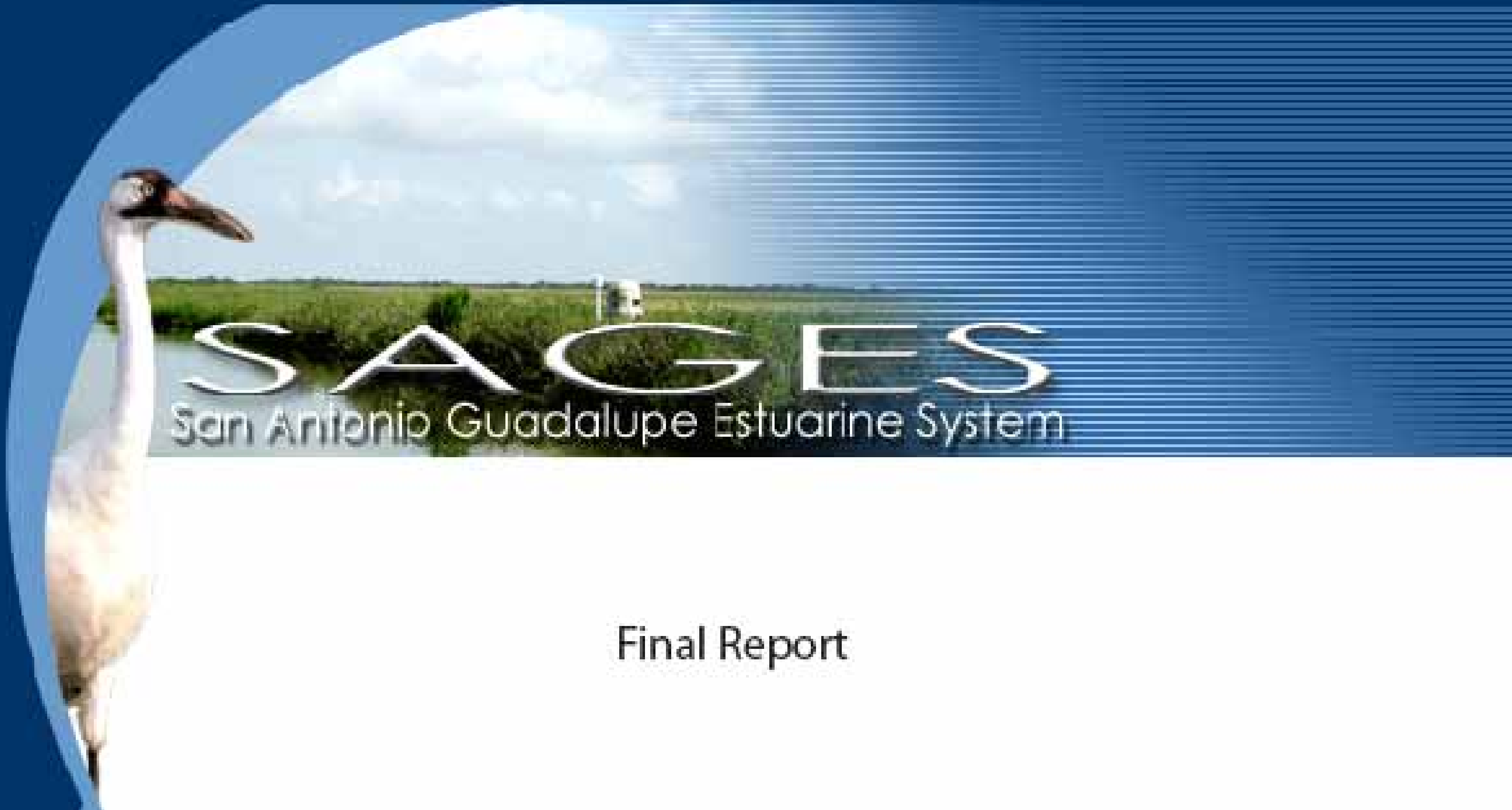

Final Report

Linking Freshwater Inflows and Marsh Community Dynamics in San Antonio Bay to Whooping Cranes

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Executive Summary

Linking Freshwater Inflows and Marsh Community Dynamics in San Antonio Bay to Whooping Cranes

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Introduction

From 2002 through 2009, faculty and students from the Department of Wildlife and Fisheries Sciences at Texas A&M University conducted field, laboratory, and modeling studies to investigate the diet, behavior, and habitat of the whooping crane (*Grus americana*) at Aransas National Wildlife Refuge (ANWR), Texas. During this period the research team also conducted complementary studies of environmental conditions in San Antonio Bay. The project was called the San Antonio Guadalupe Estuarine System (SAGES) project, and was funded primarily by the Guadalupe Blanco River Authority and the San Antonio River Authority, with additional support provided by the San Antonio Water System and the Texas Water Development Board. The U.S. Fish and Wildlife Service provided in-kind support through lodging, the use of boating facilities, and other logistics.

The overall goal of the SAGES project was to use empirically-generated and existing available data to evaluate the relationship between freshwater inflows feeding San Antonio Bay and the health of the endangered whooping crane population at ANWR. Field research included several studies of wetland processes, plant ecology, and the abundance and distribution of blue crabs in the salt marshes of ANWR. Investigations also focused on the behavioral responses of whooping cranes to changes in abundance and distribution of foods (blue crab [*Callinectes sapidus*], wolfberry fruit [*Lycium carolinianum*], and others), abiotic factors, and human-induced disturbances within and adjacent to ANWR. Finally, empirical findings were integrated to produce a simulation model with the capabilities of predicting crane response to changes in food supply, temperature, salinity, and water levels in and around the ANWR salt marsh. The study design was guided by inputs from the project sponsors, State of Texas agencies with knowledge of how freshwater inflows can impact estuarine ecology, and a team of experienced scientists from throughout the U.S. and whose expertise included most aspects of crane and estuarine ecology.

As guided by the peer review team, the SAGES team chose to focus on two primary areas of study. The first area of study was the ecology of key crane foods, namely blue crabs and wolfberries. The primary study objective was to determine how environmental parameters influenced the abundance and distribution of these foods. The second area was on the behavioral ecology of cranes. The main objectives here were to document the food habits and time-activity budgets of cranes, as well as investigate the effects of abiotic conditions, food abundance, and human disturbance on the crane's energy balance. The team anticipated that these areas of study would allow for substantial gains in knowledge of whooping cranes, but also recognized that the limited duration of the SAGES project would not allow for a totally comprehensive evaluation of the effects of altered freshwater inflows.

The Studies

Figure 1 is a map of San Antonio Bay and the Blackjack Peninsula showing three whooping crane territories that were intensively studied by the SAGES team. The hydrology and food abundance research was conducted in the Boat Ramp Channel, Pump Canal and Middle Sundown Bay territories; crane behavior was observed in two additional territories at the south end of Blackjack Peninsula. A brief synopsis of the field and laboratory studies follows. Please see Appendix A for a more thorough description of each study.

Core SAGES Studies

1. *J. Bryan Allison* characterized sediment movement in tidal creeks and concluded that wave action from barge traffic can affect tidal-creek hydrodynamics.
2. *Rachel Butzler* studied space and time patterns of wolfberry plants in the territories and documented that peak berry abundance generally occurred at the same time as crane arrival in the fall and that the berry supply was exhausted by the end of December.
3. *Carrie Miller* studied pond algal and nutrient dynamics and contributed to the understanding of how water levels impact marsh inundation and hydrologic connectivity.
4. *George Gable* examined relationships between water quality and plankton communities and, among other outcomes, determined that Cedar Bayou has a limited effect on ecological conditions in Mesquite Bay.
5. *Matthew Driffill* studied the relationship between water levels in tidal creeks and adjacent marshes and quantified how inundation connects marshes to the bay and creek system.
6. *Christopher Llewellyn* conducted a laboratory study that showed wolfberries are less productive in saline water during mid-summer. Also, inundation regime had no apparent effect on productivity during this same period.

7-9. *Danielle Greer* was responsible for a series of studies relating to the foraging behavior and diet of whooping cranes and the larval settlement, juvenile recruitment, and juvenile and adult abundance patterns of blue crabs. Shallow bays adjacent to mature salt marshes functioned as both terminal settlement habitat and critical nursery habitat. Additionally, water temperature during spawning/larval export best predicted settlement of larval crabs. While shallow bays provided important nursery habitat for young blue crabs, interior marsh ponds were important habitats for dispersing juvenile and adults crabs. Overall benefits of foraging differed among foods in the crane's diet, depending on the resource targeted, and food abundance patterns during winter; wolfberry fruits, snails, and insects were of particular importance to cranes.

10. *Kristin LaFever* observed whooping crane behavior and found that foraging is the dominant activity among territorial birds and that human activities at ANWR did not have a detrimental impact on territorial cranes.
11. *Karine Gil* developed a model that simulated population dynamics of the whooping crane and predicted substantial continued growth of the ANWR flock.
12. *William Grant and Todd Swannack* developed a spatially-explicit hydrological connectivity model using light detection and ranging (LIDAR) and environmental data that simulates patterns of water level changes and connectivity within ANWR.

Complementary SAGES Studies

13. *Stephen Davis et al.* found that plankton dynamics were driven by seasonal and freshwater inflow effects. The United States Geological Survey funded this complementary project.
14. *Stephen Davis et al.* conducting intensive spatial surveys, found that estuarine-wide water quality and circulation patterns are driven to a great extent by variations in freshwater inflows. Texas Sea Grant funded this complementary project.

Non-SAGES, ANWR Studies

15. *Steven Zeug et al*. compared the ecology of natural and created marshes and observed that blue crabs have a consistent role in the food chain regardless of their size.
16. *David Hoeinghaus and Stephen Davis* used stable isotope analysis and found that larger size classes of blue crabs were more associated with "connected" pond edge habitats in ANWR marshes than the smaller ones.
17. *Katherine Roach et al.* defined the importance of connectivity in shaping aquatic food webs in ANWR marshes.

Access to the theses, dissertations and publications from these studies may be found at http://sages.tamu.edu.

San Antonio Bay

The team's studies show a clear effect of river inflows on water quality patterns across the greater bay ecosystem. However, during periods of low inflow, the impacts of factors such as wind and tides became more noticeable. Pass Cavallo represents the major source of Gulf of Mexico inputs into the bay. Further, the data indicate that Cedar Bayou represents a minor exchange path for Gulf water into the estuary, as the water quality signature of inputs from Cedar Bayou diminishes within a short distance of the bayou. Freshwater inflows to the bay tended to flow in a southwest direction along Blackjack Peninsula and along the estuarine marshes at ANWR. Not surprisingly, patterns of salinity in San Antonio Bay were strongly correlated with those in tidal creeks of Blackjack Peninsula.

ANWR Marsh and Vegetation

Given the higher elevation of the marsh relative to mean sea level, the ANWR salt marsh is infrequently inundated, typically a result of spring high tides, storm surges, and high-water periods. The team estimated high year-to-year variability in marsh inundation, which governs the frequency and duration of surface water connections between tidal waters (*i.e.*, creeks and bays) and marsh ponds. These surface water connections are the path for aquatic organisms to migrate between bays and ponds. With extended periods of marsh exposure and disconnection, marsh ponds can completely dry out—leading to death of resident aquatic organisms—or the resident aquatic organisms can be sufficiently depleted by wading birds (*e.g.*, whooping cranes) and other consumers. Either way, prey items in these ponds are replenished through subsequent inundation and connection events.

The ANWR marsh vegetation community is comprised of a mixed, high-marsh plant community. Wolfberry plants had a frequency of occurrence at the three sites of about 30% and were most productive in early spring and late summer, prior to flowering and fruiting in fall. Peak wolfberry fruit abundance coincided with crane arrival in October each year. Based on the team's observations and those from other studies in the region, salinity immediately prior to and leading up to the late summer leafing period may be an important factor in fruit production. Berry density at the ANWR marsh sites was negatively correlated with bay water salinity, thus when salinity is high, berry density is low. Soil porewater salinity correlated with surface water salinity at these sites, but we had less than one year of reliable soil salinity data. Future effort should be made to focus on the relationship between surface water salinity and soil salinity across the ANWR marshes, as well as on the effects of local precipitation.

Blue Crab Settlement, Recruitment, and Abundance Patterns

The team found that larval crabs were significantly influenced by the following abiotic factors: water temperature, precipitation, water level, and wind speed and wind direction. Juvenile and adult crabs had a complex, non-linear relationship with spatial location, habitat type, salinity, wind speed and water level. Simpler models failed to explain the variation in crab numbers. We were not able to define significant relationships between settlement or recruitment rate and juvenile or adult abundance.

We believe this particular field study is one of the first studies to have sampled blue crabs (*e.g.* nekton) within habitats of interior salt marsh and is believed to be the first study to examine patterns of crab abundance in a mature salt marsh where emergent vegetation is dominated by high-marsh halophytes. We found that shallow bay habitats were important nursery habitats for young blue crabs and interior marsh ponds were important habitats for dispersing juvenile adult crabs. Small crabs were more typically found in submerged vegetation and algae-dominated bay waters. Larger crabs were found proportionately more often in pond-edge habitats, and the largest crabs were found in open-water pond habitats of the interior marsh. These connected, interior marsh ponds were significant contributors to total numbers and standing stock of crabs.

Whooping Crane Behavior

Whooping cranes spent 65% of daylight hours foraging. While in the salt marsh their diet consisted of wolfberry fruit, blue crabs, clams, snails, insects, fiddler crabs (*Uca spp*), snakes, and fish. Wolfberry fruit and snails and insects were consumed in the highest quantities, required the least effort during foraging, and generally were associated with the most efficient foraging behavior. Blue crabs were the most optimal food in relation to protein, and clams were a significant source of biomass. Whooping cranes foraged most efficiently during the winter of 2005-2006 when water levels were lowest.

A diversity of human activities occurred in the vicinity of crane territories. The most common type of human activity was motor boating, representing 50% of all human stimuli that occurred during the study. Other relatively common disturbance stimuli that occurred in the vicinity of crane territories were barges, shrimp boats, air boats, tour boats, airplanes, and helicopters. Both positive and negative responses to human stimuli were observed for crane family groups. The effects of human activities in the vicinity of ANWR did not appear to detrimentally affect crane energetics.

The Model

The team developed a quantitative simulation model as a tool to aid in assessing the potential impact of changes in freshwater inflow into San Antonio Bay on whooping cranes. The final form of the quantitative model evolved from the team's initial conceptualization of the San Antonio Bay-ANWR salt-marsh ecosystem, which views the ecosystem as being influenced by regional environmental factors that affect hydrology and landscape features within the marsh. These factors, in turn, affect the abundance of the two most important food resources (wolfberry fruits and blue crabs) within whooping crane territories and, as a result, may have an impact on the energy budget of the cranes. The model consists of three equations derived from our empirical studies and three equations taken from the scientific literature. The team does not view its quantitative model as all-inclusive, but rather, as a useful simplification of a complex system that focuses attention on evaluating the most likely links between freshwater inflow and whooping crane ecology that could be explored with the resources at the team's disposal.

Despite these limitations, the model does suggest relationships that are of potential importance to assessing crane ecology and that may be relevant to evaluation of future freshwater diversions. These relationships include the following:

- The food supply for cranes appears to be more than adequate to meet their energy needs. None of the study results indicated that habitat conditions at Blackjack Peninsula are marginal for crane survival and well-being.
- Bay salinity is demonstrably higher when freshwater inflows are low; however, the relationship between salinity and crane energetics is still uncertain.
- Wolfberry abundance is lower when bay salinity is high. The team does not know the extent to which marsh salinity is dependent on bay salinity, nor does the team understand the interactive effect of bay salinity and marsh inundation patterns on marsh soil salinity.
- Consistent with prior studies, the relationship between blue crab abundance and the environment is complex and was best explained by a suite of environmental factors.

Summary

The team found that the diet of the whooping crane is varied and included blue crabs, wolfberry fruit, clams, snails, and insects. The dominant food resources (blue crabs and wolfberries) were affected by several factors: freshwater inflow, bay salinity, tides, and temperature. Simulation results for the 11-year period of 1997-2007 found that the metabolic energy present in wolfberry fruit and blue crabs, and in blue crabs alone, always exceeded the estimated daily energy requirements of four adult cranes in each of the three representative crane territories, except under extreme marsh environment conditions.

Figure 1. Map of San Antonio Bay and Blackjack Peninsula.

Acknowledgments

We thank the Guadalupe-Blanco River Authority and the San Antonio River Authority for direct funding and sponsorship of the SAGES project. We also thank the San Antonio Water System and the Texas Water Development Board for contributing funding. In addition, we thank Tom Stehn and the U.S. Fish and Wildlife Service at the Aransas National Wildlife Refuge for its personnel and logistical support, Brian Johns of the Canadian Wildlife Service for his assistance with breeding ground data analysis, Tom Minello of the National Marine Fisheries Service for his assistance with crab field methods and data analyses, Margarita Mieres for her assistance with the management of technical workshops, Laura Weber for hours of editorial assistance, as well as the Department of Wildlife and Fisheries Sciences and Texas AgriLife Research for their support of this project. Further, we recognize George Ward from the University of Texas, Dan Roelke from Texas A&M University, Lee Wilson, and the San Antonio Guadalupe Estuarine System workshop participants for important questions, ideas, and discussions throughout the project.

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List of Acronyms

Acronym	Definition
ANOVA	Analysis of Variance
ANWR	Aransas National Wildlife Refuge
BJ	Blackjack Territory
BR	Boat Ramp Territory
CDOM	Chromophoric Dissolved Organic Matter
COW	Connected Open Water
CPE	Connected Pond Edge
CW	Carapace Width
CWS	Canadian Wildlife Service
DO	Dissolved Oxygen
ESV	Emergent Salt-marsh Vegetation
G	Grams
GBRA	Guadalupe-Blanco River Authority
GIWW	Gulf Intracoastal Waterway
KCAL	Kilocalories
LGWSP	Lower Guadalupe Water Supply Project
LIDAR	Light Detection and Ranging Images
LS	Lobstick Territory
M	Meters
MB	Mustang Bay
MSS	Mean Summer Salinity
PC	Pump Canal Territory
PEG	Plankton Ecology Group
PL	Pipeline Territory
PPT	Parts per Thousand (measure of salinity)
PWB	Peak Wolfberry Density
SAGES	San Antonio Guadalupe Estuarine System
SARA	San Antonio River Authority
SAV	Submerged Aquatic Vegetation
SAWS	San Antonio Water System
SB	Sundown Bay Territory
TCOON	Texas Coastal Ocean Observation Network
TWDB	Texas Water Development Board
UOW	Unconnected Open Water
UPE	Unconnected Pond Edge
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
WBNP	Wood Buffalo National Park

1. Introduction

Linking Freshwater Inflows and Marsh Community Dynamics in San Antonio Bay to Whooping Cranes

1. Introduction

1.1 Lower Guadalupe Water Supply Project

On 18 May 2001, the Guadalupe-Blanco River Authority (GBRA), the San Antonio River Authority (SARA), and San Antonio Water System (SAWS) announced the Lower Guadalupe Water Supply Project (LGWSP). This joint project was intended to provide a new and reliable source of water for the San Antonio area while protecting the ecological values of freshwater inflows to San Antonio Bay. The sponsoring organizations of the LGWSP were participants in Region L (Figure 1.1) of the state water planning process under Texas State Senate Bill 1 of 1997, and the LGWSP was part of the Texas State Water Plan (TSWP) approved by the Texas Water Development Board (TWDB) in December 2001. The TSWP included efforts to diversify sources of water resources supplied to users in Region L.

Figure 1.1 shows the outline of Region L and of the Guadalupe River and San Antonio River drainage basins. Also shown are San Antonio Bay, which is the estuary fed by the freshwater flows of the basins and Aransas National Wildlife Refuge (ANWR), which is the wintering habitat for the only non-experimental breeding flock of whooping cranes.

1.2 Human Population Growth, Water Demand and Freshwater Inflows

The need for continued planning and evaluation of water management strategies for Texas is critical, as is apparent from predictions that the population of Texas will more than double from 20.9 million in 2000 to 45.6 million by 2060; likewise within Planning Region L alone, the population is expected to double from 2.0 million in 2000 to 4.3 million residents by 2060 (http://www.twdb.state.tx.us/wrpi/data/proj/popproj.htm). Moreover, projections from the TSWP indicate water demand in Region L will concurrently increase 42% from 2000 demands of 896 thousand acre feet per year to 1.3 million acre feet per year by 2060.

Numerous studies have shown (Copeland, 1966; Ward *et al.*, 2002) that the amount and timing of fresh water inflows to estuaries can greatly impact biological productivity and that water supply developments have the potential to alter inflows and affect that productivity. Projects such as the LGWSP thus need to be designed and implemented to meet both human and ecological needs.

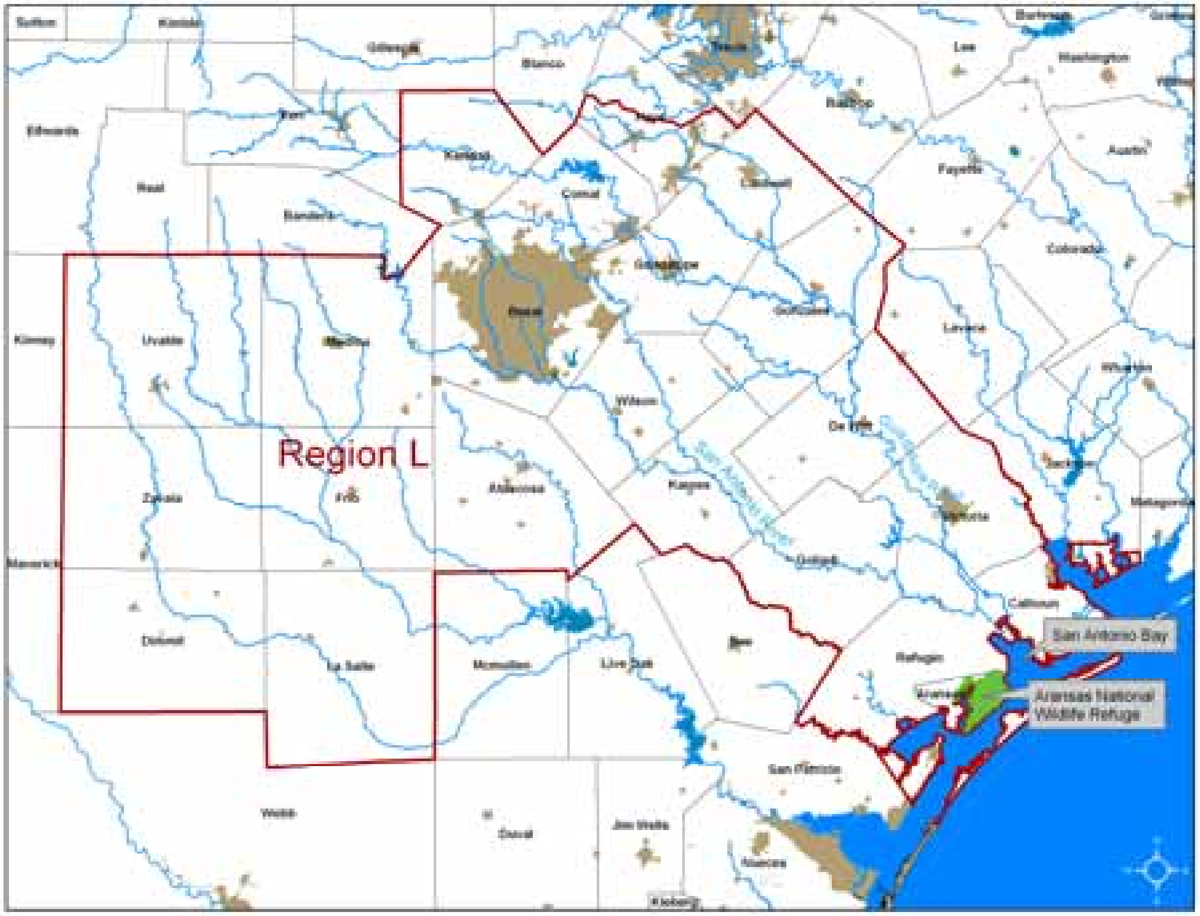


Figure 1.1. Map of Region L and the Guadalupe River and San Antonio River drainage basin.

1.3 Overview of the SAGES Project

The San Antonio Guadalupe Estuarine System Project (SAGES) was funded by the sponsors of the LGWSP and tasked to determine if increased diversions from the Guadalupe Basin could have a meaningful and adverse impact on whooping cranes and, if so, how the project might be modified to mitigate that impact. The study commenced in December 2002 and will finish when this report is finalized in 2009. During 2004, SAWS discontinued its participation in the LGWSP and the project was deferred. However, GBRA and SARA were determined to fund the SAGES studies to completion, and shortly thereafter, the TWDB provided funding to SAGES. Total project funding was $2.14 million. Section 2 of this report describes the design of the SAGES study and summarizes individual research projects. More extensive descriptions of the empirical studies may be found in Appendix A. Section 3 presents the results of an ecological model that simulates important relationships between freshwater inflow and whooping crane energy budgets. Study conclusions are presented in Section 4 and literature cited is section 5.

2. Study Design and Emprical Results

2. Study Design and Empirical Results

2.1 *The SAGES Project*

Given the significant increases in projected demand for water within Region L during the next 50 years and the concern over the ecological needs of the San Antonio Guadalupe Estuary, the LGWSP sponsors funded detailed studies by Texas A&M University to evaluate the linkages between fresh water inflows and mash community dynamics and whooping cranes. The overall approach of the SAGES project was to use empirically-generated data and data available from the literature to define these relationships. In particular, evidence for increased mortality and changes in whooping crane energetics related to differences in freshwater inflows was sought. The study was initiated in December 2002 and will terminate in August 2009, costing the sponsors $2.14 million.

2.2 *Technical Workshops*

Although the knowledge of whooping crane ecology has grown in the last two decades, nothing is known about the linkages between freshwater inflows and crane responses. At the outset of the project, the SAGES team recommended that a series of workshops with biological and ecosystem-modeling experts be used to assist in defining the scope of the project and to suggest guidance for specific field methods and modeling concerns. So the team conducted two workshops and a list of workshop participants and affiliations is given in Table 2.1. Based on these workshops, the initial conceptualization of the potential link between freshwater inflows and whooping cranes was developed (see Figure 2.1).

The SAGES team initiated field studies to quantify how hydrological forcings (tides, freshwater inflows, wind, precipitation) impact materials exchange (nutrients and sedimentation), inundation regimes, vegetation dynamics, blue crabs (*Callinectus sapidus*), and wolfberry (*Lycium caroliniaum*) abundance and availability in the marsh ecosystems within crane territories. The workshop participants suggested that the inundation regime within the marsh territories recognize the dynamics associated with connected and unconnected-pond habitats. The SAGES group recognized that factors such as human disturbance should be evaluated, and that a most important measure of success for cranes would be related to food availability and crane energetics.

We developed a series of studies to observe and quantify the relationships defined by Figure 2.2. A summary of these studies and important findings may be found in Table 2.2. In all, the SAGES project supported 12 empirical studies and two complementary projects in San Antonio Bay. The complementary studies were supported by (1) U.S. Geological Service and the National Institutes of Water Resources, and (2) Texas Sea Grant. In addition, three non-SAGES funded studies emerged to study trophic relationships and connectivity within the marshes of ANWR. All empirical studies, including specific methods, findings, and relation to the model, supported by the sponsors and complementary studies may be found in Appendix A. Individual field projects addressed regional hydrology, marsh hydrology, water quality in marshes and sloughs, wolfberry fruit and blue crab availability, abundance and distribution, human disturbances, and crane foraging behavior and energetics.

Table 2.1. Scientific Advisory Panel. Individuals who attended one or both of two workshops in February 2003 and September 2004.

