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A LOW INTENSITY SAMPLING METHOD FOR ASSESSING BLUE CRAB ABUNDANCE AT ARANSAS NATIONAL WILDLIFE REFUGE AND PRELIMINARY RESULTS ON THE RELATIONSHIP OF BLUE CRAB ABUNDANCE TO WHOOPING CRANE WINTER MORTALITY

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Abstract: We sampled blue crabs (*Callinectes sapidus*) in marshes on the Aransas National Wildlife Refuge, Texas from 1997 to 2005 to determine whether whooping crane (*Grus americana*) mortality was related to the availability of this food source. For four years, 1997 - 2001, we sampled monthly from the fall through the spring. From these data, we developed a reduced sampling effort method that adequately characterized crab abundance and reduced the potential for disturbance to the cranes. Four additional years of data were collected with the reduced sampling effort methods. Yearly variation in crab numbers was high, ranging from a low of 0.1 crabs to a high of 3.4 crabs per 100-m transect section. Mortality among adult cranes was inversely related to crab abundance. We found no relationship between crab abundance and mortality among juvenile cranes, possibly as a result of a smaller population size of juveniles compared to adults.

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Key words: Aransas-Matagorda National Wildlife Refuge, blue crab, *Callinectes sapidus*, feeding ecology, *Grus americana*, mortality, whooping crane.

Blue crabs (*Callinectes sapidus*) are an important food source for the migratory Aransas-Wood Buffalo whooping cranes (*Grus americana*) during their winter stay at the Aransas National Wildlife Refuge (NWR), Texas (Stevenson and Griffith 1946, Allen 1952, Hunt and Slack 1989, Chavez-Ramirez 1996, Nelson et al. 1996). Hunt and Slack (1989) reported that crabs constituted 42.9% and 40.1% of the total mean volume of winter food consumed by whooping cranes during the winters of 1983-1984 and 1984-1985 respectively. Chavez-Ramirez (1996) found that crabs made up a mean of 90.2% (62-98%) and 61.5% (18.4-97.6%) of percent daily energy uptake during the winters of 1992-1993 and 1993-1994 respectively. From these findings, we hypothesized that a shortage of crabs could induce whooping crane winter mortality.

Intensive sampling of crab abundance was conducted from September through April, in 1997 through 2001. Our objective was to develop from these data a low intensity sampling design that could be successfully carried on by refuge staff and pose the least disturbance to wintering whooping cranes. Data from this sampling design would be sufficient to monitor long-term variation in crab abundance and to examine correlations between crab abundance and whooping crane mortality. Here we provide our data including four years, 2002 through 2005, in which we collected data in March using the low intensity procedures.

STUDY AREA

Data collection on crab abundance was conducted in the coastal salt marsh along the eastern edge of Blackjack Peninsula of the Aransas NWR located on the southeast coast of Texas (Fig. 1). The marsh lies parallel to the Intracoastal Waterway and is bordered by Dunham and Sundown Bays. The vegetation is dominated by Virginia glasswort (*Salicornia virginica*), saltwort (*Batis maritima*), bushy seaoxeye (*Borrichia frutescens*), Carolina wolfberry (*Lycium carolinianum*), saltgrass (*Distichlis spicata*), and smooth cordgrass (*Spartina alterniflora*) (Chavez-Ramirez 1996). We established three 1200 to 1400-m transects (A, B, and C) along the bottoms of natural bayous and the edges of ponds in three areas of the marsh. Each transect was partitioned into 100-m sections in which the entire section was classified as either bayou or pond habitat. Bayous were tidal inlets and creeks ranging in width from 0.7 m to 31.3 m. Ponds were small bodies of water connected to the bay through tidal inlets and ranged from a mean diameter of 62.8 m to 504.6 m. Sections were typically contiguous with one another; however, several had small breaks between them in order to keep each section 100% bayou or pond habitat. The number of sections in bayou and pond habitat in each transect were: Transect A, 6 bayou, 6 pond; Transect B, 12 bayou, 1 pond; Transect C, 10 bayou, 4 pond. Transects A and B were located west of Sundown Bay on the southwest and northeast sides of the Old Pump Canal, and Transect C was located to the northeast of Dunham Bay (Fig. 1). The Old Pump Canal is a 1,350 m long channel that runs perpendicular

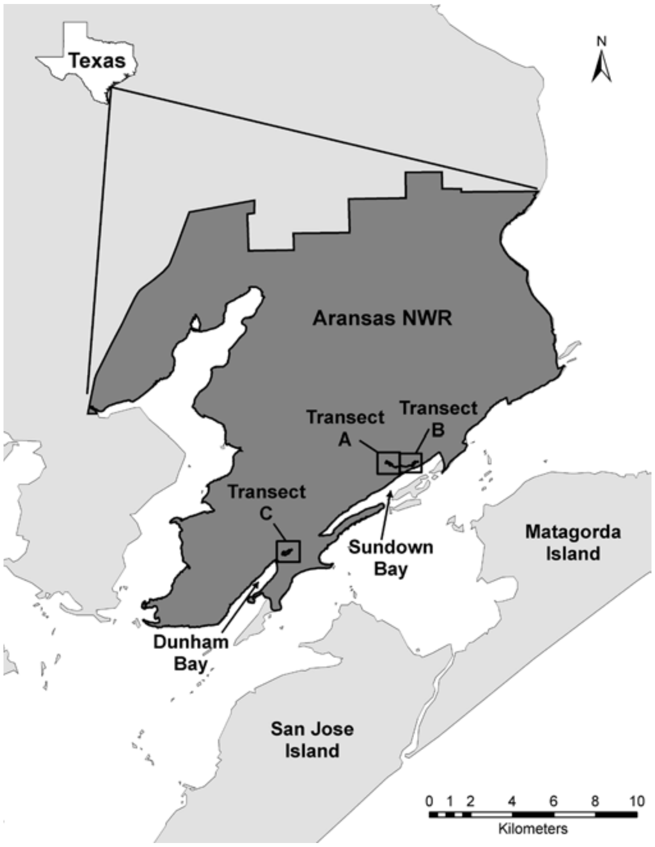


Figure 1. The locations of study transects in Aransas National Wildlife Refuge, Texas.

from Sundown Bay into the marsh. Each 100-m section was marked with stakes, and its location was recorded to sub-meter accuracy using a Trimble GPS Pathfinder® Pro-XR receiver global positioning system (GPS) unit. Spatial analyses were conducted using ArcView 3.3® geographic information system (GIS). The shortest distance from each transect to open water (i.e., Dunham or Sundown Bay) was 417.6 m for Transect A, 434.5 m for Transect B via the pump canal and 897.3 m for Transect C via a natural bayou.

