

Rough Draft

Model Description

Overview

The model was developed to simulate the population dynamics of blue crabs in Aransas and Copano bays in response to selected environmental and management variables identified by the stakeholders who participated in the Mission-Aransas National Estuarine Research Reserve Program. In the model, Aransas and Copano bays are divided into 139, approximately 1.5km x 1.5km, spatially-explicit grid cells, and crab population levels fluctuate weekly as the result of recruitment, growth, movement, natural mortality, and fishing mortality. Under environmental conditions typical of these bays, juvenile crabs appear in Aransas Bay from the middle of May through November. Larval stages are not represented explicitly. Crabs increase carapace width with each molt, with molting frequency depending on water temperature. Crabs are considered sub-adults when they complete their 12th molt and are considered adults when they complete their 20th molt. Juvenile crabs move toward the mouth of the Aransas River, sub-adults and adult males move randomly within Aransas Bay and Copano Bay, and adult females move toward the sea. Rates of movement are stochastic and are slightly faster during warmer months (April through October) than during cooler months (November through March). Natural mortality rate, which is based on maximum longevity, is constant and independent of size. However, crabs also die if exposed to lethal water temperatures or if they become too old, and the maximum number of third instar juveniles that can survive is limited by the number of first instar juveniles in the system. Fishing mortality rate is assumed to be the difference between natural and total mortality rates, with the later estimated empirically. Rates of recruitment, growth, movement, natural mortality, and fishing mortality all are probabilistic.

Environmental Conditions

The time series of weekly water temperatures and salinities used in the model are based on data collected from 2007 to 2012 as part of the Mission-Aransas National Estuarine Research Reserve (MA-NERR) System-Wide Monitoring Program (SWMP). The SWMP consists of five sampling stations distributed throughout the MA-NERR, four of which are located within Aransas and Copano bays (Fig. 1). These stations record water temperature and salinity at 15-minute intervals. Since water temperatures tended to be homogeneous throughout the bays during any given week, and seasonal patterns were quite similar from year to year, we calculated a single water temperature for each week of the year as the weekly mean of the values recorded during that week at all stations over all six years, and assigned this single mean value to each of the 139 grid cells. Since salinity exhibited more spatial and temporal variability, we calculated a different time series of weekly salinities for each grid cell for years representative of (1) high, (2) low, and (3) normal freshwater inflows, respectively (139 grid cells x 3 types of years = a total of 417 time series). We identified the data used to represent high-inflow years (2007 and 2010) and low-inflow years (2009, 2011, and 2012) based on histograms of all of the salinity values in the data set for each year (Fig. 2), and we used all of the data from 2007 to 2012 to represent normal years. Using each of the three subsets of data, we calculated the mean salinity for each sampling

station for each week of the year, and assigned these mean values to the grid cells in which the sampling station was located. We then calculated salinity values for the grid cells located along straight lines running between sampling stations along the long axis of each bay (the red lines in Fig. 1) via linear interpolation. Finally, we sequentially calculated salinity values for the rest of the grid cells as the means of the values of adjacent cells as we moved perpendicularly away from the straight lines connecting the sampling stations. Since graphs of the resulting weekly time series appeared a bit erratic, for purposes of visualization, we smoothed the curves by replacing the weekly values with four-week moving averages.

Recruitment

Juvenile crabs (first molt "J1s") appear in Aransas Bay from the middle of March (week 12) through November (week 48) (Ward, 2012). Magnitude of recruitment of simulated crabs is calibrated such that a 10-year simulation will run in approximately 2 minutes on a personal computer (recruitment-index = 100, i.e., 100 J1's are added to a randomly-chosen cell in Aransas Bay each week during the recruitment period). Note that the magnitude of recruitment of juveniles is not related to the number of mature females. This is based on the "saturation hypothesis" (e.g., Caley et al. 1996), which assumes that all habitats are filled with megalops, and subsequent densities of juveniles are governed entirely by the environment.

Growth

Crabs increase carapace width with each molt, with molting frequency depending on water temperature. The probability of molting is calculated as a function of the number of degree-days accumulated since the last molt (DDaccum), however, degree-days are accumulated only if the temperature is $\geq 10.8\text{C}$ (Brylawski and Miller, 2006). Brylawski and Miller (2006) estimated probability of molting as:

$$\text{probability of molting} = 0.669 \cdot \ln(\text{DDaccum}) - 3.71$$

Their equation was based on laboratory experiments and a field enclosure study, and represented observed crab growth in Chesapeake Bay well. However, to achieve maturity within one year (Perry, 1975; Ward, 2012), assuming maturity occurs at the 20th molt (Van Engel, 1958), under water temperatures typical of Aransas and Copano bays, we decreased the slope of the equation to 0.65:

$$\text{probability of molting} = 0.65 \cdot \ln(\text{DDaccum}) - 3.71$$

Brylawski and Miller (2006) estimated an average growth per molt of 119.5%. However, to achieve a carapace width of 173mm by the 20th instar (Ward, 2012) under water temperatures typical of Aransas and Copano bays, we increased the growth-per-molt to 123.8%.

Movement

Juvenile crabs move toward the mouth of the Aransas River, sub-adults and adult males move randomly within Aransas Bay and Copano Bay, and adult females move toward the sea (Ward, 2012). Rates of movement are stochastic and are slightly faster during the warmer months of April (week 14) through October (week 44) than during the cooler months of November (week 45) through March (week 13). During warmer months first to fifth instar juveniles, sixth to eleventh instar juveniles, sub-adults, adult males, and adult females move at velocities between zero and 0.5, 1, 1.5, 2, and 3 km / week, respectively; during cooler months first to fifth instar juveniles, sixth to eleventh instar juveniles, sub-adults, adult males, and adult females move at velocities between zero and 0.5, 0.5, 1, 1, and 1.5 km / week, respectively (Zack Darnell, pers. comm.). We considered crabs to be sub-adults when they completed their 12th molt and adults when they completed their 20th molt.

Natural Mortality

Natural mortality rate (M) is based on maximum longevity (tmax in years) (Hewitt and Hoenig, 2005):

$$\ln(M) = 1.44 - 0.982 * \ln(t_{max})$$

$$\text{and } M = 4.22 / (t_{max}^{0.982}) \text{ (Hewitt and Hoenig, 2005)}$$

Assuming $t_{max} = 8$ yrs (Hewitt and Hoenig, 2005), $M = 0.548/\text{year}$.

Converting from an annual rate to a weekly rate (Mwk):

$$M_{wk} = 1 - (1 - M)^{(1 / 52)} = 1 - (1 - 0.548)^{(1 / 52)} = 0.015$$

In addition to this baseline natural mortality rate, crabs also die when exposed to water temperatures $<2C$ or $>35.5C$ (Tagatz, 1968), or when their age exceeds 3 years (Texas Parks and Wildlife, 2009). (Note that the t_{max} used to estimate natural mortality rate based on longevity refers to the maximum age ever observed in the stock, that is, physiological longevity (Hewitt and Hoenig, 2005), however, the vast majority of crabs in Texas waters die before reaching 3 years of age (Texas Parks and Wildlife, 2009)) Finally, “excess” third instar juveniles die if the ratio of third to first instars in the system exceeds a threshold value. Pile et al. (1996) empirically related the mean annual densities of third instar, fifth, seventh, and ninth instar larvae to the mean annual density of first instar larvae in Chesapeake Bay. Drawing upon their density-dependent relationships, we defined a maximum allowable ratio of third instars (J3s) to first instars (J1s), estimated as the mean ratio calculated from the three pairs of data points closest to the origin in their Fig. 6a (Pile et al. 1996, p. 287; $(0.4285 / 0.125 = 3.428)$, $(0.5714 / 0.3125 = 1.82848)$, $(1.1428 / 0.5 = 2.2856)$, $(3.428 + 1.82848 + 2.2856) / 3 = 2.514$). When this ratio is exceeded (number of J3s / J1s > 2.514), an appropriate number of randomly-selected third instars die.

Total and Fishing Mortality

Sutton and Wagner (2007) estimated an average annual (from 1982 through 2005) total instantaneous mortality rate (Z) for crabs in Aransas Bay of 1.17 (Sutton and Wagner 2007, Table 11, p. 35). Thus, the finite annual total mortality rate $= 1 - e^{-Z} = 0.689633$, and the finite weekly total mortality rate $= 1 - (1 - 0.689633)^{(1/52)} = 0.022$. Assuming that the fishing mortality rate is equal to the total mortality rate minus the natural mortality rate, we estimated the fishing mortality rate as $0.022 - 0.015 = 0.007$. Only crabs exceeding the legal harvest size (carapace width ≥ 127 mm (5 inches), Ward 2012, Appendix C, p. C2) are harvested.