Name	Institution
Felipe Chavez-Ramirez	Platte River Whooping Crane Trust, Wood River, NE
Daniel Childers	Florida International University, Miami, FL
Vince Guillory *	Louisiana Dept. of Wildlife & Fisheries
Brian Johns **	Canadian Wildlife Service, Saskatchewan, Canada
Thomas Minello	Southeast Fisheries Science Center, Galveston, TX
Denise Reed	University of New Orleans, Montegut, LA
Kenneth A. Rose	Dept. Oceanography & Coastal Sciences, Baton Rouge, LA
Ed Rykiel	Washington State University, Richland, WA
Fred Sklar	Everglades Florida Bay Division, West Palm Beach, FL
Tom Stehn	Aransas National Wildlife Refuge, Austwell, TX
Robert Twilley	University of Louisiana, Lafayette, LA
Tom Wagner	Texas Parks & Wildlife Dept., Rockport, TX

* Did not participate in September 2004 workshop

** Did not participate in February 2003 workshop

Figure 2.1. Initial conceptual model of SAGES Project

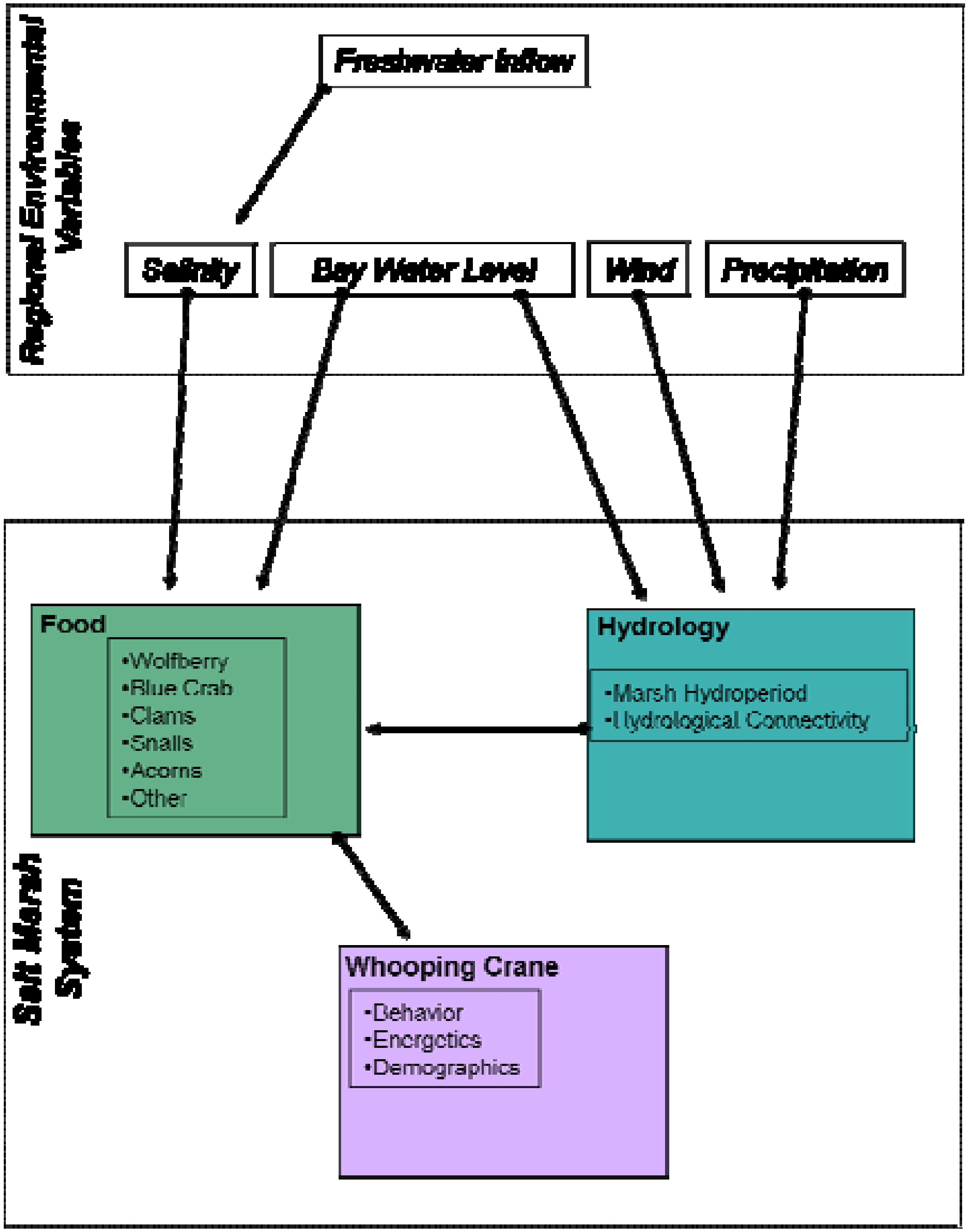
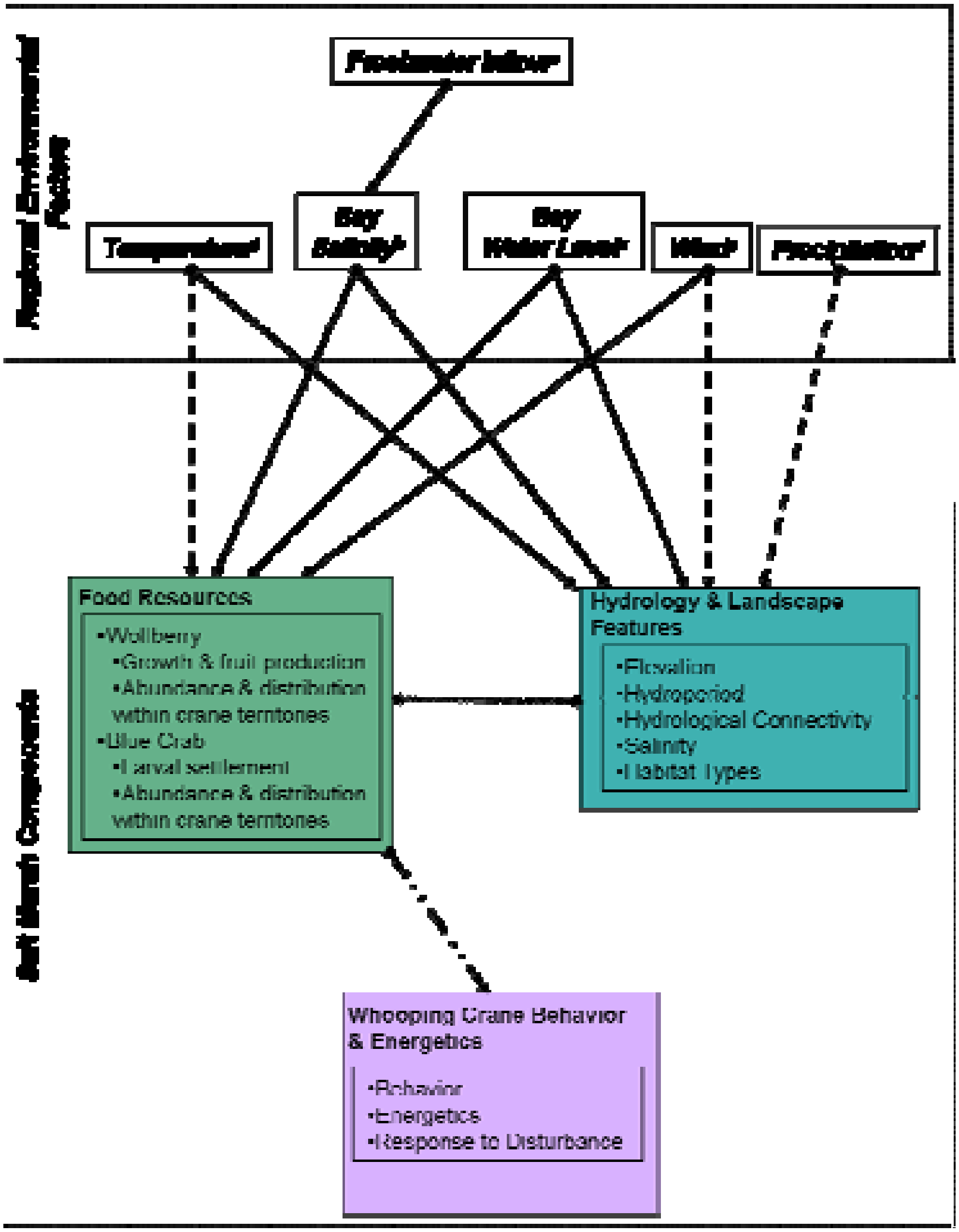


Figure 2.2. Diagram indicating field data collected at Aransas National Wildlife Refuge (ANWR) on hydrology and landscape features within the marsh, whooping crane food resources, and whooping crane behavior, as well as regional environmental data on freshwater inflow from the Guadalupe and San Antonio Rivers, water level, salinity and wind in San Antonio Bay, and precipitation and temperature at ANWR. Solid arrows represent statistically significant correlations and dashed arrows statistically insignificant correlations between environmental and field data. Dotted arrows represent empirical relationships established among field data and dashed-dotted arrows represent relationships based on field data and literature values.



(a) Guadalupe (http://waterdata.usgs.gov/tx/nwis/inventory/?site_no=08176500&) and San Antonio River (http://waterdata.usgs.gov/tx/nwis/inventory/?site_no=08188500&) gauges
(b) GBRA1 gauge: http://lighthouse.tamucc.edu/pq/127/do
(c) Seadrift gauge: http://lighthouse.tamucc.edu/overview/031
(d) Aransas National Wildlife Refuge: (http://www.ncdc.noaa.gov/oa/ncdc.html)

Table 2.2. Summary of Empirical Studies

Personnel	Study Title	Study Area	General Methods	Key Data	Findings In A Nutshell
Core SAGES Studies					
1. J. Bryan Allison – Stephen E. Davis (thesis committee member)	*Characterization of sediment movement in tidal creeks adjacent to the Gulf Intracoastal Waterway at Aransas National Wildlife Refuge, Austwell, TX: Study of natural factors and effects of barge drawdown currents*	ANWR study sites (BR, PC, SB)	Periodic sampling and measurement of flow, nutrients, and sediment content of tidal creeks	Tidal creek water level, flow/discharge, bedload transport, suspended solids, nutrient concentrations	Barge passages can affect tidal creek hydrodynamics comparable to daily tides and can also affect sediment transport
2. Rachel Butzler – Stephen E. Davis (thesis advisor)	*Spatial and temporal patterns of Lycium carolinianum Walt. (the Carolina Wolfberry) in the salt marshes of Aransas National Wildlife Refuge*	ANWR study sites (BR, PC, SB)	Vegetation plots: species counts, morphometrics, soil porewater and surface water depth and salinity, Transects: species counts, biomass	Distribution patterns of wolfberries; time and space relationships in wolfberry fruit production	Wolfberry shows broad distribution across ANWR and growth shows strong seasonal dynamics
3. Carrie Miller – Stephen E. Davis and Dan Roelke (thesis co-advisors)	*Pattern and process influencing algal biomass in hydrologically dynamic salt ponds in a subtropical salt marsh*	ANWR study sites (BR, PC, SB)	Sampling of water quality, water level, benthic organic matter and algal biomass in tidal ponds	Time and space trends in algal dynamics, organic matter, and nutrient dynamics in ponds relative to connectivity	Hydrologic connectivity affects algal biomass and nutrient levels in ANWR ponds
4. George Gable – Stephen E. Davis and Dan Roelke (thesis co-advisors)	*Spatio-temporal patterns of biophysical parameters in a microtidal, bar-built, subtropical estuary of the Gulf of Mexico*	Mesquite Bay	Monthly fixed station sampling of water quality and plankton community in conjunction with Dataflow sampling across Mesquite Bay	Nutrients, organic matter, productivity, plankton community structure, temperature, chlorophyll *a*, CDOM, turbidity, and salinity/conductivity	From a water quality standpoint, Cedar Bayou exchanges do not greatly affect water quality in Mesquite Bay
5. Matthew Driffill – Stephen E. Davis (thesis advisor)	*Hydrologic Connectivity Across a Tidal Marsh-Pond Landscape at Aransas National Wildlife Refuge (TX, USA)*	ANWR study sites (BR, PC, SB)	Water level recording; elevation mapping and modeling, automated sampling of tidal creek water quality	Inundation frequencies based on tidal patterns, tri-daily tidal creek nutrient concentrations (N and P)	Analysis of historical patterns of hydrologic connectivity relative to present still in progress
6. Christopher Llewellyn – Stephen E. Davis (REU advisor)	*The Effects of Salinity and Inundation on Leaf Abundance of the Carolina Wolfberry, Lycium carolinianum: A Greenhouse Experiment*	Laboratory experiments based at TAMU	Wolfberry plants grown in water with different salinity (freshwater and 35 ppt) and inundation regimes	Growth and leaf counts as a function of salinity and inundation during the summer	Overall leaf loss was greater during in the high salinity treatment relative to freshwater, inundation had no discernible effect
7. Danielle Greer – R. Douglas Slack (PhD advisor)	*Patterns in blue crab density and total abundance in shallow salt-marsh and bay habitats of the Texas Gulf Coast*	ANWR study sites (BR, PC, SB)+BJ	Monthly crab collections & habitat / environmental measurements	Crab biomass and density by habitat over time and associated largely physical factors	Widest range of crab sizes was observed in submerged aquatic vegetation and this habitat proved to be a significant contributor to crab numbers.

Table 2.2. Summary of Empirical Studies (Continued)

Personnel	Study Title	Study Area	General Methods	Key Data	Findings In A Nutshell
Core SAGES Studies (Continued)					
8. Danielle Greer – R. Douglas Slack (PhD advisor)	*Blue crab settlement and recruitment patterns in shallow habitats of the Texas Gulf Coast*	ANWR study sites (BR, PC, SB)+MB	New techniques for collecting crab megalope; monitor recruitment	Patterns of crab megalope settlement and juvenile recruitment and associated factors	Water temperature during period of spawning and larval export were most significant predictor of larval settlement.
9. Danielle Greer – R. Douglas Slack (PhD advisor)	*Whooping crane foraging ecology: gains, costs, and efficiency of foraging during winter*	ANWR study sites (BR, PC, SB)+BJ	Direct observations of foraging, identification of food and effort required	Food preferences and relative efficiencies in crane foraging	Wolfberry fruit and snails/insects were consumed in highest quantities, required the least effort during foraging and were associated with most efficient foraging behavior.
10. Kristin E. LaFever – R. Douglas Slack (thesis advisor)	*Spatial and temporal winter territory use and behavioral responses of whooping cranes to human activities*	BR, PC, PL, LS, BJ	Direct observations of activity: when/where; and disturbances	Time-activity budgets; spatial/temporal patterns of habitat use; and disturbance stimuli	Current levels of human activities are not having detrimental impacts on whooping crane population
11. Karine Gil – William Grant (PhD advisor)	*Projecting population dynamics of the endangered whooping crane*	Published data	Development and calibration of model	New data are projections; breeding ages adjusted from prior models	Projected population trends projected suggest population size will surpass the carrying capacity by the year 2024.
12. William Grant and Todd Swannack	*Modeling hydrological connectivity in salt marsh ecosystems*	Guadalupe Estuary	Development of spatially-explicit hydrological-connectivity model based on LIDAR and environmental data	Simulates patterns of water level changes and hydrological connectivity within ANWR	Model captures general trends but needs further calibration
Complementary Studies					
13. Stephen Davis, Daniel Roelke, Carrie Miller, George Gable, Hsiu Ping Li, and Kung Jen Liu	*Reduced freshwater inflows and productivity in the guadalupe estuary: use of high-resolution spatial mapping (funded by TX Sea Grant)*	San Antonio Bay and Espiritu Santo Bay	Dataflow monitoring: Intensive estuarine-wide spatial surveys of water quality at monthly intervals	Temperature, Chlorophyll *a*, CDOM, turbidity, and salinity/conductivity	Estuarine circulation and water quality driven to a great extent by freshwater inflows
14. Stephen Davis, Daniel Roelke, Carrie Miller, George Gable, Hsiu Ping Li, and Kung Jen Liu	*Bridging the gap between plankton dynamics and spatial variability in water quality in the guadalupe estuary (texas): The importance of freshwater pulses (funded by USGS)*	San Antonio Bay and Espiritu Santo Bay	Monthly sampling of water quality and biological parameters at fixed stations, lab experiment: hydrologic pulsing effects on plankton dynamics	Nutrients, organic matter, productivity, plankton community structure, chlorophyll *a*	Plankton dynamics showed seasonal and freshwater inflow effects

Table 2.2 Summary of Empirical Studies (Continued)

Personnel	Study Title	Study Area	General Methods	Key Data	Findings In A Nutshell
Non-SAGES ANWR Studies					
15. Steven Zeug, David Hoeinghaus, Virginia Shervette, and Stephen E. Davis (published in 2007)	*Community structure and foodweb dynamics in created and natural wetlands along Aransas National Wildlife Refuge*	ANWR natural and created marsh and adjacent bay bottom in lower Sundown Bay	Drop trap sampling from shallow bay and marsh edge	Inventory species, biomass and size class from bay bottom and created and natural marsh edge habitat	Substrate complexity and quality accounted for differences observed between natural and created marshes
16. David Hoeinghaus and Stephen E. Davis (published in 2007)	*Diet and trophic position of blue crabs relative to size in ANWR marsh*	ANWR sites – SD, BR tidal creek, pond, bay	Seining, dip netting, plant and detritus collection	Tissue and sediment stable isotope (^{13}C and ^{15}N) analysis	Crabs showed omnivorous signature regardless of size, but appeared to be more associated with “connected” edge habitat at larger size classes
17. Katie Roach, David Hoeinghaus, Jeffrey Wozniak, and Stephen E. Davis (manuscript in prep)	*Importance of connectivity in shaping aquatic food webs in ANWR marsh*	ANWR sites – SD, BR tidal creek, pond, bay	Seining, dip netting, plant and detritus collection	Tissue and sediment stable isotope (^{13}C and ^{15}N) analysis	Hydrologic connectivity is related to food web length and species-specific trophic position for several fish species

2.3 The Whooping Crane

The whooping crane (*Grus americana* L.), perhaps the most well known endangered bird in North America, breeds in wetlands of Wood Buffalo National Park (WBNP) in Canada and winters on coastal wetlands of Texas. Most of these wintering birds are found within the boundaries of ANWR, over 4,300 km from their breeding grounds. Reduced to fewer than 16 individuals in 1941, the whooping crane has made a slow comeback from the brink of extinction. At the onset of the SAGES project, during the winter of 2002 - 2003, 185 birds wintered on ANWR and in the surrounding area. Currently, the Wood Buffalo-Aransas population is the only viable wild, non-experimental population of whooping cranes in North America and has briefly exceeded 250 individuals.

The ability of whooping cranes to survive the winter and breed successfully in spring after their long migration depends on the physical condition of the adult birds. Chavez-Ramirez (1996) reported that breeding success of whooping cranes at Wood Buffalo National Park is closely tied to the availability of food to the cranes while they are on coastal wetlands during the winter. Hunt and Slack (1989) documented that more than 90% of the whooping crane diet is composed of animal material, with the blue crab serving as the dominant food item. In addition to blue crabs, other important food items included the fruit from the wolfberry plant , razor clams (*Tagellus plebius*), and acorns (*Quercus virginiana).* Chavez-Ramirez (1996) reported that blue crabs accounted for 62% to 98% of the energetic intake for whooping cranes during the winter. In some months though, wolfberry fruits at the marsh-upland interface, razor clams from open shallow bays, and even crayfish (*Cambarus hedgpethi*) from upland sites can comprise important food items.

2.4 Study Area

The Coastal Bend region of Texas includes numerous bays and estuaries that are ecologically and economically important. One such estuary, the Guadalupe River Estuary, is fed by freshwater inflow primarily from the Guadalupe River and the San Antonio River that merges with the Guadalupe just above the head of the estuary. The Guadalupe Estuary is a relatively small (551 km^2 (136,097 acres)) and shallow (mean water depth is ~1 meters (m) (3 ft)) lagoonal estuary along the Texas Gulf Coast (Figure 2.3). Indirect exchange with the Gulf of Mexico occurs primarily through passes at the northern (Pass Caballo) and southern (Aransas Pass) ends of Matagorda Island; therefore, tides are relatively small (< 0.2 m, (0.65 ft)). These characteristics favor the importance of wind forcing and freshwater inflows as important driving mechanisms in the estuary. Mean annual rainfall in this region is 91 cm / yr, and the estuary has a mean annual inflow balance of $2.5*10^9$ m^3 / year (2,026,782.98 acre feet / year) (TDWR 1980). The Guadalupe Estuary is a source of commercially important finfish ($80*10^3$ kg / year (88 tons / year) and shellfish species ($1545*10^3$ kg / year (1700 tons / year); TDWR 1980). This estuary encompasses the wintering grounds of the only non-experimental, migratory population of whooping cranes in the world. San Antonio Bay is the major bay within the Guadalupe Estuary and exhibits salinity patterns that are inversely correlated with 28-day cumulative inflow from the Guadalupe River (Montagna and Kalke, 1992). Due to the indirect exchanges with the Gulf of Mexico, high inflows into this system can also result in low to no salinity throughout much of the bay (Montagna and Kalke 1992; Davis and Roelke, 2002). Based on analyses of benthic infaunal communities by Montagna and Kalke (1992), freshwater inputs from the Guadalupe River flow along the western boundary of the bay towards the salt marsh along the Blackjack Peninsula, as these communities exhibit the community structure and biomass typical of lower salinity conditions. Based on the same analyses, they concluded that saline water from the Gulf of Mexico enters primarily through Pass Cavallo and penetrates San Antonio Bay from the east—through Espiritu Santo Bay (Montagna and Kalke 1992). Davis and Roelke (unpublished data) confirmed these findings through monthly, high-resolution (Dataflow) mapping of surface water quality along the Guadalupe Estuary as part of a complementary studies funded by USGS and Texas Sea Grant (see Figure 2.4).

Despite small diurnal tides, bay water levels vary significantly annually and inter-annually as a result of wind patterns, storm events, and other large scale forcings. Data from the Seadrift tide gauge (http://lighthouse.tamucc.edu/overview/031) located in eastern San Antonio Bay during the period of the SAGES project indicated that mean daily water levels in the bay represented a normal distribution with a mean of 0.497 m (1.63 ft) and a standard deviation of 0.151 m (0.50 ft). Bay levels were typically highest in September and October (*i.e.*, leading up to the crane's wintering period) and lowest in December and January (*i.e.*, during the middle of the wintering period) over the duration of our study (Figure 2.5). Furthermore, annual bay levels were significantly lower in 2006 relative to other study years (Figure 2.6).

Aransas National Wildlife Refuge represents a major parcel of undeveloped land along the southwestern edge of the Guadalupe Estuary (Figure 2.3). Approximately 2,800 ha of salt marsh at ANWR provide food and habitat to many terrestrial and estuarine species; most well known is whooping crane. ANWR salt marshes lie predominantly at the mid- to high-intertidal elevation range and are therefore infrequently inundated. Based on our observations over the years, these marshes are inundated primarily as a result of wind forcing and spring tides. A narrow fringe (1–2 m (3-6 ft) in width) of *Spartina alterniflora* Loisel. borders ANWR marshes at the interface with the bay and along many of the tidal creeks as well as some of the more frequently connected sloughs and ponds. The bulk of the salt marsh area is comprised of a mixed high-marsh community that includes *Aster tenuifolius* L., *Batis maritima* L., *Borrichia frutescens* (L.) DC., *Distichlis spicata* (L.) Greene, *Lycium carolinianum* Walt. (Carolina wolfberry), *Monanthochloe littoralis* Englem., *Salicornia bigelovii* Torr., *Salicornia virginica* L., and *Sueada linearis* (Ell.) Moq. This mixed community grades into an upland transition zone dominated by *Spartina spartinae* (Trin.) Hitchc. and other grass and sedge species.

In early 2003, we identified three sampling sites along tidal channels for this study. Tidal channels were selected as the focus of the water quality monitoring program because they represent the source of tidal exchange between the marsh and the adjacent bays. Further, they provide the best location for observing the effect of hydrological forcings on changes in water quality, marsh inundation regimes, and vegetation dynamics (Figure 2.7). These water quality observations also helped to provide critical links with other components of the SAGES Project including those looking at landscape (*i.e.*, hydrological) connectivity between tidal waters and intermittently-connected ponds, blue crab dynamics, and whooping crane foraging and behavioral patterns across ANWR salt marshes.

Our three main sites for water quality testing included the Boat Ramp (BR) channel, Pump Canal (PC), and a tidal creek in lower Sundown Bay (SB, Figure 2.7). They were selected according to their spatial distribution along the Blackjack Peninsula and their position along the salinity axis of the Guadalupe River Estuary. The SB site was furthest from the river mouth and was expected to have the highest mean annual salinity while the BR site was closest and expected to exhibit the lowest mean annual salinity of the three sites (Figure 2.4). (Note that two other territories and sites were selected for crab sampling and whooping crane observation).

The three primary sites represented a range of channel types that fed the heterogeneous matrix of marshes and ponds that prevailed at ANWR. The SB site is a natural, unaltered tidal channel, the PC site is an artificially straightened channel that is directly connected to the Gulf Intracoastal Waterway (GIWW) through upper Sundown Bay, and the BR site runs parallel to the GIWW and has been partially modified with a levee running parallel to the creek and the GIWW.

Figure 2.3. Image of the Guadalupe River Estuary showing the Blackjack Peninsula, Mesquite Bay, St. Charles Bay, San Antonio Bay, the Guadalupe River delta and the Aransas National Wildlife Refuge.

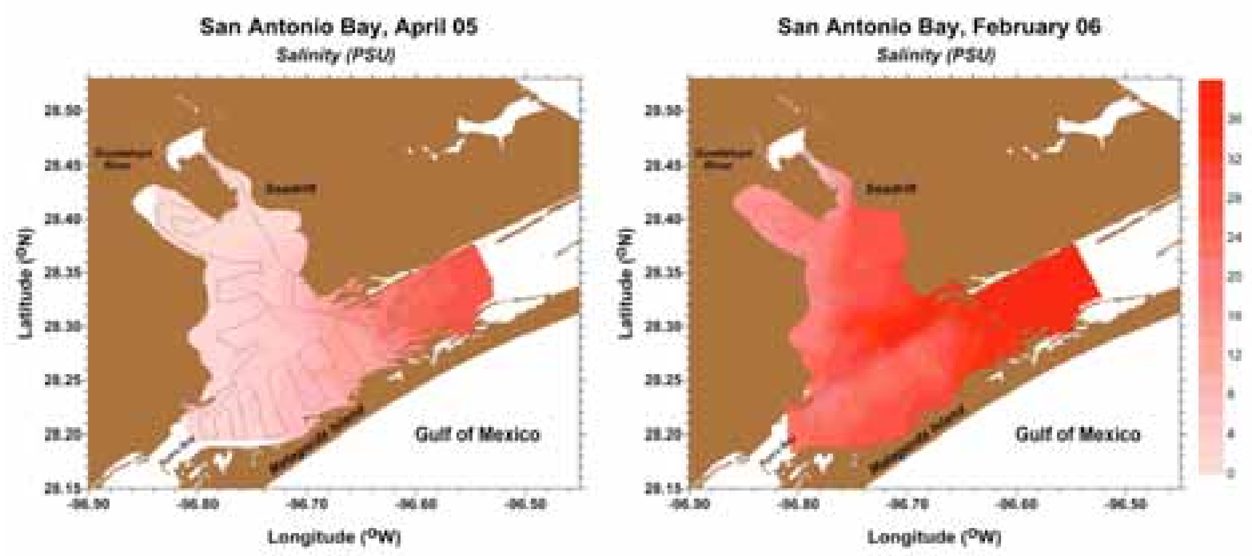


Figure 2.4. Interpolation plots of salinity data from Guadalupe Estuary transects sampled using Dataflow—an *in situ*, flow-through, high-resolution water quality mapping technique. The panel on the left shows saltwater penetrating San Antonio Bay through Espiritu Santo Bay following a period of high river inflow. The panel on the right shows low salinity river inflow penetrating the estuary along the western margin (*i.e.*, along ANWR) and wrapping around to the east in lower San Antonio Bay. Salinity is reported in practical salinity units (parts per thousand (ppt).

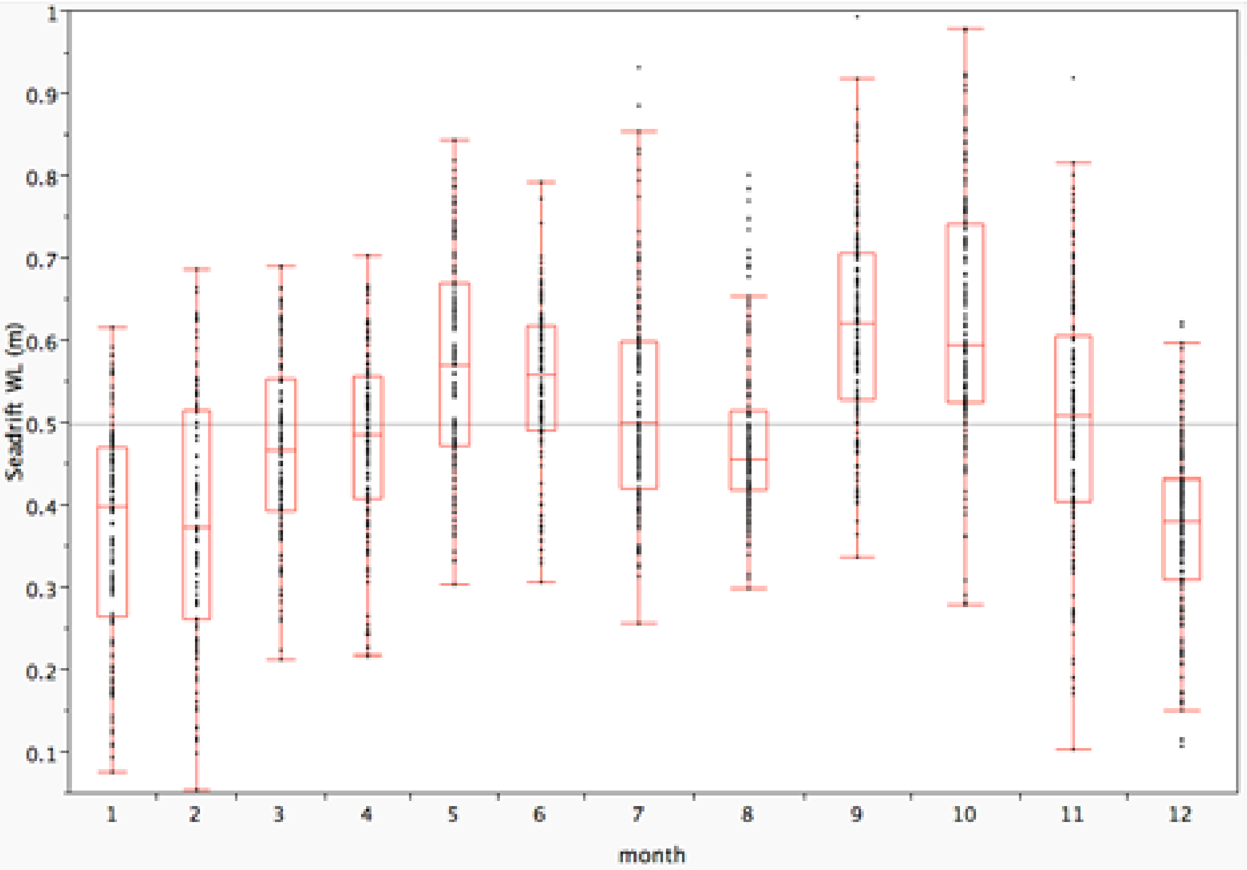


Figure 2.5. Box-and-whisker plots showing distributions of bay water level data from the Seadrift gauge (http://lighthouse.tamucc.edu/overview/031) over the duration of the SAGES field studies (July 2003 through December 2007) broken down by month. Black dots represent the data points. The box contains 50% of the data with the horizontal line within the box representing the median, the lower bound of the box representing the 25th percentile and the upper bound representing the 75th percentile. The intersection of the horizontal and vertical lines outside the box represents the 10th and 95th percentiles.

