Niche overlap, threshold food densities, and limits to prey depletion for a diving duck assemblage in an estuarine bay

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Supplement. Additional information regarding sampling methodology and habitat modeling of diving ducks

DUCK BODY MASS, FAT CONTENT, AND DIET

Birds were observed foraging for a minimum of 10 min before collection. Immediately after retrieving the birds, we injected 70% ethanol into the upper digestive tract to stop digestion. Within 1 h of collection, contents of the esophagus-proventriculus were removed and stored in 70% ethanol. Food items were identified to family, or to species if possible. Length of bivalve shells was measured to the nearest 0.1 mm. For each duck collected, liver and kidneys were removed for contaminants analyses, the remaining carcass (including feathers) was ground to a homogenate, and subsamples were analyzed for lipid content by Soxhlet extraction in ethyl ether. Ash content was determined by combustion of samples in a muffle furnace, and body protein content was calculated by subtracting water, lipid, and ash content from ingesta-free body mass.

PREY SIZE SELECTION

To investigate size selection of prey by different diving duck species, 3 replicate samples of available benthic prey were taken with an Ekman grab (15 × 15 × 15 cm) near the site where each duck was collected. Benthic samples were rinsed through a 0.5 mm sieve in the field, and stored in 70% ethanol. Shell lengths of all bivalves were measured to the nearest 0.1 mm.

RADIO-TELEMETRY

Veterinarians surgically implanted radio-transmitters into the abdominal cavity of each bird. Transmitter packages were cylindrical, measured 45 × 15 mm, weighed 19 to 24 g (≤3% of the ducks' body mass), and were equipped with a 23 mm whip antenna that extended through the

skin from the dorsal posterior of the body (Advanced Telemetry Systems). Isoflurane was used as anesthetic during surgery. All birds were kept for 5 to 24 h after surgery to monitor recovery, during which an electrolyte solution was given by intubation or subcutaneous injection every 4 to 5 h to minimize risk of dehydration. Birds were released at the capture location. All birds were handled in accordance with Animal Care and Use protocols approved by the Western Ecological Research Center of the US Geological Survey. To reduce any effects of capture and transmitter implantation, data collected during the first 7 d after release were excluded from analyses.

To determine if radio transmitters in the center of San Pablo Bay could be heard from shore via our null-peak vehicle-mounted antenna system, we placed test transmitters on weather buoys located near the center of the Bay. Transmitters were attached a few centimeters above the water line to simulate a duck sitting on the water. Test transmitters were detected from all shoreline monitoring locations used in this study. The maximum distance at which the test transmitter was heard over the open water from shore was 10 km.

Telemetry surveys with vehicle-mounted, dual null-peak antenna systems were conducted daily between 05:00 and 21:00 h from 1 November 1998 to 30 March 1999 and 30 October 1999 to 24 March 2000 (scaup), and from 12 November 2003 to 26 April 2004 and 5 November 2004 to 8 April 2005 (scoters). Each day was divided into 4 periods: dawn (the hour before official sunrise), dusk (the hour after official sunset), daytime, and nighttime. The goal was to obtain 1 radio-location during each of these daily periods once per week for each instrumented bird. During mid-winter in San Francisco Bay, sunset was about 17:00 h and sunrise about 07:00 h, so many nighttime locations were obtained. Bird locations were determined by triangulation. Azimuth error for the null-peak systems used in this study was previously established as 1.5°, with mean distance (±1 SE) between calculated and true location of test transmitters of 58 ± 35 m (Warnock & Takekawa 1995). Foraging at the time of radio-location was inferred from distinct attenuation of radio signal strength during dives, and percent time spent feeding was calculated as the percentage of radio-locations for which feeding was detected. Aerial flights were conducted weekly to locate missing birds and acquire better fixes for those with weak radio signals. Chronology of departure of radio-marked diving ducks from San Pablo Bay is shown in Fig. S1.
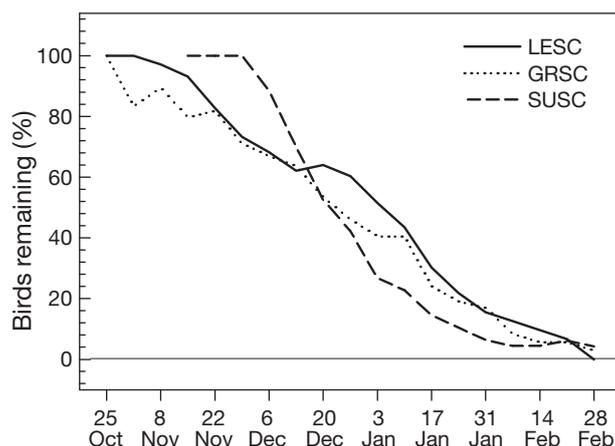