METHODS

Data collection included recording water temperature and surface salinity at the beginning and end of each 100-m section, tallying blue crabs and estimating their carapace width (CW). Salinity and water temperature were measured using a YSI® Model 30 SCT meter (accurate to ±0.1 ppt). Salinity for a given transect section was calculated as the average of readings taken at the beginning and end of the section. During surveys in April 2001, the salinity meter failed. On 16 April, salinity readings were taken only from Transect A and 2/3 of Transect B. On 17 April, salinity measurements were recorded by using a salinity refractometer (accurate to ± 1.0 ppt). For the rest of April, salinity was recorded using a YSI® Model 85 SCTDO system (accurate to ± 0.1 ppt). We estimated missing values for salinity on the 16th by extrapolating from data collected on the 15th and the 17th and the partial data from the 16th (See Pugesek and Baldwin 2003). Water temperature was calculated as the average for each transect on each calendar day.

Along each transect, crabs were counted and categorized according to estimated carapace width: Class 1 (0<CW≤4 cm), Class 2 (4<CW≤8 cm), Class 3 (8<CW≤12 cm), Class 4 (12<CW≤16 cm), Class 5 (CW>16 cm), and Undetermined (undetermined size).

Field seasons are referred to as Year 1 (Y1)(1997-1998), Year 2 (Y2)(1998-1999), Year 3 (Y3)(1999-2000), or Year 4 (Y4)(2000-2001). We attempted to collect 15 days of data in September, prior to the arrival of whooping cranes at Aransas NWR, and another 15 days of data immediately after the cranes had departed in April. During the months of October through March, we planned data collection for three days per month to minimize disturbance to cranes present on the refuge. In Y1, we were unable to collect data during October because of heavy rains and in December and January because of cold temperatures and low water levels. In Y2, tropical storms Charley and Frances interrupted data collection. As a result of heavy rains and storm surge, water in the marsh was very high and turbid, preventing us from collecting data until mid-October, during which only two days of data were collected instead of the planned 15 days in September and three days in October. In Y3, the only major setback was that the 15 consecutive days planned for September were postponed until October because of high water turbidity. In Y4, data were not collected in January because of cold temperatures and low water levels, and April data collection was cut short because of high and turbid water.

The daily primary water level was recorded using the tide gauge at the refuge's boat ramp. Crab count data were collected only when water levels were within a range of 0.5 m - 0.8 m mean low tide. Sections were excluded when water turbidity made it impractical to observe crabs. For any given section, the minimum visibility required to collect crab count data was that the substrate could be observed at 0.6 m or more from the bank. Beginning in Y3, sections were classified into two categories according to water clarity: high or adequate. Sections were considered high when the entire substrate was visible. Sections were adequate if a portion of the substrate was obstructed by turbid water but was still clear enough to satisfy the minimum visibility requirements.

Crab count data were collected in 2002 (Y5), 2003 (Y6), 2004 (Y7), and 2005 (Y8) using methods identical to those described above. Crabs were counted in Transects A and B on three dates in the later part of March. Data were collected within the previously described water level ranges. Salinity and water temperature data were not collected.

Whooping cranes were censused weekly from mid-October through April using the methodology of Stehn and Taylor (2008). Mortality was detected primarily when one territorial adult or its juvenile disappeared. In the winter of 2001-2002, for example, 136 territorial adults and 15 juveniles were present, accounting for 151 out of the total flock size of 176. Thus, mortality could be readily detected on approximately 86% of the flock, and this value remains consistent from year to year. Mortality goes undetected on the remainder of the population. Sub-adult cranes wander among territories and will stray on rare occasions off of the usual wintering grounds. Also, an adult crane may occasionally lose its mate and re-pair as quickly as 72 hr. The exceptional case of rapid re-pairing may also cause mortality to be underestimated.

Statistical Analyses

Environmental variables (i.e., salinity, water temperature, habitat type, distance from open water, and water level) were analyzed to determine the extent to which they affected crab abundance, and would require consideration in developing a reduced sampling effort. All among-year analyses of Y1 through Y4 data were made with only those months sampled in every year (i.e., November, February, March, and April). Within-year analyses included every month sampled in that year. We excluded from analyses those crab counts collected at water temperatures below 17°C because previous research reported decreased crab activity and a tendency among crabs to burrow into the substrate below this threshold (Jaworski 1972, Adkins 1982, Steele and Perry 1990, Chavez-Ramirez and Slack 1995). We used analysis of variance (ANOVA) and regression to analyze salinity, water temperature and water level data. We used transects as the sampling unit in our analyses of salinity, with the exception of the analysis of salinity gradients, where the sampling unit was the 100-m section. ANOVAs involving water temperature used transects as the sampling unit. Regressions involving water temperature and analyses of water level used the calendar day as the sampling unit. All other analyses used the 100-m section as the sampling unit. In some analyses, crab count data did not exhibit a normal distribution or homogeneous variance; therefore, count data were converted into a categorical variable with three categories of crab abundance: low ($n = 0$), mid ($n = 1$ or 2), and high ($n \geq 3$). We examined the categorical count data with year, month, transect, and habitat variables using log-linear models. All variables were modeled with crossed effects with the exception of habitat which was nested within transects.

Size classes were combined as necessary for among-month comparisons in order to meet the assumption for minimum expected frequency required for the chi-square test. Mean class size per month was calculated to illustrate the temporal shift in crab size within and among years. Comparisons were made between data collected at Aransas NWR and historical crab data (1982-94) on mean length of crabs collected using 6.1-m trawls by the Coastal Fisheries Division, Texas Parks and Wildlife Department (McEachron and Fuls 1996). We made comparisons by estimating mean CW of crabs observed in Aransas NWR. Each class size was assigned its median value (e.g., Class 1 = 20 mm, Class 2 = 60 mm, etc.), and then a mean CW was calculated for each month.

