fledged birds

² Mammalian predator-free populations

Discussion

Compared with other waterfowl, most of which (60%, n = 113) are heavily depredated by mammalian predators, the Laysan Teal has very low adult mortality (**Table 3**). In contrast, Laysan Teal duckling mortality is very high, and a primary demographic parameter limiting population growth. Despite the importance of the pre-fledging period to the dynamics of waterfowl populations, brood biology is the most poorly understood aspect of waterfowl ecology (Sedinger 1992). Mortality of Mallard *Anas platyrhynchos* ducklings from numerous studies ranged from 0.56–0.66, and mortality was attributed mainly to predation and exposure (Mauser *et al.* 1994; Sargeant & Raveling 1992). In contrast, mortality of Laysan Teal ducklings was higher (0.90–0.70) despite the absence of mammalian predators. The importance of nutrition to duckling mortality is more difficult to assess, and has probably been underestimated or confounded with depredation (Sedinger 1992).

Evidence from Laysan Teal duckling carcasses and behavioural observations on Laysan suggest that overcrowded brood-rearing habitat contributes to duckling trauma and brood separations. Brood separation can lead to mortality due to exposure, especially in young ducklings from 1–6 days of age (Moulton & Marshall 1996). Downy ducklings have under-developed capacities for thermoregulation, thus are dependent on their female parents and brood mates for warmth (Marshall 1992). On Laysan, many conditions may lead to brood separation: crowded conditions at freshwater seeps and ephemeral freshwater wetlands, seabird and human disturbance, plus long distance or frequent brood movements to suitable brood-rearing habitats (i.e. fresh water and high prey densities). Biologists frequently observed distressed lone ducklings. Some were mistaken for fresh carcasses and collected, but ducklings 'revived' once warmed in a biologist's pocket (M.H. Reynolds, personal observation). Exposure is difficult to determine during post mortem examination

because ducks dying from exposure have few pathognomonic lesions, but the presence of lipid reserves in the livers of downy ducklings and lack of other lesions indicating cause of death suggest that they succumbed to exposure after brood separation.

Moulton & Weller (1984) reported adult mortality by sexual attack and seabird collision during 1979–80 studies, but no adult carcasses from 1993 (Work *et al.* 2004) or 1998–2001 exhibited signs of trauma. Most ducklings, in contrast, died of traumatic injuries that included crushed skulls, gaping wounds, haemorrhages and lesions. Aggression has been observed towards ducklings by non-breeding adult ducks, and occasionally by females with broods towards a duckling not belonging to her. Stray ducklings are often bitten or charged if they approach a non-parent (M.H. Reynolds, personal observation). One such attack was observed to cause duckling mortality (Boswell & Keitt 1995). Attacks on ducklings by adult ducks have been reported in other species in crowded habitats where food is limited (Pienkowski & Evans 1982). Ducklings are also susceptible to trauma by albatrosses and other large seabirds that are abundant on Laysan. Harassment of Laysan ducklings by Laysan Albatross *Diomedea immutabilis* and Great Frigatebird *Fregata minor* has been observed (M.H. Reynolds, personal observation). Ducklings escaped seabird harassment by hiding in vegetative cover or diving underwater, or were defended by the female parent. In 1992, USFWS field staff found 10 ducklings with crushed skulls. Seabird attack was suspected as the cause of

death (Newton & Chapelle 1992).

Although adult mortality appeared unaffected by the 1998 drought, few females bred and those that produced ducklings experienced high duckling mortality. A late summer drought in 2003 did not affect duckling production, but resulted in both adult and juvenile mortality.

In 1993 a drought and epizootic threatened the population. Mortality of Laysan Teal was attributed to starvation associated with infection with *Echinuria uncinata*, a nematode parasite that caused lesions in the proventriculus (Work *et al.* 2004). It was suspected that low water levels and poor food resources contributed to emaciation and that high parasite burdens could be attributed to poor body condition or increased exposure of ducks to the intermediate host of the nematode as ducks congregated around the few remaining freshwater seeps (Work *et al.* 2004). This catastrophic event resulted in a population decline that lasted a decade (Reynolds 2002). The presence of a case of botulism in a Laysan Teal carcass collected in 2003 was an alarming finding and drew attention to the potential of other epizootics. Avian botulism has historically been responsible for epizootic mortalities of waterfowl in the main Hawaiian Islands (Morin 1996; T.M. Work, unpublished data) and certainly has the potential to cause massive mortalities of Laysan Teal.

Management implications

Interrelated factors govern the Laysan Teal's population dynamics: weather, food resources, wetland

condition and inter and intra-specific population density on Laysan Island. The population was believed to be self-regulating at approximately 400–500 adult birds (Moulton & Marshall 1996; Moulton & Weller 1984); yet random or consecutive disasters such as the 1993 drought and epizootic (David & Hunter 1994; Work *et al.* 2004) or Laysan's well documented rabbit introduction in 1903 (Dill & Bryan 1912) could inhibit population stability.

Botulism is readily managed by assiduous removal of carcasses, scaring away waterfowl from areas known to be toxic, or aggressive management of water levels. Because of limited logistics and the remote location of Laysan Island, carcass collection is probably the only viable management measure for this mortality factor. Developing assays to detect and confirm botulism in the field would be critical to permit timely intervention in the event of botulism mortality in Laysan Teal on Laysan.

A strategy to restore species viability is to maintain the population on Laysan and establish additional populations on other islands (Aldrich 1980; Reynolds & Kozar 2000; Sincock & Kridler 1977; U.S. Fish and Wildlife Service 2004), at sufficient numbers that the species is resistant to catastrophic, demographic and environmental uncertainties. The establishment of additional populations would require removal of threats that were likely to have caused the original extirpation of the species.

Evidence suggests that Laysan Teal populations on the main Hawaiian Islands were adversely affected by introduced mammalian predators, rats *Rattus exulans* in particular (Burney

et al. 2001). Alien species, indirectly harmful to the historical Laysan and/or extirpated Lisianski populations, include rabbits, mice, invasive weeds and possibly predatory insects (Olson & Ziegler 1995; Warner 1963). On Lisianski, unsustainable harvest by shipwrecked islanders contributed to extirpation of the Laysan Teal (Rauzon 2001).

Storms, drought-related food reductions, disease and the island's limited carrying capacity are among the factors limiting the Laysan Island population (A. Marshall, personal observation; M.H. Reynolds, unpublished data). Prior to 1923, there was a brackishwater permanent pond southwest of the lake, but it was filled by shifting sands caused by the rabbit infestation of the early 1900s (Ely & Clapp 1973). Other freshwater seeps were probably degraded or filled by the shifting sands. Fresh and brackishwater seeps surround the lake and serve as drinking areas for finches, shorebirds and waterfowl (Moulton & Weller 1984). Female parents used these freshwater seeps, emergent vegetation and ephemeral wetlands as brood nurseries (A. Marshall, personal observation; M.H. Reynolds, unpublished data). Duckling mortalities due to trauma, brood separation and emaciation in 1999–2003 suggest overcrowding and a lack of sufficient brood-rearing habitat on Laysan. Restoration of freshwater seeps should be investigated, as improved brood-rearing habitat on Laysan may reduce crowding and duckling mortality due to trauma. Management of brood-rearing habitat may be beneficial during severe droughts or to provide more

fledglings for proposed translocations to establish additional populations on predator-free islands.

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