Fig. S1. *Aythya affinis, A. marila,* and *Melanitta perspicillata.* Chronology of departure from San Pablo Bay of 58 lesser scaup (LESC) and 59 greater scaup (GRSC) radio-tagged in 1998–1999 and 1999–2000, and of 53 surf scoters (SUSC) radio-marked in 2003–2004 and 2004–2005

Our sampling scheme was designed to obtain locations during each targeted time period and, as noted in the next section, an average of 6 h d^{-1} of sampling occurred during the nocturnal period. Daytime automobile traffic in the urbanized San Francisco Bay area constrained our mobility; so the greatest staff effort was dedicated to obtaining diurnal locations, leaving less time to obtain nocturnal locations. However, based on diurnal, crepuscular, and nocturnal locations, there was no evidence that space use varied in consistent diel patterns. Instead, an individual bird typically remained in the same general location for several days or weeks, and its movements within that area were mostly aligned with tidal schedules.

BEHAVIOR AND COSTS OF SURFACE ACTIVITIES, AERIAL FLIGHT, AND DIVING

Behavior. Diving ducks were observed through a 6 to 130× telescope (Questar Corporation) around San Pablo Bay during daylight from October to March 1988–1989 and 1989–1990. Focal individuals were observed continuously for 3 min. Duration in seconds of the following behaviors was recorded on cassette tapes: sleeping (head tucked under wing), comfort movements (preening, wing-flapping), resting (floating on the water surface without swimming, including pauses between dives), surface-swimming, dabbling (tipping up to feed without diving), and diving (under water). Social behaviors (aggressive or otherwise) were rarely if ever observed. Focal individuals were selected in 2 ways: (1) randomly, by swinging the scope across the visible range of birds and selecting the bird closest to the center of the field of view where the scope came to rest, and (2) by selecting individuals that were actively foraging. Overall time-activity budgets, and number of dives per minute of observations, were based only on randomly selected birds. Durations of dives, and of pauses at the surface between dives, were derived from both types of samples. Results of behavior observations are in Table S1.

Table S1. Mean ±1 SE for time-activity budgets, dives per minute, and duration of dives and subsequent pauses at the water surface by scaup (including lesser and greater scaup) and surf scoters in San Pablo Bay from October 1988 to March 1989, and December 1989 to February 1990. For time budgets, n = 80 scaup and 142 scoters; for dives min^{-1} during all daylight hours, n = 145 scaup and 167 scoters; for dives min^{-1} during foraging periods only, n = 62 scaup and 16 scoters; for dive duration, n = 78 scaup (381 dives) and 66 scoters (245 dives); and for pause duration, n = 61 scaup (335 pauses) and 58 scoters (231 pauses)

	Scaup	Surf scoter
Sleeping (%)	32 ± 5	42 ± 4
Resting (%)	17 ± 3	12 ± 2
Comfort movements (%)	11 ± 2	9 ± 2
Surface swimming (%)	24 ± 3	19 ± 2
Surface feeding (%)	8 ± 3	1 ± 0[a]
Diving (%)	9 ± 2	17 ± 2[a]
Dive rate, all daylight hours (dives min^{-1})	0.89 ± 0.08	0.49 ± 0.06[a]
Dive rate while feeding (dives min^{-1})	1.71 ± 0.10	1.13 ± 0.12[a]
Dive duration (s)	18.3 ± 0.7	26.9 ± 0.8[a]
Pause duration (s)	12.0 ± 0.8	15.4 ± 0.8[a]