Salinity gradients within each transect were examined to determine if they affected crab abundance. These analyses

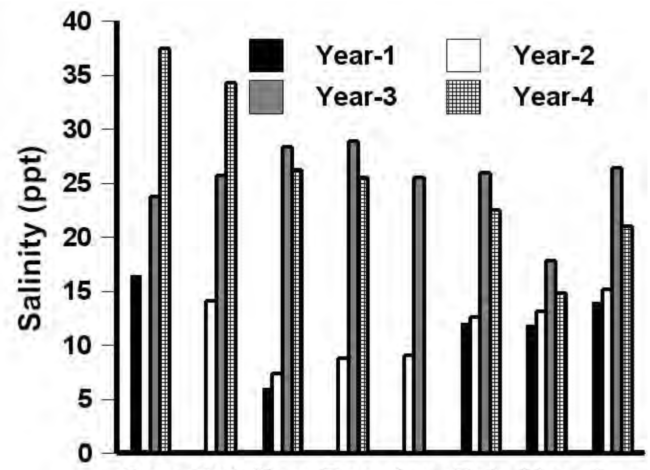


Figure 2. Mean salinity levels, measured daily at each transect, as a function of year and month (ppt).

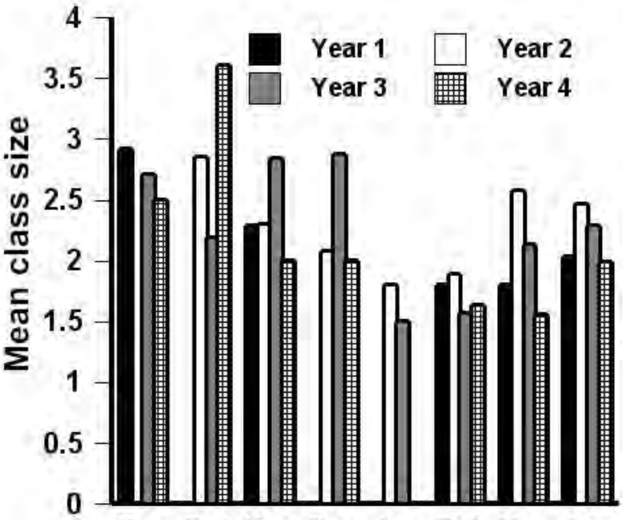


Figure 3. Mean water temperatures, measured daily, as a function of year and month (C°).

were conducted with a subset of the data where data were collected on several consecutive or near consecutive days (i.e., September 1997, October 1999, and April 1998, 1999, 2000). We computed the minimum and maximum salinities among sections within each transect on each date of data collection. A difference score was calculated as the maximum minus minimum salinity reading in each transect. A difference score was also computed for crab abundance using crab counts from the sections with the maximum and minimum salinity readings. Regression analysis was performed on the difference scores to determine whether a relationship existed between the magnitude of the salinity gradient and the difference in crab abundance.

Table 1. Statistical results of 1-way ANOVAs comparing water temperature among years, months and transects.

Variable	Time	df	*F* value	*P* value
Year		3,256	15.54	0.001
Month	Y1	4,126	66.30	0.001
	Y2	6,84	6.14	0.001
	Y3	7,142	14.48	0.001
	Y4	6,67	16.71	0.001
Transect	Y1	2,126	1.75	0.178
	Y2	2,84	1.02	0.366
	Y3	2,142	2.19	0.116
	Y4	2,67	0.58	0.560

Table 2. Statistical results of 1-way ANOVAs comparing water levels among years and months.

	Year	df	*F* value	*P* value
Year		3,86	4.26	0.008
Month	Y1	4,42	4.10	0.007
	Y2	6,28	1.33	0.284
	Y3	7,47	4.20	0.002
	Y4	6,22	6.94	0.001

Table 3. Regression analysis of crab abundance and water levels.

Year	df	*F* value	r^2 value	*P* value
Y1	1,42	9.55	0.194	0.003
Y2	1,27	5.84	0.178	0.023
Y3	1,46	0.30	0.006	0.588
Y4	1,21	1.14	0.052	0.298

Data were inspected for violations of statistical assumptions and transformed as necessary to meet the assumptions of the statistical analyses employed (Sokal and Rohlf 1969).

RESULTS

Intensive Sampling Y1 through Y4

Salinity levels varied significantly among transects during two of the four years (Y1: $F_{2,126} = 33.73$, $P \leq 0.001$; Y2: $F_{2,84} = 2.60$, $P = 0.081$; Y3: $F_{2,142} = 0.22$, $P = 0.806$; Y4: $F_{2,67} = 3.35$, $P = 0.041$). Transect C consistently exhibited higher mean salinities than the other two transects in all years (Mean salinity for Transects A, B, and C respectively: Y1, 9.96, 11.34, 14.91; Y2, 10.30, 11.86, 12.24; Y3, 25.02, 25.33, 25.48; Y4, 23.83, 24.93, 29.08). Salinity varied significantly among years ($F_{3,256} = 170.78$, $P \leq 0.001$) and among months in each year (Y1: $F_{4,126} = 12.41$, $P \leq 0.001$; Y2: $F_{6,84} = 45.52$, $P \leq 0.001$; Y3: $F_{7,142} = 27.00$, $P \leq 0.001$)(Fig. 2). In Y1, Y2, and Y4, salinities were highest in early fall and then declined through the winter. In Y1 and Y2, salinity levels increased in the spring from relatively low fall and winter levels. In contrast, salinities were uniformly high throughout most of Y3 (Fig. 2). The relatively high salinity levels in Y3 and Y4 were coincident with drought that the region was experiencing. Salinity was least variable during March.

The relationship of salinity to crab abundance was negative in Y2, while in Y1, Y3 and Y4, the relationship was nonsignificant (Y1: $F_{1,42} = 1.04$, $r^2 = 0.024$, $P = 0.314$, NS; Y2: $F_{1,27} = 22.90$, $r^2 = 0.459$, $P < 0.001$; Y3: $F_{1,46} = 3.85$, $r^2 = 0.077$, $P = 0.056$, NS; Y4: $F_{1,21} = 0.93$, $r^2 = 0.042$, $P = 0.346$, NS). No association was found between crab abundance and salinity gradients within each transect using regression analysis ($F_{1,421} = 0.36$, $r^2 = 0.001$, $P = 0.550$, NS).