Relation between simulated crabs and crabs sampled in the real system

To relate simulated crabs to crabs sampled in the real system, we calibrated a conversion factor that determines the number of real crabs represented by each simulated crab (5000), as well as the relative “trapability” of different sized crabs sampled by a 38mm mesh otter trawl (Table 1), such that simulated samples were similar to observed samples collected from San Antonio Bay by the Texas Parks and Wildlife Department (using a 38mm mesh otter trawl) from 1982 to 2008. The conversion factor adjusts the overall magnitude of the simulated samples and the relative trapabilities adjust the size-class distribution of the crabs in the samples. The rationale for the size-specific trapabilities is that crabs with a carapace width smaller than the mesh size of the trawl are less likely to be trapped, and larger, more mobile crabs that can flee from the approaching trawl are less likely to be trapped. Neither the conversion factor nor the relative trapabilities affect model behavior, they only affect the presentation of simulation results.

Model Verification

We verified that the calibrated model was capable of producing reasonable patterns of crab (1) recruitment (juveniles appear in Aransas Bay from the middle of March through November; Fig. 3), (2) growth (crabs achieve their 20th molt within approximately one year; Fig. 4), and (3) movement (juvenile crabs move toward the mouth of the river, sub-adults and adult males move randomly within the bays, and adult females move toward the sea, with rates of movement being slightly faster during the warmer months; Fig. 5) under water temperatures typical of Aransas and Copano bays. We also verified that (4) unlimited growth of the simulated population was prevented by the density-dependent relationship between the third instars and the first instars (the population exhibited a dynamic equilibrium under water temperatures typical of Aransas and Copano bays; Fig. 6), and (5) estimates of crab densities and mean and median carapace widths based on simulated trawl samples were similar to estimates based on actual trawl samples collected from San Antonio Bay by the Texas Parks and Wildlife Department from 1982 to 2008 (density estimates fluctuated seasonally between approximately 10 and 90 individuals / ha, and estimates of both the mean and median carapace widths fluctuated between approximately 40 and 90mm; Fig. 7).

Model Evaluation

After verifying that the model had been calibrated successfully to produce the expected (“targeted”) patterns of crab population dynamics and individual crab growth, we evaluated the capability of the model to simulate (1) annual Texas commercial crab landings for Aransas-Copano Bay and (2) crab population biomass density estimates based on otter-trawl samples from Aransas-Copano Bay. We also examined the sensitivity of model predictions of mean carapace width, population density, and annual harvest to both doubling and halving the estimated natural mortality rate. Finally, we discuss our decision to omit explicit representation of two processes that initially were suggested for inclusion in the model: the effects of (1) changes in salinity and (2) predation by whooping cranes on crab population dynamics.

Annual Texas commercial crab landings from 1996 to 2005 ranged from 56×10^3 to 608×10^3 kg (Table 9, p.32 in Sutton and Wagner 2007), whereas annual harvests simulated over a 10-year period under the baseline fishing mortality rate (0.007) and water temperatures typical of Aransas and Copano bays ranged between approximately 380×10^3 and 450×10^3 kg (Fig. 8). Both mean and median simulated harvests (409×10^3 and 404×10^3 kg, respectively) were higher than mean and median observed landings (275×10^3 and 295×10^3 kg, respectively), and simulated harvests were less variable (standard deviation of the mean was 22×10^3 kg compared to 190×10^3 kg for the observed landings). These differences were due in large part to the extremely low commercial harvests in 1999 and 2000 (83×10^3 and 56×10^3 kg, respectively). Crab population biomass density estimates based on otter-trawl samples from 1996 to 2005 ranged from 25 to 130 mg/m^3 (Fig. 34, p. 161 in Ward 2012), whereas simulated population biomass density estimates based on weekly simulated trawl samples fluctuated seasonally between approximately 25 and 390 mg/m^3 (Fig. 9a). Mean annual estimates of simulated population biomass densities based on weekly simulated trawl samples were noticeably greater than estimates calculated from reported otter-trawl samples, although the latter fell within 2 standard deviations of the mean of annual estimates based on weekly simulated trawl samples (Fig. 9). Doubling and halving the natural mortality rate had no noticeable effect on model predictions of mean carapace width, but population density was reduced by about 60% and predicted mean annual harvest by more than one-half when natural mortality rate was doubled, and population density was increased by about 25% and predicted mean annual harvest more than doubled natural mortality rate was halved (Fig. 10). Minimum and median predicted annual harvests were close to the mean and variability among harvest levels was relatively lower when natural mortality rate was doubled, whereas maximum and median predicted annual harvests noticeably exceeded the mean and variability among harvest levels was relatively higher when natural mortality rate was halved.

Two processes that initially were hypothesized to play an important role in the population dynamics of crabs in Aransas and Copano bays were salinity changes resulting from changes in freshwater inflow and predation by whooping cranes. The model still includes weekly changes in salinity patterns throughout the two bays under different inflow regimes (described above). However, salinity is not included explicitly in any of the equations that govern model behavior, although the effect of salinity is implicit in the rules governing the migration of the adult females toward the sea. Predation by whooping cranes no longer is included in the model.

Salinity effects: The effect of salinity changes resulting from changes in freshwater inflow on crab populations remains controversial, in large part because it often is viewed as an integral part of the debate over the levels of freshwater inflow required to maintain the health of bay ecosystems. While it is certain that level of freshwater inflow affects bay salinity gradients, and that crab population level is an important indicator of bay health, available empirical evidence suggests that changes in crab population levels are not tightly linked to changes in salinity *per se*. A review of the literature on crab life history and physiology is beyond the scope of the present study, but we have provided quotes from each of two recent studies that summarize the rationale for not including salinity effects on crabs in the model in the appendix.

Whooping crane predation: While whooping cranes prey upon crabs and may have a noticeable local effect on crab densities near their winter territories, crane predation is unlikely to be an important factor affecting the population dynamics of crabs in Aransas and Copano bays. Cranes are present only during winter and few are likely to forage in these bays. Whooping cranes migrate south from Canada during fall, arriving at the Aransas National Wildlife Refuge (ANWR) in November, and leave ANWR on their spring migration back to Canada by April (Gil-Weir et al., 2012). Cranes are territorial on their wintering grounds, with most of the territories located in the ANWR and on Matagorda Island, with perhaps 16 territories located on San José Island, which borders Aransas Bay (Stehn and Prieto 2010, Table 1, p. 42). Assuming that (1) each of these 16 territories contains an adult male and an adult female (32 cranes), (2) all of these cranes arrive on day-of-year 305 and leave on day-of-year 91 (151 days feeding in Aransas Bay), and (3) all of these cranes satisfy 100% of their daily energy requirements by eating crabs, we can estimate the biomass of crabs that would be necessary to meet these energy requirements would be about 8×10^3 kg (Excel file: Crab calories, forSept2013sheet). To put this into perspective, annual commercial crab harvests in Aransas Bay have been as high as $1232 \text{ kg} \times 10^3$ (in 1980) and as low as $56 \text{ kg} \times 10^3$ (in 2000), with harvests from 2001 to 2005 ranging from 295 to $608 \text{ kg} \times 10^3$ (Sutton and Wagner 2007, Table 9, p. 32). Based on field estimates of the percent of crane diets consisting of crabs – 0, 90, 28, 28, and 28 in November, December, January, February, and March, respectively, during the winter of 2004-2005, and 20, 0-7, 0-7, 0-7, and 0-7 in November, December, January, February, and March, respectively, during the winter of 2005-2006 (Slack et al., 2009, pp. 138-139), more reasonable estimates of the biomass of crabs that would be necessary to meet the energy requirements of 32 cranes might range from about 3×10^3 kg (based on data from 2004-2005) to about 0.5×10^3 kg (based on data from 2005-2006). Assuming that a more reasonable estimate of the number of cranes foraging in Aransas and Copano bays might be around a half a dozen (Zack Darnell, pers. comm.), crane consumption of crabs might range from about 0.56×10^3 kg (based on data from 2004-2005) to about 0.01×10^3 kg (based on data from 2005-2006).

Simulation of Environmental and Management Scenarios

We initially simulated the population dynamics of blue crabs in Aransas and Copano bays in response to the following six environmental and management scenarios: (1) normal, (2) low, and (3) high freshwater inflow, and (4) normal, (5) low, and (6) high fishing mortality. To simulate each of the first three scenarios, we used as input (driving variables) to the model the time series of weekly water temperatures and salinities for each grid cell corresponding to the level of freshwater inflow being simulated, with all other variables set at their baseline values. To simulate each of the second three scenarios, we set the fishing mortality rate its baseline level, twice its baseline level, and half its baseline level, with all other variables set at their baseline values. During each simulation, we recorded model predictions of mean carapace width, population density, and annual harvests. Since results of simulations run during model evaluation indicated that model predictions of population density and mean annual harvest were sensitive to changes in the estimate of natural mortality rate (Fig. 10), we also simulated each of the second three scenarios with natural mortality rate doubled and halved.