[a]Different from scaup, *t*-test, p ≤ 0.01

For radio-marked birds, feeding was inferred from intermittent attenuation of telemetry signals (Fig. S2; Lewis et al. 2005). Radio-locations were obtained from 05:00 to 21:00 h, which on average included about 6 h d^{-1} of nocturnal observations. Maximum time spent feeding of almost 9 h d^{-1} was observed in LESC and GRSC in February, after numbers of all 3 species had declined substantially. To model threshold prey densities required for profitable foraging, we increased time spent feeding to 10.5 h d^{-1} for all species. This value reflected the possibility that percent time foraging (1) might increase during the period from 21:00 h until 05:00 h when no radio-locations were obtained, and (2) might increase before complete abandonment of the habitat due to inadequate foraging profitability.
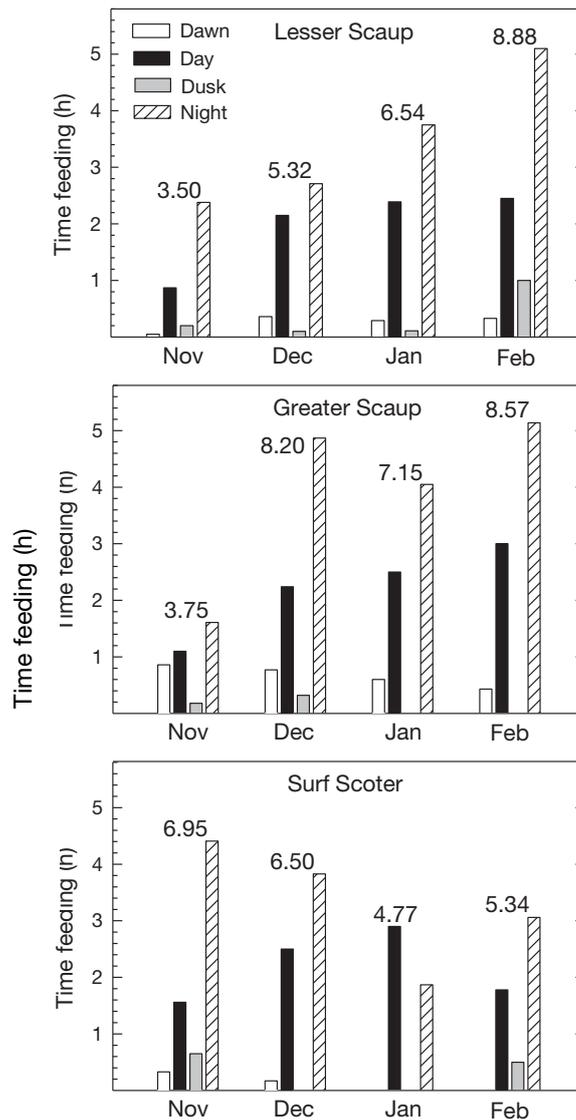

Fig. S2. *Aythya affinis, A. marila*, and *Melanitta perspicillata.* Mean time spent feeding per day in San Pablo Bay by lesser scaup and greater scaup in 1998 to 2001, and by surf scoters in 2003 to 2005, during dawn (the hour before sunrise), daytime, dusk (the hour after sunset), and nighttime in different months. Feeding was inferred from intermittent attenuation of radio signals. Monthly mean of total time spent feeding over 24 h is annotated. For these plots, the level of feeding activity from 1 h after sunset to 21:00 h (when data collection ended for the day) was assumed to continue until 1 h before sunrise