Water temperature varied significantly among years, but not among transects within a year (Table 1). Among-month variation in water temperature was significantly different each year with all years exhibiting a general decline in temperatures during the winter and then an increase in the spring (Fig. 3). No association was found between the daily means of temperature and crab abundance in any year using regression analysis (Y1: $F_{1,42} = 2.75$, $r^2 = 0.061$, $P = 0.105$, NS; Y2: $F_{1,27} = 0.060$, $r^2 = 0.002$, $P = 0.813$, NS; Y3: $F_{1,46} = 0.88$, $r^2 = 0.019$, $P = 0.353$, NS; Y4: $F_{1,20} = 1.35$, $r^2 = 0.063$, $P = 0.260$, NS).

Water levels varied significantly among months in three of the four years and also varied significantly among years (Table 2). A small negative relationship existed between water levels and crab abundance during Y1 and Y2 (Table 3). Ponds did not exhibit a relationship between water levels and crab

Table 4. Water level effects on crab abundance according to habitat type.

Habitat	Year	df	*F* value	r^2 value	*P* value
Pond	Y1	1,42	2.18	0.049	0.147
	Y2	1,27	1.22	0.043	0.280
	Y3	1,46	3.64	0.073	0.063
	Y4	1,21	0.94	0.043	0.344
Bayou	Y1	1,42	14.62	0.258	0.001
	Y2	1,27	9.31	0.256	0.005
	Y3	1,46	0.18	0.004	0.676
	Y4	1,21	1.07	0.048	0.314

Table 5. Log-linear analysis of crab abundance in relation to year, month, transect, and habitat type (bayou or pond).

Source	df	Chi-Square	*P* value
crab*year	6	237.86	0.001
crab*month	6	102.44	0.001
crab*transect	4	7.73	0.102
crab*habitat(transect)	6	8.80	0.185
crab*year*month	18	156.62	0.001
crab*year*transect	12	35.07	0.001
crab*month*transect	12	29.06	0.004

abundance; however, a significant negative relationship was observed in bayous in Y1 and Y2 (Table 4).

Bayous had high water clarity 65.8% of the time while ponds were high 78.3% of the time. Despite variability in water clarity, crab abundance did not vary significantly between high and adequate sections ($F_{1,137} = 1.20$, $P = 0.276$). We also found no relationship between the distance to open water and crab abundance ($F_{1,149} = 0.28$, $r^2 = 0.002$, $P = 0.599$).

Log-linear analysis was used to examine the variation in crab abundance among years, months, transects, habitat, and interactions among those variables. Crab abundance varied significantly among years (Tables 5-6). Considering only those months sampled in each year, yearly crab densities (crabs/100 m) in order of decreasing abundance were as follows: Y2 = 14.1 (SE = 7.59), Y3 = 1.5 (SE = 0.69), Y1 = 1.4 (SE = 0.59), and Y4 = 0.35 (SE = 0.12). Crab abundance also varied significantly among months in every year (Tables 5-6). All four years exhibited a similar pattern in crab abundance with numbers spiking in October or November and then declining through the winter. By spring, crab abundance increased substantially from winter levels, with the exception of Y2, which displayed only a slight increase in April. The interaction term of year and month was also significant, probably reflecting high variability in crab abundance during different year/month combinations such as Y2 described above (Tables 5-6). The main effect of transect was not significant. We did observe significant interaction terms for year and transect and month and transect. Both were the result of high variability in crab abundance in Transect C. We did not observe a relationship between habitat type and crab abundance (Tables 5-6).

Class size varied significantly among years ($\chi^2_{12} = 345.02$, $P \leq 0.001$) and among months in each year (Y1: $\chi^2_{12} = 337.29$, $P \leq 0.001$; Y2: $\chi^2_{18} = 1831.65$, $P \leq 0.001$; Y3: $\chi^2_{12} = 97.21$, $P \leq 0.001$) (Fig. 4). Y4 was excluded from the analysis because of small sample size (64% of cells had counts < 5). In the Y3 analysis, December, January, and February were excluded because of small sample sizes. Larger crabs were observed in Y2 and in Y3. The number of crabs in each size class exhibited a similar temporal pattern in each year by declining during the winter and increasing in the spring (Fig. 5).

The computed mean CW for each class size for each study year was: Y1 ≈ 6.6 cm; Y2 ≈ 7.0 cm; Y3 ≈ 7.0 cm; Y4 ≈ 5.9 cm. Our results fall within the range reported in trawl samples in both bays (Aransas Bay: Mean 7.1 cm, Range = 5.6 - 8.4 cm, *n* = 12 yr; San Antonio Bay: Mean 7.3 cm, Range = 4.7 - 9.3, *n* = 12 yr).

Restricted Sampling Effort

In order to determine whether a restricted sampling effort was sufficient to characterize crab abundance, we compared Y1 through Y4 March data from Transects A and B to: 1) April data collected in all transects and 2) data collected for the full year, November through April. Mean total crabs per section for the March Transect A and Transect B counts combined were Y1: 0.4, Y2: 2.4, Y3: 0.6 and Y4: 0.1. Table 7 shows the relationship between these counts and yearly counts of total crabs, large crabs (Classes 3, 4, and 5) and adult crabs (Classes 4 and 5) for three April variables: mean, maximum (peak crab numbers), and sum (the number of crabs summed over the data collection period) (Note: April data are derived from all three transects, A, B, and C). Also provided are Kendall's Tau, a nonparametric correlation that proceeds by comparing variables whose observations are ranked in order of ascendance and without assumptions of normality. March means and April data excluded sections with adequate water clarity; however, no substantive differences were obtained when sections with adequate water clarity were included in a similar analysis and compared to these results.

Given the small sample size, only a perfect match of rankings with no ties between March mean total crabs and

Table 6A. Blue crab abundance (mean crab/100 m; SE) by month and transect, Y1.

Transect	September	November	February	March	April	All Months
A	0.7 (0.09)	1.4 (0.58)	0.2 (0.06)	0.3 (0.11)	1.8 (0.18)	0.9 (0.31)
B	0.3 (0.04)	2.2 (0.65)	0.5 (0.20)	0.6 (0.22)	2.1 (0.25)	1.1 (0.42)
C	0.6 (0.12)	2.7 (0.75)	0.3 (0.09)	0.6 (0.19)	4.1 (0.67)	1.7 (0.75)
A, B and C Transects	0.5 (0.09)	2.1 (0.27)	0.3 (0.06)	0.5 (0.07)	2.7 (0.51)	1.2 (0.49)

Table 6B. Blue crab abundance (mean crab/100 m; SE) by month and transect, Y2.