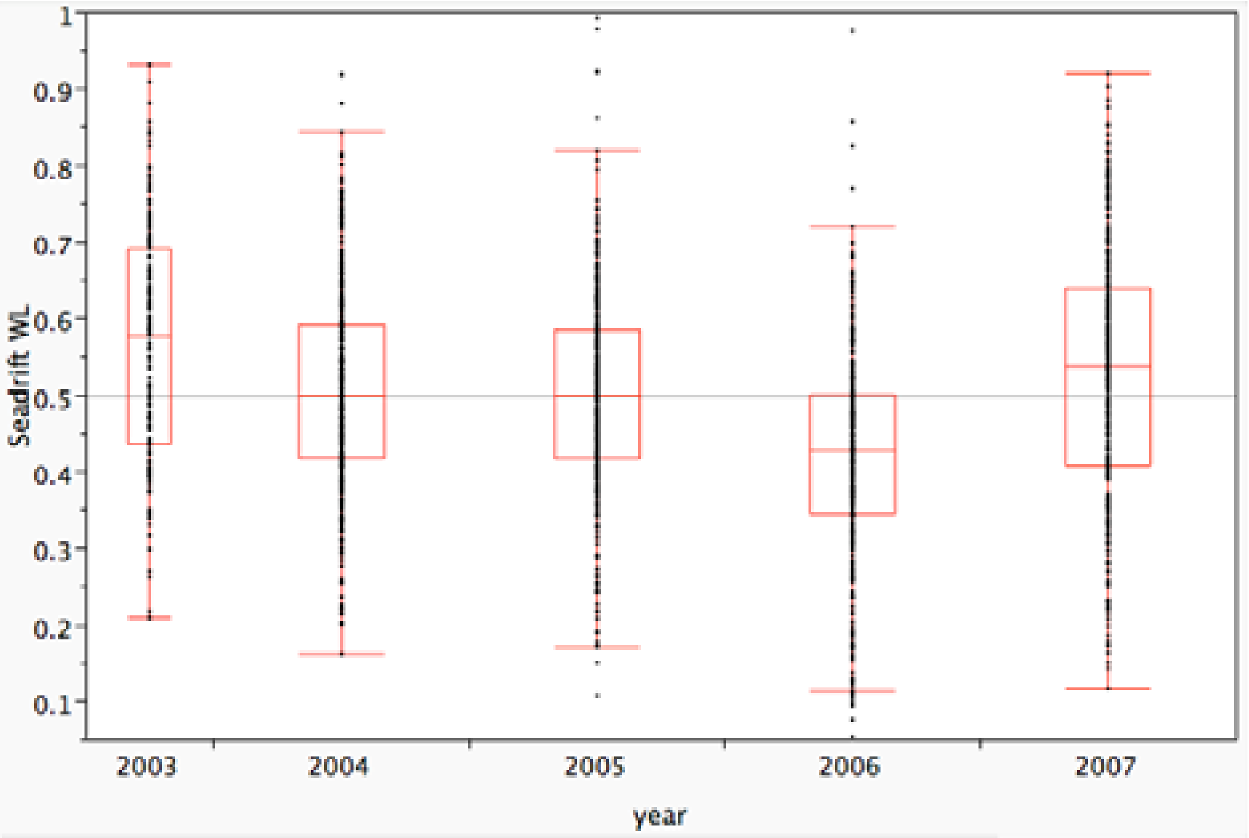


Figure 2.6. Box-and-whisker plots showing distributions of bay water level data from the Seadrift gauge (http://lighthouse.tamucc.edu/overview/031) over the duration of the SAGES field studies (July 2003 through December 2007) broken down by year. Black dots represent the data points. The box contains 50% of the data with the horizontal line within the box representing the median, the lower bound of the box representing the 25th percentile and the upper bound representing the 75th percentile. The intersection of the horizontal and vertical lines outside the box represents the 10th and 90th percentiles.

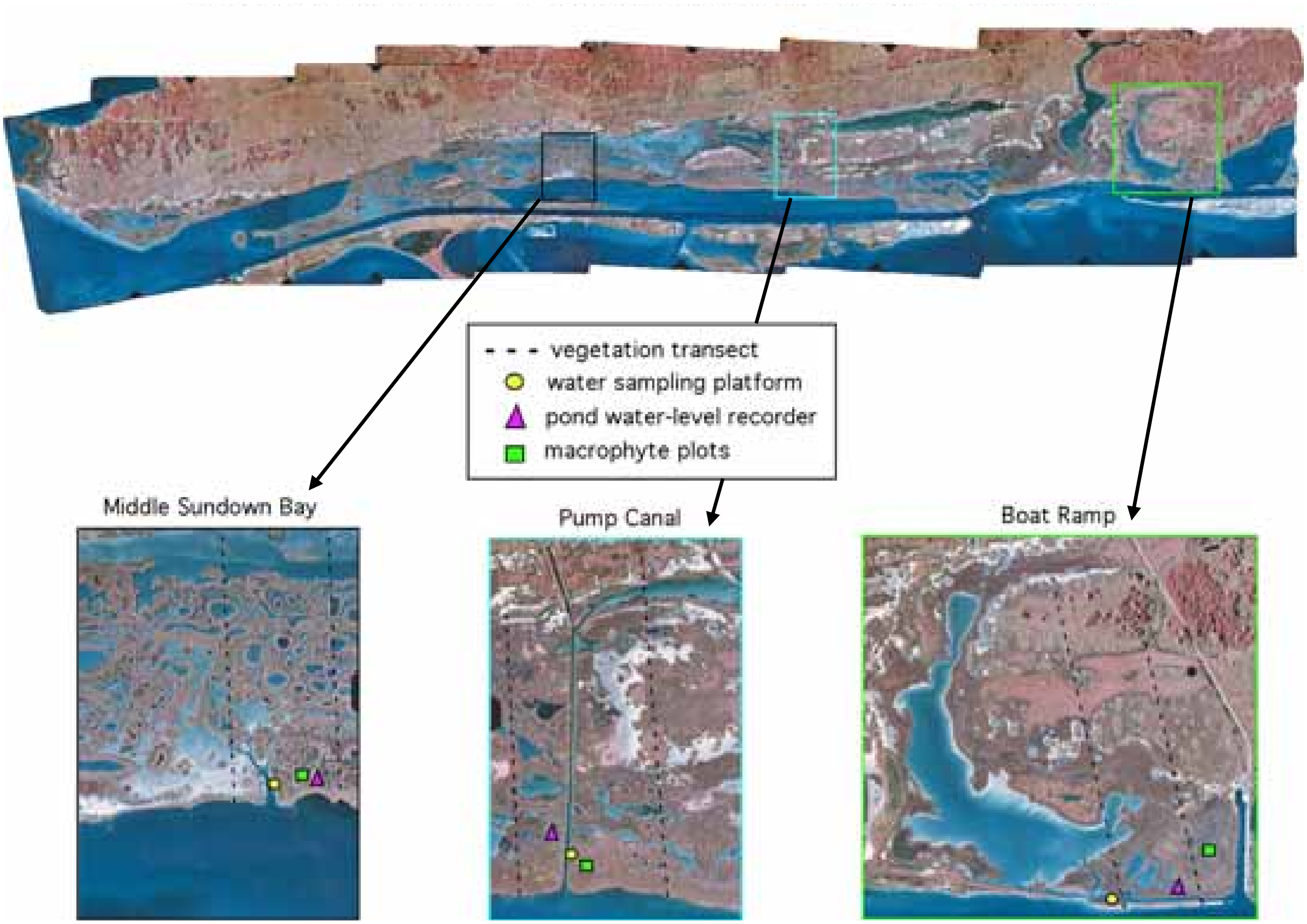


Figure 2.7. Overlay of multiple images showing the stretch of ANWR salt marsh along the Blackjack Peninsula and GIWW. Three primary territories are outlined and blown-up to show locations of tidal channels sampling platforms relative to vegetation sampling locations (plots and transects) and locations of pond water level recorders. Descriptions of each territory (total area and areas occupied by each habitat type) can be found in Butzler (2006).

2.5 SAGES Goal and Project Objectives

The overall goal of the SAGES project was to use empirically-generated and available data to evaluate the relationship between freshwater inflows feeding San Antonio Bay and the health of the endangered whooping crane population at ANWR. Field research included several studies of wetland processes, macrophytes, and blue crabs in the salt-marsh of ANWR. Investigations also focused on the behavioral responses of whooping cranes to changes in abundance and distribution of foods (blue crab, wolfberry fruit, and others), abiotic factors, and human-induced disturbances within and adjacent to ANWR. Finally, empirical findings were integrated to produce a simulation model with the capabilities of predicting crane response to changes in food supply, temperature, salinity, and water levels in and around the ANWR salt marsh. Specific project objectives were as follows:

1. Quantify patterns of habitat use by whooping cranes in relation to changes in human-induced disturbances at ANWR,

2. Evaluate relationships among water temperature, water salinity, water depth, other physical factors, and blue crab abundance in salt-marsh habitats of ANWR,

3. Determine changes in whooping crane foraging behavior and capture rates in relation to abundance of blue crab and wolfberry fruit,

4. Quantify macrophytic responses in saltwater marshes to intra- and inter-annual variability in freshwater inflows, salinity, and inundation,

5. Develop a simulation model relating freshwater inflows feeding San Antonio Bay to wolfberry fruit abundance and the abundance of blue crabs to whooping cranes in saltwater marshes of ANWR.

2.6 Summary of Empirical Studies

The results from the empirical studies have added considerably to the knowledge of the greater San Antonio Bay ecosystem. The team identified several key relationships among environmental variables and marsh components. The team's results showed a clear effect of river inflows on water quality patterns across the greater bay ecosystem. Freshwater inflows to the bay tended to flow in a southwest direction along Blackjack Peninsula and along the estuarine marshes at ANWR. Freshwater inflow was strongly, inversely correlated with bay salinity: as freshwater inflow decreased, bay salinity increased. Patterns of salinity in San Antonio Bay were also strongly correlated with salinities in the tidal creeks of Blackjack Peninsula and therefore bay salinity can be used as an indicator of marsh salinity. Results from both field and laboratory experiments indicated salinity was an important factor in wolfberry fruit production. More specifically, salinity immediately prior and leading up to the late summer leafing period was inversely correlated with peak wolfberry abundance. The team found that blue crab abundance was significantly correlated with habitat type, territory and three abiotic factors: bay water level, wind speed as measured in the bay, and bay salinity. In addition to blue crabs and wolfberries, the team confirmed that the whooping crane diet consisted of several more food items including snails, insects, snakes, fish and clams, and that whooping cranes spend approximately 65% of daylight hours foraging. Human disturbance did not appear to detrimentally affect foraging behavior. The relationships established through the empirical studies were used to develop a quantitative, systems-level simulation model that was used to determine the impacts of freshwater inflows on whooping crane energetics. A detailed description of the simulation model follows in Section 3.

3. The Model

3. The Model

3.1 Model Overview

We developed a quantitative simulation model as a tool to aid us in assessing the potential impact of changes in freshwater inflow into San Antonio Bay on the whooping cranes that spend the winter at ANWR. The final form of the quantitative model evolved from our initial conceptualization of the San Antonio Bay-ANWR salt marsh ecosystem, which was based on workshops with our scientific advisory committee (Table 2.1) and the results of our empirical studies, the majority of which were conducted on the ANWR during the four-and-a-half years between February 2003 and December 2007 (Appendix A).

Our initial conceptual model viewed the ecosystem as being influenced by regional environmental factors that affect hydrology and landscape features within the marsh. In turn, the hydrology and landscape features affect the abundance of food resources within whooping crane territories and, as a result, may have an impact the behavior and energy budget of whooping cranes (Figure 3.1). This initial conceptualization led to the development of 15 empirical studies, each of which was intended to provide information that elucidated one or more of the possible links between freshwater inflow and whooping cranes (Figure 3.2). Obviously, we do not view our conceptual model and the accompanying empirical studies as all-inclusive, but rather, as a useful simplification of a complex system, which focuses attention on evaluating the most likely links between inflow and cranes that could be explored with the resources at our disposal.

Our attempts to establish empirical links between freshwater inflow and whooping cranes involved an information-theoretic approach (Burnham and Anderson 2002) to statistically evaluate a suite of hypotheses that related, in an ecological context, the regional environmental factors to the salt marsh components. This approach involved (a) developing a set of hypotheses that could ecologically explain the patterns observed in the field data, (b) evaluating these hypotheses using appropriate statistical methods to correlate the environmental data with our field data (see Appendix A for statistical details), and (c) drawing upon the results from these statistical analyses to parameterize the simulation model. We obtained the regional environmental data from five monitoring stations whose data are freely available via the Internet at the following addresses:

(a) *Guadalupe River discharge*:
http://waterdata.usgs.gov/tx/nwis/inventory/?site_no=08176500&
(b) *San Antonio River discharge*:
http://waterdata.usgs.gov/tx/nwis/inventory/?site_no=08188500&
(c) *Seadrift monitoring station*: http://lighthouse.tamucc.edu/overview/031
(d) *ANWR weather gauge*: http://www.ncdc.noaa.gov/oa/ncdc.html
(e) *GBRA1 gauge:* http://lighthouse.tamucc.edu/pq/127/do
Note*:* The GBRA1 gauge is funded by GBRA

Figure 3.1. Diagram indicating potential links between freshwater inflow to San Antonio Bay from the Guadalupe and San Antonio rivers and whooping cranes at ANWR. Potential links from freshwater inflow and other regional environmental factors to whooping cranes are mediated by hydrology and landscape features within the marsh which, in turn, influence the abundance of food resources within whooping crane territories.

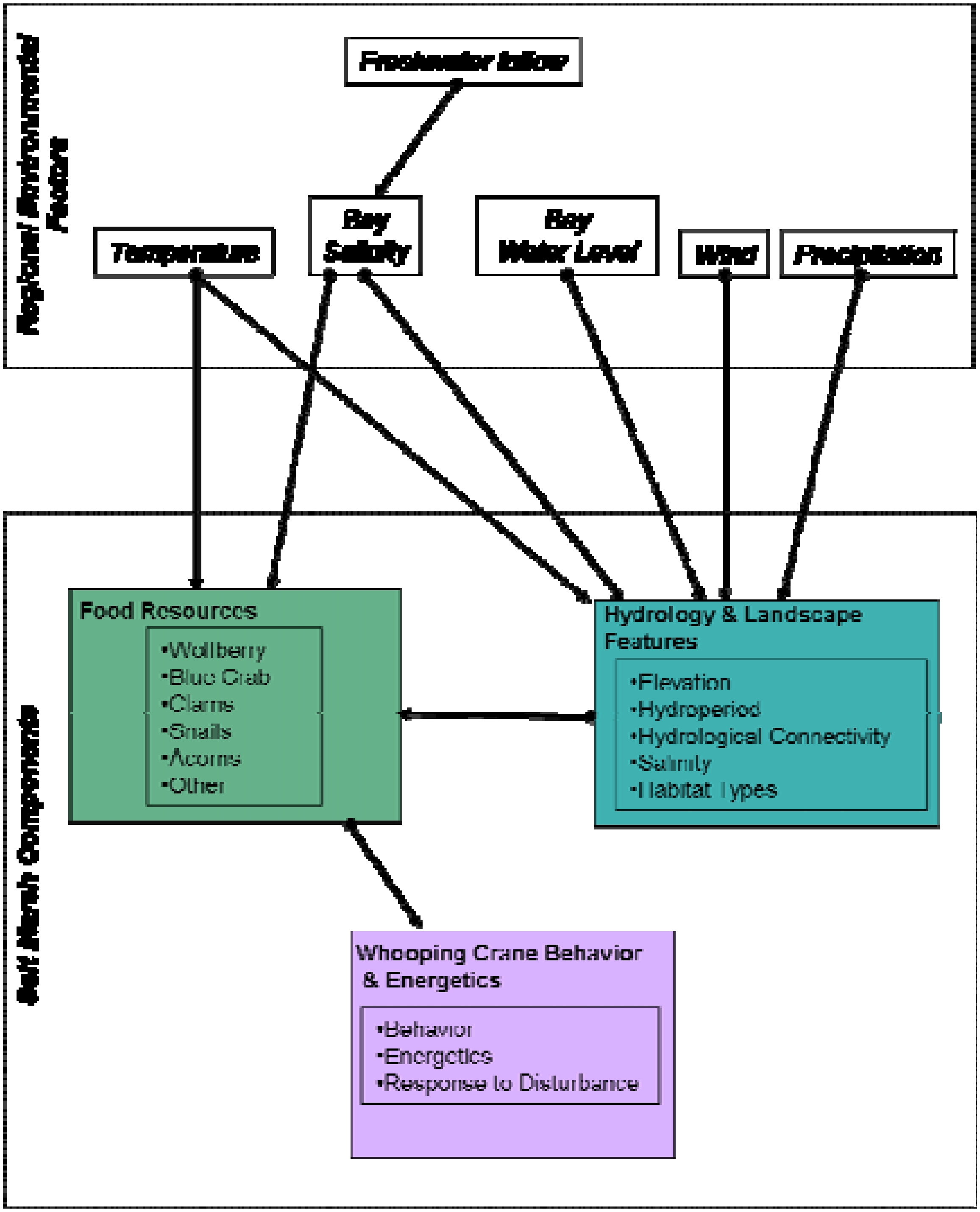
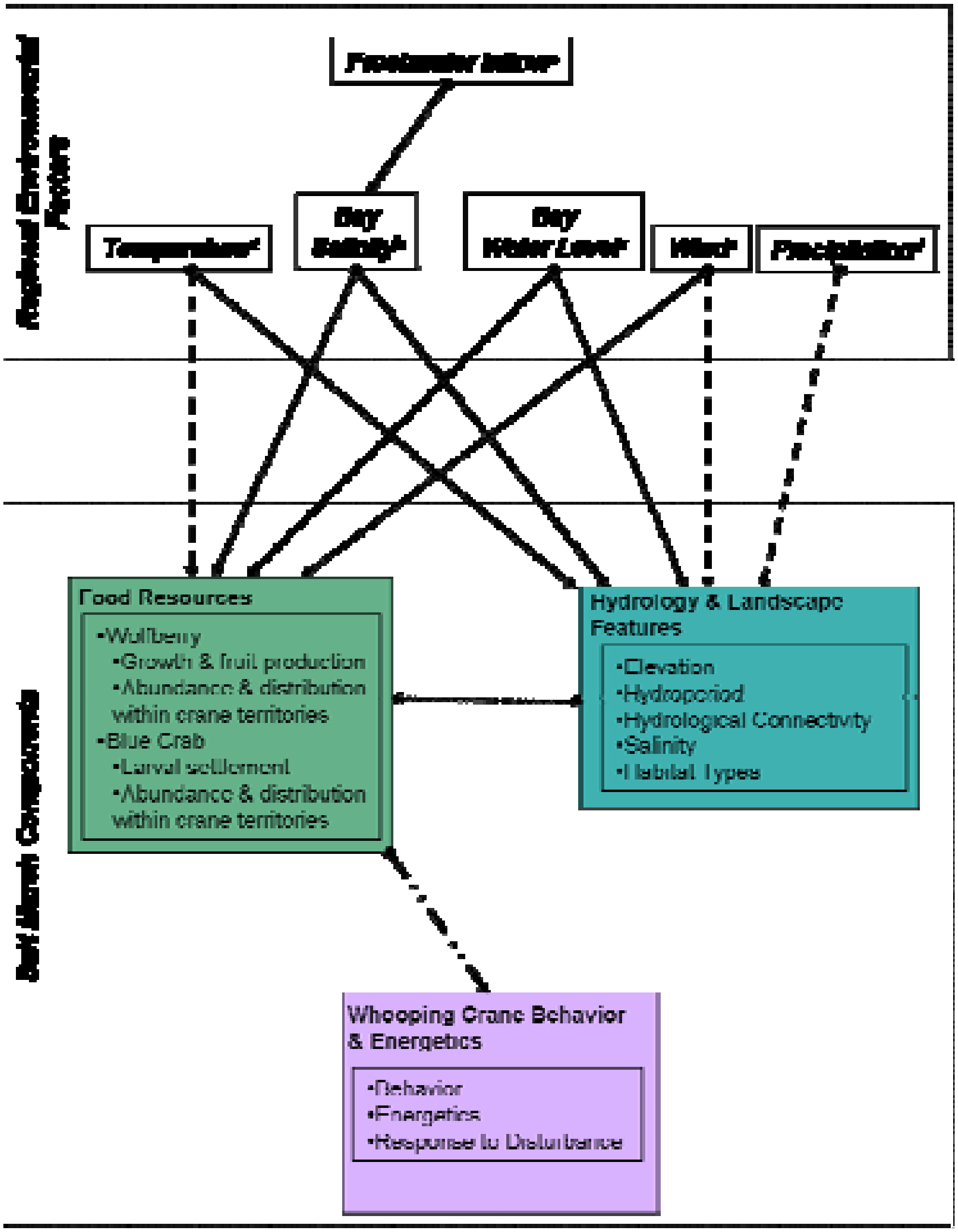


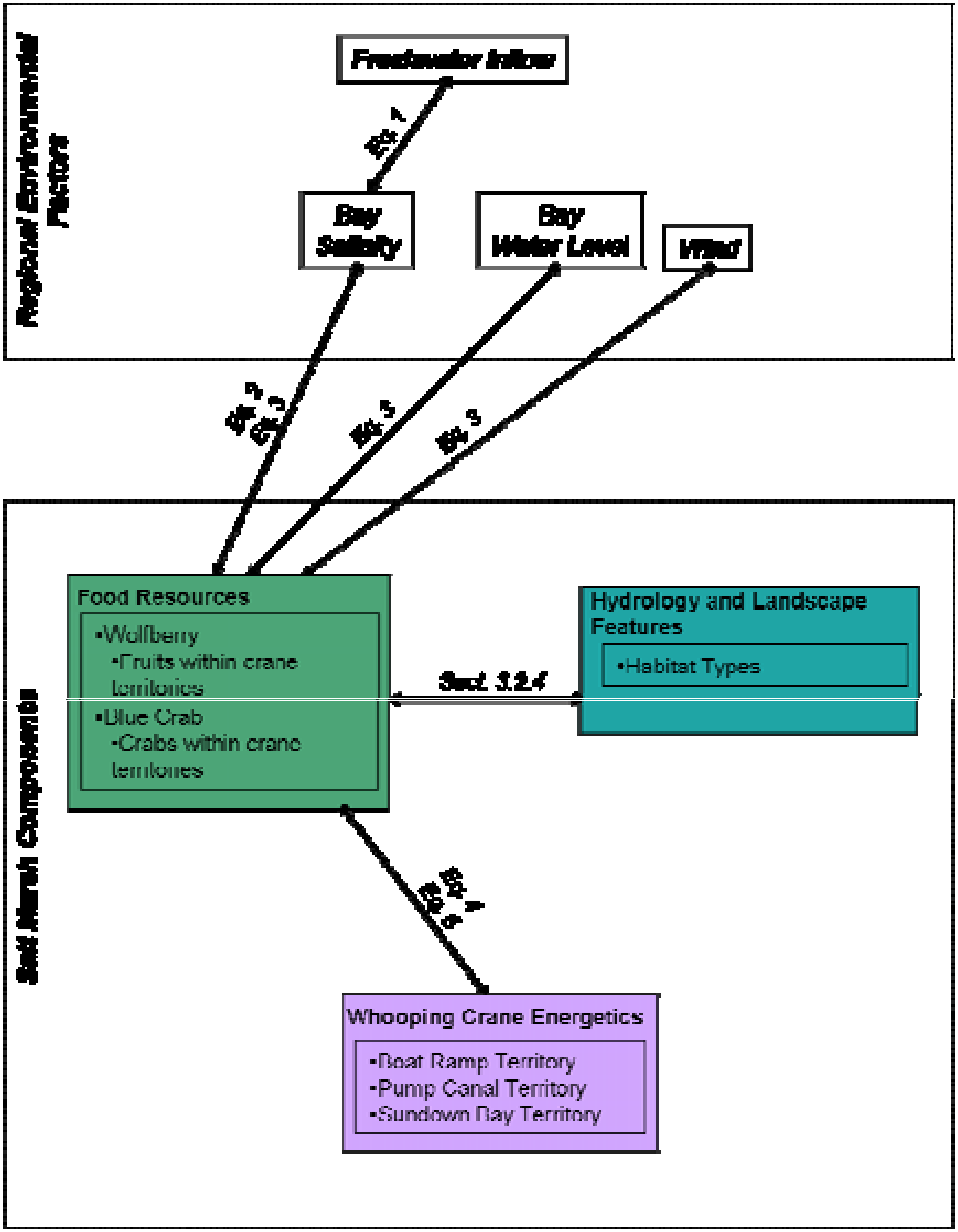
Figure 3.2. Diagram indicating field data collected at Aransas National Wildlife Refuge ANWR on hydrology and landscape features within the marsh, whooping crane food resources, and whooping crane behavior, as well as regional environmental data on freshwater inflow from the Guadalupe and San Antonio rivers, water level, salinity and wind in San Antonio Bay, and precipitation and temperature at ANWR. Solid arrows represent statistically significant correlations and dashed arrows statistically insignificant correlations between environmental and field data. The dotted arrow represents empirical relationships established among field data, and the dashed-dotted arrow represents relationships based on field data and literature values. Note this figure is identical to Figure 2.2



(e) Guadalupe (http://waterdata.usgs.gov/tx/nwis/inventory/?site_no=08176500&) and San Antonio River (http://waterdata.usgs.gov/tx/nwis/inventory/?site_no=08188500&) gauges
(f) GBRA1 gauge: http://lighthouse.tamucc.edu/pq/127/do
(g) Seadrift gauge: http://lighthouse.tamucc.edu/overview/031
(h) Aransas National Wildlife Refuge: (http://www.ncdc.noaa.gov/oa/ncdc.html)

Based on ecologically-interpretable empirical relationships among the regional environmental factors and the salt marsh components, we parameterized a simulation model that predicts whooping crane energy balance as a function of the interaction of freshwater inflows, bay water level and wind (Figure 3.3). More specifically, model dynamics are driven by time-series data that are recorded continuously at three locations near the study area, including freshwater inflow (m^3/day) to San Antonio Bay from the Guadalupe and San Antonio rivers, and water level (m) and wind velocity (km/hr) in San Antonio Bay. Model predictions include changes in water salinity within the marsh, the abundance of wolfberries and blue crabs as well as whooping crane energy balance, within each of three representative whooping crane territories (BR, PC, SB, Figure 2.7).

Figure 3.3. Diagrammatic representation of the model used to simulate potential effects of freshwater inflow to San Antonio Bay from the Guadalupe and San Antonio Rivers on energy budgets of whooping cranes at Aransas National Wildlife Refuge (ANWR). Numbers next to arrows refer to equations in Table 3.1 or sections in the text.



3.2 Model Description

3.2.1 Salinity as a function of freshwater inflow

We represented salinity as:

$$Salinity_t = 4*10^9 * (discharge_t^{-1.0589}) \qquad (1)$$

where $salinity_t$ (ppt) represents salinity within the marsh at time *t* and $discharge_t$ (m^3/day) represents the 28-day cumulative discharge from the Guadalupe River (http://waterdata.usgs.gov/tx/nwis/inventory/?site_no=08176500&) plus the San Antonio River (http://waterdata.usgs.gov/tx/nwis/inventory/?site_no=08188500&) at time *t*. The salinities used to parameterize this relationship were those recorded in San Antonio Bay (GBRA1 gauge, http://lighthouse.tamucc.edu/pq/127/do) during the study (Figure 3.4, Table 3.1). We assumed that, for our purposes, the inflows taken from these gauges were a good indicator of inflow into the estuary. We recognize that inflow into the estuary can be affected by sources below the gauges. Equation 1 does not suggest that a specific inflow causes an exact measure of salinity at GBRA1, only that our indicator (28d cumulative discharge) of inflow is statistically correlated with salinity at GBRA1. Further, we assumed that salinity in San Antonio Bay was a good index of salinity conditions within the marsh. Equation 1 is the result of a statistical analysis that examined the correlation between inflow from the Guadalupe and San Antonio rivers and salinity measured at GBRA1. We explored nine different statistical correlations in order to determine the correlation that best explained the relationship. Statistical correlations included daily, weekly, and monthly inflows for (1) Guadalupe River and GBRA1, (2) San Antonio River and GBRA1 and (3) the cumulative discharge of Guadalupe and San Antonio Rivers correlated with GBRA1. Equation 1 provided the strongest correlation of the combinations tested.

Estuarine salinity patterns are driven primarily by tidal exchanges and river inflows that vary seasonally in response to drivers of estuarine flushing and circulation. Wind direction and speed, direct precipitation, and groundwater exchanges can also contribute to spatial patterns of surface water quality in estuaries and estuarine marshes. However, salinity patterns in estuaries along the Gulf of Mexico coast of the United States (U.S.) are primarily driven by surface water runoff (Solis and Powell 1999). This is especially true for estuaries along the mid-Texas coast that typically have low groundwater exchange and relatively low annual precipitation. Here, freshwater inflows have been directly linked to estuarine productivity and health (Copeland 1966; Ward *et al.* 2002). Therefore, establishing a link between river inflows and salinity is necessary to begin to understand water quality patterns in these estuarine systems.