Surface activities. Energy costs of activities at the water surface were based on respirometry of captive ducks. From October through January, monthly mean water temperatures in San Pablo Bay typically range from 7 to 10°C at the bottom and 13 to 16°C at the surface (Orsi 1999b). For scaup floating on the water surface, we used values for LESC of 7.82 W kg^{-1} for resting and 11.46 W kg^{-1} for preening, both measured at a water temperature of 8°C (Kaseloo & Lovvorn 2005). For SUSC, we used values for white-winged scoters *Melanitta fusca* of 5.91 W kg^{-1} for resting and 12.19 W kg^{-1} for preening on water at 9°C (Richman & Lovvorn 2008). For surface-swimming, we used 12.1 W kg^{-1} measured for mallards *Anas platyrhynchos* swimming at an efficient speed of 0.5 m s^{-1} in water at 23°C (Prange & Schmidt-Nielsen 1970), assuming that heat generated by exercising muscles would replace increased heat lost to colder water (Kaseloo & Lovvorn 2005, Lovvorn 2007).

Aerial flight. Energy costs of aerial flight were calculated with Flight for Windows 1.22 (2008) software (www.bio.bristol.ac.uk/people/pennycuick.htm), as explained by Pennycuick (2008). These simulations required body mass, wing span, and wing area as input. Our simulations focused on adult females. Body mass of adult females in early winter averaged (±1 SD) 0.731 ± 0.066 kg for 11 LESC, 0.983 ± 0.153 kg for 14 GRSC, and 0.912 ± 0.079 kg for 19 SUSC. Measurements of 2 captive adult female LESC yielded means (±1 SD) of 0.716 ± 0.006 m for wing span, and 664 ± 25 cm^2 for wing area (including the section of the body between the wings, Pennycuick 2008). For 2 wild adult female SUSC shot in New Brunswick, Canada in autumn, values were 0.796 ± 0.034 m and 780 ± 102 cm^2. Based on the mean ratio of 6 other morphological measurements for 11 GRSC versus 9 LESC (adult females) collected in San Pablo Bay from November to December (1.134), and the ratio of wing area to wing span (979.9 cm^2 m^{-1}) in SUSC which have similar body mass, values for GRSC were estimated as 0.812 m for wing span and 796 cm^2 for wing area. Flight speed for all 3 species was assumed to be 65 km h^{-1} (Tucker & Schmidt-Koenig 1971, Bruderer & Boldt 2001). Based on these values, and assumed conversion efficiency of 0.23 for converting chemical energy to mechanical power by the muscles (Pennycuick 2008), the estimated cost of flight was 82 W kg^{-1} for LESC, and 79 W kg^{-1} for GRSC and SUSC. We had no data on distances flown per day, and arbitrarily assumed 5 km d^{-1}. In uncertainty analyses, we also explored the consequences of varying times spent in flight in terms of observed flight times caused by human disturbance (see section below on 'Ranges of variables for uncertainty analyses').

Diving. Costs of diving were based on respirometry of captive ducks in tanks 2 m deep with water at 8 to 9°C (Richman & Lovvorn 2009). (The mean dive depth for radio-tagged individuals of all 3 duck species in San Pablo Bay was about 2 m; see 'Results'. The typical range of monthly mean water temperatures at the bottom from October through January in San Pablo Bay was 7 to 10°C; Orsi 1999b.) For LESC in that study (mean body mass 0.553 kg), costs were estimated as 10.5 W kg^{-1} during descent, 10.1 W kg^{-1} while foraging at the bottom, and 5.8 W kg^{-1} during passive ascent (driven by positive buoyancy when the birds stopped stroking their feet at the bottom). Costs of diving paid during the subsequent pause at the surface were accounted for (Kaseloo & Lovvorn 2005, Richman & Lovvorn 2008). Vertical speed was 0.74 m s^{-1} during both descent and ascent.

We applied these metabolic costs for LESC to the congeneric, larger GRSC. For GRSC (0.983 kg), we used body mass to interpolate between vertical speeds of LESC weighing 0.553 kg and those of congeneric canvasbacks *Aythya valisineria* averaging 1.068 kg (descent at 0.86 m s^{-1}, ascent at 0.75 m s^{-1}, Lovvorn 1994) to yield 0.84 m s^{-1} during descent and 0.75 m s^{-1} during ascent for GRSC.