Changing the time series of weekly water temperatures and salinities to represent normal, low, and high freshwater inflow scenarios had no noticeable effect on model predictions of mean carapace width, population density, or mean annual harvest, although the maximum annual harvest was slightly lower under low freshwater inflow conditions and slightly higher under high freshwater inflow conditions (Fig. 11). Doubling and halving the fishing mortality rate (assuming the baseline natural mortality rate) had no noticeable effect on model predictions of mean carapace width or population density, but predicted mean annual harvest increased by about 75% when fishing mortality rate was doubled and decreased by almost half when fishing mortality rate was halved (Fig. 12). Median predicted annual harvests were close to the mean and variability among harvest levels was relatively low for all three scenarios. Predictions of the effects of the different fishing mortality rates were not changed noticeably when natural mortality rate was halved, and were not changed qualitatively when the natural mortality rate was doubled (Fig. 13). However, with natural mortality rate doubled, predictions of population density were reduced by about half and predicted mean annual harvests decreased by about two thirds. Predictions of mean carapace width were unchanged.

Table 1. The relative “trapability” of different sized simulated crabs sampled by a simulated 38mm mesh otter trawl (probability of a crab of a given size being sampled in any given week of simulated time).

Stage	Approximate Carapace Width (mm)	Relative Trapability
<= 11	< 23	0
12	29	0.25
13	36	1
14	45	0.9
15	57	0.8
16	71	0.7
17	89	0.5
18	111	0.2
19	139	0.01
20	173	0.0001

DRAFT

Figure Legends

Figure 1. Map of Aransas and Copano bays indicating locations (yellow dots) of the four sampling stations that provided the data used to calculate the weekly water temperatures and salinities used in the model. These stations are part of the Mission-Aransas National Estuarine Research Reserve (MA-NERR) System-Wide Monitoring Program (SWMP).

Figure 2. Histogram of the number of measurements in the data set for each year that fall into the indicated salinity category.

Figure 3. Seasonality of recruitment of first instar juvenile crabs simulated under water temperatures typical of Aransas and Copano bays.

Figure 4. Growth of crabs recruited as first-instar juveniles during the indicated week of the year simulated under water temperatures typical of Aransas and Copano bays. Y-axis values represent the number of days between recruitment and completion of the 20th molt of 10 crabs chosen randomly from the simulated population.

Figure 5. Dispersion patterns of juvenile (yellow dots), sub-adult and adult male (black triangles), and (c) adult female (red triangles) crabs in (a) January and (b) June simulated under water temperatures typical of Aransas and Copano bays.

Figure 6. Crab population densities (individuals / ha; blue line) and the ratio of third to first instars (green line) simulated under water temperatures typical of Aransas and Copano bays. The maximum allowable ratio of third instars to first instars also is shown (red line).

Figure 7. Estimates of crab densities (individuals / ha; green line) and mean (blue line) and median (red line) carapace widths (mm) based on (a) actual samples collected from San Antonio Bay by the Texas Parks and Wildlife Department using a 38mm mesh otter trawl from 1982 to 2008 (as summarized in Fig. 26, p.148 in Ward 2012), and (b) simulated samples collected using a 38mm mesh otter trawl under water temperatures typical of Aransas and Copano bays.

Figure 8. Mean, standard deviation, maximum, minimum, and median of annual Texas commercial crab landings for Aransas-Copano Bay (kg x 1000) recorded for the ten-year period from 1996 to 2005 (red bars; based on Table 9, p. in Ward 2012), and simulated annual harvests under the baseline fishing mortality rate (0.007) and water temperatures typical of Aransas and Copano bays (blue bars).

Figure 9. Comparison of annual crab population biomass density (mg/m^3) estimates based on otter-trawl samples from Aransas-Copano Bay collected from 1996 to 2005 (based on Fig. 34, p. 161 in Ward 2012) with (A) weekly and (B) mean annual simulated population biomass density estimates based on simulated trawl samples. In part A, the blue line indicates annual estimates based on actual trawl samples and the red line represents weekly estimates based on simulated trawl samples. In part B, the blue line indicates annual estimates based on actual trawl samples,

the red line represents mean annual estimates based on simulated trawl samples, and green and purple lines represent plus and minus two standard deviations of the mean simulated estimates, respectively.

Figure 10. (a) Mean carapace width (mm), (b) density (individuals/ha), and (c) mean, standard deviation, maximum, minimum, and median of annual harvests of crabs simulated under the normal, low, and high natural mortality rates. Blue, red, and green lines and bars represent normal, low (one-half normal) and high (twice normal) natural mortality rates, respectively.

Figure 11. (a) Mean carapace width (mm), (b) density (individuals/ha), and (c) mean, standard deviation, maximum, minimum, and median of annual harvests of crabs simulated under the normal, low, and high freshwater inflow scenarios. Blue, red, and green lines and bars represent normal, low and high freshwater inflow scenarios, respectively.

Figure 12. (a) Mean carapace width (mm), (b) density (individuals/ha), and (c) mean, standard deviation, maximum, minimum, and median of annual harvests of crabs simulated under the normal, low, and high fishing mortality rates. Blue, red, and green lines and bars represent normal, low (one-half normal) and high (twice normal) fishing mortality rates, respectively.

Figure 13. (a) Mean carapace width (mm), (b) density (individuals/ha), and (c) mean, standard deviation, maximum, minimum, and median of annual harvests of crabs simulated under the normal, low, and high fishing mortality rates, with natural mortality set at twice versus one-half its baseline value. Blue, red, and green lines and bars represent normal, low (one-half normal) and high (twice normal) fishing mortality rates, respectively.

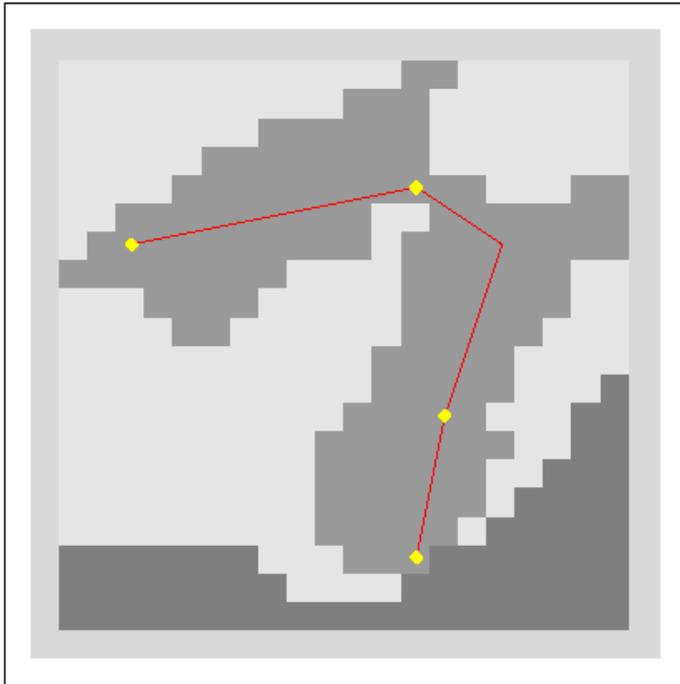


Figure 1. Map of Aransas and Copano bays indicating locations (yellow dots) of the four sampling stations that provided the data used to calculate the weekly water temperatures and salinities used in the model. These stations are part of the Mission-Aransas National Estuarine Research Reserve (MA-NERR) System-Wide Monitoring Program (SWMP).