Transect	October	Nov-Dec	Mid-Dec	January	February	March	April	All Months
A	0.9 (0.27)	43.1 (5.28)	22.0 (4.16)	4.9 (0.88)	9.7 (1.19)	2.8 (0.92)	4.4 (0.36)	12.5 (5.75)
B	1.1 (0.48)	32.6 (2.52)	10.4 (1.80)	10.4 (1.56)	12.2 (1.25)	2.1 (0.52)	4.2 (0.36)	10.4 (4.05)
C	0.3 (0.17)	32.7 (4.05)	26.1 (5.36)	6.9 (1.33)	9.8 (1.32)	7.0 (0.80)	7.7 (0.71)	12.9 (4.45)
A, B and C	0.8 (0.17)	36.1 (2.46)	19.5 (3.33)	7.4 (1.14)	10.6 (0.58)	4.0 (1.08)	5.4 (0.80)	11.9 (4.64)

Table 6C. Blue crab abundance (mean crab/100 m; SE) by month and transect, Y3.

Transect	September	October	November	December	January	February	March	April	All Months
A	1.8 (0.30)	2.2 (0.24)	1.2 (0.21)	0.2 (0.07)	0 (0)	0.04 (0.04)	0.7 (0.16)	2.2 (0.20)	1.0 (0.29)
B	0.5 (0.17)	3.4 (0.23)	2.0 (0.30)	0.1 (0.07)	0.1 (0.04)	0.2 (0.07)	0.6 (0.10)	3.6 (0.28)	1.3 (0.46)
C	0.9 (0.38)	8.4 (0.70)	1.1 (0.28)	0.2 (0.10)	0 (0)	0.3 (0.11)	1.0 (0.32)	4.3 (0.43)	2.0 (0.91)
A, B and C	1.1 (0.38)	4.4 (1.90)	1.4 (0.28)	0.2 (0.03)	0.03 (0.03)	0.2 (0.08)	0.8 (0.12)	3.4 (0.62)	1.4 (0.50)

Table 6D. Blue crab abundance (mean crab/100 m; SE) by month and transect, Y4.

Transect	September	October	November	December	February	March	April	All Months
A	0.03 (0.03)	0.04 (0.04)	0.03 (0.03)	0.04 (0.04)	0.13 (0.09)	0.03 (0.03)	0.44 (0.10)	0.11 (0.06)
B	0.08 (0.05)	0.08 (0.06)	0.26 (0.10)	0.16 (0.06)	0.17 (0.10)	0.13 (0.07)	0.69 (0.12)	0.22 (0.08)
C	0 (0)	0.05 (0.05)	0.57 (0.20)	0.42 (0.16)	0.13 (0.09)	0.67 (0.19)	0.92 (0.28)	0.39 (0.13)
A, B and C	0.04 (0.02)	0.06 (0.01)	0.29 (0.16)	0.21 (0.11)	0.14 (0.01)	0.28 (0.20)	0.68 (0.14)	0.24 (0.08)

April observations of mean, maximum, and sum would result in a significant Kendall's Tau. Rankings of March mean total crabs, Y2 the highest, followed by Y3, Y1, and Y4, matched perfectly the ranking of mean total crabs observed in April. The maximum and sum of April counts had some discordance in rankings caused by influxes of very small crabs in some years. Considering only large crabs (Classes 3, 4, and 5) in the April counts resulted in perfect rankings with March mean total crabs in all three measures. Considering only adult crabs (size classes 4 and 5) in the April counts yielded slightly less favorable results with ranks of mean and sum perfectly matched with March mean total crabs, and maximum with two matching ranks and two ties.

The relationship between March mean total crabs in Transects A and B, and crab counts per section for the entire sampling period November through April for all transects (A, B, and C) was significant for total crabs, large crabs, and adult crabs (Table 8). Listed means excluded sections with inadequate water clarity, but significance levels of Kendall's Tau remained the same in all cases when analysis included sections with inadequate water clarity.

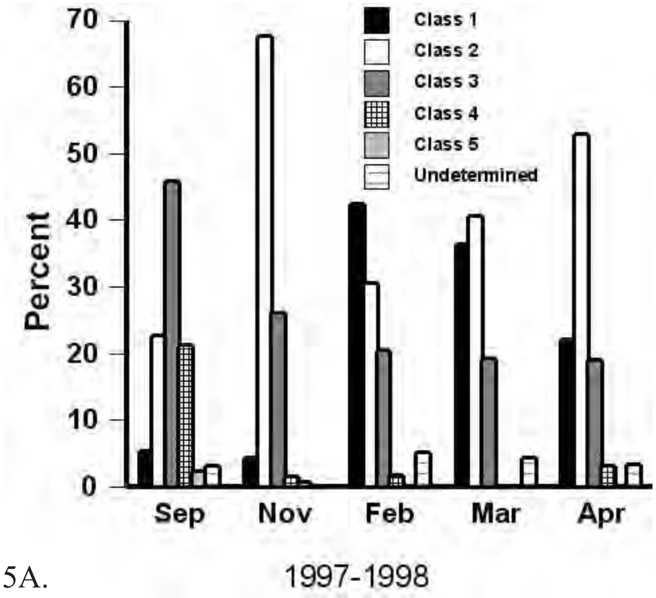
In all analyses, rankings of March mean total crab count perfectly matched rankings of counts for total crabs, large crabs, and adult crabs. Kendall's Tau in each case was significant. Thus, a low intensity sampling regime using Transects A and B counting total crabs for a three-day period produces the same rank ordering of years as does sampling for a two-week period in April or sampling for the entire period of November through April.

We compared March mean total crab counts for Transects A and B between years in order to determine how well this method would categorize years as high, medium, or poor. Included in this analysis are Y5, Y6, Y7 and Y8 data. The mean total crab count for Y5 was 0.8, Y6 and Y7, 3.4, and Y8, 1.6 crabs per section. Data did not meet the assumptions of normality required for analysis of variance. We categorized crab count data as low (zero crabs per section), medium (one or two crabs per section), and high (three or more crabs per section) and proceeded with categorical analysis of the data using Fisher's Exact Test (Tables 9 and 10). By all measures, Y2, Y6, and Y7 had the highest number of crabs and were the only years that had more than 25% of sections with three or more crabs per section in the March counts. Y1 and Y4, the low count years, had zero crabs per section in a very large percentage of sections (77.1% and 86.5%). Y3 and Y5 had a fairly substantial number of sections (47.3% and 46.1%) with at least one or two crabs per section.