In the Guadalupe River Estuary, river inflows are especially important due to the small size of the estuary relative to total annual freshwater inflow volume. Additionally, the presence of Matagorda Island decreases hydrological connectivity and limits direct exchange with the Gulf of Mexico. As a result, surface water quality conditions, particularly salinity, in ANWR tidal creeks and coastal marshes are likely to reflect conditions in nearby San Antonio Bay. Certainly wind, direct precipitation, and local runoff accounted for deviations from the ANWR tidal creek/bay salinity relationships we observed in this study (Figure 3.5). In fact, data from our three sites suggest a coupling between cumulative monthly precipitation, mean river discharge, and tidal creek salinity (see Figure 2 in Butzler and Davis 2006). However, the overall set of relationships between 28-day lagged inflows versus bay salinity (Figure 3.4) and bay salinity versus salinity at each tidal creek (Figure 3.5) accounted for much of the variability without inclusion of these other variables. Trends in tidal creek salinity followed salinity patterns observed in the bay, but tidal creek salinity was generally higher than bay salinity (Figure 3.6).

Figure 3.4. Relationship between surface water salinity at GBRA1 (ppt) and 28-day cumulative inflow (m^3/day) from the Guadalupe and San Antonio rivers. The correlation coefficient (r^2) was calculated from the exponential trend line (Eq. 1). Solid blue and dotted red lines represent 95% mean confidence and individual prediction intervals, respectively. Prediction interval estimates were truncated at 0. Data were collected from February 2004 – December 2007. Inflow (discharge) data were not transformed mathematically but rather are actual discharge values in m^3/day (Note: 1 acre foot = 1233.49 m^3).

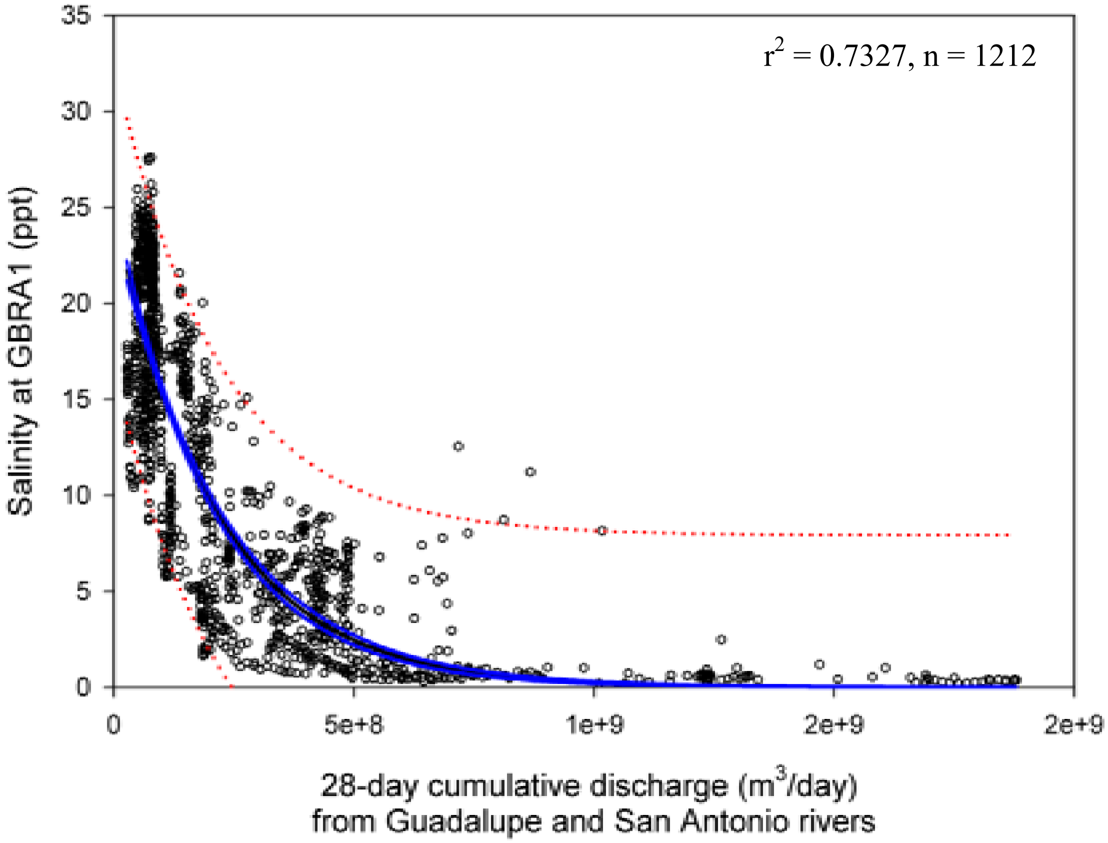


Table 3.1. Summary of model equations, acronyms, units of measure and definitions used in simulation model. Equations 1 – 3 are based on field data recorded during a four-year field study from 2003 – 2006 at Aransas National Wildlife Refuge. Equations 4 – 6 are based on information from the scientific literature. See text for variable definitions and other details, and figures for graphical representations of relationships and associated measures of variability (confidence intervals, r^2, sample size).

Equations (Eq. #)

Salinity as a function of freshwater inflow (Sect. 3.1.1, Figure 3.4)

$Salinity_t = 4*10^9 * (discharge_t^{-1.0589})$ (1)

Peak wolfberry density as a function of salinity (Sect. 3.1.2, Figure 3.7)

$PWB_1 = 22.881e^{-0.1813*MSS}$ (2a)

$PWB_2 = 7.5404e^{-0.1753*MSS}$ (2b)

$PWB_3 = 74.662e^{-0.1645*MSS}$ (2c)

1 = Boat Ramp, 2 = Pump Canal, 3 = Sundown Bay

Blue crab density as a function of habitat type, salinity, water level, and wind velocity (Sect. 3.1.3)

$BC_{1,1,t} = e^{(0.3751 + 0.01661 + 1.2431(ht) + 1.844(wlt) + 0.1010(Salt) - 0.2597(wst))}$ (3a)

$BC_{1,2,t} = e^{(0.3751 + 0.01661 + 0.1745(ht) + 1.844(wlt) + 0.1010(Salt) - 0.2597(wst))}$ (3b)

$BC_{1,3,t} = e^{(0.3751 + 0.01661 + 0.0(ht) + 1.844(wlt) + 0.1010(Salt) - 0.2597(wst))}$ (3c)

$BC_{2,1,t} = e^{(0.3751 + 0.1203 + 1.2431(ht) + 1.844(wlt) + 0.1010(Salt) - 0.2597(wst))}$ (3d)

$BC_{2,2,t} = e^{(0.3751 + 0.1203 + 0.1745(ht) + 1.844(wlt) + 0.1010(Salt) - 0.2597(wst))}$ (3e)

$BC_{2,3,t} = e^{(0.3751 + 0.1203 + 0.0(ht) + 1.844(wlt) + 0.1010(Salt) - 0.2597(wst))}$ (3f)

$BC_{3,1,t} = e^{(0.3751 - 0.1369 + 1.2431(ht) + 1.844(wlt) + 0.1010(Salt) - 0.2597(wst))}$ (3g)

$BC_{3,2,t} = e^{(0.3751 - 0.1369 + 0.1745(ht) + 1.844(wlt) + 0.1010(Salt) - 0.2597(wst))}$ (3h)

$BC_{3,3,t} = e^{(0.3751 - 0.1369 + 0.0(ht) + 1.844(wlt) + 0.1010(Salt) - 0.2597(wst))}$ (3i)

Whooping crane energy balance (Sect. 3.1.5)

$METWB_{i,t} = TWB_{i,t} * wt_{WB} * GE_{WB} * MEC_{WB}$ (4)

$METBC_{i,t} = TBC_{i,t} * wt_{BC} * GE_{BC} * MEC_{BC}$ (5)

$EB_{i,t} = (METWB_{i,t} + METBC_{i,t}) / (DER * NC_{i,t})$ (6)

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t = time step

i = 1 = Boat Ramp, i = 2 = Pump Canal, i = 3 = Sundown Bay

j = 1 = bay, j = 2 = connected pond, j = 3 = intermittently-connected pond

Table 3.1 (Continued).

Abbreviations	Definition	Equation number
PWB	Peak wolfberry density (number of berries per square meter)	1
MSS	Mean summer salinity (calculated as average of daily salinity)	2
BC	Blue crab (number of blue crabs per square meter)	3
e	Base of natural logarithm	3
ht	Habitat type	3
wl	28-day mean water level (meters above sea level at Seadrift)	3
Sal	28-day mean salinity (ppt)	3
ws	28-day mean windspeed (km/hr)	3
$METWB$	Metabolic energy present from wolfberries (kcal)	4
TWB	Total number of wolfberries present in a territory	4
wt_{WB}	Average weight of individual wolfberry (grams)	4
GE_{WB}	Gross energy content of wolfberries (kcal/g)	4
MEC_{WB}	Metabolizable energy coefficient for individual wolfberry	4
$METBC$	Metabolic energy present from blue crabs (kcal)	5
TBC	Total number of blue crabs present in a territory	5
wt_{BC}	Average weight of blue crabs in the 11-30 mm size class (grams)	5
GE_{WB}	Gross energy content of blue crabs (kcal/g)	5
MEC_{WB}	Metabolizable energy coefficient for blue crabs	5
EB	Whooping crane energy balance within each territory (kcal)	6
DER	Daily metabolic energy requirement of adult whooping crane (kcal)	6
NC	Number of adult whooping cranes present on a territory	6

Figure 3.5. Relationship between salinities (ppt) of the tidal creeks sampled in each whooping crane territory ((A) Boat Ramp, (B) Pump Canal and (C) Sundown Bay) and salinities recorded at the GBRA1 gauge in San Antonio Bay. Black lines represent trend lines from linear regression (with associated r^2 and sample sizes (n)). Black dashed and red dotted lines represent 95% confidence and prediction intervals, respectively. Data were collected from 24 February 2004 to 25 February 2005.

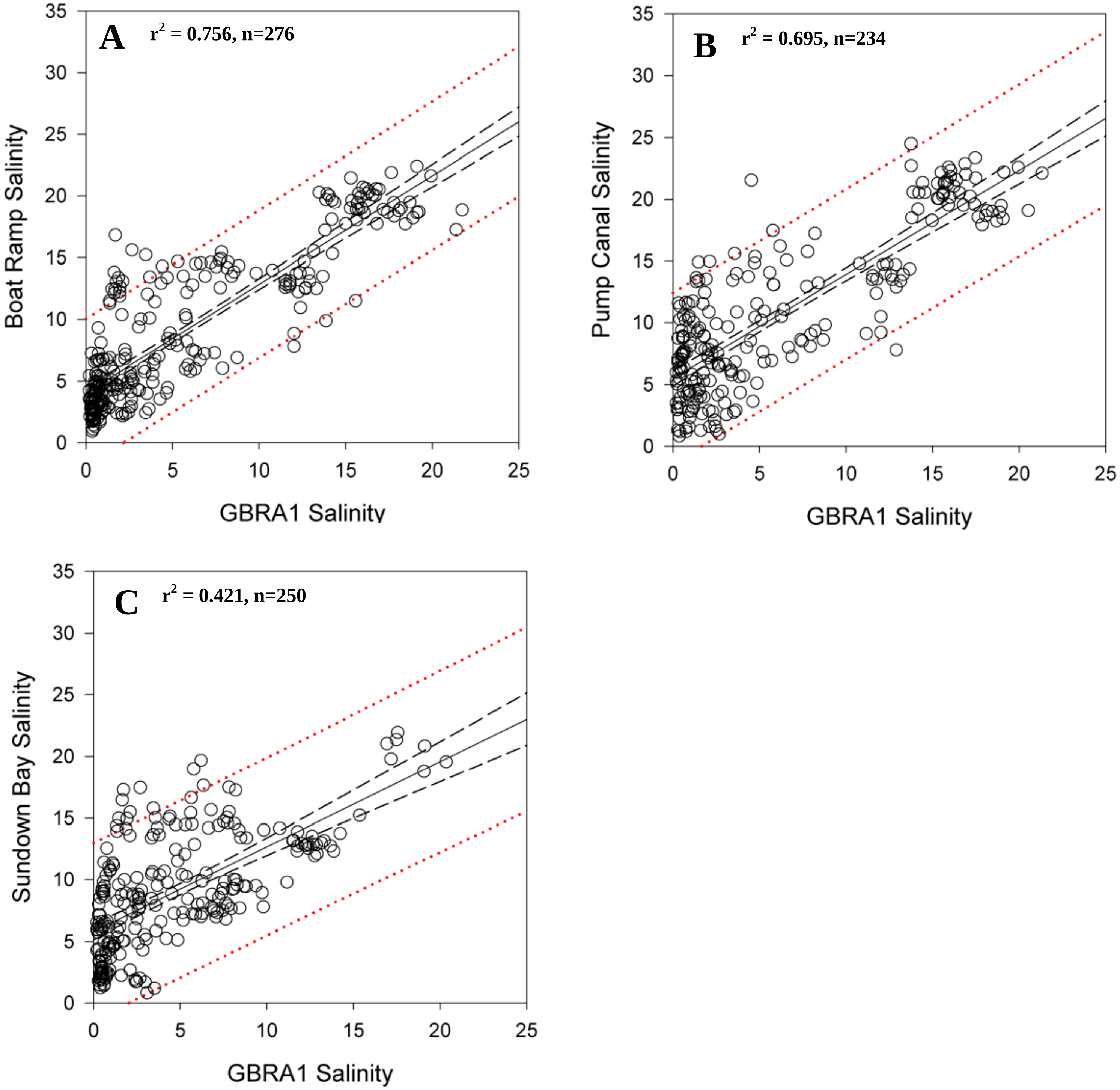
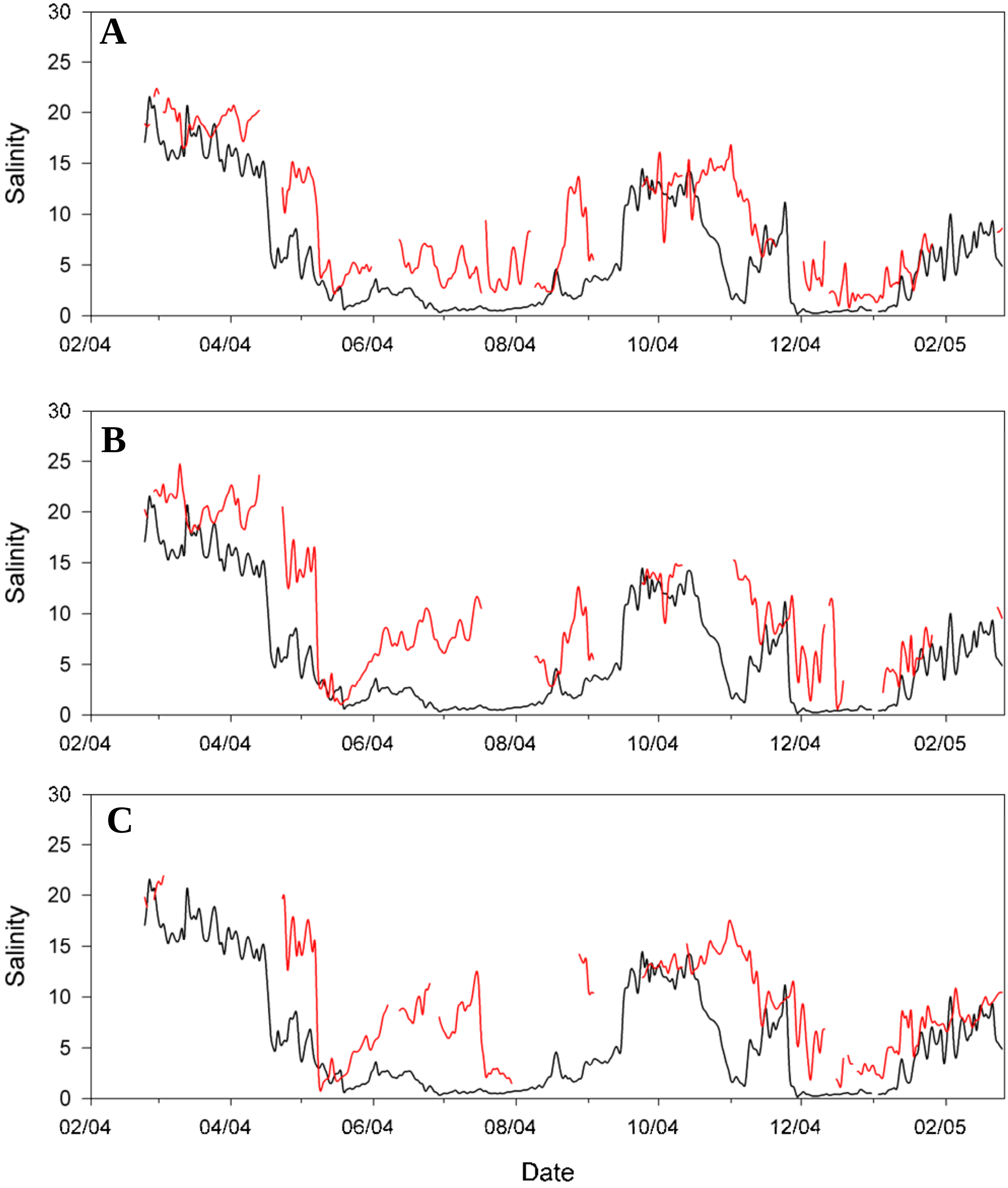


Figure 3.6. Salinities (ppt) recorded at the GBRA1 gauge in San Antonio Bay (black line) and salinities of the tidal creeks sampled in each whooping crane territory (red lines, (A) Boat Ramp, (B) Pump Canal and (C) Sundown Bay). Data were collected from 24 February 2004 to 25 February 2005. Gaps in tidal creek salinities represent periods when gauges were not working.



3.2.2 Peak wolfberry density as a function of salinity

We represented peak wolfberry density as:

$$PWB_i = b1_i e^{b2i*MSS} \qquad (2)$$

where PWB_i represents peak wolfberry density (wolfberries / m^2) within crane territory *i*, *MSS* represents mean summer salinity, calculated as the mean of $salinity_t$ (Eq. 1) from June 1 to August 31, and $b1_i$ and $b2_i$ are parameter estimates (Table 3.1). These relationships are based on correlations between field estimates of berry density (wolfberries / m^2) and *MSS* (Figure 3.7). Note that PWB_i represents ripe berries. We assumed that peak berry density occurred on October 15 and that berry density in each territory subsequently declined exponentially ($WB_{i,t} = PWB_i\ e^{-bi*tt}$) such that berries had disappeared by January 1 (*i.e.*, b_i was calculated such that $WB_{i,t} < 0.1\ m^{-2}$ on January 1; $t = 1, 2, 3$, etc., on October 15, 16, 17, etc.). During our study, peak berry density occurred during October (Figure 3.8). Berry abundance declines rapidly such that virtually no berries are on the landscape by the end of the calendar year. Berries are either eaten by whooping cranes, other animals, or senesce (Godfrey and Wooten 1981).

Extended periods of increased salinity can result in negative effects on estuarine marsh plant community structure and composition (Howard and Mendelssohn 1999, 2000). The ecological linkages between bay salinity and wolfberry growth and fruit abundance at our coastal marsh sites are based on our understanding of the interaction between season, salinity, and marsh processes. Results from our field studies (see Appendix A, empirical study #2) suggest that *MSS* was important in affecting fall wolfberry fruit abundance. This is based on our collective phenological observations of *L. carolinianum* as well as those of Dunton *et al.* (2001). Our work consistently showed that throughout the summer there was a dramatic decrease in wolfberry leaf abundance as temperatures and estuarine salinity rose (both typically peaking in August), which coincides with low sea levels and low marsh inundation across the ecosystem, likely enhancing soil porewater salinity (salinity of water in soil pore spaces) in the marsh. In late summer, leaf abundance begins to increase, coinciding with cooler temperatures and increased freshwater inputs to the estuary.

Carolina wolfberry is a salt-tolerant (halophytic) species that is typically limited to saline soils. These plants are usually poor competitors in less saline or upland environments but persist in saline habitats as a result of a number of adaptations allowing them to cope with salt, such as salt exclusion and excretion. As has been shown for other halophytes, we expected that wolfberries would perform better under low salinity stress—especially during the summer months when evapotranspiration rates are highest. Results of our summertime greenhouse study with wolfberries supported this, as the high salinity treatment (35 ppt or seawater salinity) had a more negative effect on wolfberry growth than the freshwater treatment (see Appendix A, empirical study #6). In this experiment, the increased salinity treatment (35 ppt) resulted in an 80% loss in wolfberry leaf abundance over the course of the eight-week summertime experiment, compared with only a 49% loss of leaves for the freshwater treatment.

Leaf loss is typical for plants during this hot, dry time of year, but our greenhouse study and the field results from Dunton *et al.* (2001) in the Nueces River suggest that freshwater conditions can extend the summer-time growth of these plants and result in more photosynthate for flower and fruit production in the fall. Therefore, we considered summer-time salinity conditions within the marsh to be important in fruit production as conditions during this period affect the period of growth leading up to flower and fruit production. Our synthesis of data from the macrophyte plots suggests that the inter-annual fluctuations in mean summer-time salinity (June-August) at the GBRA1 gauge station correlate well with trends in fall wolfberry fruit production (Figure 3.7). In general, years with lower summer-time salinity led to increased fall fruit production at all three marsh sites. Interestingly, this relationship agrees with anecdotal information from the last two winter seasons at ANWR: In the 2007-2008 winter, high wolfberry density was observed following a rather wet summer in 2007; whereas, noticeably lower wolfberry density in the 2008-2009 winter followed a considerably drier summer in 2008 (T. Stehn, USFWS, personal communication).

We are not implying that surface water salinity is the sole factor accounting for wolfberry fruit production in ANWR marshes. Instead, we suggest that freshwater inflows in addition to regional climatic factors such as precipitation, temperature, wind, etc.that affect bay salinity patterns are related to wolfberry fruit production. The affect on wolfberries is likely due to the influence of these factors on marsh evapotranspiration, physico-chemical conditions in the marsh soil (redox, salinity, etc.) and subsequent plant physiological response. Another important factor affecting soil physico-chemical conditions within the marsh is the frequency and duration of marsh inundation. Frequent and extended inundation of the marsh would result in porewater soil salinity that more closely approximates surface water salinity, while less frequent and shorter duration inundation would lead to salt accumulation in the soils—especially during the hot, dry summer months.

A drawback of our marsh study is that we were unable to effectively sample porewater salinity at all three ANWR marsh sites. This is important to point out because the marsh plants are rooted in the marsh soil, and they not only derive resources (water and nutrients) from the soil, but they also respond to stressors in the soil such as anoxia, toxins such as sulfide, and salt. However, studies have shown that in addition to having a direct impact on marsh plant health (Alexander and Dunton, 2002), the quantity and temporal patterns of freshwater inundation have been shown to have a direct impact on soil porewater salinity. Early work by Hackney and de la Cruz (1978) showed a direct correlation between increasing surface water salinity and adjacent pore water salinity in a Mississippi tidal marsh. Furthermore, they demonstrated that with increasing distance from freshwater inflow, salinity levels increased in both surface and porewaters. Along the Texas coast, as freshwater inflows increased, both surface water and pore water salinity were inversely correlated (Alexander and Dunton 2002). Even our limited ANWR marsh porewater data suggest a clear, positive relationship between porewater salinity and tidal creek salinity (see Figure 2 in Butzler and Davis 2006). As such, the correlation between surface and pore water salinity supports our rationale of using surface water salinity measurements or estimates (from regression output) as a proxy for ANWR marsh salinities.

Given the need to relate bay salinity to tidal creek salinity at each of our three sites, we first sought to establish a relationship between Guadalupe River inflows and salinity at the GBRA1 station. This station is near the middle of the estuary, along the general flow path of freshwater entering San Antonio Bay (*i.e.*, within the estuarine circulation path), and in close proximity to our marsh sites at ANWR. Therefore, the GBRA1 site should provide us with a long-term, freshwater inflow-dependent reference point. Linking river inflows to salinity at this site also provides us with a platform for the development of site-specific relationships between ANWR tidal creek salinity and GBRA1 salinity. This final step is of importance, as it allows us to understand how varying salinity regimes affect the marsh ecosystem components such as wolfberry fruit abundance.

Figure 3.7. Correlations between mean summer salinity (*MSS*, calculated as the average of daily salinities between 1 June and 31 August) at GBRA1 and peak wolfberry density at each of three whooping crane territories. These values are more a function of the number of wolfberry plants in each sample plot rather than a measure of fruit production per plant at each site. Red squares represent Sundown Bay, blue diamonds represent Boat Ramp, and green triangles represent Pump Canal.

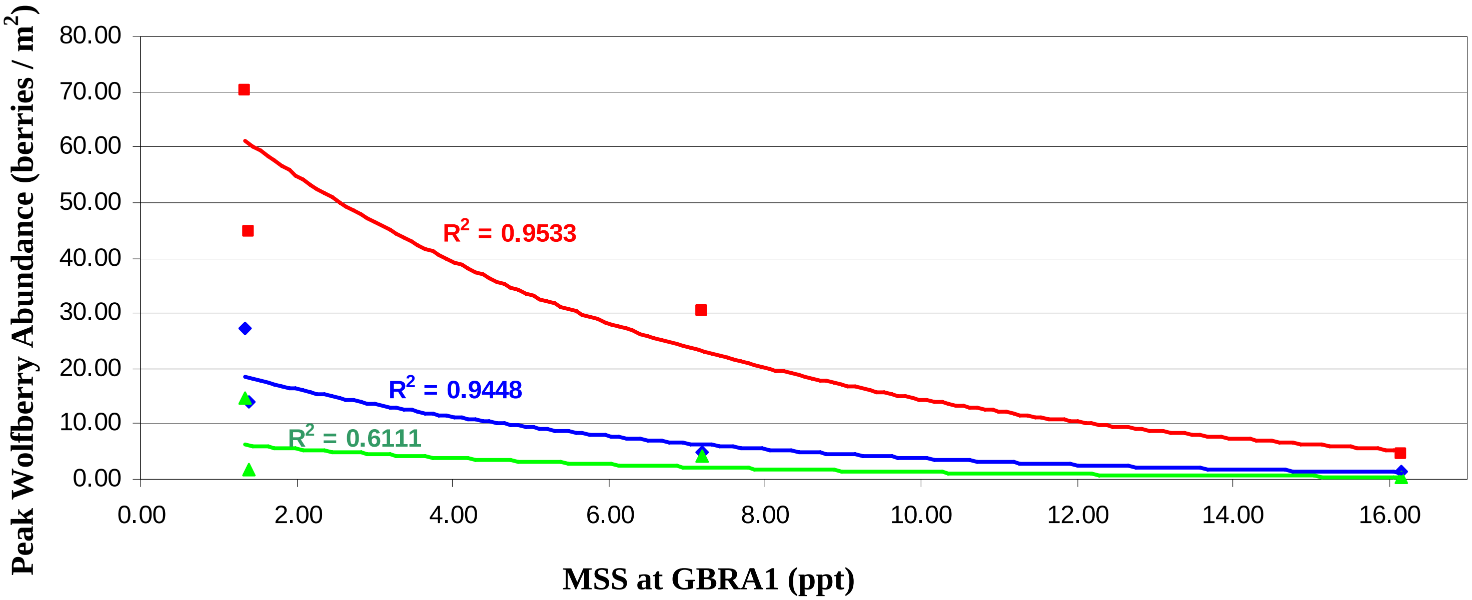
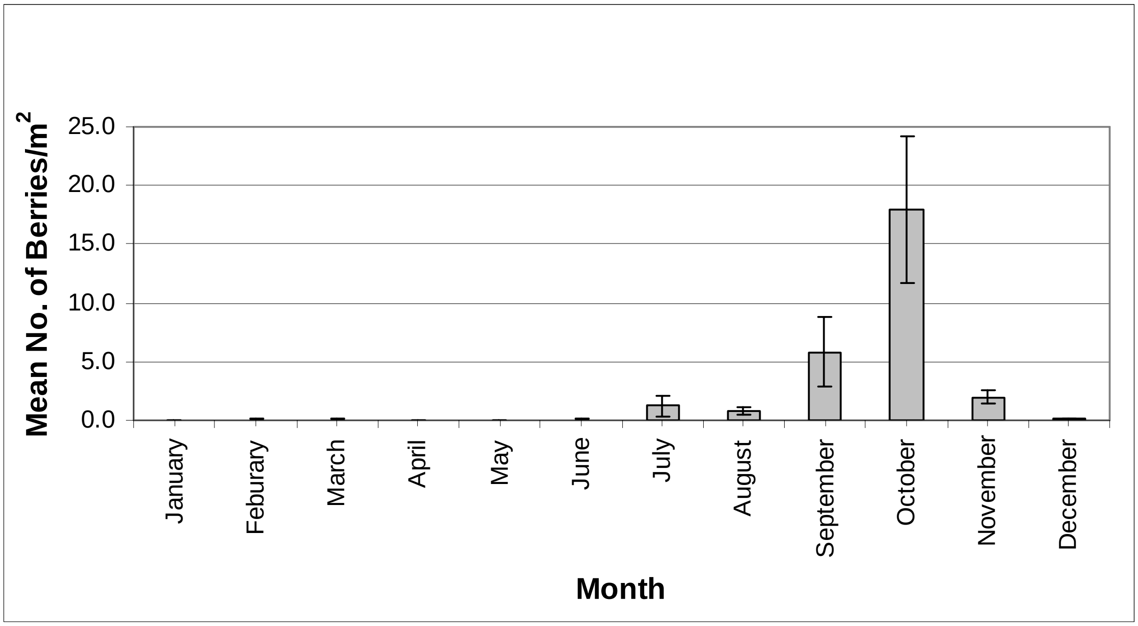


Figure 3.8. Mean number of wolfberries (± std. error) collected in the three whooping crane territories in the indicated month during a four-year field study from 2003 – 2006 at ANWR.