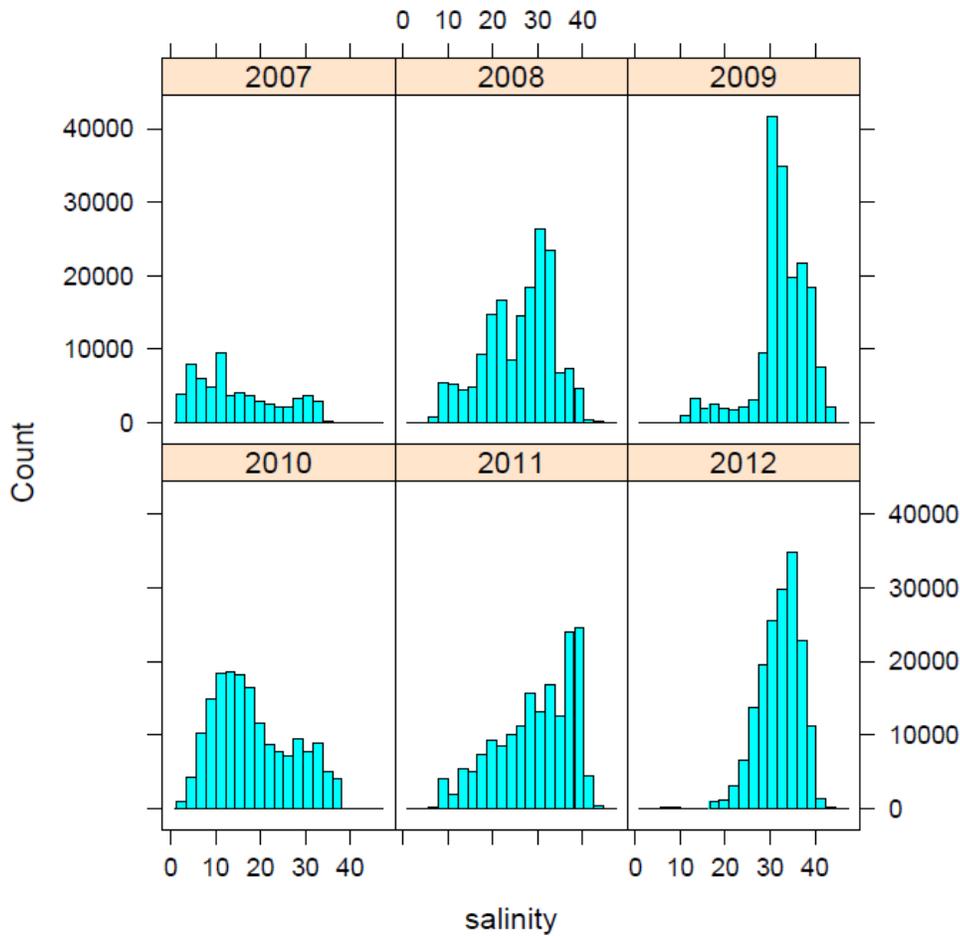


Figure 2. Histogram of the number of measurements in the data set for each year that fall into the indicated salinity category.

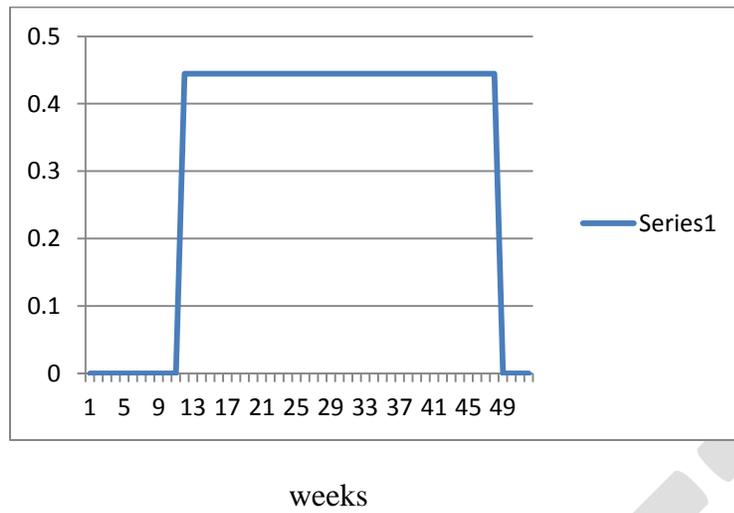
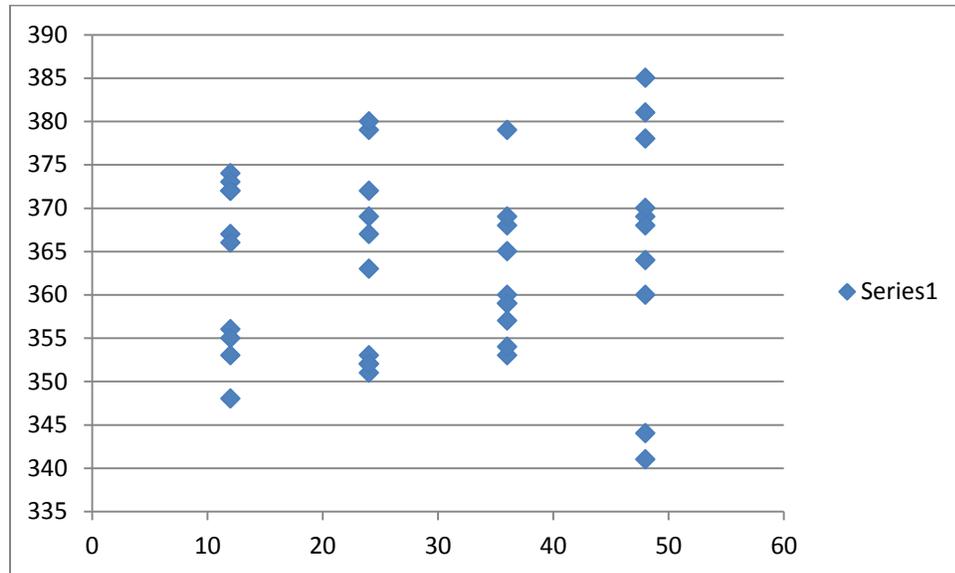


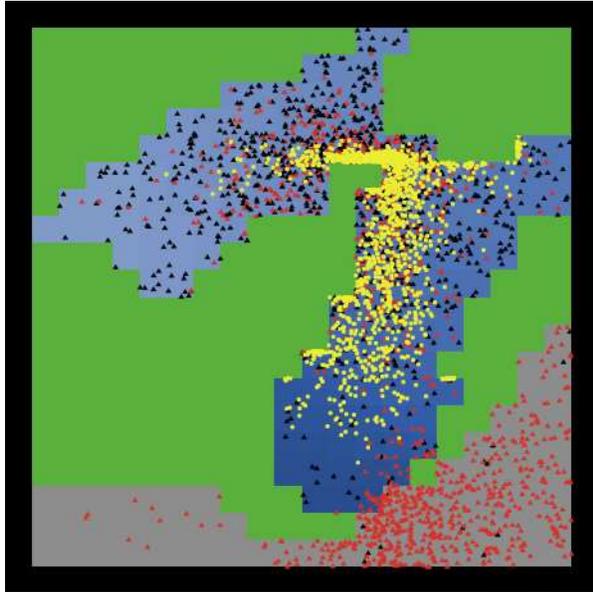
Figure 3. Seasonality of recruitment of first instar juvenile crabs (individuals / ha) simulated under water temperatures typical of Aransas and Copano bays.



Week of recruitment as first-instar juveniles

Figure 4. Growth of crabs recruited as first-instar juveniles during the indicated week of the year simulated under water temperatures typical of Aransas and Copano bays. Y-axis values represent the number of days between recruitment and completion of the 20th molt of 10 crabs chosen randomly from the simulated population.

A. January



B. June

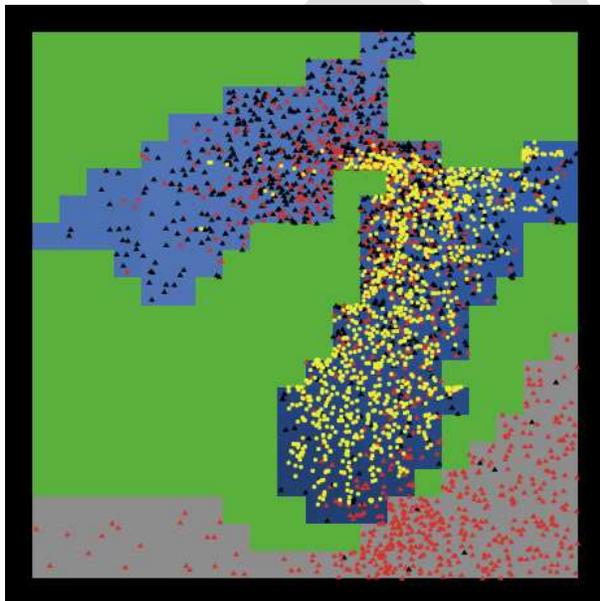


Figure 5. Dispersion patterns of juvenile (yellow dots), sub-adult and adult male (black triangles), and (c) adult female (red triangles) crabs in (a) January and (b) June simulated under water temperatures typical of Aransas and Copano bays.