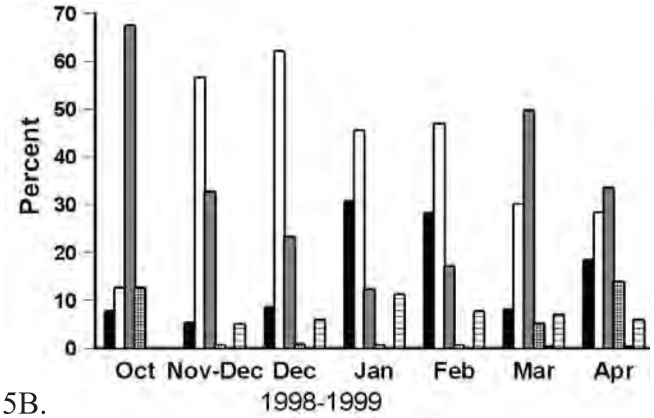
Most of the between-year comparisons of the proportions of the three categories differed significantly (Table 10). The null was rejected in 23 of 28 comparisons indicating that the March total crab counts in Transects A and B had sufficient statistical power to discriminate between almost all of the years. The Fisher's Exact Test failed to reject the null hypothesis in only five pairs of years in which mean total crab counts were very similar, Y4 compared to Y1 (means 0.1 and 0.4), Y5 compared to Y3 (means 0.8 and 0.6), Y6 compared to Y7 (means 3.4 and 3.4), Y2 compared to Y8 (means 2.4 and 1.6), and Y5 compared to (means 0.8 and 1.6). These results suggest that we should categorize the eight years of data as: high quality, Y7, Y6 and Y2; medium quality, Y8, Y5 and Y3; and poor quality, Y4 and Y1. Since 2003 and 2004 differed significantly from the previous high count obtained in 1999, it is possible to expand the yearly ranking to include a fourth extremely high category.

Crab Counts and Crane Mortality

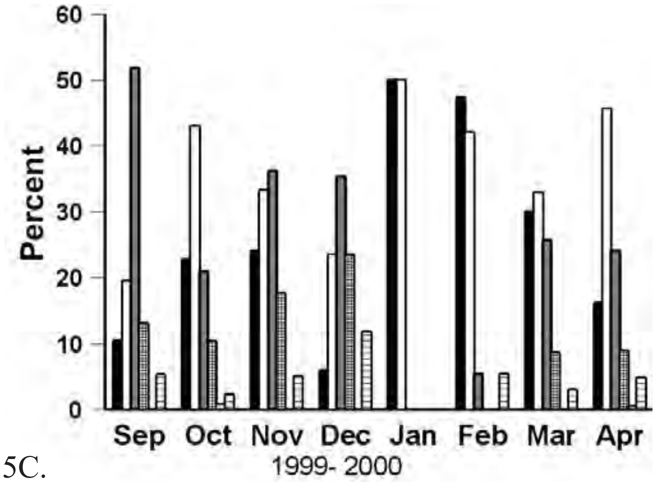
The March mean total crab count ranged from a low of 0.1 crabs per section to a high of 3.4 crabs per section (Table 11). Crane mortality ranged from zero to four mortalities among adults and zero to two mortalities among juveniles. The



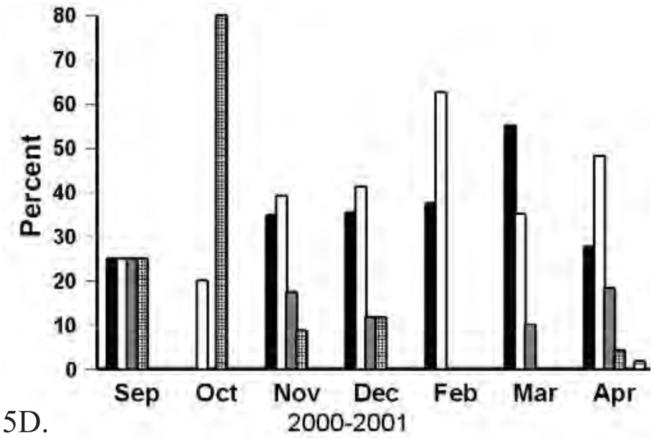
5A.



5B.



5C.



5D.

Figure 5. Percent of crabs in each class size by month and year: A. Y1: 1997-1998; B. Y2: 1998-1999; C. Y3: 1999-2000; D. Y4: 2000-2001.

Table 7. Within-year comparisons of the restricted sampling subset of yearly data (March mean total crab counts for Transects A and B) with three types of April crab counts (total crab, large crabs, and adult crabs) and three variables for each type of count (mean, maximum, and sum). Kendall's Tau and significance level (*P*) are provided for each comparison.

	Year	Mean	Maximum	Sum
Total crabs				
	Y1	2.4	42	1365
	Y2	5.3	34	1966
	Y3	3.7	21	1103
	Y4	0.9	7	74
Kendall's Tau and *P*		1.0 (0.04)	0.33 (0.49)	0.67 (0.17)
Large crabs				
	Y1	0.5	8	299
	Y2	2.5	22	919
	Y3	1.3	9	375
	Y4	0.2	2	16
Kendall's Tau and *P*		1.0 (0.04)	1.0 (0.04)	1.0 (0.04)
Adult crabs				
	Y1	0.1	3	41
	Y2	0.8	6	283
	Y3	0.3	3	98
	Y4	0.0	1	2
Kendall's Tau and *P*		1.0 (0.04)	0.91 (0.07)	1.0 (0.04)

Table 8. Within-year comparisons of the restricted sampling subset of yearly data (March mean total crabs for Transects A and B) with full year counts, November through April. Kendall's Tau and significance *P* are provided for each comparison.

	Total crabs	Large crabs	Adult crabs
Y1	1.4	0.4	0.1
Y2	9.8	3.3	0.4
Y3	2.8	0.9	0.3
Y4	0.3	0.1	0.0
Kendall's Tau and *P*	1.0 (0.04)	1.0 (0.04)	1.0 (0.04)

correlation between March mean total crab count and adult mortality was significant (Spearman's r_s = - 0.92, $P < 0.002$). The correlation between crab abundance ranking and adult mortality was also significant. The Spearman's rank correlation, using the three-category ranking scheme, was r_s = - 0.80, $P <$ 0.02. Adding a fourth category (extremely high) resulted in a Spearman's rank correlation of r_s = - 0.86, $P < 0.01$.