Unlike the *Aythya* spp. (LESC and GRSC) which swim by foot propulsion only, scoters can use their wings as well as feet for propulsion during descent; scoters use only feet while foraging at the bottom (Richman & Lovvorn 2008). As scoters can reduce costs of descent to 2 m depth by about 34% by swimming with wings as well as feet (Richman & Lovvorn 2008), and we used the cost of propulsion by wings plus feet in simulations for SUSC, one might expect their costs to be lower than for scaup which use only their feet. However, based on

measurements in the same dive tank and respirometer, mass-specific costs of white-winged scoters (W kg^{-1}) were 16% higher for descent (12.2 versus 10.5) and 33% higher for bottom foraging (13.4 versus 10.1) than for LESC (Richman & Lovvorn 2008). This anomaly might result partly from greater nervousness of scoters in respirometers (Richman & Lovvorn 2011), but also from higher heat production from using both leg and wing muscle groups, or greater heat loss from swimming with extended wings and greater turbulence (Lovvorn 2007). For white-winged scoters (mean body mass 1.092 kg) diving with wings and feet to a depth of 2 m at 8 to 9°C, costs were estimated as 12.2 W kg^{-1} during descent, 13.4 W kg^{-1} while foraging at the bottom, and 5.9 W kg^{-1} during passive ascent (Richman & Lovvorn 2009). Vertical speed was 0.45 m s^{-1} during descent and 0.56 m s^{-1} during passive ascent.

CONSUMPTION BY ECTOTHERMIC PREDATORS

Consumption of prey by major ectothermic predators from October through January was estimated based on data from San Francisco Bay or similar environments (Table S2). We assumed a mean water temperature of 12°C (Orsi 1999b), and calculated metabolic rates at that temperature from available data or fitted equations. To estimate *Corbula* consumed (in kJ), we assumed that all bivalves eaten were *Corbula* 6 to 12 mm long (see Poulton et al. 2004), with an energy content of 0.15 kJ clam^{-1} and assimilation efficiency for energy of 0.79 (Zhao et al. 2001). Except for starry flounders, which occurred almost entirely at subtidal depths (Baxter 1999), available data were not adequate to determine movements of these predators into intertidal areas at high tide to feed. Consequently, we assumed that ectothermic predators captured in subtidal areas exerted all their trophic impacts there. Predator densities measured by annual trawl surveys in San Pablo Bay (Orsi 1999a) were applied evenly throughout the subtidal shoals (0 to −6 m MLLW) to calculate their total impact on the prey biomass available to birds.

There may be partitioning by size of shared prey among ducks and ectothermic predators. Most decapods including Dungeness crabs can show strong size selection of bivalve prey (Juanes 1992); however, crabs can modify prey sizes used according to availability (cf. Micheli 1995), and may show little size selection when feeding on a preferred prey species (Mascaró & Seed 2000). Bivalve size selection has not been studied in post-juvenile sturgeon or flatfish. Lacking data for our system, we assumed that these ectothermic predators consume sizes of the dominant clam (*Corbula*) according to availability.

Of the species listed in Table S2, densities of starry flounders and Dungeness crabs were measured with bottom trawls, whereas densities of white sturgeon were estimated from returns of tagged fish by anglers. White sturgeon densities in San Pablo Bay appear to vary greatly both annually and seasonally. For the mean of 71 200 sturgeon from 1955 to 1987 in Suisun and San Pablo Bays (Kohlhorst et al. 1991), and a combined area for those bays of ~448 km^2 (Accurso 1992:13–14), we estimated a density of 160 km^{-2} for sturgeon (Table S2). For comparison with energy consumed by ectothermic predators (Table 5), numbers of additional ducks of each species that could be supported from October through January were also estimated (Table S3).