Draft: Blue Crab Simulation Model for Aransas and Copano Bays, TX, USA

Developed for Mission-Aransas NERR Science Collaborative: Balancing Freshwater Needs for a Changing Environment.
2013

W. E. Grant, Hsiao-Hsuan Wang

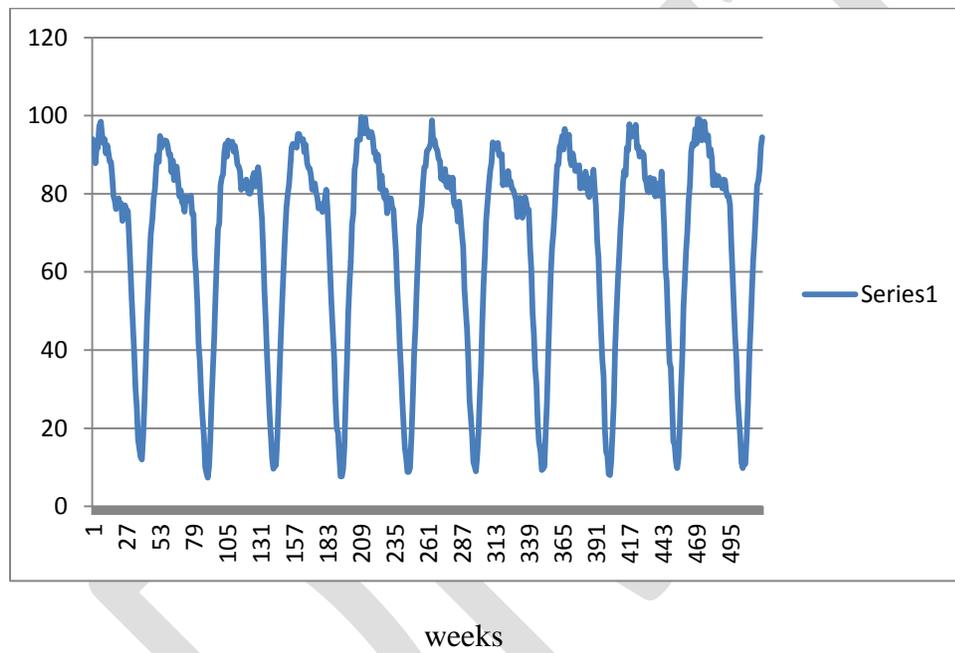
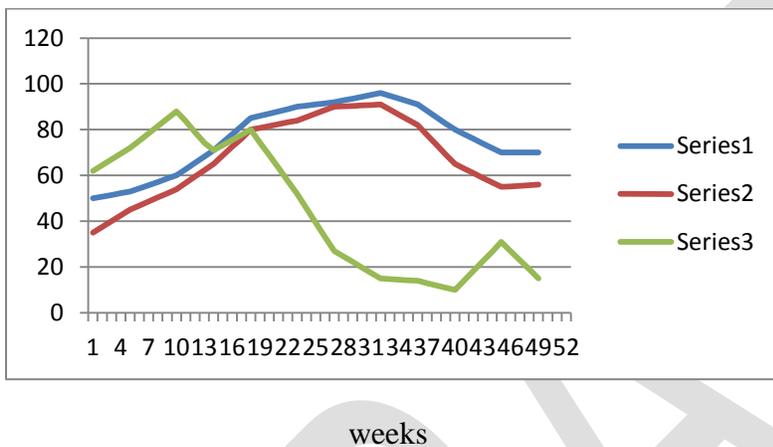


Figure 6. Crab population densities (individuals / ha) simulated under water temperatures typical of Aransas and Copano bays.

A. Observed (San Antonio Bay)



B. Simulated (Aransas and Copano Bays)

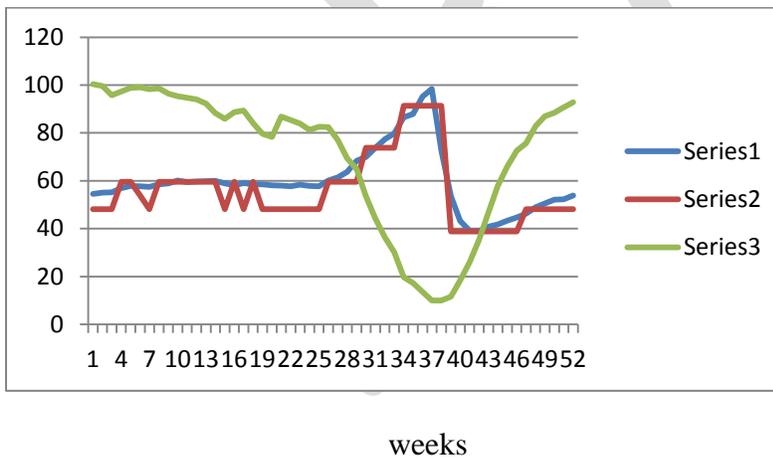


Figure 7. Estimates of crab densities (individuals / ha; green line) and mean (blue line) and median (red line) carapace widths (mm) based on (a) actual samples collected from San Antonio Bay by the Texas Parks and Wildlife Department using a 38mm mesh otter trawl from 1982 to 2008 (as summarized in Fig. 26, p.148 in Ward 2012), and (b) simulated samples collected using a 38mm mesh otter trawl under water temperatures typical of Aransas and Copano bays.

DRAFT

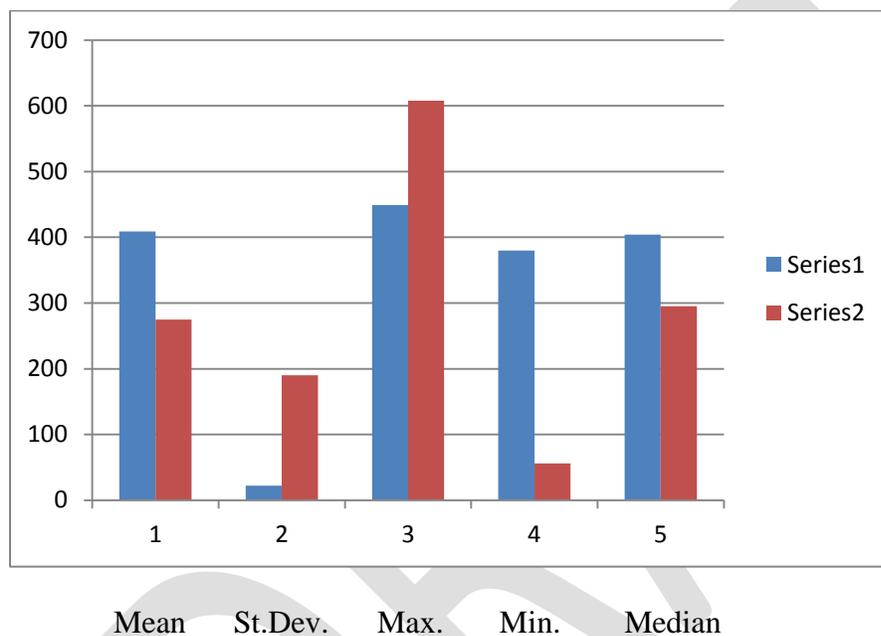
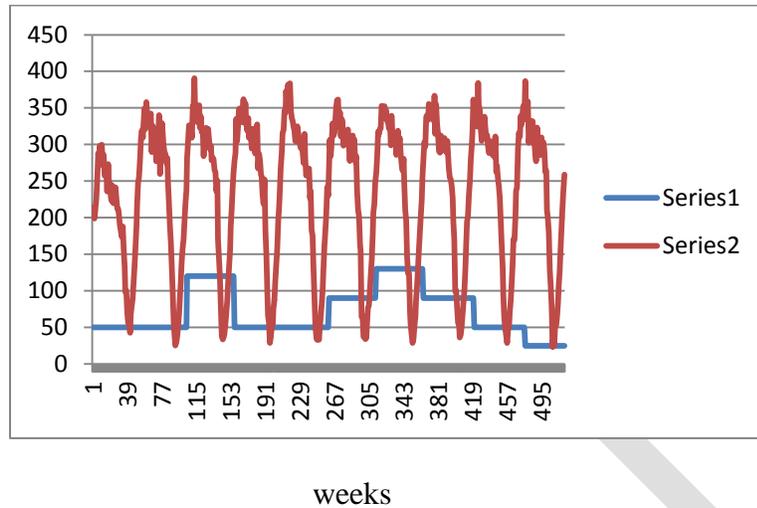


Figure 8. Mean, standard deviation, maximum, minimum, and median of annual Texas commercial crab landings for Aransas-Copano Bay (kg x 1000) recorded for the ten-year period from 1996 to 2005 (red bars; based on Table 9, p. in Ward 2012), and simulated annual harvests under the baseline fishing mortality rate (0.007) and water temperatures typical of Aransas and Copano bays (blue bars).

A.



B.