No significant differences were found between March mean total crab count and crane juvenile mortality (Spearman's r_s = - 0.0, $P = 0.99$) or between crab abundance rank and crane juvenile mortality (Spearman's r_s = -0.01, $P = 0.97$ and r_s = 0.08, $P = 0.85$ for the three-rank and the four-rank schemes respectively). No significant differences were found between March mean total crab count and total (adult plus juvenile) crane mortality (Spearman's r_s = - 0.50, $P = 0.21$) or between crab abundance rank and total crane mortality (Spearman's r_s = -0.43, $P = 0.29$ and r_s = - 0.42, $P = 0.30$ for the three-rank and the four-rank schemes respectively).

Summing the number of adult cranes observed in the eight seasons thus far yields a total of 1053 adults, 8(0.8%) of which died during the overwintering period. In total, 160 juveniles were observed during this period, 6(3.6%) of which died during the overwintering period. The proportion of adult deaths was significantly lower compared to that of juvenile deaths (Fisher's exact test, $P < 0.01$). Ninety five percent confidence limits for death during the eight seasons were as follows: adults (0.4180 - 1.0367); juveniles (1.7446 - 6.0510).

DISCUSSION

Crab Abundance and Environmental Variables

Results indicated that statistical control (e.g. analysis of covariance) was unnecessary to remove bias due to ecological variables known to influence crab abundance; however, we caution the reader that results presented here likely differ from those that might have been obtained in a completely randomized experimental design. Our objective was to control extraneous variation and not to explore the interactions of ecological variables. For example, our results on the relationship between salinity and crab abundance were restricted to a narrow range

Table 9. Frequencies and the percentage of yearly total of sections containing low, medium, and high crab counts in March.

	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8
Low	54 (77.1)	37 (52.1)	28 (50.9)	32 (86.5)	24 (46.1)	14 (25.0)	11 (20.4)	23 (41.1)
Medium	13 (18.6)	16 (22.5)	26 (47.3)	5 (13.5)	24 (46.1)	17 (30.3)	15 (27.8)	20 (35.7)
High	3 (4.3)	18 (25.3)	1 (1.8)	0 (0.0)	4 (7.7)	25 (44.6)	28 (51.8)	13 (23.2)

of water levels and would likely have differed from a study that explored the relationship within the full range of tidal conditions.

Salinity was related to crab abundance in only a minor way in one year. Other researchers have reported that salinity affects blue crab distribution (More 1969, Daud 1979, Hammerschmidt 1982, Van Engel 1982, Perry and McIlwain, 1986; Cody et al. 1992, Steele and Bert 1994). Sherry and Chavez-Ramirez (1998) reported a negative correlation between blue crab abundance and salinity.

Blue crabs have been described as having gender (More 1965, Tatum 1982, Perry and McIlwain 1986, Cody et al. 1992, Steele and Bert 1994) and age-specific (More 1965, Perry and Stuck 1982) differences in salinity preferences. These preferences may also change as crabs respond to seasonal cues that cause them to migrate to and from the marshes for growth, reproduction, etc. Our finding of a weak relationship between crab abundance and salinity is likely due to restricted sampling conditions. The narrow range of water levels and turbidity that we used for sampling meant that we avoided sampling during periods of drought, flooding, and storm surge when conditions were relatively unstable or rapidly changing.

Little evidence was found linking water temperature to crab abundance. Data were excluded from analyses when water temperature was at or below 17° C on the basis of a report that crab activity at the Aransas NWR refuge decreased and crabs often burrowed into the substrate at this temperature (Chavez-Ramirez and Slack 1995). Others have observed that blue crabs become less active at 15° C and often migrated to deeper water (Jaworski 1972, Adkins 1982, Steele and Perry 1990). More (1969) and Jaworski (1972) described crabs burrowing into the mud when the water became cold. This behavior was observed on numerous occasions when water temperatures dropped below 17° C.

Habitat type and distance to open water were not found to affect crab abundance. We observed that crabs tended to be less common in ponds during periods of low water level. Most ponds contained a gentle sloping bottom usually devoid of vegetation, with the exception of certain areas containing smooth cordgrass. Unless the water was at or above the vegetation zone, crabs were less likely to inhabit those areas. Also, low water levels can potentially reduce crab abundance in the marsh through mortality or forced migration to deeper waters. Similar observations have been reported in Texas (Chavez-Ramirez 1996) and Louisiana (Sherry and Chavez-Ramirez 1998). Statistical tests reported here indicated that these observations played only a minor role in overall crab abundance because of the narrow range of water levels selected for sampling.

Since the accuracy of our data depended upon the ability to observe crabs, water turbidity could have influenced results. In general, increased turbidity and high water levels occurred concomitantly. As water levels rose, turbid water from the Intracoastal Waterway infiltrated the marsh. These turbid waters made detecting crabs more difficult, and bayous were usually more susceptible to this problem than were ponds. We excluded data from all sections where water turbidity made crab counts impractical. Visibility was still an issue at times, particularly in the warmer months because of increased abundance of large fish, mullet (*Mugil cephalus*) and red drum (*Sciaenops ocellatus*), and shrimp (*Litopenaeus spp.*), whose activity disturbed bottom sediments. We found no significant difference in crab abundance between sections of high and adequate clarity.

The decline in crabs throughout the winter may be attributed in part to predation by whooping cranes. A similar winter

Table 10. Between-year comparisons of the restricted sample total crab count categories (low, medium, and high) for all years of the study. Fisher's Exact Test probabilities are provided for between-year comparisons in corresponding rows and columns. Shaded *P*-values are not significant.

	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8
Y1	-	-	-	-	-	-	-	-
Y2	0.001	-	-	-	-	-	-	-
Y3	0.001	0.001	-	-	-	-	-	-
Y4	0.464	0.001	0.001	-	-	-	-	-
Y5	0.001	0.01	0.417	0.001	-	-	-	-
Y6	0.001	0.01	0.001	0.001	0.001	-	-	-
Y7	0.001	0.001	0.001	0.001	0.001	0.730	-	-
Y8	0.001	0.243	0.002	0.001	0.08	0.047	0.006	-

Table 11. March mean crab abundance, crab abundance ranking, adult crane mortality, juvenile crane mortality, and combined adult and juvenile mortality observed during eight years from 1998 through 2003.