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

We represented daily blue crab density as:

$$BC_{i,j,t} = \mathrm{e}^{(0.3751 + b1\mathrm{i} + b2\mathrm{j} + 1.844(wlt) + 0.1010(Salt) - 0.2597(wst))} \qquad (3)$$

where $BC_{i,j,t}$ represents the density (number of crabs/m^2) 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 ws_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, $r_{\text{ave,}} = 0.792$) 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 (SAGES report, 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 / m^2 (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 (Livingston et al., 1976; Daud, 1979; Laughlin, 1979; Van Engel, 1982; Heck and Cohen, 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. (1971) 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). Pugesek 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., (2001) in that blue crab abundance is best explained by a suite of environmental factors that cannot be simplified into single-factor predictive models.

3.2.4 Wolfberry and crab abundances within crane territories

We calculated the total number of wolfberries and blue crabs within each crane territory at time t ($TWB_{i,t}$ and $TBC_{i,t}$, respectively) based on $PWB_{i\ t}$, $BC_{i,j,t}$, and the area (m^2) of potential wolfberry habitat (Table 3.2A) and crab habitat (Table 3.2B) within each territory. We assumed potential wolfberry habitat was limited to marsh (see Section 3.2.2) and potential crab habitat was limited to bay, connected ponds, and intermittently connected ponds (see Section 3.2.3). We delineated marsh, open water, connected ponds, and intermittently connected ponds based on 2004 aerial color infrared digital ortho-quarter quads (*i.e.*, satellite images) using aerial photography interpretation techniques. These techniques use recognition elements (*e.g.*, shape, size, pattern, shadow, color, texture, association, site) to identify features of interest on the ground (Avery and Berlin 1992).

Table 3.2. Areas in hectares (acres) of potential (A) wolfberry and (B) blue crab habitats (separated into Bay, connected pond (CP), and intermittently connected pond (ICP) habitat types) in the three whooping crane territories at ANWR.

A

Territory	Wolfberry Habitat in hectares (acres)
Boat Ramp	87.88 (217.56)
Pump Canal	71.96 (177.82)
Sundown Bay	17.44 (42.35)

B

Territory	Blue Crab Habitat in hectares (acres)		
	Bay	*CP*	*ICP*
Boat Ramp	0	28.47 (70.35)	2.62 (6.47)
Pump Canal	4.45 (10.99)	3.2 (7.9)	1.33 (3.29)
Sundown Bay	2.01 (4.9)	13.93 (34.42)	1 (2.47)

3.2.5 Whooping crane energy balance

We calculated an index of whooping crane energy balance within each territory (i) at time t ($EB_{i,t}$) based on our estimates of numbers of wolfberries and blue crabs ($TWB_{i,t}$ and $TBC_{i,t}$). We calculated the metabolizable energy (kcal) contained in $TWB_{i,t}$ ($METWB_{i,t}$) and $TBC_{i,t}$ ($METBC_{i,t}$) as:

$$METWB_{i,t} = TWB_{i,t} * wt_{WB} * GE_{WB} * MEC_{WB} \qquad (4)$$

$$METBC_{i,t} = TBC_{i,t} * wt_{BC} * GE_{BC} * MEC_{BC} \qquad (5)$$

where wt_{WB} and wt_{BC} represent the weight of wolfberries (0.44 g each, Chavez-Ramirez 1996) and blue crabs (between 11 and 30 mm carapace width, 0.939 g each, Greer, in progress), and GE_{WB} and GE_{BC} represent the gross energy content of wolfberries (1.214 kcal / g) and blue crabs (0.785 kcal / g), and MEC_{WB} and MEC_{BC} represent the metabolizable energy coefficient of wolfberries (0.438) and blue crabs (0.355), all as reported by Nelson *et al.* (1996). We then calculated $EB_{i,t}$ as:

$$EB_{i,t} = (METWB_{i,t} + METBC_{i,t}) / (DER * NC_{i,t}) \qquad (6)$$

where DER represents the daily energy requirement of a free-living 5 kg whooping crane (465 kcal, Nelson, 1995) and $NC_{i,t}$ represents the number of cranes occupying territory i at time t. Thus, $EB_{i,t} > 1.0$ indicates a positive energy balance and $EB_{i,t} < 1.0$ a negative energy balance for the cranes in territory i at time t.

Our estimate of daily whooping crane energy was 465 kcal per bird per day (Nelson, 1995). This estimate represents the cost of free existence and was calculated from Time Energy Budgets (TEB) of captive whooping cranes at Patuxent Environmental Science Center, Maryland, USA. This estimate provides a reasonable estimate for free living whooping cranes and has been validated by measurements of daily energy expenditure (DEE) for captive whooping cranes (Nelson, 1995).

Whooping crane wintering territories generally have either two adults or two adults plus a young-of-the-year. In order to take into account energy requirements of wild whooping cranes, we estimated that each territory contained 4 adults, thereby creating an energy requirement of 1860 kcal/day per territory (4 birds* 465 kcal/day). If there were only 2 birds on a territory, our daily energy estimate per bird would be 930 kcal/day (i.e., 1860 kcal/day / 2 whooping cranes = 930 kcal/day per bird). If there were 3 birds on each territory, our energy estimate per bird was 620 kcal / day (i.e., 1860 kcal/day / 3 whooping cranes= 620). During our study, the following number of whooping cranes occupied our territories:

2003-2004

Boat Ramp:	2 adults
Pump Canal:	2 adults

Sundown Bay: 3 birds (2 adults and 1 juvenile)

2004-2005
Boat Ramp: 3 birds (2 adults and 1 juvenile)
Pump Canal: 3 birds (2 adults and 1 juvenile)
Sundown Bay: 2 adults

2005-2006
Boat Ramp: 3 birds (2 adults and 1 juvenile)
Pump Canal: 2 adults
Sundown Bay: 3 birds (2 adults and 1 juvenile)

According to field data collected by Chavez-Ramirez (1996), the average daily energy expenditure (DEE) for an 11-month period (October 1992 through April 1993, October and December 1993, January and March 1994) was 604.74 kcal/day[1]. It is important to note that Chavez-Ramirez's (1996) data were recorded during a non-high mortality year (1992-1993) and a high mortality year (1993-1994) (Nelson, 1996; T. Stehn, pers. comm.). The SAGES study had two non-high mortality years (2003-2004, 2004-2005) and one high mortality year (2005-2006).. Note that we are specifically referring to high mortality as over-wintering mortality events when greater than 2.7% of the flock die.

When three birds are on a territory, our estimate is comparable to the daily energy expended as observed in the field (Chavez-Ramirez, 1996) (i.e., 620 kcal/day compared to 604 kcal/day). If two birds are on a territory, our estimate is 326 kcal/day more than the mean daily energy expended by whooping cranes as estimated by Chavez-Ramirez (1996).

3.3 Model evaluation

We evaluated the usefulness of the simulation model as a tool for assessing potential impacts of changes in freshwater inflow on the whooping cranes at ANWR by examining (1) the performance of model equations that were based on statistical correlations among field data and (2) the sensitivity of model predictions to uncertainty in the estimates of parameters not based on statistical analysis of field data. The former included evaluation of equations predicting salinity, density of wolfberries, and density of blue crabs (Table 3.1), and the latter included evaluation of the sensitivity of the whooping crane energy balance to changes in our estimates of the proportions of crane territories composed of wolfberry and blue crab habitat types (Section 3.2.4). Our criterion for assessing overall usefulness of the model was its ability to predict the energy balance of whooping cranes within each territory over a wide range of freshwater inflow rates into San Antonio Bay. Our primary concern was that we neither overestimate abundance of crane food resources (specifically, wolfberries and blue crabs) nor underestimate crane energy requirements at the territory level.

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[1] Chavez-Ramirez reported values in kilojoules (kj). We converted kj into kilocalories (kcal) using the conversion: 1 kcal = 4.1868 kj

3.3.1 Evaluating performance of model equations

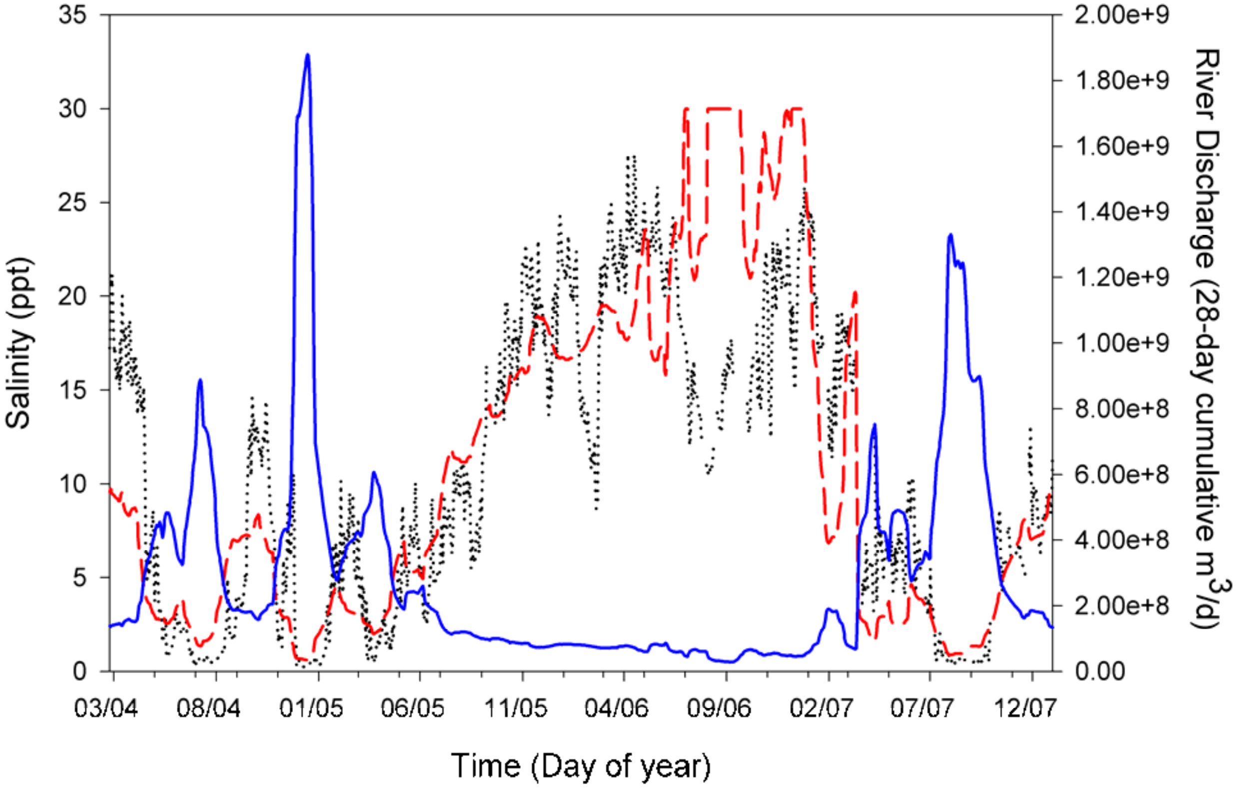
We evaluated performance of the model equations based on statistical correlations among field data (Table 3.1) by assessing the predictions of these equations generated by ranges of values of the independent variables that were broader than those observed during the study.

3.3.1.1 Evaluation of equation predicting salinity

We evaluated our salinity equation (Eq. 1) by assessing the reasonableness of salinity predictions based on the 28-day cumulative discharges from the Guadalupe River plus the San Antonio River from 24 February 2004 to 31 December 2007, which included a wide range of inflow rates. Salinities predicted at high and moderate inflow rates were similar to salinities observed at the GBRA1 gauge (Figure 3.9), but salinities predicted at low inflow rates (28-day cumulative discharges $< 2*10^7$ m^3 /day), were unrealistically high (> 40 ppt). Thus, we put an upper bound on the predictions of Eq. 1 such that predicted salinities did not exceed 30 ppt, which is 1 ppt higher than the maximum salinity observed at GBRA1 from 2003 to 2007.

Regarding comparisons of predicted salinities to data from GBRA1, note that the gauge may not have been operating properly during some periods when observed salinity values dropped precipitously while predicted values continued an upward trend (*e.g.*, periods of time from August 2006 to November 2006, Figure 3.9). Of course, we cannot rule out the possibility that factors not included in Eq. 1 (*e.g.*, wind velocity and direction, tides) may have caused these precipitous declines in salinity.

Figure 3.9. Relationship between freshwater inflow (solid blue line) and both observed salinity (at GBRA1, black dotted line) and predicted salinity (Eq. 1, red dashed line) during a 3-year period from March 2004 to December 2007. The secondary Y-axis refers to 28-day cumulative discharge (m^3/day) from the Guadalupe and San Antonio Rivers.



3.3.1.2 Evaluation of equations predicting peak wolfberry density and blue crab density

We first evaluated our peak wolfberry density (Eq. 2) and daily blue crab density (Eq. 3) equations by assessing the reasonableness of predictions of these equations calculated from time-series data on freshwater inflow to San Antonio Bay from the Guadalupe and the San Antonio Rivers (used to predict salinities via Eq. 1) and water level and wind velocity recorded at the Seadrift gauge in San Antonio Bay from 1997 to 2007. We then evaluated the wolfberry and crab equations by examining predictions based on various modifications to the 1997 – 2007 time series of salinities (as predicted by Eq. 1), water levels, and wind velocities which represented even broader ranges of environmental conditions. For these calculations, we modified one environmental factor at a time by a constant percentage (+100, +50, or -50%) over the entire 11-year period, while the other factors remained unmodified. For example, if observed salinity was 15, a 100% increase would result in a salinity value of 30.

Predicted wolfberry and blue crab densities calculated over the 11-year period from the unmodified time-series data appeared reasonable. Predicted peak wolfberry densities ranged from about 52 berries/m^2 in the SB territory to less than 0.1/m^2 in the PC territory (Tables 3.3A-C). Using the salinity values predicted by Eq. 1, the predicted densities of wolfberries were consistently lower than observed densities in all three territories, ranging from 30 to 60% of observed values, but did capture observed trends in densities among the three territories (Figure 3.10). Predicted blue crab densities ranged from almost 13 crabs/m^2 in the bay habitat of PC to less than 1/m^2 in the connected and intermittently connected pond habitats of all three territories (Tables 3.3A-C). Predicted blue crab abundances at the territory level calculated for the period for which we have field data (2004 – 2006) followed trends observed in the field (Figure 3.11). Blue crab abundances were largest at the PC territory and lowest at the BR territory (Figure 3.11).

Predicted wolfberry and blue crab densities calculated over the 11-year period from the modified time-series data appeared to respond reasonably to these modifications. Predicted peak wolfberry densities ranged from about 62 berries/m^2 in SB, when salinities were reduced by one half, to essentially zero (0.01 berries/m^2) in BR and PC, when salinities were doubled (Tables 3.3A-C). Predicted blue crab densities ranged from slightly over 54 crabs/m^2 in the bay habitat of PC, when water levels were doubled to less than 1.5/m^2 in all three habitats of all three territories, when salinities or water levels were reduced by one half or wind velocities were increased by one half (Tables 3.3A-C). Thus, crab density calculations were most responsive to changes in bay water level and relatively less responsive to changes in salinity and wind velocity.

Figure 3.10. Comparison of simulated peak wolfberry density (peak number of berries/m^2 per year, gray bars) to peak wolfberry density (peak number of berries/m^2 per year, black bars) observed in the field at each whooping crane territory ((A) Boat Ramp, (B) Pump Canal, and (C) Sundown Bay) during a four-year field study from 2003 – 2006.

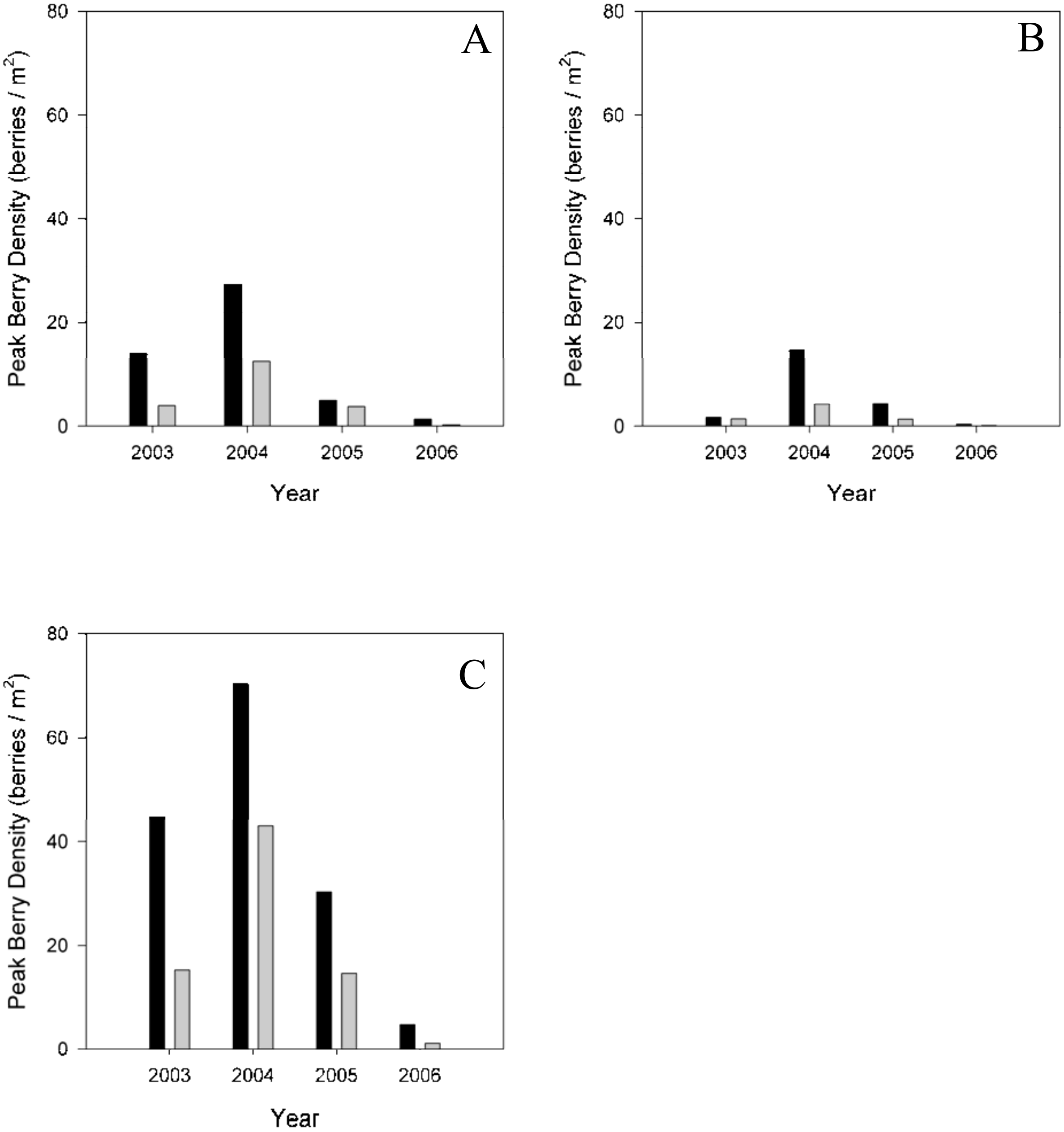


Figure 3.11. Comparison of observed blue crab abundance (total number of crabs/year, black bars) to simulated blue crab density (total number of crabs/year, gray bars) at each of three whooping crane territories ((A) Boat Ramp, (B) Pump Canal, and (C) Sundown Bay) during a three-year field study from 2004 – 2006.

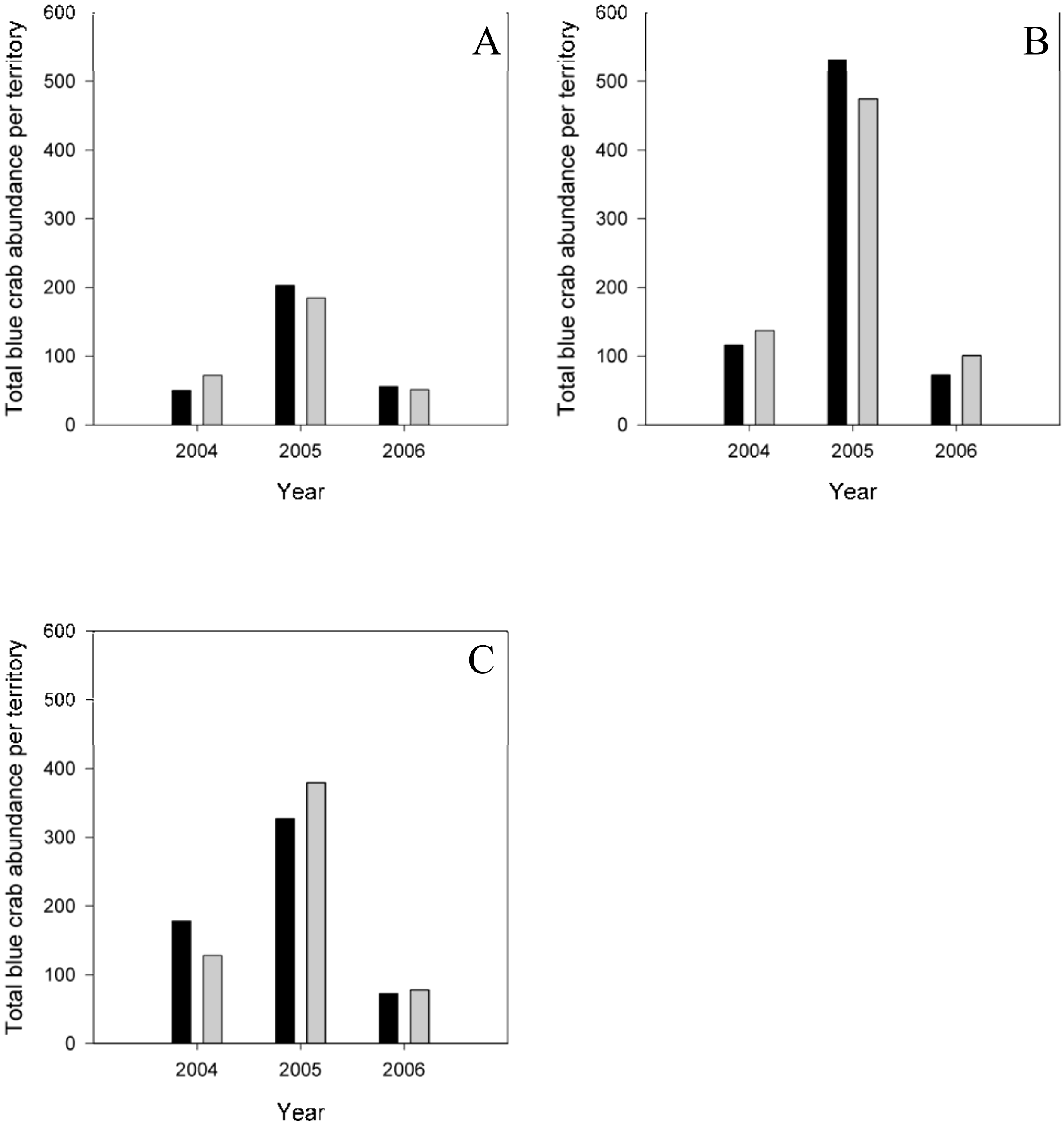


Table 3.3A. Simulated peak wolfberry (berries/m^2) and daily blue crab (crabs/ m^2) densities at **Boat Ramp** resulting from the indicated modifications (relative to baseline values) of the 1997 – 2007 time series of salinities, water levels, and wind velocities. Maximum and minimum values that occurred during each 11-year simulation are separated by commas. Blue crab densities are presented by habitat type (Open Bay = *Bay*; Connected Ponds = *CP*; and Intermittently-connected Ponds = *ICP*).

Environmental Parameter	**Modification**	**Wolfberry Density**	**Crab Habitat Type**	**Crab Density**
Salinity	+ 100%	10.27, 0.01	Bay	12.47, 2.71
			CP	4.28, 0.93
			ICP	3.6, 0.78
	+ 50%	12.55, 0.06	Bay	12.06, 2.62
			CP	4.14, 0.9
			ICP	3.48, 0.76
	Baseline	15.33, 0.23	Bay	11.65, 2.38
			CP	4, 0.82
			ICP	3.36, 0.69
	- 50%	18.73, 0.87	Bay	5.57, 1.41
			CP	1.91, 0.49
			ICP	1.61, 0.41
Water Level	+ 100%	15.33, 0.23	Bay	49.08, 2.54
			CP	16.86, 0.87
			ICP	14.16, 0.73
	+ 50%	15.33, 0.23	Bay	23.92, 2.46
			CP	8.21, 0.84
			ICP	6.90, 0.71
	Baseline	15.33, 0.23	Bay	11.65, 2.38
			CP	4, 0.82
			ICP	3.36, 0.69
	- 50%	15.33, 0.23	Bay	5.68, 1.46
			CP	1.95, 0.50
			ICP	1.64, 0.42
Wind Velocity	+ 100%	15.33, 0.23	Bay	5.6, 0.22
			CP	1.92, 0.08
			ICP	1.61, 0.06
	+ 50%	15.33, 0.23	Bay	5.6, 0.57
			CP	1.92, 0.2
			ICP	1.61, 0.16
	Baseline	15.33, 0.23	Bay	11.65, 2.38
			CP	4, 0.82
			ICP	3.36, 0.69
	- 50%	15.33, 0.23	Bay	16.48, 4.01
			CP	5.66, 1.38
			ICP	4.76, 1.16

Table 3.3B. Simulated peak wolfberry (berries/ m^2) and daily blue crab (crabs/ m^2) densities at **Pump Canal** resulting from the indicated modifications (relative to baseline values) of the 1997 – 2007 time series of salinities, water levels, and wind velocities. Maximum and minimum values that occurred during each 11-year simulation are separated by commas. Blue crab densities are presented by habitat type (Open Bay = *Bay*; Connected Ponds = *CP*; and Intermittently-connected Ponds = *ICP*).

Environmental Parameter	**Modification**	**Wolfberry Density**	**Crab Habitat Type**	**Crab Density**
Salinity	+ 100%	3.48, 0.01	Bay	13.84, 3.01
			CP	4.75, 1.03
			ICP	3.99, 0.87
	+ 50%	4.22, 0.03	Bay	13.37, 2.91
			CP	4.59, 1
			ICP	3.86, 0.84
	Baseline	5.12, 0.09	Bay	12.93, 2.64
			CP	4.44, 0.91
			ICP	3.73, 0.76
	- 50%	6.21, 0.32	Bay	6.18, 1.57
			CP	2.12, 0.54
			ICP	1.78, 0.45
Water Level	+ 100%	5.12, 0.09	Bay	54.45, 2.81
			CP	18.7, 0.97
			ICP	15.71, 0.81
	+ 50%	5.12, 0.09	Bay	26.53, 2.72
			CP	9.11, 0.94
			ICP	7.65, 0.79
	Baseline	5.12, 0.09	Bay	12.93, 2.64
			CP	4.44, 0.91
			ICP	3.73, 0.76
	- 50%	5.12, 0.09	Bay	6.30, 1.62
			CP	2.16, 0.56
			ICP	1.82, 0.47
Wind Velocity	+ 100%	5.12, 0.09	Bay	6.21, 0.25
			CP	2.13, 0.08
			ICP	1.79, 0.07
	+ 50%	5.12, 0.09	Bay	6.21, 0.63
			CP	2.13, 0.22
			ICP	1.79, 0.18
	Baseline	5.12, 0.09	Bay	12.93, 2.64
			CP	4.44, 0.91
			ICP	3.73, 0.76
	- 50%	5.12, 0.09	Bay	18.28, 4.44
			CP	6.28, 1.53
			ICP	5.27, 1.28

Table 3.3C. Simulated peak wolfberry (berries/ m^2) and daily blue crab (crabs/ m^2) densities at **Sundown Bay** resulting from the indicated modifications (relative to baseline values) of the 1997 – 2007 time series of salinities, water levels, and wind velocities. Maximum and minimum values that occurred during each 11-year simulation are separated by commas. Blue crab densities are presented by habitat type (Open Bay = *Bay*; Connected Ponds = *CP*; and Intermittently-connected Ponds = *ICP*).

Environmental Parameter	Modification	Wolfberry Density	Crab Habitat Type	Crab Density
Salinity	+ 100%	36.1, 0.08	Bay	10.7, 2.33
			CP	3.68, 0.8
			ICP	3.09, 0.67
	+ 50%	43.29, 0.35	Bay	10.34, 2.25
			CP	3.55, 0.77
			ICP	2.98, 0.65
	Baseline	51.92, 1.16	Bay	9.99, 2.04
			CP	3.43, 0.7
			ICP	2.88, 0.59
	- 50%	62.26, 3.85	Bay	4.78, 1.21
			CP	1.64, 0.42
			ICP	1.38, 0.35
Water Level	+ 100%	51.92, 1.16	Bay	42.1, 2.18
			CP	14.46, 0.75
			ICP	12.14, 0.63
	+ 50%	51.92, 1.16	Bay	20.51, 2.11
			CP	7.05, 0.72
			ICP	5.92, 0.61
	Baseline	51.92, 1.16	Bay	9.99, 2.04
			CP	3.43, 0.7
			ICP	2.88, 0.59
	- 50%	51.92, 1.16	Bay	4.87, 1.25
			CP	1.67, 0.43
			ICP	1.40, 0.36
Wind Velocity	+ 100%	51.92, 1.16	Bay	4.8, 0.19
			CP	1.65, 0.07
			ICP	1.38, 0.05
	+ 50%	51.92, 1.16	Bay	4.8, 0.49
			CP	1.65, 0.17
			ICP	1.38, 0.14
	Baseline	51.92, 1.16	Bay	9.99, 2.04
			CP	3.43, 0.7
			ICP	2.88, 0.59
	- 50%	51.92, 1.16	Bay	14.14, 3.44
			CP	4.86, 1.18
			ICP	4.08, 0.99

3.3.2 Examining sensitivity of model predictions to uncertainty in non-statistically estimated parameters

The most important parameter estimates that were not based on statistical analysis of field data were the sizes of whooping crane territories and the proportions of the areas within these territories occupied by wolfberry and blue crab habitats. We examined the sensitivity of model predictions to uncertainty in estimates of these parameters by incrementally decreasing the values of each parameter, one at a time, by a factor of 0.1, simulating system dynamics over an 11-year period and noting the effects on simulated energy balances of whooping cranes. For each simulation, model dynamics were driven by time-series data from 1997 to 2007 on freshwater inflow to San Antonio Bay from the Guadalupe and San Antonio Rivers and water level and wind velocity recorded at the Seadrift gauge in San Antonio Bay. We assumed that cranes arrived each year at the wintering grounds on 16 October and left on 7 April, which are the average arrival and departure dates, and that each territory contained 4 adult birds. During this period, we recorded the number of days the total energy available within each territory, in the form of wolfberries plus crabs, was not sufficient to meet the daily energy requirements of the cranes within that territory. Since normally only 2 or 3 birds live on a territory, a breeding pair and perhaps 1 young-of-the-year, these simulations represented an overestimate of whooping crane energy requirements for the territory level.