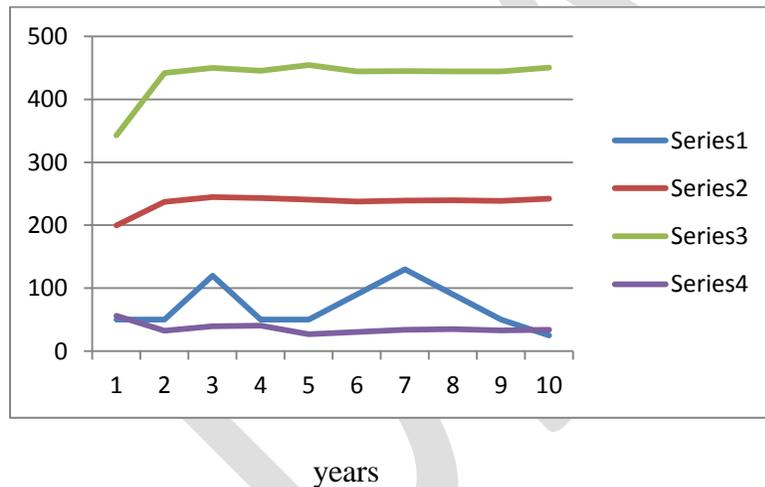
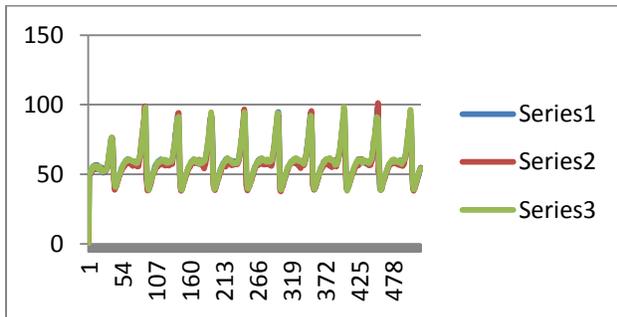


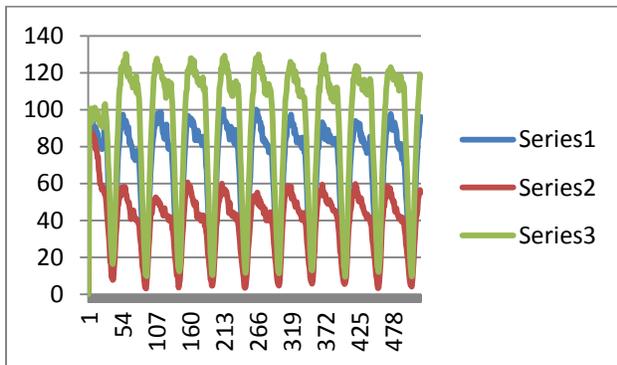
Figure 9. Comparison of annual crab population biomass density (mg/m^3) estimates based on otter-trawl samples from Aransas-Copano Bay collected from 1996 to 2005 (based on Fig. 34, p. 161 in Ward 2012) with (A) weekly and (B) mean annual simulated population biomass density estimates based on simulated trawl samples. In part A, the blue line indicates annual estimates based on actual trawl samples and the red line represents weekly estimates based on simulated trawl samples. In part B, the blue line indicates annual estimates based on actual trawl samples, the red line represents mean annual estimates based on simulated trawl samples, and green and purple lines represent plus and minus two standard deviations of the mean simulated estimates, respectively.

DRAFT

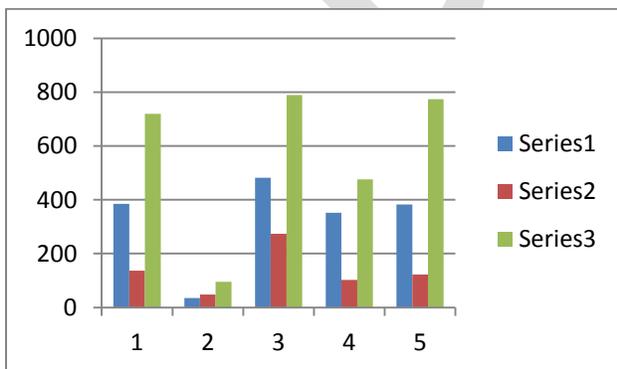
A. Mean carapace width



B. Density



C. Annual harvest

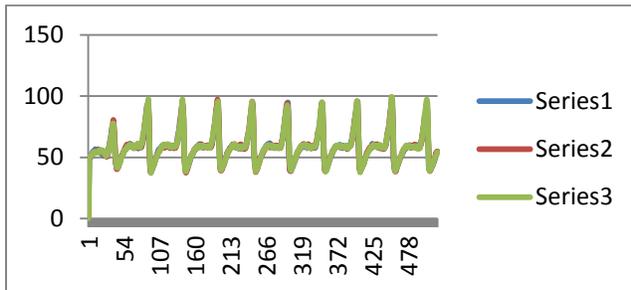


Mean St.Dev. Max. Min. Median

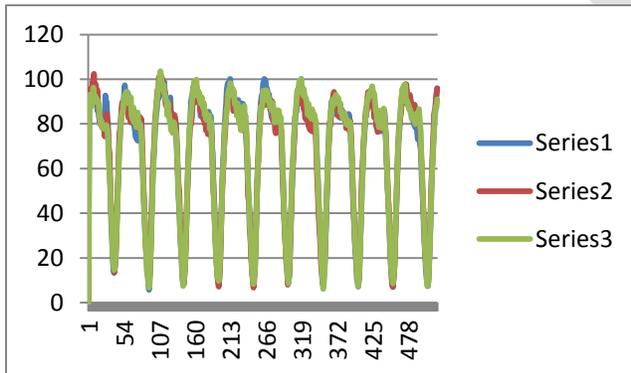
Figure 10. (a) Mean carapace width (mm), (b) density (individuals/ha), and (c) mean, standard deviation, maximum, minimum, and median of annual harvests of crabs simulated under the

normal, low, and high natural mortality rates. Blue, red, and green lines and bars represent normal, low (one-half normal) and high (twice normal) natural mortality rates, respectively.

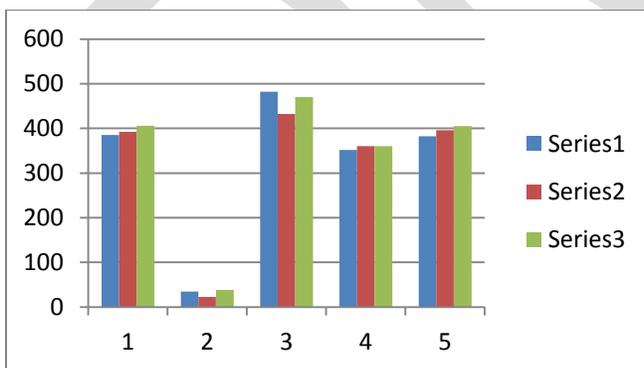
A. Mean carapace width



B. Density



C. Annual harvest

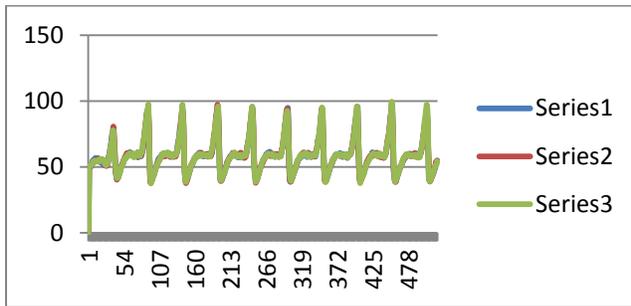


Mean St.Dev. Max. Min. Median

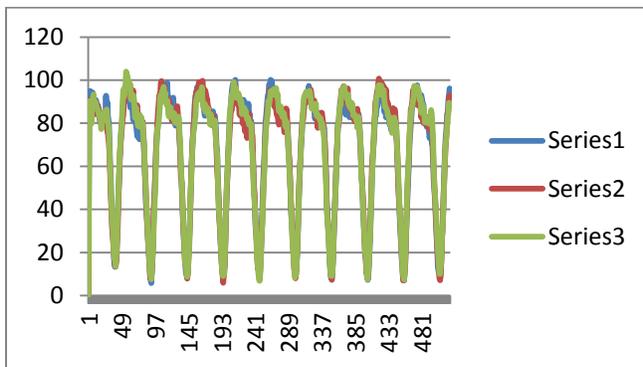
Figure 11. (a) Mean carapace width (mm), (b) density (individuals/ha), and (c) mean, standard deviation, maximum, minimum, and median of annual harvests of crabs simulated under the normal, low, and high freshwater inflow scenarios. Blue, red, and green lines and bars represent normal, low and high freshwater inflow scenarios, respectively.