RANGES OF VARIABLES FOR UNCERTAINTY ANALYSES

For uncertainty analyses, the value of each parameter in 300 iterations of the model to predict profit per dive was randomly chosen from the ranges listed in Table 1. To examine effects of mean shell length (and thus energy content) of *Corbula* independently of numbers per m^2, we varied the mean length between 5 and 12 mm (means in 1990, 1993, 1995, and 2000–2001 were 9.1, 5.0, 10.1, and 8.4, respectively; see 'Results'). Intake rates depend on both the functional response and time at the bottom over which the functional response is applied. We varied number of prey ingested per second at the bottom between ±10% of intake rate predicted from the functional

response (0.986 prey s^{-1}) for the mean *Corbula* density in 1990 (1162 m^{-2}) (Richman & Lovvorn 2004). Effects of varying water depth and prey density on profit per dive were evaluated in separate analyses—see 'Results'. We varied the estimated mean time spent at the bottom during a single dive by LESC (12.9 s) between ±1 SD (6.2 s) of the mean total dive duration observed for scaup (including both LESC and GRSC) in the field (see 'Results'). Time spent feeding during the diel period may change with prey availability, and differed between GRSC and LESC by 24% in the same years (1998 to 2001, see 'Results'). We varied feeding time per day between 3.50 and 8.88 h, the range of monthly values from November to February inferred for LESC from radio-telemetry signals (see 'Results'). Dive rate (dives min^{-1}) during feeding periods was varied between ±1 SD (0.79) of the mean for scaup (both species combined) observed in the field (1.71; see 'Results'). To assess the potential importance of flight costs up to situations in which flight time is greatly increased due to boating disturbance, we applied reported rates of such flights by *Aythya* spp. (Kahl 1991, Knapton et al. 2000) to an assumed 8 h day to yield a maximum of 29 min of flight per day; values were varied between 0 and 29 min d^{-1}.

Table S2. Parameters for estimating bivalve consumption by ectothermic predators from October through January (123 d) in shallow subtidal areas of San Pablo Bay (0 to –6 m MLLW)

Species	Mean body length (mm)	Mean body mass (kg)	Metabolic rate (W kg^{-1})	Bivalve fraction in diet	Mean density of predator (no. km^{-2})
White sturgeon	900[a]	2.90[b]	0.35[c]	0.65[d,e]	160[f]
Starry flounder	410[g]	1.50[g]	0.31[h]	0.75[a,i,j]	650[k]
Dungeness crab	40[l]	0.011[m]	0.20[n]	0.55[o]	250, Oct–Dec[l]
	80[l]	0.081[m]	0.20[n]	0.14[o]	120, Jan[l]

Sources: [a]Ganssle (1966); [b]Keenlyne & Maxwell (1993); [c]Ruer et al. (1987); [d]McKechnie & Fenner (1971); [e]Urquhart & Regalado (1991); [f]Kohlhorst et al. (1991); [g]Smith & Kato (1979); [h]Fonds et al. (1992); [i]Kline (2000); [j]Orcutt (1950); [k]Baxter (1999); [l]Hieb (1999); [m]Stevens & Armstrong (1984); [n]Gutermuth & Armstrong (1989); [o]Stevens et al. (1982)

Table S3. *Aythya affinis, A. marila*, and *Melanitta perspicillata*. Mean daily numbers of diving ducks in San Pablo Bay based on bi-monthly aerial counts in October through January 1988–1989 and 1989–1990 (Fig. 8), and additional numbers supportable in subtidal habitat (0 to –6 m MLLW) over this 123 d period if the prey base of *Corbula* clams was the same as in fall 1990, 1993, or 1995, and relative numbers of duck species were the same. Total numbers of scaup in aerial counts were assumed to be 44% LESC and 56% GRSC in 1988–1989, and 74% LESC and 26% GRSC in 1989–1990 (see text). Numbers of use-days can be calculated by multiplying duck numbers by 123 d

Year of counts	Species	Mean daily number Oct to Jan	Additional number supportable, Oct to Jan		
			1990	1993	1995
1988–1989	LESC	12 724	55 068	99 770	136 904
	GRSC	16 326	47 291	84 233	136 230
	SUSC	7 616	21 245	36 103	61 686
1989–1990	LESC	50 941	63 188	134 428	209 822
	GRSC	17 898	15 824	35 284	62 974
	SUSC	12 501	10 445	22 257	42 597

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