Results of sensitivity analyses indicated that either territory sizes or the proportion of crab habitat within territories could be reduced by at least 60% before days occurred in which energy available was insufficient to meet crane energy requirements (Figure 3.12). Even a 90% reduction in the proportion of wolfberry habitat failed to produce days in which total metabolic energy present was insufficient. Energy present from wolfberries typically decreases rapidly from its peak in mid-October and is no longer sufficient to satisfy crane energy requirements by mid- to late-December (Figure 3.13). During this time period (15 October – 31 December), decreasing the proportion of wolfberry habitat in both BR and PC increased the number of years that the daily energetic requirements of 4 adult whooping cranes could not be met by wolfberries alone. That is, during some of the years, the energy present from wolfberries "ran out" before 31 December (Figure 3.14) and thus whooping cranes could not subsist solely on wolfberries. In SB, even under baseline conditions, wolfberry abundance was below the threshold required to sustain 4 adult whooping cranes during the period wolfberries were present (Figure 3.14).

Figure 3.12. Effects of proportional decreases in (A) sizes of their territories (relative to current or baseline [BL] size), and (B) proportions of the areas within these territories occupied by blue crab habitat on the energy balance of whooping cranes. Effects are presented in terms of number of days during an 11-year (4,015-day) simulation of historical (1997 to 2007) environmental conditions in which energy available within the indicated territory (Boat Ramp [black bars], Pump Canal [gray bars], Sundown Bay [open bars]) was below the daily energetic requirements of 4 cranes. (Decreases in proportions of the areas within territories occupied by wolfberry habitat did not produce any days with an overall energy deficiency.)

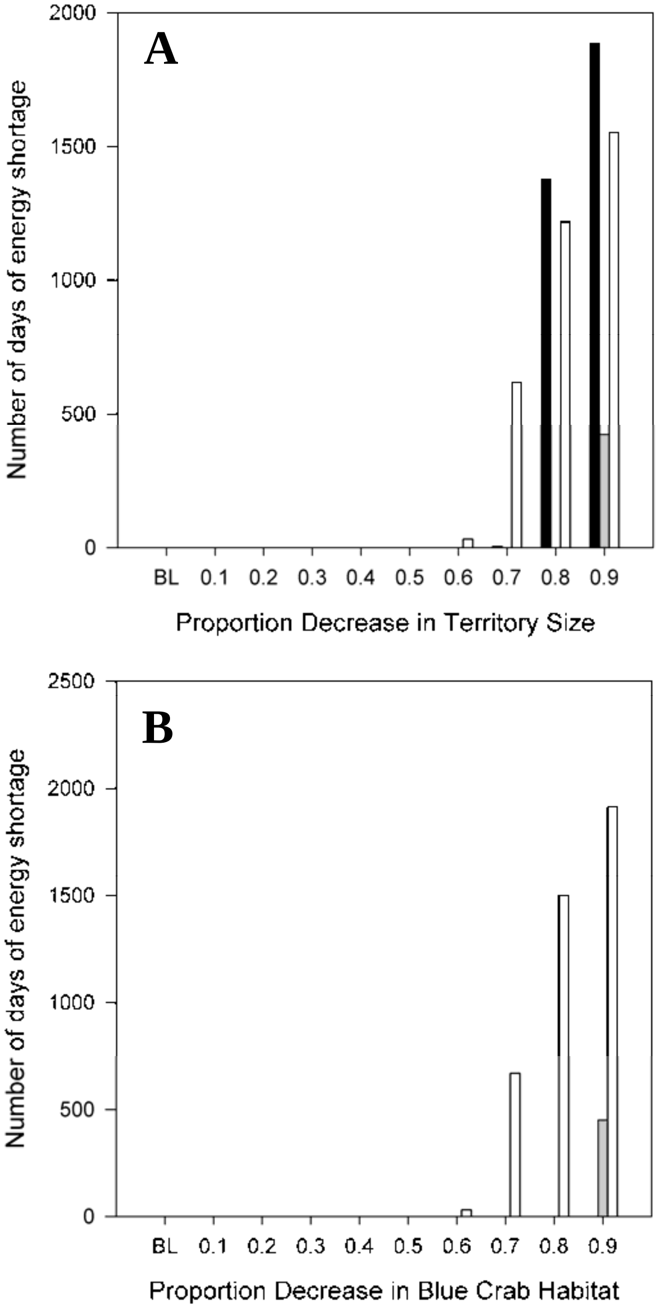


Figure 3.13. Effect of decreases in proportion of area of wolfberry habitat within crane territories on wolfberries as an energy source for whooping cranes. Effects are presented in terms of number of years (bars) during an 11-year simulation of historical (1997 to 2007) environmental conditions in which energy available from wolfberries within the (A) Boat Ramp, (B) Pump Canal, and (C) Sundown Bay territories became insufficient to meet the daily energetic requirements of 4 cranes before the end of the wolfberry season (1 Jan.). *BL* refers to the baseline, or historical, scenario.

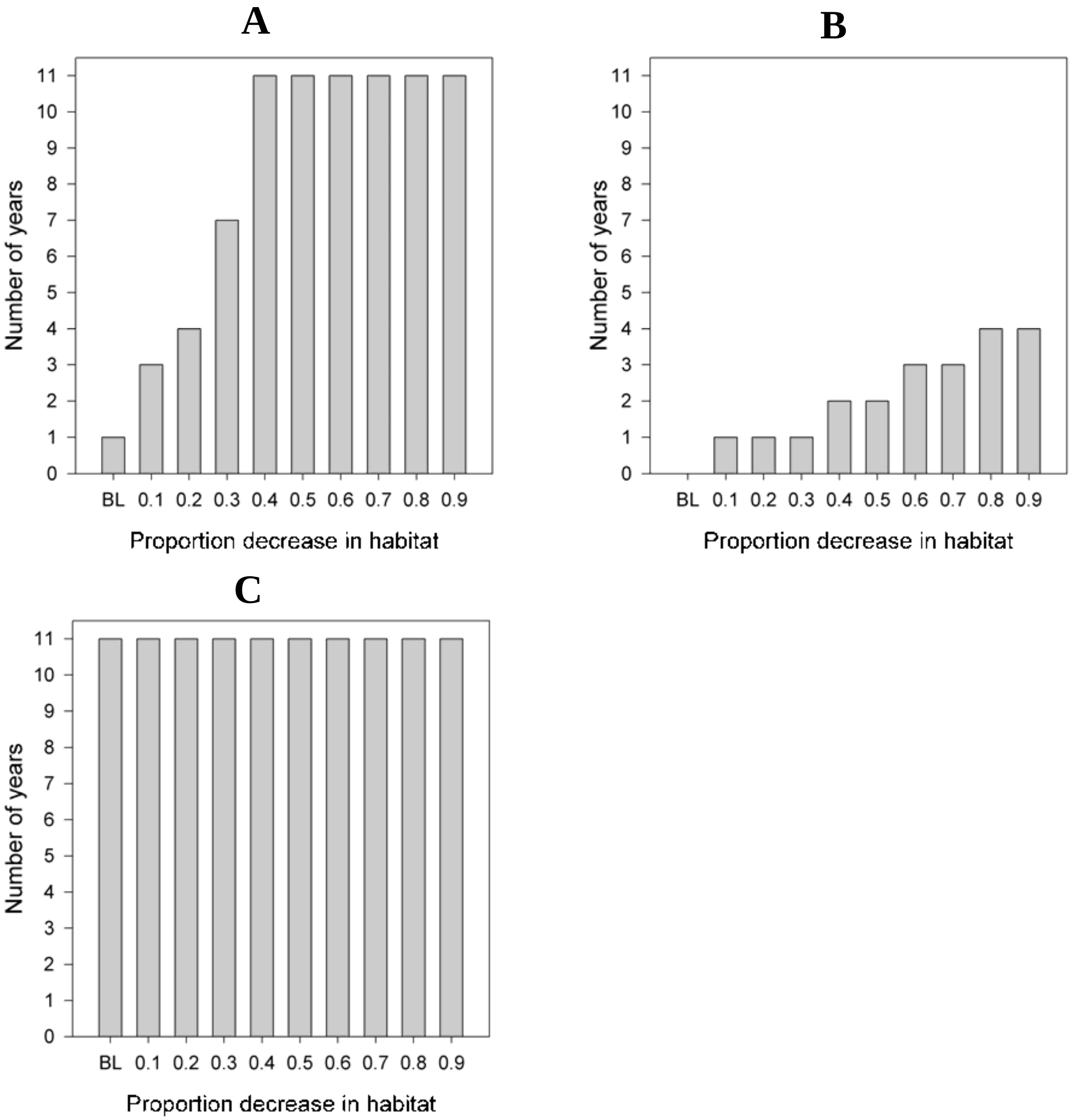
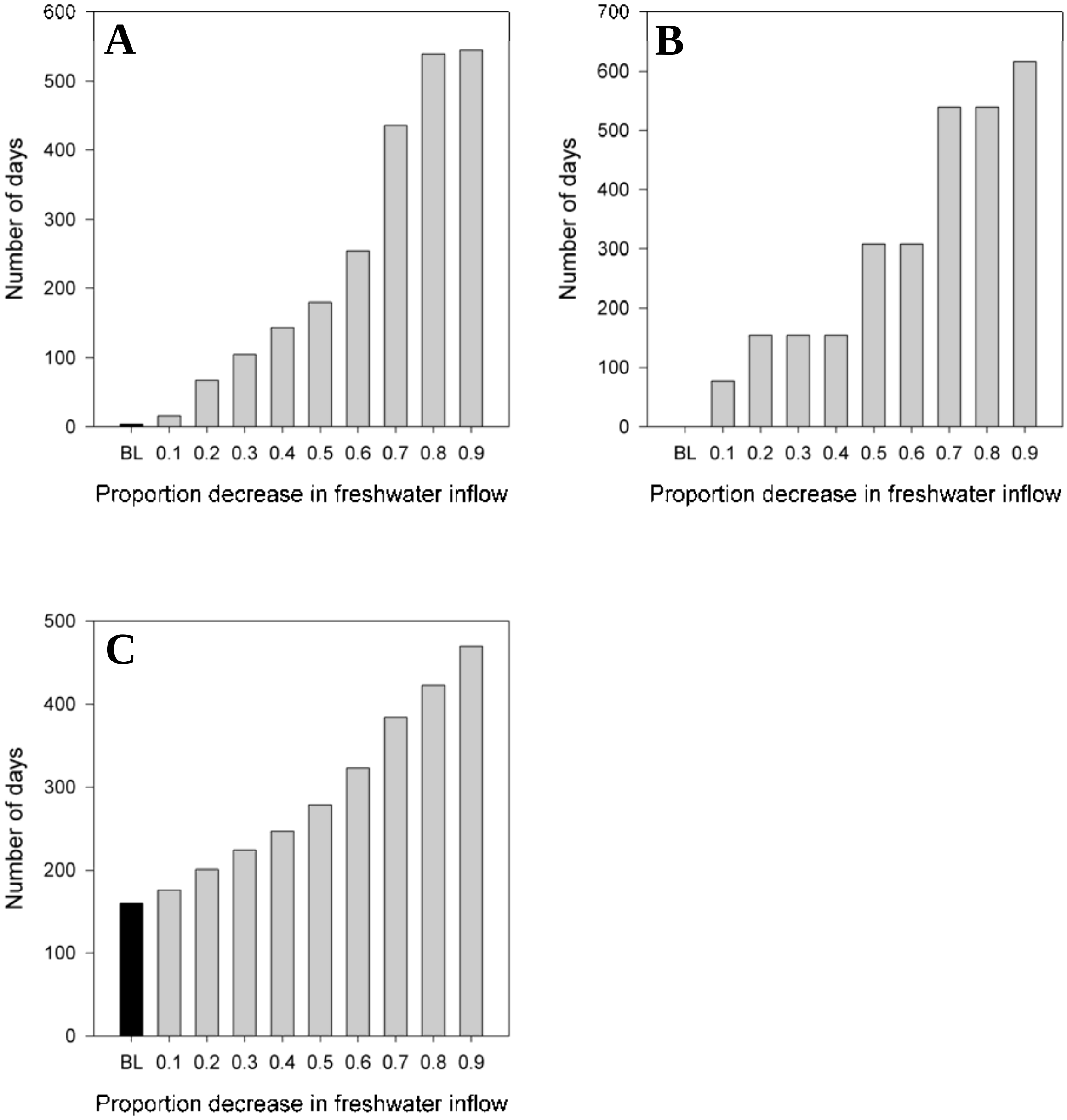


Figure 3.14. Effects on the role of wolfberries as an energy source for whooping cranes considering proportional decreases in freshwater inflow (relative to historical, or baseline [BL] inflow) to San Antonio Bay from the Guadalupe and San Antonio rivers. Effects are presented in terms of number of days during an 11-year simulation of historical (1997 to 2007) environmental conditions in which energy available from wolfberries within the (A) Boat Ramp, (B) Pump Canal, and (C) Sundown Bay territories became insufficient to meet the daily energetic requirements of 4 cranes before the end of the wolfberry season (1 Jan.). Under baseline conditions wolfberries never became insufficient before 1 January in the Pump Canal territory.



3.4. Simulation of freshwater inflow scenarios

Before applying the model to simulate the potential impact of changes in freshwater inflow into San Antonio Bay on the energy balance of whooping cranes wintering at ANWR, we want to clarify the broader context within which simulation results should be interpreted. As we emphasized in Section 3.1, the model should not be viewed as all-inclusive, but, rather, as a potentially useful, predominantly empirically-based, simplification of a complex ecosystem. Specifically, the model represents the potential impact on whooping crane energy balance of changes in freshwater inflow via inflow-induced changes in Bay and marsh (tidal creek) salinity, and resulting changes in densities of wolfberry fruits and blue crabs within the marsh, taking into account the potential effects of temperature, wind, and Bay water level on blue crab densities (Figure 3.2).

We verified that the model simulates the trends in marsh salinity and densities of wolfberry fruits and blue crabs we observed in the field when driven by the data on freshwater inflows, Bay salinity, temperature, wind, and Bay water levels recorded during our study (Figures 3.10 and 3.11). Of course, we want to use the model to simulate system dynamics over a broader range of conditions than we were able to observe in the field, and, indeed, it is a common practice to simulate extreme conditions, including those that are unlikely to occur in the real system, in order to document the full range of simulation model behavior (e.g., Grimm, 1999). However, it is important to understand that, as with any empirical model, our confidence in model predictions decreases as the conditions simulated depart from those observed during our field study.

Thus, the simulations presented below should be interpreted within this broader context. That is, they should NOT be interpreted as inferring the overall role that freshwater inflows play in maintaining the general ecological integrity of bays and estuaries. Further, the simulated dynamics of wolfberry fruits and blue crabs should NOT be interpreted as unequivocal over the entire range of environmental conditions conceivable in the marshes of ANWR.

We simulated the five scenarios using an 11 year historical time series from 1997 through 2007 on daily freshwater inflow to San Antonio Bay from the Guadalupe and San Antonio rivers (Section 3.2.1), salinity recorded at the GBRA1 gauge (Section 3.2.1), and/or water level and wind velocity recorded at the Seadrift gauge (Section 3.2.3). Once again we assumed that cranes arrived each year at the wintering grounds on 16 October and left on 7 April, and that each territory contained four adult birds. The first scenario represented simulating the time series without modification (our baseline scenario). The next three scenarios represented combinations of environmental variables (bay water levels, wind velocities, and salinities) that (1) pushed the system toward maximum abundances of crane food resources by increasing bay water levels by 100% and decreasing both wind velocities and salinities by 50%, (2) pushed the system toward minimum abundances of blue crabs by increasing bay water levels by 50%, increasing wind velocities by 100%, and leaving salinities unchanged from baseline levels, and (3) represented sea-level rise by increasing bay water levels by 100%, leaving wind velocities unchanged from baseline levels, and increasing salinities by 100%. The final simulation explored a 123,348,920 m^3/year (100,000 acre feet/year) reduction in freshwater inflow, applied uniformly throughout the year, with other environmental variables at their baseline levels. For these simulations, we used the historical time-series of freshwater inflows, but adjusted the resulting salinities as predicted by Eq. 1 in the desired manner. For each simulation within each crane territory, we recorded the maximum and minimum peak densities of wolfberries, the maximum and minimum densities of blue crabs, and the number of days that the net energy balance of the cranes was negative.

Results from the baseline simulation are reported in Tables 3.4A-C. Results from the next three scenarios suggested that when environmental conditions coincided to push the system toward maximum abundances of crane food resources, crab densities would be increased to roughly five times the highest level observed in the first set of simulations (Tables 3.5A-C). When environmental conditions coincided to push the system toward minimum abundances of crabs, crab densities would be decreased to roughly one-half the lowest level observed in the first set of simulations. Peak wolfberry densities increased much less when the system was pushed toward maximum abundances of food resources and did not change noticeably when the system was pushed toward minimum crab abundances. When environmental conditions represented increased salinity and water levels (sea-level rise), crab densities increased to somewhat less than 4 times the highest level observed in the first set of simulations, while peak wolfberry densities decreased to somewhat less than one-third the highest level observed in the first set of simulations. These general trends were similar across all territories and habitat types. No days occurred in which net energy balance of the cranes was negative in any of the territories, except in SB when environmental conditions coincided to push the system toward minimum abundances of crabs. Under these conditions, the cranes had a negative energy balance for 913 days (about 47% of the time that cranes were present on the territories). Finally, our results suggested that a 123,348,920 m^3/year (100,000 acre feet/year) reduction in freshwater inflow, applied uniformly throughout the year, assuming other environmental factors repeated their historical (1997 to 2007) trends, had no noticeable effect on peak wolfberry densities, or on maximum or minimum blue crab densities (Table 3.6A). There were no days in which net energy balance of the cranes was negative at any of the territories (Table 3.6B).

3.5 Model summary

In summary, simulation results indicated the metabolic energy present in wolfberries and blue crabs, and in blue crabs alone, always exceeded the estimated daily energy requirement of four adult whooping cranes in each of the three representative whooping crane territories, except in SB under the scenario that pushed the system toward minimum abundances of blue crabs (bay water levels decreased by 50%, wind velocities increased by 100%, and salinities at baseline levels). The metabolic energy present in wolfberries alone exceeded the estimated daily energy requirement of four adult whooping cranes for variable periods of time each year depending on environmental conditions and territory size.

Table 3.4. Simulated peak wolfberry (berries/ m^2) and daily blue crab (crabs/ m^2) densities for **(A) Boat Ramp, (B) Pump Canal, and (C) Sundown Bay** resulting from an 11-year time series f historical (1997–2007) values of daily freshwater inflows to San Antonio Bay from the Guadalupe and San Antonio Rivers. Maximum and minimum values that occurred during each 11-year simulation are separated by commas. Blue crab densities are presented by habitat type (Open Bay = *Bay*; Connected Ponds = *CP*; and Intermittently-connected Ponds = ICP). Number of days during the simulation in which total energy available from wolfberries and blue crabs was insufficient to meet the energetic requirements of four cranes is also presented.

Territory	**Wolfberry Density**	**Crab Habitat Type**	**Crab Density**	**Days of Energy Shortage**
(A) Boat Ramp	15.33, 0.23	Bay	11.65, 2.38	0
		CP	4.00, 0.82	
		ICP	3.36, 0.69	
(B) Pump Canal	5.12, 0.09	Bay	12.93, 2.64	0
		CP	4.44, 0.91	
		ICP	3.73, 0.76	
(C) Sundown Bay	51.92, 1.17	Bay	9.99, 2.04	0
		CP	3.43, 0.70	
		ICP	2.88, 0.59	

Table 3.5A. Simulated peak wolfberry (berries/ m^2) and daily blue crab (crabs/ m^2) densities at **Boat Ramp** resulting from the indicated modifications (relative to historical [baseline] values) of the 1997 – 2007 time series of daily water levels and wind velocities, and modifications to salinities predicted from baseline freshwater inflows by Eq. 1. Maximum and minimum values that occurred during each 11-year simulation are separated by commas. Blue crab densities are presented by habitat type (Open Bay = *Bay*; Connected Ponds = *CP*; and Intermittently-connected Ponds = *ICP*). Scenarios represent combinations of environmental conditions that: (1) push the system toward maximum abundances of crane food resources, (2) push the system toward minimum abundances of blue crabs, and (3) represent sea-level rise. Number of days during the simulation in which total energy available from wolfberries and blue crabs was insufficient to meet the energetic requirements of four cranes is also presented.

	Scenario Description	Parameter	Modification	Wolfberry Density	Crab Habitat Type	Crab Density	Days of Energy Shortage
1	Increase Overall Food Decreased Salinity Increased WL Decreased WV	Salinity	-50%	18.73, 0.87	Bay	73.94, 3.87	0
		Water Level	+100%		CP	25.40, 1.33	
		Wind Vel.	-50%		ICP	21.33, 1.12	
2	Decrease Crab Density Decreased Salinity Decreased WL Increased WV	Salinity	Baseline	15.33, 0.23	Bay	5.6, 0.22	0
		Water Level	-50%		CP	1.92, 0.08	
		Wind Vel.	+100%		ICP	1.61, 0.06	
3	Long-Term Alterations Increased Salinity Increased WL Baseline WV	Salinity	+100%	10.27, 0.01	Bay	52.55, 3.10	0
		Water Level	+100%		CP	18.05, 1.06	
		Wind Vel.	0.0		ICP	15.16, 0.89	

Note that a whooping crane year is 174 days

Table 3.5B. Simulated peak wolfberry (berries/ m^2) and daily blue crab (crabs/ m^2) densities at **Pump Canal** resulting from the indicated modifications (relative to historical [baseline] values) of the 1997 – 2007 time series of daily water levels and wind velocities, and modifications to salinities predicted from baseline freshwater inflows by Eq. 1. Maximum and minimum values that occurred during each 11-year simulation are separated by commas. Blue crab densities are presented by habitat type (Open Bay = *Bay*; Connected Ponds = *CP*; and Intermittently-connected Ponds = *ICP*). Scenarios represent combinations of environmental conditions that: (1) push the system toward maximum abundances of crane food resources, (2) push the system toward minimum abundances of blue crabs, and (3) represent sea-level rise. Number of days during the simulation in which total energy available from wolfberries and blue crabs was insufficient to meet the energetic requirements of four cranes is also presented.

	Scenario Description	**Parameter**	**Modification**	**Wolfberry Density**	**Crab Habitat Type**	**Crab Density**	**Days of Energy Shortage**
1	Increase Overall Food Decreased Salinity Increased WL Decreased WV	Salinity	-50%	6.21, 0.32	Bay	82.02, 4.29	0
		Water Level	+100%		CP	28.17, 1.47	
		Wind Vel.	-50%		ICP	23.66, 1.24	
2	Decrease Crab Density Decreased Salinity Decreased WL Increased WV	Salinity	Baseline	5.12, 0.09	Bay	6.21, 0.25	0
		Water Level	-50%		CP	2.13, 0.08	
		Wind Vel.	+100%		ICP	1.79, 0.07	
3	Long-Term Alterations Increased Salinity Increased WL Baseline WV	Salinity	+100%	3.48, 0.01	Bay	58.29, 3.44	0
		Water Level	+100%		CP	20.02, 1.18	
		Wind Vel.	0.0		ICP	16.82, 0.99	

Note that a whooping crane year is 174 days

Table 3.5C. Simulated peak wolfberry (berries/ m^2) and daily blue crab (crabs/ m^2) densities at **Sundown Bay** resulting from the indicated modifications (relative to historical [baseline] values) of the 1997 – 2007 time series of daily water levels and wind velocities, and modifications to salinities predicted from baseline freshwater inflows by Eq. 1. Maximum and minimum values that occurred during each 11-year simulation are separated by commas. Blue crab densities are presented by habitat type (Open Bay = *Bay*; Connected Ponds = *CP*; and Intermittently-connected Ponds = *ICP*). Scenarios represent combinations of environmental conditions that: (1) push the system toward maximum abundances of crane food resources, (2) push the system toward minimum abundances of blue crabs, and (3) represent sea-level rise. Number of days during the simulation in which total energy available from wolfberries and blue crabs was insufficient to meet the energetic requirements of four cranes is also presented.

	Scenario Description	**Parameter**	**Modification**	**Wolfberry Density**	**Crab Habitat Type**	**Crab Density**	**Days of Energy Shortage**
1	Increase Overall Food Decreased Salinity Increased WL Decreased WV	Salinity	-50%	62.26, 3.85	Bay	63.42, 3.32	0
		Water Level	+100%		CP	21.78, 1.14	
		Wind Vel.	-50%		ICP	18.30, 0.96	
2	Decrease Crab Density Decreased Salinity Decreased WL Increased WV	Salinity	Baseline	51.92, 1.17	Bay	4.8, 0.19	913*
		Water Level	-50%		CP	1.65, 0.07	
		Wind Vel.	+100%		ICP	1.38, 0.05	
3	Long-Term Alterations Increased Salinity Increased WL Baseline WV	Salinity	+100%	36.1, 0.08	Bay	45.07, 2.66	0
		Water Level	+100%		CP	15.48, 0.91	
		Wind Vel.	0.0		ICP	13.00, 0.77	

Note that a whooping crane year is 174 days.

*represents days of energy shortage during entire 11 year simulation (11 years = 1914 days of whooping crane presence). That is, 47.7% (913 / 1914) of the 11 year simulation resulted in an energy shortage

Table 3.6. (A) Simulated peak wolfberry (berries/ m^2) and daily blue crab (crabs/ m^2) densities in the indicated whooping crane territory resulting from a reduction of 123,348,920 m^3/year (100,000 acre feet / year, applied uniformly throughout the year) relative to historical (baseline) values of the 1997 – 2007 time series of daily freshwater inflows. Maximum and minimum values that occurred during each 11-year simulation are separated by commas. Blue crab densities are presented by habitat type (Open Bay = *Bay*; Connected Ponds = *CP*; and Intermittently-connected Ponds = *ICP*).

(B) Number of days during the simulation that the daily energetic requirements of 4 adult whooping cranes in the indicated territory were not met by wolfberries (*WB*) alone (during the wolfberry season), by blue crabs (*BC*) alone, and by wolfberries and blue crabs combined (*Total*). The simulated wolfberry season begins on 15 October and ends on 31 December, a total of 847 days during the 4015-day simulation, thus days of wolfberry energy shortage were registered only during these 847 days.

A

Territory	**Freshwater Inflow Reduction**	**Wolfberry Density**	**Crab Habitat Type**	**Crab Density**
Boat Ramp	337,942 m^3 / day (273.97 acre-feet/day)	15.33, 0.23	Bay	11.65, 2.38
			CP	4.00, 0.82
			ICP	3.36, 0.69
Pump Canal	337,942 m^3 / day (273.97 acre-feet/day)	5.12, 0.09	Bay	12.93, 2.64
			CP	4.44, 0.91
			ICP	3.73, 0.76
Sundown Bay	337,942 m^3 / day (273.97 acre-feet/day)	51.9, 1.15	Bay	9.99, 2.04
			Con	3.43, 0.70
			ICP	2.88, 0.59

B

	Days of Energy Shortage		
Territory	**WB**	**BC**	**Total**
Boat Ramp	4 (0.4%)	0	0
Pump Canal	0	0	0
Sundown Bay	160 (18.8%)	0	0

4. Conclusions

4. Conclusions of the Study

From 2002 through 2009, faculty and students from the Department of Wildlife and Fisheries Sciences at Texas A&M University conducted field, laboratory and modeling studies to investigate the diet, behavior, and habitat of the whooping crane at ANWR, Texas. The overall goal of the SAGES project was to use empirically-generated and existing available data to evaluate the relationship between freshwater inflows feeding San Antonio Bay and the health of the population of endangered whooping cranes at ANWR. Field research included several studies of wetland processes, plant ecology, abundance and distribution of blue crabs, and behavioral ecology of whooping cranes in the salt marshes of ANWR. Empirical findings were integrated into a simulation model with the capabilities of predicting crane responses to changes in food supply, temperature, salinity, and water levels in and around the ANWR salt marshes. The study design was guided by inputs from the project sponsors, State of Texas agency personnel with freshwater inflow and estuarine ecology experience, and a team of internationally-known scientists whose expertise included most aspects of crane and estuarine ecology.

As essentially nothing was known about the effects of freshwater inflows on crane ecology, the SAGES team chose to focus on two primary areas of study. The first area of study was the ecology of key crane foods, namely blue crabs and wolfberries. The primary study objective was to determine how environmental factors influenced the abundance and distribution of these foods. The second major area of study was on the behavioral ecology of cranes. The main objectives here were to document food habits and time-activity budgets of cranes, while investigating the effects of environmental conditions, food abundance, and human disturbance on the crane's energy balance.