DRAFT

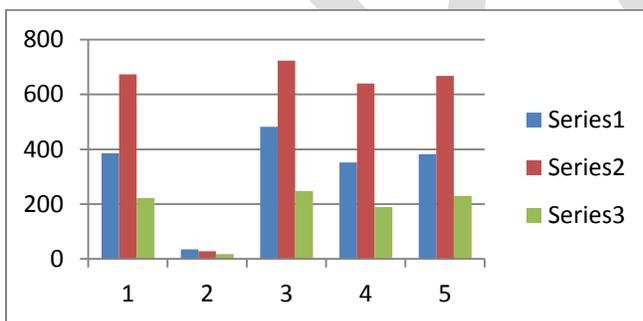
A. Mean carapace width



B. Density



C. Annual harvest



Mean St.Dev. Max. Min. Median

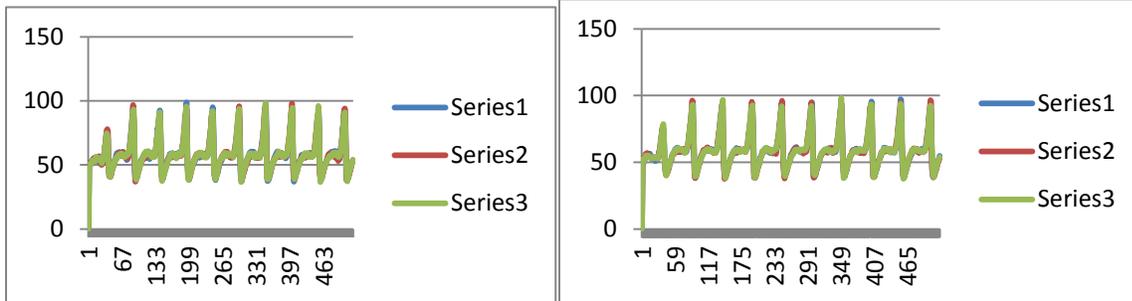
Figure 12. (a) Mean carapace width (mm), (b) density (individuals/ha), and (c) mean, standard deviation, maximum, minimum, and median of annual harvests of crabs simulated under the normal, low, and high fishing mortality rates (with natural mortality rate at its baseline value). Blue, red, and green lines and bars represent normal, low (one-half normal) and high (twice normal) fishing mortality rates, respectively.

DRAFT

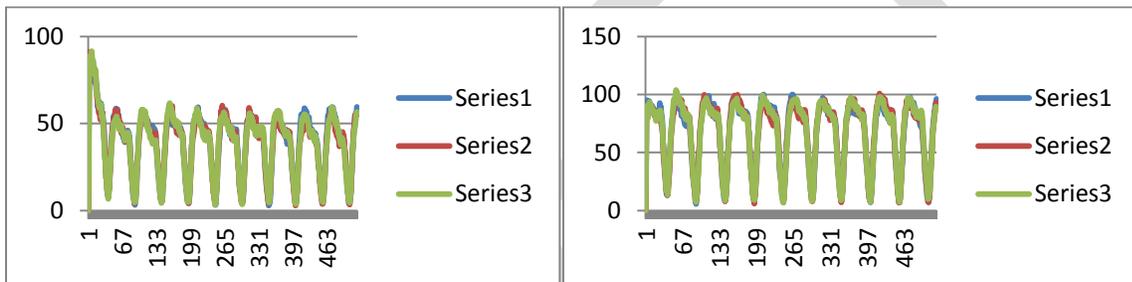
Twice Baseline Natural Mortality Rate

One-half Baseline Natural Mortality Rate

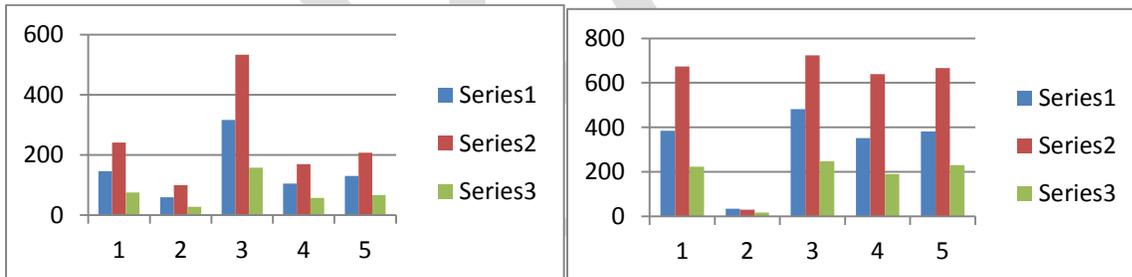
A. Mean carapace width



B. Density



C. Annual harvest



Mean St.Dev. Max. Min. Median

Mean St.Dev. Max. Min. Median

Figure 13. (a) Mean carapace width (mm), (b) density (individuals/ha), and (c) mean, standard deviation, maximum, minimum, and median of annual harvests of crabs simulated under the normal, low, and high fishing mortality rates, with natural mortality set at twice versus one-half its baseline value. Blue, red, and green lines and bars represent normal, low (one-half normal) and high (twice normal) fishing mortality rates, respectively.

Appendix

What follows are rather lengthy quotes from each of two recent studies that summarize the rationale for not including salinity effects crabs in the model. The first quote comes from pp. vii-viii in the Executive Summary in Ward (2012), which summarizes a wealth of published scientific information about blue crabs. While the study was directed specifically at San Antonio Bay, it includes information specific to the other major bays along the Texas coast, as well as life history and ecological information about blue crabs which is generally applicable. The second quote comes from Section 3.2.3, pp.42-43, in SAGES Final Report (Slack et al., 2009), which reports results of a large field study conducted at the Aransas National Wildlife Refuge.

From pp. vii-viii in the Executive Summary in Ward (2012):

“Evaluation of abundance versus salinity for individual trawl-event data, and for data averaged monthly and over the entire region of the (San Antonio) bay, disclosed no significant variation with temperature or salinity. The above annual pulse of abundance is out of phase with the annual rise and fall of temperature, so the lack of correlation between these variables is not surprising. With respect to salinity, blue crabs are osmoregulators that survive — even thrive — in a wide range of salinity. The only stage of the blue-crab life cycle that requires a narrow range of salinity and temperature is the larval, which needs the warm saline conditions of the ocean. It is seeking these salinity conditions that impels the post-insemination migration of the female to the sea. Otherwise, the blue crab is a remarkably effective osmoregulator, which accounts for its abundance from Sabine Lake to the Laguna Madre. This may also account for the general lack of a simple relationship between salinity and blue-crab density in the TPWD monitoring data for San Antonio Bay. Acclimation is important in the tolerance of the blue crab to a range of salinity. On the lower Texas coast, and in San Antonio Bay in particular, the main threat that salinity presents is its sudden reduction to zero during a major flood hydrograph. The ubiquity of blue crabs in the shallow, marshy regions of San Antonio Bay and other Texas estuaries, which are also typically low-salinity zones, may be for reasons other than lower salinity, as suggested by recent studies on decapod habitat use in estuaries.

Freshwater inflow provides several mechanisms that could plausibly increase the abundance of blue crabs, besides moderating salinity, and therefore it is warranted to seek a direct relation between abundance and inflow. For San Antonio Bay, the correlation proved negligible, though there are some time-lagged responses that suggest an avoidance or mortality response to inflow events, followed by a later increase in abundance perhaps due to beneficial effects of inflow. These analyses are very preliminary and employ only linear statistics. A more sophisticated time-series analysis will be necessary to expose a relation between blue crabs and inflow (as well as salinity).”

From Section 3.2.3, pp.42-43, in SAGES Final Report (Slack et al., 2009):

“Section 3.2.3 Crab density as a function of habitat type, salinity, water level, and wind velocity

We represented daily blue crab density as:

$$BC_{i,j,t} = e^{(0.3751 + b1i + b2j + 1.844(wlt) + 0.1010(Salt) - 0.2597(wst))} \quad (3)$$

where $BC_{i,j,t}$ represents the density (number of crabs/m²) of crabs between 11 and 30 mm carapace width in territory i , habitat j at time t ; $b1_i$ and $b2_j$ are parameter estimates for categorical variables (Table 3.1) representing the effect of territory (BR, PC, SD) and habitat type (bay, connected pond, intermittently-connected pond); wl_t and wst_t represent the 28-day moving averages of water level (m) and wind velocity (km/hr), respectively, recorded at the Seadrift gauge in San Antonio Bay (<http://lighthouse.tamucc.edu/overview/031>), and Sal_t represents the 28-day moving average of *salinity* _{t} (Eq. 1).

Equation 3 resulted from our evaluation of a large set of generalized linear mixed models correlating various size classes of crabs with environmental variables (see Appendix A, empirical studies #10 and 11) for a complete description of model selection procedures). We selected a model (Eq. 3) that predicted crab density relatively well at the ecosystem level (Pearson product-moment correlation factor, $r_{ave} = 0.792$) for small crabs (11 to 30mm carapace width). Although this size class is slightly smaller than what whooping cranes eat, given the rapid growth of crabs (14 mm/month, Adkins, 1972), we assumed that it provided a good estimate of recruitment into the size classes consumed by cranes.

Our results indicated that blue crabs have a complex, non-linear relationship with spatial location (i.e., territory), habitat type, salinity, wind speed and water level. Simpler models failed to explain the variation in crab numbers. Within our multivariate model, salinity was a statistically significant factor, and was positively correlated with blue crab abundance, however, it is important to note that our model is not a single-factor model and contains four other variables that act synergistically with salinity to explain the abundance and distribution of blue crabs. Our sensitivity analysis of model parameters (Slack et al., 2009, Tables 3.3A-C) indicated that, compared to all of the other variables in the equation, salinity was the least important. In fact, doubling salinity (that is, a 100% increase in salinity), holding other parameters constant, resulted in an increase of less than 1 crab / m² (Tables 3.3A-C). Water level was the most important continuous variable in our equation. Simulating a 100% increase in water level, holding other parameters constant, resulted in a 300% increase in simulated blue crab abundance (Tables 3.3A-C).