Year	Mean crab number	Abundance ranking	Adult mortality	Juvenile mortality	Total mortality
Y1	0.4	low	1	0	1
Y2	2.4	high	0	0	0
Y3	0.6	medium	1	0	1
Y4	0.1	low	4	2	6
Y5	0.8	medium	1	1	2
Y6	3.4	high	0	1	1
Y7	3.4	high	0	1	1
Y8	1.6	medium	1	1	2

decline in crab abundance was reported by Chavez-Ramirez (1996). Another factor causing the decline in crab numbers during winter could be water temperatures. As described earlier, crabs may migrate to deeper waters to avoid cold temperatures.

Crab Size Distribution

Our results on mean class sizes of crabs were consistent with those obtained by deep water surveys conducted in the refuge area. This result supports a hypothesis that our method of sampling crabs reflects the size distributions of crabs found in the larger ecosystem. Estimates of mean class size were higher during years of high crab abundance and lower during years of low crab abundance. The combined effect of crab abundance and size further accentuates the disparity in food supply for cranes during high quality and low quality years. Commercial crab harvesting may affect the size structure of crabs at Aransas NWR, by removing large adult crabs from the population. Chavez-Ramirez (1996) stated that crab traps numbering in the hundreds were set in the bays surrounding marshes used by whooping cranes.

Restricted Sampling

The intensive sampling that we conducted, fall through spring with three transects, was designed to investigate the variability in the system so that we could make informed judgments about the time of the year that was best and what level of sampling intensity would adequately categorize a given year. We encountered difficulty in sampling crabs during September and October. Water levels and clarity were extremely variable during this period because of storms, including tropical storms and hurricanes, in the Gulf of Mexico, and water depths were generally high as a consequence of fall equinal tides. For this reason, we deemed September through October too unreliable to plan seasonal data collection.

November through February was more efficacious for reliable data collection, although some negatives were apparent. It was during this time period that cranes were wintering in the marshes. It would seem logical that this would be the time that we would want to measure crab abundance, when it really counted for the cranes. However, the cranes themselves posed problems in that they might have been consuming crabs in our transects and we had no way to measure the precise impact of this activity on the crab abundance we measured. Also, in some years, crabs moved into the marsh and appeared to conduct low intensity spawning activities that might upwardly bias estimates of crab abundance. Water temperatures during winter months might at any time drop below the 17^{o}C threshold that caused crabs to burrow into the substrate, thereby reducing their movement and observation. Finally, variability in water levels and salinity was reduced but not as much as in late spring.

April is arguably the best time to sample crab abundance. Each year during this period, the crabs conducted major breeding activities in the marsh. Large number of crabs moved into the marsh from the Intracoastal Waterway, typically resulting in the highest counts of any month. We believe that the waters inside the barrier islands, including the Intracoastal Waterway, acted as a reservoir for the crab population. Our measure of crab abundance in the marsh was an indirect relative measure of population size in the larger estuarine habitat but one that was potentially biased by tidal influences, water levels, water temperatures, salinity, and crane foraging behavior. The drive to breed and the requirement to mate in the marshes may ameliorate the effects of those physical factors that influence crab abundance in the marsh. In addition, the timing of breeding during April eliminated any bias resulting from crane foraging as the cranes had already left the area for their breeding grounds in Canada. However, the exact timing of spawning is variable from year to year, and we discovered that continuous sampling for at least two weeks was required to observe a peak in crab abundance. Plans for continuous sampling for a two week period could easily be disrupted by inclement weather.

For the reasons stated above, we selected late March as the best time for sampling. During this period, variability in salinity was low (See Fig. 2), and water levels and temperatures were stable and reliably within the cutoff levels established for optimal sampling (see Methods). Because some of the cranes had also recently departed for their breeding grounds in Canada, there was less risk of disturbance caused by the presence of biologists. Transects A and B were selected because crab counts in Transect C tended at times (especially during March and April) to be the most dissimilar of the three transects (see Table 6). Transects A and B also shared a more common physical location in terms of distance to open water, location in the marsh, and surrounding vegetative habitats.

Crab Abundance and Whooping Crane Mortality

Our study is the first to demonstrate a relationship between crab abundance and adult whooping crane mortality. Most years ranged from 0 to 2 total adult and juvenile mortalities, but mortality climbed to 4 adults and 2 juveniles in the year we measured the lowest crab abundance. It is possible, therefore, that there exists a critical threshold level of crab abundance below which cranes are in danger of suffering inordinately high levels of mortality. Further data collection will help to verify and delineate dangerous threshold levels if such levels exist.

Juveniles were nearly four times more likely to die at the wintering grounds than were adults. In spite of a higher juvenile mortality rate, we found no significant relationship between juvenile mortality and crab abundance. We offer two possible explanations for this finding. First, the number of juveniles present each year was less than 16% of the number of adults present. The smaller sample of juveniles likely provides less opportunity for variation in survival rate to be accurately measured. Second, we do not know the extent to which parental care provided by adults may compensate for low crab abundance. Parents may compensate for low crab abundance by feeding juveniles and retaining a lower percentage of forage for themselves. Parental care is known to result in increased adult mortality in long-lived species such as the California Gull (*Larus californicus*) that have life histories similar to that of whooping cranes (Pugesek 1981, 1983, 1987, 1993, 1995; Pugesek and Diem 1983, 1990). California Gulls that feed and care for offspring over a longer duration of parental care are less likely to survive. For similar reasons, it is possible that adult mortality increases among adults with offspring in their care.

While years of mid to high levels of crab abundance produce little crane mortality, years of low abundance are associated with significant crane mortality. Whooping cranes, unlike short-lived species with high reproductive rates, require years to mature and produce few offspring per breeding attempt over a long life span. As a consequence, even low levels of adult mortality can significantly impair the capacity of the population to grow or maintain stable numbers relative to short-lived species that can quickly recover to their maximum carrying capacity. Future research should include continued data collection on crab abundance and crane mortality to more accurately delineate levels of crab abundance necessary to avoid adult and possibly juvenile mortality. In addition, modeling of the demographic consequences of winter mortality should be employed to determine the potential impacts of future mortality events on the viability of the whooping crane population.

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