The team's studies show a clear effect of river inflows on water quality patterns across the greater bay ecosystem. During periods of low inflow, the impacts of factors such as wind and tides became more noticeable. Freshwater inflows into the bay tended to flow in a southwest direction along Blackjack Peninsula and along the estuarine marshes at ANWR. Not surprisingly, patterns of salinity in San Antonio Bay were strongly correlated with those in tidal creeks of Blackjack Peninsula.

Given the higher elevation of the marsh relative to mean sea level, the ANWR salt marshes are infrequently inundated, typically as a result of spring high tides, storm surges, and high-water periods. The team found that high year-to-year variability in marsh inundation governs the frequency and duration of surface water connections between tidal waters and marsh ponds. Through these surface water connections, aquatic organisms are able to migrate between bays and ponds. With extended periods of disconnection, marsh ponds can completely dry out, leading to death of resident aquatic organisms, or the resident aquatic organisms can be sufficiently depleted by wading birds (*e.g.*, whooping cranes) and other consumers. Either way, prey organisms in these ponds are replenished through subsequent inundation and connection events.

The ANWR marsh vegetation community is comprised of a mixed, high-marsh plant community. Carolina wolfberry plants had a frequency of occurrence at the three sites of about 30% and were most productive, in terms of leaf growth, in early spring and late summer, prior to flowering and fruiting in fall. Peak wolfberry fruit abundance coincided with crane arrival each year. Based on the team's observations and those from other studies in the region, salinity immediately prior to and leading up to the late summer leafing period may be an important factor in fruit production. Berry density at the ANWR marsh sites was negatively correlated with bay water salinity, thus the higher the salinity, the lower the number of berries.

This SAGES study project one of a few studies to have sampled nekton (*e.g.*, blue crabs) within habitats of interior salt marshes and, is believed to be the first study to examine patterns of crab abundance in a mature salt marsh where emergent vegetation is dominated by high-marsh halophytes. We found that larval crabs were significantly influenced by the following abiotic factors: water temperature, precipitation, water level, wind speed, and wind direction. Juvenile and adult crabs had a complex, non-linear relationship with spatial location, habitat type, salinity, wind speed and water level. Simpler models failed to explain the variation in crab numbers. Although we were not able to define significant relationships between settlement or recruitment rates and juvenile or adult abundance, we did find that shallow bay habitats were important nursery habitats for young blue crabs and interior marsh ponds were important habitats for dispersing juvenile and adult crabs. Small crabs were more typically found in submerged vegetation and algae-dominated bay waters. Larger crabs were found proportionally more often in pond-edge habitats, while the largest crabs were found in open-water pond habitats of the interior marsh. These connected, interior marsh ponds were significant contributors to total numbers and standing stock of crabs.

Whooping cranes spent 65% of daylight hours foraging. While in the salt marsh their diet consisted of wolfberry fruit, blue crabs, clams, snails, insects, fiddler crabs, snakes, and fish. Wolfberry fruit and snails/insects were consumed in the highest quantities, required the least effort during foraging, and were generally associated with the most efficient foraging behavior. Blue crabs were the most optimal food in relation to protein, and clams were a significant source of biomass. Whooping cranes foraged most efficiently during the winter of 2005-2006, which was when water levels were lowest.

A diversity of human activities occurred in the vicinity of crane territories. Common human disturbances in the vicinity of crane territories included barges, shrimp boats, air boats, tour boats, airplanes, and helicopters, with motor boating representing more than 50% of all human disturbances. The effects of human activities in the vicinity of ANWR did not appear to detrimentally affect crane energetics.

The team developed a quantitative simulation model as a tool to aid in assessing the potential impact of changes in freshwater inflow into San Antonio Bay on whooping cranes. The final form of the quantitative model evolved from the team's initial conceptualization of the San Antonio Bay-ANWR salt marsh ecosystem, which viewed the ecosystem as being influenced by regional environmental factors (temperature, precipitation, wind, bay salinity, and bay water levels) that affect hydrology and landscape features within the marsh. These factors, in turn, affect the abundance of the two most important food resources (wolfberry fruits and blue crabs) within whooping crane territories and, as a result, impact the energy budget of the cranes.

The simulation model suggests relationships that are of potential importance to the assessment of crane ecology and that may be relevant to the evaluation of future freshwater diversions. The food supply for cranes appears to be more than adequate to meet their energy needs during the time period simulated. None of the study results indicated that habitat conditions at Blackjack Peninsula are marginal for crane survival and well-being. Simulation results for the 11-year period of 1997-2007 found that the metabolic energy present in wolfberry fruit and blue crabs together, and in blue crabs alone, always exceeded the estimated daily energy requirements of four whooping cranes in each of the three crane territories, except under extreme marsh environment circumstances.

The relationship between salinity and crane energetics is still uncertain. The team does not know the extent to which marsh salinity is dependent on bay salinity, nor does the team understand the interactive effect of bay salinity and marsh inundation pattern on marsh soil salinity. Consistent with prior studies, bay salinity is demonstrably higher when freshwater inflows are low, wolfberry abundance is lower when bay salinity is high, and that blue crab abundance was best explained by a suite of environmental factors that could not be simplified into single-factor predictive models.

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Appendix

Appendix A: Empirical Studies

Core SAGES Studies

1. Characterization of sediment movement in tidal creeks adjacent to the Gulf Intracoastal Waterway at Aransas National Wildlife Refuge, Austwell, TX: Study of natural factors and effects of barge drawdown currents

Graduate student project: J. B. Allison – Stephen Davis (Project supervisor)

Project Overview
This was a study conducted in the summer of 2004 and led by J. B.Allison, a M.S. student in the Department of Geology and Geophysics at Texas A&M University. The primary objective of this research was to quantify sediment and flow dynamics in ANWR tidal creeks in response to natural variations in tidal, inflow, and wind conditions. Allison gave special attention to the importance of vessel traffic and the nature of this traffic (frequency of barge passages, barge type and size, etc.) on these dynamics. This work was carried out at each of the three territory sites described earlier (Figure 2.7). A secondary objective of this research was to relate observed patterns in suspended sediment and floc transport and forcing functions to tidal creek and coastal marsh sustainability at ANWR.

Barge passages create tidal-like oscillations over short time intervals (i.e., a matter of minutes), with velocities and water-level changes that are comparable if not exceeding natural velocities and water-level changes (see Figure A1). Depending on the frequency of barge passages in a single day, this activity may result in an unnatural import or export of sediment into or out of the system. The effects of barges and other boats on sediment movement and erosion have been studied within main canals such as the GIWW or navigable rivers like the Mississippi (Maynord and Siemsen, 1991; Stockstill and Berger, 2001), but not within the tributaries or associated tidal creeks of those canals or rivers. Drawdown currents and their ecological effects are mentioned by Stockstill and Berger (2001), but their work was mainly focused within the main channels of dug canals like the GIWW and major rivers like the Mississippi. They established that barges create currents and drawdown of the water level that affect the surrounding waters outside the channels. Stockstill and Berger (2001) have modeled these effects at locations along the Mississippi River, the Illinois Waterway, and coincidentally, in Sundown Bay at ANWR.

Through their model Stockstill and Berger (2001) found that barge-induced currents within Sundown Bay are strongly toward the GIWW. As a whole, the drawdown lags behind the vessel. This is supported by field observations during which drawdown currents become easily visible within a given tidal creek after the barge passed the creek mouth. Throughout Sundown Bay, drawdown varies between 5 and 10 cm, and current velocities between 20 and 40 cm per second. The barges in Stockstill and Berger's model (2001) are also assumed to be fully loaded barge trains because they induce the maximum currents and water level changes within a bay. The model does not recognize or simulate the secondary currents once the barge has passed.

Bedload transport may also be driven by these small-scale barge-induced changes in creek current direction and velocity. In ANWR creeks, often a thick (5-10 cm) layer of unconsolidated floc-like material along the bottom of the channels mobilizes over longer time intervals (hours to days). This material is both organic and inorganic in character and is mainly composed of detritus from algae and submerged aquatic vegetation in addition to re-suspended sediment (personal observation). Little is known about the specific sources and fate of this material in ANWR tidal systems.

Over six, non-consecutive weeks water-level and velocity were automatically monitored in the tidal creeks. Automated water samplers extracted water samples that were analyzed for suspended sediment. In addition, bedload traps were deployed in one creek to monitor sediment movement along the channel bottom. Inflow exceeded outflow during much of the study. However, we found that flow data were often unreliable and likely spurious, as a result of prevailing southeasterly winds that created standing waves especially in Sundown Bay and Pump Canal sites. Sampling of bedload material showed that this material moved with current direction. It also appeared to move in response to barge-induced outflow currents. Analysis by Davis *et al.* (*in press*) showed a significant difference in bedload transport over a sequence of barge passages at the Pump Canal site. Barges passing on the GIWW exert influence on water level, flow direction, and velocity within tidal creeks. Natural factors such as winds, tides, and freshwater input from upland runoff or river discharge also impact suspended and bedload sediments, as Allison found total suspended solids concentrations increased with diurnal wind patterns and increasing salinity.

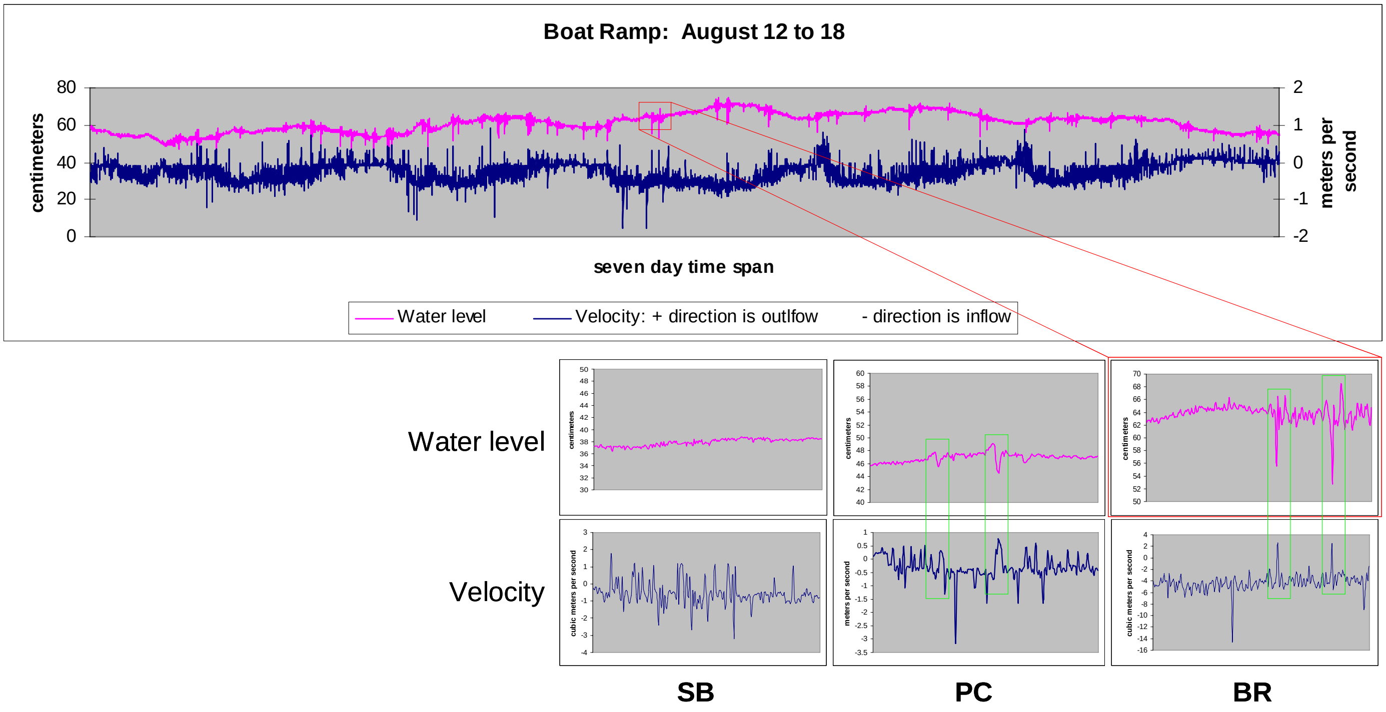


Figure A1: Water level (pink) and current velocity (blue) data collected at one-minute intervals during a one-week time span at the Boat Ramp site. The gentle fluctuation in water level over each 24-hour period is due to the daily tide. Each pulse in the record is likely associated with a passing vessel. The effect of a pair of barge draw-down currents is highlighted and tracked across all three tidal creek stations (below). The influence is greatest at the Boat Ramp site and lowest at the Sundown Bay site—likely as a result of proximity to the GIWW and the presence of a barrier island.

2. Spatial and temporal patterns of *Lycium carolinianum* Walt. (the Carolina Wolfberry) in the salt marshes of Aransas National Wildlife Refuge

Graduate student project: Rachel Butzler – Stephen Davis (thesis advisor)

Project Overview

This was led by R. Butzler, a M.S. student in the Department of Wildlife & Fisheries Sciences at Texas A&M University. This study ended in early 2005, but data collection continued at her sites through the winter of 2006-2007. Her research centered on marsh plant research and included monitoring of the Carolina wolfberry in each of the three ANWR salt-marsh sites. Previous research indicated that the wolfberry was an important macrophyte to this marsh ecosystem, as it contributes 21-52% of the whooping crane's energy intake in the early wintering period. This research focused particularly on spatial and temporal monitoring of the wolfberry as well as the effects of salinity and inundation on the plants.

Field research efforts were divided into two segments devised to address two specific objectives: to determine the distribution patterns of the marsh vegetation community (including *L. carolinianum)* across the marshes of the ANWR and to determine wolfberry phenology and fruit production patterns throughout the year and along the ANWR marsh salinity gradient. The first segment of the project, conducted during the summers of 2003 and 2004, assessed the spatial variability in the marsh plant community. This segment of the project was conceived to determine 1) which species were most often associated with *L. carolinianum,* 2) whether *L. carolinianum* abundance varied between sites along an estuarine gradient, and 3) which environmental parameters had the most significant impact on *L. carolinianum* distribution patterns. The objectives of the second segment of the project were to 1) develop a non-destructive method to estimate and track changes in aboveground biomass of *L. carolinianum*, 2) to determine growth patterns (including berry production) of *L. carolinianum* using permanent vegetation quadrats, and 3) to relate growth patterns to environmental factors such as salinity and water levels.

Vegetation was sampled along duplicate transects at each of the three territories in both summers (Figure 2.7). Each transect started at the interface of the bay and ended at the upland transition zone, usually indicated by the presence of *Spartina spartinae*. The length of each transect depended on where *S. spartinae* was found. Duplicate 0.25 m^2 quadrats were randomly tossed approximately every 50 m and live aboveground biomass was harvested. Plants were separated, counted, and dried at 60º C for 48 hours and weighed for biomass. In total, 116 quadrats were sampled and harvested in 2003 and 126 in 2004.

To determine the growth patterns of *L. carolinianum*, nine permanent vegetation plots (three per site) were established to track temporal dynamics (i.e., growth patterns) of *L. carolinianum*. Plots were $1m^2$ quadrats made of 1/2" ID PVC. The locations of theses plots were selected based on the presence of *L. carolinianum* and the plot's proximity to water quality stations. Plots were revisited monthly from November 2003 to February

2005. All plant species were identified, counted, and recorded monthly. Each *L. carolinianum* in the plot was tagged with a unique number, and morphologic characteristics (stem diameter at base of the plant, plant height, number of leaves, branches, open buds, closed buds, live flowers, dead flowers, mature berries, and premature berries) were measured monthly. To determine the non-destructive estimation of biomass, between 10 and 15 *L. carolinianum* individuals were harvested from each site four times throughout one growing year. A total of 118 plants were sampled. Ten morphologic measurements were taken from each plant the same as those from permanent plots - stem diameter, plant height, number of leaves, branches, open buds, closed buds, live flowers, dead flowers, mature berries, and premature berries), and each individual was dried at 60°C to obtain above-ground biomass. These measurements were entered into a stepwise regression as independent variables to determine which variables best explained patterns of aboveground biomass, the dependent variable. This equation could subsequently be applied to the measurement from permanent macrophyte plots to estimate aboveground biomass of *L. carolinianum.*

Species diversity and composition along transects were similar at the three sites, with all sites containing the same 6-7 common species. While *Spartina alterniflora* was only a minor part of this vegetation community, it dominates the few low inter-tidal, fringe areas present. Species composition exhibited little variability between years of the study (Table A1). Densities and biomass of *L. carolinianum* were not significantly different across sites or between years. *L. carolinianum,* while important to salt marsh ecology, accounts for only a small portion of the overall biomass. Based on correlation coefficients, *L. carolinianum* was found in association with some of the common species in the vegetation community, indicating that its growth and survival requirements are typical to the salt marshes at ANWR.

Repeated sampling of *L. carolinianum* in permanent plots along the estuarine gradient showed that *L. carolinianum* exhibits strong temporal patterns with leaf production peaking in early spring and again just prior to flower production and peak berry abundance. Flowering of *L. carolinianum* occurred in October and November with peak berry abundance coinciding with the cranes' arrival in late October and early November. Berries appeared in October, November, and December and were virtually non-existent in the marshes for the remainder of the year. Stepwise regression showed stem diameter alone was a good estimator of aboveground biomass of this species in ANWR marshes, accounting for 94% of the variability ($p<0.001$). Changes in aboveground biomass followed no distinct patterns in the year of monitoring, perhaps due to the woody stem of the plant. Spatial patterns in *L. carolinianum* were not explained by water quality parameters alone. Instead, other soil properties (*e.g.*, elevation, soil porewater salinity, redox levels, and nutrients) may help to account for the spatial variability. The publication by Butzler and Davis (2006) provides more detail regarding the results of the study.

Table A1: Frequency of each salt-marsh macrophyte species found along transects sampled in Fall 2003 and 2004.

	2003			2004		
	Boat Ramp	Pump Canal	Sundown Bay	Boat Ramp	Pump Canal	Sundown Bay
	n=32	n=54	n=30	n=42	n=52	n=32
Aster tenuifolius L.	0.09	0.07	0.33	0.14	0.19	0.28
Batis maritima L.	0.53	0.76	0.67	0.57	0.73	0.75
Borrichia frutescens (L.) DC.	0.28	0.24	0.47	0.36	0.27	0.47
Distichlis spicata (L.) Greene	0.44	0.61	0.7	0.55	0.56	0.69
Lycium carolinianum Walt.	0.28	0.39	0.37	0.29	0.35	0.28
Monanthochloa littoralis Engelm.	0.63	0.39	0.07	0.52	0.37	0.09
Salicornia spp.	0.44	0.69	0.7	0.69	0.73	0.72
Spartina alterniflora Loisel.	0.06	0.22	0.23	0	0.12	0.38
Haplopappus phyllocephalus DC.	0	0	0	0.05	0.02	0
Limonium carolinianum (Walt.) Britt.	0.03	0	0	0.05	0	0
Scirpus robustus Pursh	0	0	0	0	0.02	0
Sesuvium maritimum (Walt.) B.S.P.	0	0.02	0	0.05	0	0
Suaeda linearis (Ell.) Moq.	0.06	0.06	0	0.12	0.04	0
Sunflower	0.03	0	0	0.1	0.02	0
unknown 1	0	0.02	0	0.07	0	0

3. Pattern and process influencing algal biomass in hydrologically dynamic salt ponds in a subtropical salt marsh

Graduate student project: Carrie Miller – Stephen Davis and Dan Roelke (thesis co-advisors)

Project Overview

This study was led by Carrie Miller, a M.S. student in the Department of Wildlife and Fisheries Sciences at Texas A&M University. The overarching goal of this research project was to increase our understanding of the role of hydrologic connectivity and its influence on the accumulation of benthic microalgal biomass and organic matter in ponds at each of the three sites at ANWR. This is important because both detritus and benthic microalgae can be major sources of labile carbon for the marsh food web.

The objectives of this study were as follows: 1) to quantify benthic and suspended microalgal biomass and organic matter in the ponds, as well as salinity, inorganic N and P and identify any spatial and/or temporal patterns; 2) to determine and measure environmental gradients in order to estimate hydrologic connectivity of the ponds in relation to the surrounding marsh; and 3) to examine factors such as proximity of ponds to the open bay and to each other, precipitation, wind, season, and tide that may influence benthic microalgal biomass within the ponds.

This project considered three sites, which were sampled monthly, located along Sundown Bay, Guadalupe Estuary, TX —BR, PC, and SB. Each site included five ponds and an adjacent tidal creek as well as sloughs and larger inland bays. A nested sampling design was used, with five ponds at each of the three sites. Each pond was overlaid with a 50-60 square grid depending on the shape of the pond and cells on the grids in each pond were randomly chosen for sampling each month. Cell size was dependent on pond surface area, *i.e.*, the number of cells in each grid remained approximately the same while cell size was variable. Three replicate Petri-dish sediment cores were taken to an approximate depth of 1 cm to determine benthic chlorophyll-a and ash-free dry weight. Water depth was measured at each sampling location within a pond.

Water samples collected from each pond and the associated tidal creek were filtered in triplicate. The filtrant was saved for analysis of water column chlorophyll-*a* concentration and volatile organic matter content, while the filtrate was saved to determine inorganic nutrient concentrations of nitrate plus nitrite, ammonium, and phosphates. Salinity of the pond was determined using a refractometer. Filtrant from the water samples was analyzed for chlorophyll-a using acetone extraction and measured using a fluorometer. Total suspended solids and volatile organic matter were measured using the same method in order to determine ash-free dry weight of the benthic samples. Paired water level recorders with pressure sensors were located at each site, providing a continuous record for water level in the tidal creek and nearby pond.

This study examined algal biomass, organic matter, and nutrients in coastal salt-marsh ponds in order to determine the most accurate model describing algal dynamics and organic matter deposition in the Guadalupe Estuary. The algal biomass in both the benthos and the water column did not change significantly enough to point to Plankton Ecology Group (PEG) model dynamics. The PEG model describes the cyclic relationship between resource limitation, grazing and microalgal growth and succession (Sommer *et al.*, 1986). Instead of being temperature-driven, the Guadalupe Estuary is tidally-driven and related to the hydrodynamics of the San Antonio Bay, with high water periods typically occurring in the traditionally defined fall and spring months and low water periods occurring in the traditional summer and winter months. Since the high and low water events are repeated temporally, some seasonality may be present in the data. During the sampling period, however, inter-annual variability resulted in atypical spring (2006) water levels possibly obscuring regular patterns in the pond data. Perhaps if community composition had been assessed along with the aggregate parameter of algal biomass, as it had been in the previous Texas studies, PEG-model community succession may have been found, even with inter-annual variability in the hydrology.

High water events in the San Antonio Bay resulting in surface water connections across the marsh-pond landscape seemed to vary in duration and periodicity. During times of connection, flushing resulted in lower salinity and algal biomass, as estimated in Figure A2. During periods of disconnection, the lack of flushing allowed algae to accumulate biomass. Although salinity was also higher during times of disconnection, the relationship between salinity and chlorophyll-*a* was not strong enough to suggest that the increase in chlorophyll-*a* was attributed solely to concentration effect ($r^2 = 0.20$). The tidal creeks experienced flushing that likely resulted in a dilution effect compared to many of the ponds. Concentrations of nitrate plus nitrite, ammonium, and phosphates were typically higher in the ponds than in the tidal creek, suggesting that nutrient cycling by the biota and re-suspension of nutrients in the sediments within the ponds were a more significant source of nutrients to the ponds than input from the tidal creek during flooding (Miller *et al. in press*).

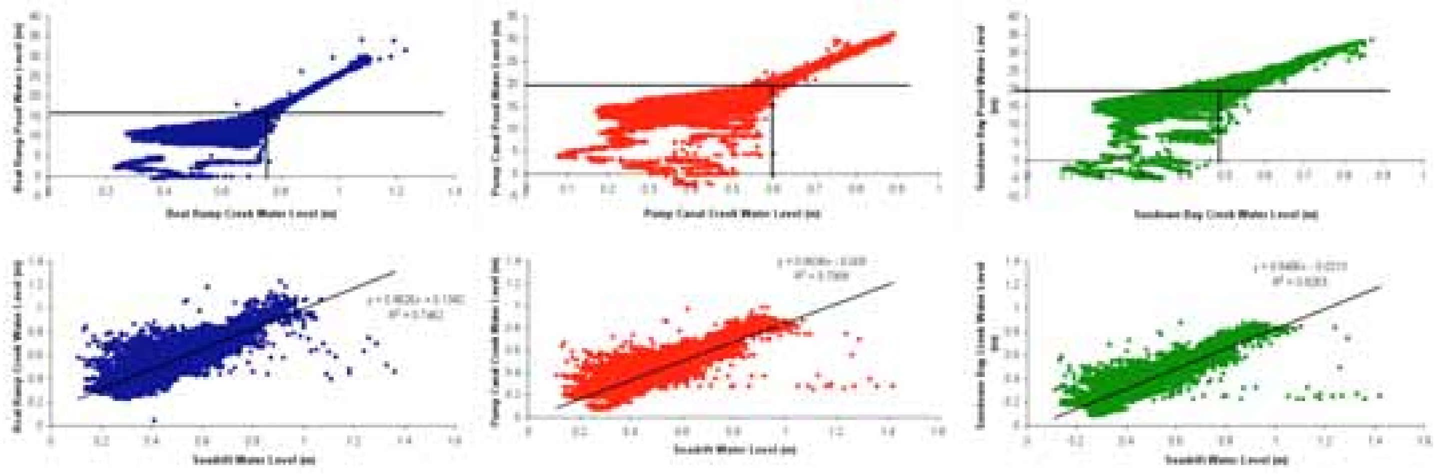


Figure A2: The top panel shows correlations between pond and creek water level at all three sites illustrating the estimated water levels required for a surface water connection between creek (*i.e.*, bay) and marsh pond. The lower panels show the correlation between tidal creek water level and Seadrift water level gauge for all three stations.

4. Spatio-temporal patterns of biophysical parameters in a microtidal, bar-built, subtropical estuary of the Gulf of Mexico

Graduate student project: George Gable – Stephen Davis & Dan Roelke (thesis co-advisors)

Project Overview

This was a study conducted between 2004 and 2005 and led by George Gable, a M.S. student in the Department of Wildlife and Fisheries Sciences at Texas A&M University. In this research, Gable sought to explore the relationships between temporal and spatial trends in plankton communities and characterizations of the physicochemical environment in Mesquite Bay—a sub-embayment of the Guadalupe Estuary. Another important goal of this work was to determine the contribution of Cedar Bayou to water quality and plankton community dynamics in Mesquite Bay. The objectives of this study were to:

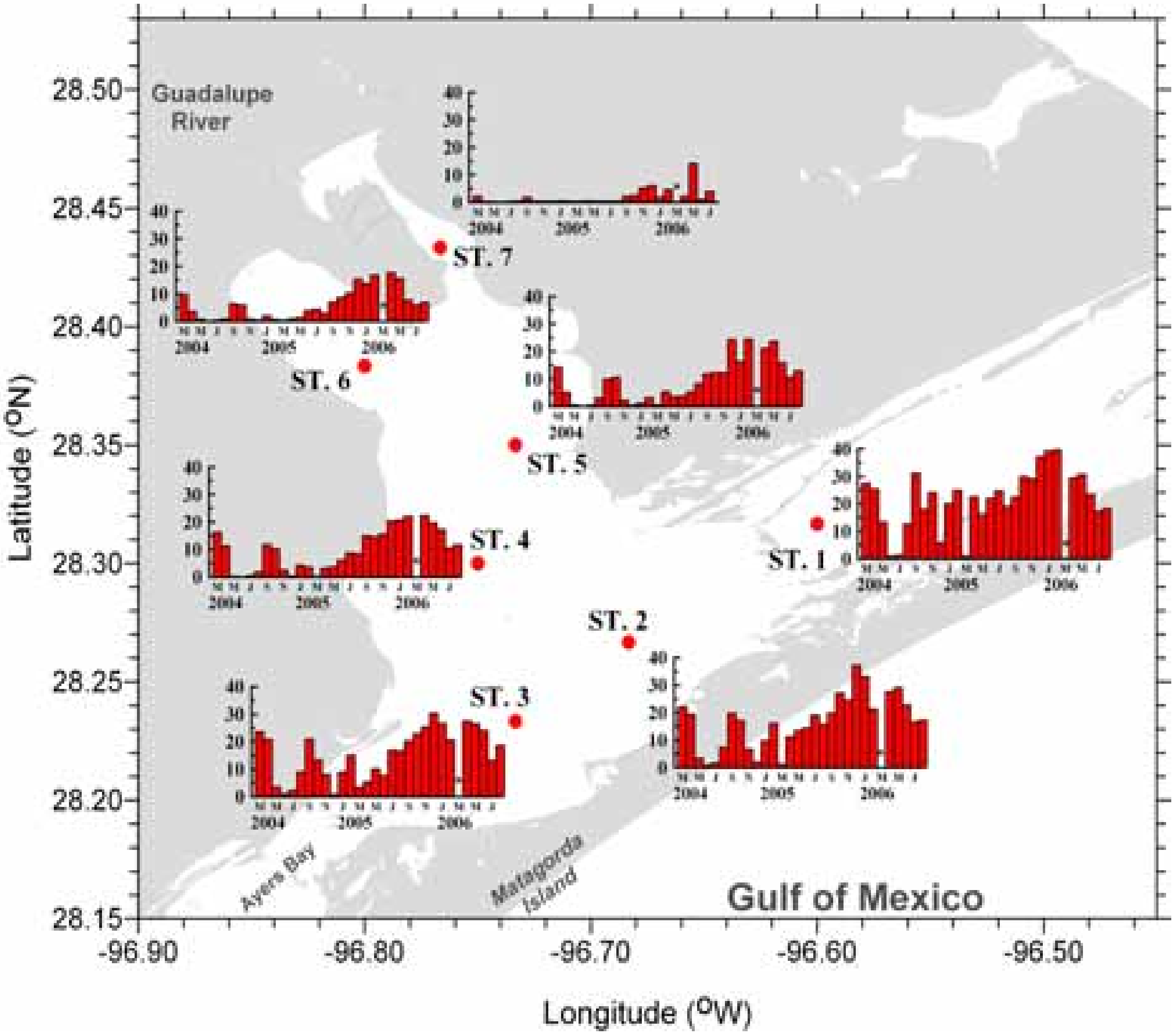
1. Quantify and characterize temporal and spatial trends in surface and benthic physical water parameters including temperature, salinity, turbidity, secchi depth, pH, and dissolved oxygen (DO) at nine fixed stations at approximately monthly time intervals.
2. Quantify and characterize temporal and spatial trends in inorganic nutrients including nitrate plus nitrite (NO_3^- and NO_2^-), ammonium (NH_4^+), and ortho-phosphate (PO_4^{3-}) at nine fixed stations at approximately monthly time intervals.
3. Quantify and characterize temporal and spatial trends in surface water column gross production and community respiration at nine fixed stations at approximately monthly time intervals.
4. Quantify and characterize temporal and spatial trends in phytoplankton biomass and zooplankton bio-volume and composition at nine fixed stations at approximately monthly time intervals.
5. Quantify and characterize temporal and spatial trends in physicochemical water parameters using a flow through Dataflow system that measures water temperature, conductivity, salinity, water clarity (beam transmittance), chlorophyll *a* (in-situ fluorescence), and dissolved organic matter (FDOM, in-situ fluorescence) on approximately similar transects.