The relationship between the distribution and abundance of blue crabs and the environment is complex (Guillory et al., 2001). Blue crab distribution and survival have been reported to be affected by several factors including salinity (which is the relationship most often explored), water temperature, water circulation, tides, bottom substrate, predation, habitat loss, food availability, inter- and intra-specific competition, among others (Oesterling and Evink, 1977; Daud, 1979; Laughlin, 1982; Van Engel, 1982; Heck Jr and Coen, 1995; Guillory et al., 2001).

The diversity of possible factors, as well as possible synergistic effects among factors, makes precise identification of the influence of specific variables difficult (Guillory et al., 2001).

Several previous studies have focused on the relationship between blue crabs and salinity, but a consensus regarding the exact effects of salinity on the distribution of blue crabs has not been reached. Daud (1979) found small blue crabs (5-10 mm CW) in shallow brackish waters and larger size classes in fresher waters. Perret et al. (1967) and Swingle (1971) noted that maximum blue crab abundance was at salinities less than 5 ‰, which contradicts the results of Christmas and Langely (1973) and Perry and Stuck (1982), who both found highest abundances at salinity above 14.9 ‰, with abundance decreasing when salinities were above 25 ‰. Hammerschmidt (1982) was unable to correlate blue crab catch data and salinity. Walther (1989) found a negative correlation between blue crab catch and salinity. The blue crab commercial harvest in the Guadalupe estuary did not have a significant relationship with salinity (Texas Department of Water Resources. 1980). Pugsek et al. (2008) estimated blue crab abundance at Aransas National Wildlife Refuge by walking transects and were unable to develop a significant relationship with salinity, water level, habitat type, or distance to open water. In laboratory studies, growth rates (Cadman and Weinstein, 1988) and percent survival (Guerin and Stickle, 1997) of juvenile blue crabs generally increased with salinity, but the effect of salinity on growth was minimal in comparison to that of temperature.

The mixed results and breadth of these aforementioned studies indicates that the relationship between blue crabs and the environment is complex and depends upon the interactions among many different variables. The results from our study agree with Guillory et al., (Guillory et al.) in that blue crab abundance is best explained by a suite of environmental factors that cannot be simplified into single-factor predictive models.”

References

- Adkins, G., 1972. A study of the blue crab fishery in Louisiana. Tech. Bull. 3. Louisiana Wildlife and Fisheries Commission, Baton Rouge, LA.
- Brylawski, B.J. and Miller, T.J., 2006. Temperature-dependent growth of the blue crab (*Callinectes sapidus*): a molt process approach. Canadian Journal of Fisheries and Aquatic Sciences, 63:1298-1308.
- Cadman, L.R. and Weinstein, M.P., 1988. Effects of temperature and salinity on the growth of laboratory-reared juvenile blue crabs *Callinectes sapidus* Rathbun. Journal of Experimental Marine Biology and Ecology, 121:193-207.
- Caley, M.J., Carr, M.H., Hixon, M.A., Hughes, T.P., Jones, G.P. and Menge, B.A., 1996. Recruitment and the local dynamics of open marine populations. Annual Review of Ecology and Systematics, 27:477-500.
- Christmas Jr., J.Y. and Langley, W., 1973. Estuarine invertebrates, Mississippi. In: J.Y. Christmas Jr. (Editor), Gulf of Mexico Estuarine Inventory and Study, Mississippi. Gulf Coast Research Laboratory.
- Daud, N.M.B., 1979. Distribution and recruitment of juvenile blue crabs, *Callinectes sapidus*, in a Louisiana estuarine system, Louisiana State University, Baton Rouge, LA.
- Gil-Weir, K.C., Grant, W.E., Slack, R.D., Wang, H.-H. and Fujiwara, M., 2012. Demography and population trends of Whooping Cranes. Journal of Field Ornithology, 83:1-10.
- Guerin, J.L. and Stickle, W.B., 1997. A comparative study of two sympatric species within the genus *Callinectes*: osmoregulation, long-term acclimation to salinity and the effects of salinity on growth and moulting. Journal of Experimental Marine Biology and Ecology, 218:165-186.
- Guillory, V., Perry, H. and VanderKooy, S. (Editors), 2001. Proceedings: blue crab mortality symposium. Report No. 90. Gulf States Marine Fisheries Commission, Ocean Springs, MS.
- Hammerschmidt, P.C., 1982. Population trends and commercial harvest of the blue crab, *Callinectes sapidus* Rathbun, in Texas bays September 1978-August 1979. Texas Parks and Wildlife, Coastal Fisheries Branch, Management Data Series, 69 pp.
- Heck Jr, K.L. and Coen, L.D., 1995. Predation and the abundance of juvenile blue crabs: a comparison of selected east and Gulf coast (USA) studies. Bulletin of Marine Science, 57:877-883.
- Hewitt, D.A. and Hoenig, J.M., 2005. Comparison of two approaches for estimating natural mortality based on longevity. Fishery Bulletin, 103:433-437.
- Laughlin, R.A., 1982. Feeding habits of the blue crab, *Callinectes Sapidus* Rathbun, in the Apalachicola Estuary, Florida. Bulletin of Marine Science, 32:807-822.
- Oesterling, M. and Evink, G., 1977. Relationship between Florida's blue crab population and Apalachicola Bay. In: R. Livingston and E. Joyce (Editor), Proceedings of the Conference on the Apalachicola Drainage System. Florida Marine Research Publ. 26. Florida Department Natural Resources, St. Petersburg, FL.
- Perret, W.S., 1967. Occurrence, abundance, and size distribution of the blue crab, *Callinectes sapidus*, taken with otter trawl in Vermilion Bay Louisiana 1964-65. Proc. Louis. Acad. Sci., 30:63-69.
- Perry, H.M., 1975. The blue crab fishery in Mississippi. Gulf Research Reports, 5:39-58.

- Perry, H.M. and Stuck., K.C., 1982. The life history of the blue crab in Mississippi with notes on larval distribution. In: H.M. Perry and W.A. Van Engel (Editor), Proceedings of the Blue Crab Colloquium. Gulf States Marine Fisheries Commission Publication 7, pp. 17-22.
- Pile, A.J., Lipcius, R.N., Montfrans, J.v. and Orth, R.J., 1996. Density-dependent settler-recruit-juvenile relationships in blue crabs. *Ecological Monographs*, 66:277-300.
- Pugesek, B., Baldwin, M. and Stehn, T.V., 2008. 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. Proceedings North American Crane Workshop, pp. 13-24.
- Slack, R.D., Grant, W.E., Davis III, S.E., Swannack, T.M., Wozniak, J., Greer, D.M. and Snelgrove, A.G., 2009. Linking freshwater inflows and marsh community dynamics in San Antonio Bay to Whooping Cranes, Texas A&M AgriLIFE, College Station, TX.
- Stehn, T.V. and Prieto, F., 2010. Changes in winter Whooping Crane territories and range 1950–2006. Proceedings of the North American Crane Workshop, pp. 40-56.
- Sutton, G. and Wagner, T., 2007. Stock assessment of blue crab (*Callinectes sapidus*) in Texas coastal waters, Texas Parks and Wildlife Department, Austin, TX.
- Swingle, H.A., 1971. Biology of Alabama estuarine areas cooperative Gulf of Mexico estuarine inventory. *Alabama Marine Research Bulletin*, 5:1-123.
- Tagatz, M.E., 1968. Biology of the blue crab, *Callinectes sapidus*, in the St. John River, FL. *United States Fisheries Bulletin*, 67:17-33.
- Texas Department of Water Resources. 1980. Guadalupe estuary: a study of the Influence of freshwater inflows. LP-107. 321 pp. Austin, TX.
- Texas Parks and Wildlife. 2009. Blue crab (*Callinectes sapidus*). <http://www.tpwd.state.tx.us/huntwild/wild/species/bluecrab/>. Date Accessed: June 29, 2013.
- Van Engel, W.A., 1958. The blue crab and its fishery in Chesapeake Bay: Part 1-Reproduction, early development, growth, and migration. *Comm Fish Rev*, 20:6-17.
- Van Engel, W.A., 1982. Blue crab mortalities associated with pesticides, herbicides, temperature, salinity, and dissolved oxygen. In: H. Perry and W.A. Van Engel (Editor), Proceedings of the blue crab colloquium. Tech. Rep. 7. Gulf States Marine Fisheries Commission, Ocean Springs, MS.
- Walther, D., 1989. The influence of salinities in lower Barataria bay upon year class strength of the blue crab, *Callinectes sapidus*. Louisiana Department of Wildlife and Fisheries, Unpublished Report, 25 pp.
- Ward, G.H., 2012. The blue crab: a survey with application to San Antonio Bay, Texas Water Development Board, Austin, TX.