This study focused on Mesquite Bay in the Guadalupe Estuary, a system characterized by reduced inflows, restricted water exchange with adjacent bay systems, and tidal exchanges with the Gulf of Mexico. Nines stations were selected at which study the effects of water exchange points and to characterize various habitat types including seagrass beds over sand and silt, open substrate next to seagrass beds, and open water habitat. Samples were collected at the 9 stations at approximately monthly time intervals. Sampling was conducted from 17 November 2004 to 29 October 2005.

Spatial variability in water quality parameters was generally low. Two-dimensional ordination plots indicated spatial heterogeneity with a more pronounced temporal trend affecting parameters including temperature, salinity as a function of inflow timing, and seasonal wind direction affecting primary production and zooplankton biovolume. Temperature was positively correlated with gross production and respiration rates during spring and late summer with sporadic positive and negative correlations with phytoplankton biomass. Both the timing and magnitude of freshwater inflow affected various physicochemical and biological parameters. High river inflow rates resulted in low estuarine-wide salinity, with spatial heterogeneity increasing over the course of the study, which was confirmed by spatial maps (Figure A3). Additionally, high river inflows led to two periods of increased inorganic nutrients and CDOM. Low salinity periods coincided with persistence of higher turbidity, likely due to decreased sediment flocculation. Gross production was low at this time, likely due to light limitation. Additionally, wind magnitude and direction created spatial heterogeneity in turbidity levels and phytoplankton biomass. Zooplankton biovolume was highest during spring and late summer with high species diversity in total rotifers. Copepod biovolume and phytoplankton biomass were positively correlated. Other zooplankton taxonomic groups exhibited variable correlations with phytoplankton biomass and other taxonomic groups.

Refer to Gable (2007) for detailed water quality and plankton enumeration results as well as high-resolution Dataflow maps of Mesquite Bay during this sampling period.

Figure A3. Interpolation plots of monthly Dataflow salinity collected from continuous transects sampled across the Guadalupe River estuary. Transects were sampled from January 2005 through August 2006 as part of studies funded by USGS and TX Sea Grant.



5. Hydrologic connectivity across a tidal marsh-pond landscape at Aransas National Wildlife Refuge (Texas, USA)

Graduate student project: Matthew Driffill – Stephen Davis (thesis advisor)

Project Overview
This was initiated in 2007 and is being led by M. Driffill, a M.S. student in the Department of Wildlife and Fisheries Sciences at Texas A&M University. This project is still in progress.

In coastal marshes, intra-marsh connectivity (*i.e.*, connectivity between hydrologic features such as tidal creeks, ponds and sloughs) is essential to a wide range of marsh ecosystem processes. In the salt marshes of ANWR, extreme tidal fluctuations drive hydrological connectivity between bays and isolated ponds. Therefore, the study of hydrologic processes in these relatively isolated pond environments will further our fundamental understanding of the significance, magnitude, and frequency of intra-marsh hydrologic connectivity events. The estuarine marsh complex at ANWR experiences a diurnal tidal range of approximately 10 cm. When considering the duration of surface water connections across the marsh landscape, this tidal range is negligible compared to the fortnightly and seasonal tidal ranges, which can reach approximately 50 cm. These larger scale tidal fluxes, in addition to storm surges associated with frontal passages and large storm events, provide the means for the variation in hydrologic connections and disconnections throughout the coastal marshes of the ANWR.

The overarching objective of this thesis project is to determine the degree of hydrologic connectivity across the surface of the intermittently flooded marshes along the Blackjack Peninsula of ANWR. Of particular interest is the characterization of the surface water connections between tidal creeks and shallow ponds that occur across much of the region and the quality of the surface water during these periods. Furthermore, this project will examine the interaction between ANWR marsh elevation and tidal water levels in shaping spatio-temporal patterns of hydrologic connectivity. Marsh hydrology (water level) and marsh surface (soil surface elevation) data were synthesized to construct a digital elevation model for the study area.

To accomplish the aforementioned objectives of this project, the following field methods were employed: 1) Paired (creek and pond) water level recorders were deployed at the three territories at ANWR. Data from these gauges was used to infer the frequency and duration of connection events over the three-year study period, and 2) Detailed spatial/elevation models of marsh inundation and connectivity as related to tide gauge data will be constructed to assess spatial patterns of connectivity at each site (see example in Figure A4).

To determine marsh hydrologic connectivity, the water level data can be plotted as a time series and analyzed to determine the frequency and the magnitude of water level connections. Data analysis thus far indicates that two distinct periods are of primary interest, 1) connection periods in which both the pond and tidal creek possessed similar water levels (occurred during increased water levels) and 2) disconnection periods in which the pond and tidal creek water levels operate independently.

Digital elevation models are built in ArcGIS to map spatial patterns of marsh elevation (see Figure A4) – these models were based on a survey of two spatial scales: fine scale (*i.e*., creek/pond) and the coarse scale (*i.e*., crane territory). Both scales were surveyed and geo-referenced to elevation benchmarks. From these benchmarks a Zeiss Elta surveyor's tool was used to take elevation points across each study site to create marsh surface interpolations. The fine scale interpolations were built by separating the points at each site into two spatial zones.

The final goal of this project is to increase the both the spatial and temporal scales of the water level findings to the temporal scale of the Seadrift water level record and the digital elevation model findings to the whooping crane territory scale. The temporal scale extrapolation will involve regressing the tidal creek sites against the Seadrift water level (relationships revealed in empirical study #3). By establishing this mathematical relationship, the data from the Seadrift gauge can then be used as a predictive tool to determine marsh inundation and connectivity patterns.

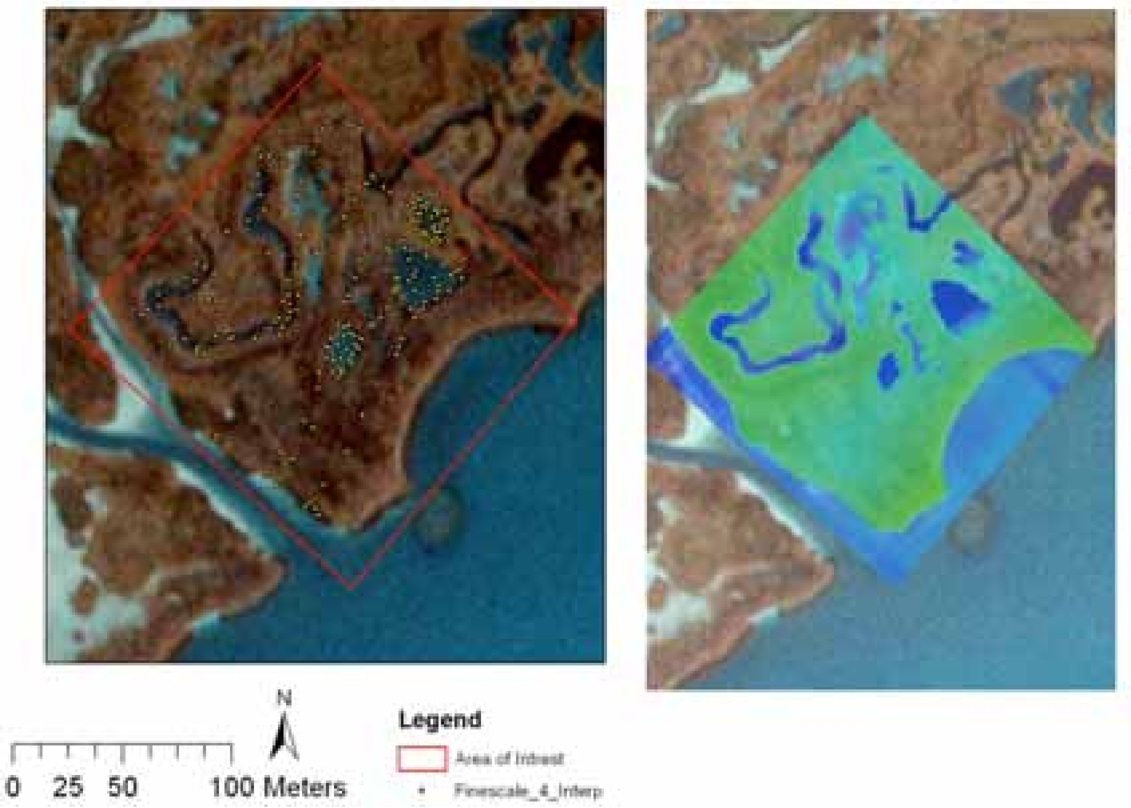


Figure A4: GIS maps showing the location of survey points at Sundown Bay creek and marsh (left) and interpolated elevation, which can then be used to simulate water level rise and connectivity at a small scale (right).

6. The effects of salinity and inundation on leaf abundance of the Carolina Wolfberry, *Lycium carolinianum*: a greenhouse experiment

Undergraduate student project: Christopher Llewellyn – Stephen Davis (research advisor)

Project Overview

This was an experiment conducted during the summer of 2007 and was led by Christopher Llewellyn, an undergraduate student in the Department of Wildlife & Fisheries Sciences at Texas A&M University.

Research regarding the Carolina wolfberry conducted at ANWR and other locations along the Texas coast indicates that salinity and inundation are the two environmental parameters that (may) have the greatest impact on growth and fruiting patterns. Modifications to freshwater inflows into the Guadalupe Estuary or changes to tidal amplitude and salinity have the potential to directly impact the marshes of ANWR and the associated vegetative community. In order to examine the effects of salinity and inundation, a controlled greenhouse experiment was conducted on campus at Texas A&M University. The primary goal of this research project was to determine how varying salinity from freshwater to saltwater, and various inundation treatments (deep, low, and mixed), and or the combination of these environmental parameters affected the growth and leaf production of *L. carolinianum*.

This experiment was conducted for a period of eight weeks and consisted of a total of ten mesocosms. Five of the mesocosms had a water column salinity of 35ppt (saltwater treatment), and five that were considered freshwater (salinity of 0 ppt). In addition, mesocosms received three inundation treatments: deep – plants submerged below the water line for entire experiment, low – plants submerged half way for entire experiment, and mixed – plants were partially submerged for the first four weeks and then completely submerged for a two-week time period, and then again moved to a partially submerged level for the remaining two weeks of the experiment. Plant height and stem diameter were measured on a weekly basis. Also on a weekly basis the total number of leaves per plant was counted as recorded from a randomly selected branch. Lastly, soil redox potential and soil pore water salinity were determined from three randomly selected pots in each treatment on a bi-weekly basis.

The inundation treatments did not result in significant variation in the number of leaves. However, while inundation did not directly affect leaf abundance, soil redox potential in the soil did vary by treatment. The deep treatment had a redox potential of -301.63, while the mixed (-179.90) and low (-99.56) treatments had more positive values. These results indicate that inundation treatments were successful in modifying the plant's physical environment, however, this environmental change did not appear to have a noticeable impact to the number of leaves per plant.

Significant change in leaf abundance was noted in the salinity treatments. The freshwater treatment resulted in an average leaf loss of -49.02% over weeks 4-8 of the experiment as compared to initial leaf numbers (Figure A5), and the saltwater treatment resulted in a 80.52% loss in the number of leaves (Figure A5). In the saltwater treatment, the leaf loss was significantly different for weeks 4, 6, and 8, as compared to the initial leaf abundances.

The results of this controlled greenhouse experiment supported the findings of the *in situ* research conducted in the marshes of ANWR, and the combined analysis of these two data sets offer a unique perspective into wolfberry growth patterns. Seasonal variability appears to have the most significant impact on the growth patterns of the wolfberry. These results also support the hypothesis that increased salinity results in additional stress for these plants. In this greenhouse experiment, the increased stress resulted in the decreased leaf abundance under high salinity conditions. Future studies should consider more realistic inundation patterns.

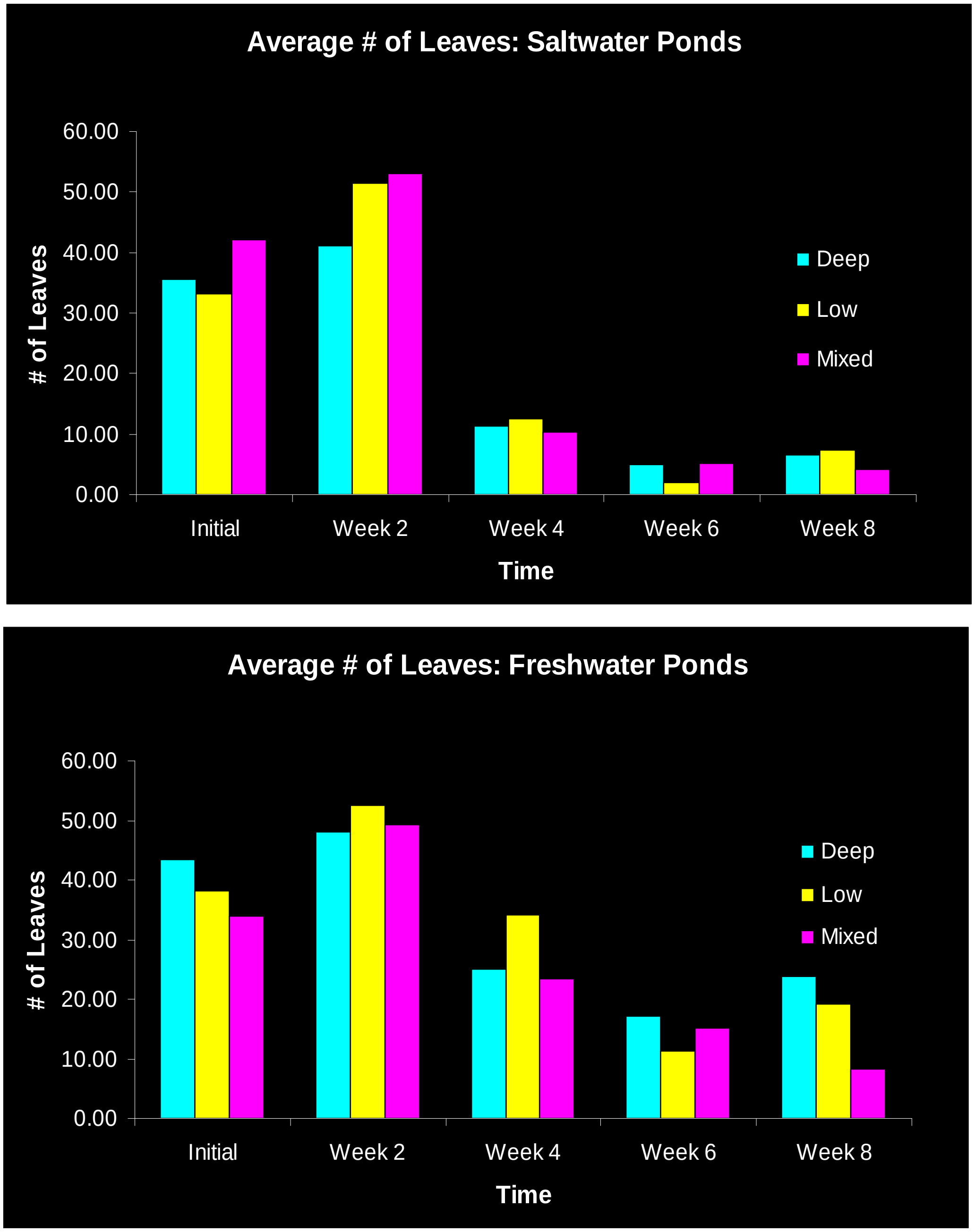


Figure A5: Graphs depicting the change in the total number of leaves over the course of the 8-week experiment in both the saltwater (top) and freshwater (bottom) ponds. Inundation treatments of deep, low, and mixed are shown as different colors.

7. Patterns in blue crab abundance in shallow salt-marsh and bay habitats of the Texas Gulf Coast

Graduate student project: Danielle Greer – R. Douglas Slack (PhD advisor)

Project Overview

This was led by D. Greer, a PhD student in the Department of Wildlife & Fisheries Sciences at Texas A&M University. This project is still in progress.

Contributions of interior salt marsh to the productivity of blue crabs have received little attention, and studies of blue crab use of salt marsh have occurred almost exclusively in young, *Spartina*-dominated marshes or peripheral *S. alterniflora* fringe. In this study, the overall goal was to examine the size-specific abundance patterns of blue crabs in shallow (< 1 m deep) habitats of the Guadalupe Estuary, Texas, where salt marsh is mature and dominated by high-marsh halophytes (*e.g.*, *Batis maritima, Salicornia* spp., *Monanthochloa littoralis, Borrichea frutescens*). The main objectives were as follows:

1. Document spatio-temporal patterns in blue crab abundance and size-class structure within and adjacent to salt marsh at both fine and large spatial-scales.
2. Investigate the effects of environmental (e.g., freshwater discharge, water temperature, vegetative cover) and random effects on blue crab abundance and size-class structure.

Methods

To facilitate both the crane and crab portions of our greater study, four of the 19 winter territories of whooping cranes located within ANWR were used as replicate study sites, including Boat Ramp (BR), Pump Canal (PC), Pipeline (PL), and Blackjack (BJ; Figure A6). The area within each study site was categorized by habitat and included (1) bay-marsh interface (bay), (2) tidal creek, (3) connected pond, (4) unconnected pond, and (5) emergent salt-marsh vegetation (ESV). Connected and unconnected ponds were each further classified as either open water (>1 m from ESV) or pond edge, thereby creating connected open water (COW), connected pond edge (CPE), unconnected open water (UOW), and unconnected pond edge (UPE) habitats. Each habitat was not necessarily represented at every study site; only PC included all habitats.

To investigate patterns in blue crab abundance, samples were collected using an incomplete-block design with repeated measures. Prior to each sampling period, four trapping locations were randomly selected per experimental unit. Regular sampling occurred in bay, and connected and unconnected pond habitats; neither tidal creek nor contiguous ESV was included in investigations.

Standard drop-trapping protocol was ineffective for quantitative measure of crab abundance in this study, because water depth in and around the salt marsh is often too shallow (0-50 cm) for boat travel, and unconnected or temporarily disconnected ponds are inaccessible via water. To facilitate sampling for blue crabs in connected waters ≥ 30 cm deep, we constructed several large, three-dimensional frames called booms and a pair of large, portable styrofoam floats to be used at each site (Figure A7). Multiple cylindrical, stainless steel drop traps (1-m diameter by 75-cm depth) were also constructed. The boom assembly was guided to predetermined locations, and release of the trap from the front arm of the boom was triggered.

To sample crab abundance in unconnected habitats and in water < 30 cm in depth, we used modified throw-trapping methodology (Figure A7). The trap was thrown by two people to ensure the trap would eventually fall vertically and the entire bottom of the trap would hit ground at the same time.

At each trapping location, several environmental characteristics were measured, including water depth, water salinity, surface water temperature, bottom substrate, water column substrate type (*e.g.*, algae) and complexity (none, low, medium, high). We also recorded date, time, shortest distance to pond or bay edge (*i.e.*, distance to nearest ESV), dominant edge ESV (*e.g.*, *Spartina alterniflora*), and the geographic location. Data for several other parameters were later obtained from remote sources within San Antonio Bay, on the Guadalupe River, or from the ANWR weather station. Blue crabs captured within the trap were collected by sweeping inside the trap with a large baitwell net (Figure A7). Crabs were placed in formalin and taken to the lab for processing. In the lab, preserved blue crabs were measured for carapace-width in millimeters (mm) and later categorized by 10-mm size classes. A subset of samples (n = 100) was randomly selected to also record biomass of crabs. From these data, we developed a regression equation relating crab biomass to size and then used it to predict the biomass of crabs not weighed.

To investigate spatio-temporal patterns in crab abundance at a fine spatial scale, we computed mean crab density (crabs/m^2) and biomass (g/m^2) and subsequently used these values to calculate the means per habitat, per habitat within study site, and per habitat and month. Patterns in mean size of captured crabs and distribution of densities and biomasses among size-classes were similarly explored. We also investigated large spatial scale patterns in crab abundance by accounting for the proportional area of habitats within study sites and computing total number (no./ha of shallow habitat) and standing stock biomass (kg/ha) of crabs. Large spatial scale measures were summarized in the same manner as fine-scale measures.

We took an information theoretic approach to investigate causes of variability in crab density and developed *a priori* biological hypotheses concerning such variability. Hypotheses were used as the basis for subsequent development of several generalized linear mixed models, which modeled density as a function of environmental and random effects. The following fourteen hypothetical sources of variation in crab density were identified:

1. *Bottom substrate*. Prior research found blue crabs 23-36 mm in size more readily buried in mud than sand (Barshaw and Able 1990). Consequently, crabs in sandy

substrate environments should incur higher predation risk (Lipcius *et al.* 2005) and experience lower foraging efficiency than crabs in muddy bottom environments (Lipcius and Hines 1986). We did not differentiate between mud and sand at each trapping location but applied the concept of readiness to bury, or potential for concealment, to these substrate categories: mud or sand, shell or oyster, and blocky clay. We hypothesized that potential for concealment and, subsequently, crab density would decrease across substrates in the aforementioned order.

2. *Water column structural complexity*. Macroinvertebrate diversity and abundance increase with structural complexity in the water column (Heck and Orth 1980, Heck and Thoman 1984, Heck and Wetstone 1977, Leber 1985, Mosknes and Heck 2006). Increases in structural complexity or surface area of submerged vegetation not only provide more space for habitation, increasing carrying capacity, and simultaneously increasing the structure's value as refuge from predation (Heck and Wetstone 1977, Leber 1985). We hypothesized that blue crab density would increase with structural complexity in the water column and, accordingly, density would increase from the complexity category of "none" to "high." We also recognized the relationship between abundance and complexity might differ among crabs of different size classes. Developmental shifts in habitat use or utilization of increasingly more spacious habitat with increases in size have commonly been observed for crabs (Beck 1995, Bertini and Fransozo 2000, Mosknes and Heck 2006, Pardo *et al.* 2007).

3. *Water column structure type*. We hypothesized that locations comprising both submerged aquatic vegetation (SAV) and algae would support the highest densities of blue crab. Nekton abundance and survival in each SAV (*e.g.*, seagrass; Pile *et al.* 1996, Wilson *et al.* 1987) and macroalgae (Wilson *et al.* 1990) have proven greater than in adjacent non-vegetated bottoms. Moreover, mesograzers (*e.g.*, amphipods) that feed on macroalgae (Dittel *et al.* 2006) and the epiphytic algae of submerged vegetation (Douglass *et al.* 2007, Larkum *et al.* 2006) are both important foods for blue crabs.

4. *Distance to the ESV edge*. Previous research findings demonstrate patterns of decreasing prevalence of crustaceans with increasing distance from interior salt-marsh vegetation (Minello *et al.* 2008) or removal of plant cover (*i.e.*, shade; Whitcraft and Levin 2007). Presuming these patterns represent a mixed strategy used by crabs to both avoid predation and maximize food acquisition, we hypothesized results from our study would be consistent with those of earlier findings and crab density would decrease with distance to ESV edge.

5. *Dominant edge ESV*. Several studies have compared blue crab use of marsh edge to that of adjacent habitats, such as SAV and non-vegetated substrates (*e.g.*, Rozas and Minello 1998, Rozas *et al.* 2007, Thomas *et al.* 1990). Little attention, however, has been given to crab use of pond edges dominated by middle- and high-marsh halophytes (see Minello 1999). In the salt marsh of this study, these species are found on islands of elevated ground. Plant stems hang over steep, abruptly sloped pond edges, providing concealment to crabs from terrestrial and aerial predators. Conversely, *S. alterniflora* is found at the edge of the salt marsh where elevational change is gradual; their stems hang over the water but also provide refuge and a source of food to crabs within the water column. Therefore, we hypothesized that

blue crab density would be higher near bay or pond edges dominated by *S. alterniflora* than edges dominated by mixed, higher-marsh species.

6. *Presence of water*. Decapods can survive out of water for extended periods in cold, humid conditions (Lorenzon *et al*. 2007, Samet *et al*. 1996, Spicer *et al*. 1990), but this dramatically elevates physiological stress (Giomi *et al*. 2008, Ridgway *et al*. 2006, Spicer *et al*. 1990) and likely increases vulnerability to terrestrial and aerial predators. We hypothesized the effect of water presence/absence on crab density would solely be evident through interactions with other variables. That is, no crabs should be found on exposed sediment flats, and crab density should depend on other environmental variables when water is present.
7. *Water depth*. Crabs may be influenced by water depth for several reasons, which led us to believe that generally more crabs would be found in deep than shallow water. Crabs may select deeper water to avoid predation from foraging wading birds or other terrestrial or aerial predators that experience limited visibility or mobility in deep versus shallow waters. Also, the volume of water available to crabs per unit area increases with depth, causing a dilution effect and decreasing risk of predation by aquatic predators. The effect of water depth may also interact with other variables, such as water temperature and structural complexity in the water column. Crabs may be buffered against extreme hot or cold surface water temperatures when water depth is high versus low, and increasing structural complexity may decrease the need for crabs to seek shelter in deeper waters.
8. *Variability in water depth*. As temporal variability in water depth (*i.e*., probability of exposure and predation) increases, blue crabs may increasingly exhibit avoidance behavior. Accordingly, they may move into deeper water, position themselves closer to pond edges, inhabit SAV or algal beds of greater complexity, or maintain contact with bottom substrates of little burrowing difficulty. The effect of variability in water depth should then be seen through interactions with other effects, such as water depth, distance to ESV, structural complexity, and bottom substrate type.
9. *Water temperature*. Water temperature is an important determinant of crab growth. Growth has been shown to generally increase from approximately 13°C to 34°C (Cadman and Weinstein 1988, Leffler 1972). We hypothesized crab density would increase with temperature in response to conditions promoting growth. However, we also believed the effect of temperature would be more pronounced in shallow than deep waters because of the greater vulnerability of crabs to extreme cold temperatures, which significantly limit mobility. While we recognized the potential lethal effects of low dissolved oxygen levels at extremely high temperatures, we believed such temperatures would infrequently be of concern in the study area and thus disregarded its effect.
10. *Water salinity*. Blue crabs are able to tolerate a wide range of salinities. However, as a euryhaline species hyperosmoregulating in salinities below 27 ppt, blue crabs incur increasingly higher metabolic demands and osmoregulatory stress with decreasing salinity (Cadman and Weinstein 1988). The greatest effect of salinity on crab growth, however, occurs through an interaction with temperature. Specifically, osmoregulatory stress is highest and growth rate is lowest in conditions of both low

salinity and low temperature (Cadman and Weinstein 1988). We hypothesized crab density would positively relate with potential for growth, which is lowest in conditions of low salinity and temperature.

11. *Water turbidity*. We predicted increasing mechanisms for turbulence (*e.g.*, wind) would increase water turbidity and subsequently increase concealment (or survival) of blue crabs in the water column (see Minello *et al*. 1987). We believed crabs in turbid conditions would be less prone to hide from predators and, therefore, less dependent on other variables regulating concealment or predation risk. For instance, they might be less tied to pond edges, soft bottom substrate, high structural complexity in the water column, shallow water depths, and so on. If true, wind speed, a proxy for turbidity, and variables describing the microenvironment should interact to explain crab density.
12. *Recruitment rate*. No study has yet quantified a significant recruitment-to-adult relationship. This is likely because numerous factors or processes combine to determine the survival, growth, and dispersal of blue crabs in each stage of the lifecycle, and processes involved act as filters so that the proportion of individuals moving from one stage to another is successively smaller (Pineda 2000). Furthermore, as earlier life-stages are associated with larger spatial and temporal scales, small changes in the proportion of individuals passing from one stage to the next can cause considerable spatial and temporal variability in resultant population numbers. However, the rate of blue crab recruitment is a seemingly logical source of variation in crab density, and as such, we hypothesized crab density would increase with increasing rates of megalopal and juvenile recruitment.
13. *Habitat type*. Differences inherent and relationally consistent among habitat types included four primary factors (1) connectivity to coastal waters and subsequent distance and difficulty of travel for immigrating crabs, (2) diversity and abundance of crab predators and prey, (3) inundation regime (including timing, frequency, duration), and (4) susceptibility to such effects as wind and tides. We hypothesized crab density would decrease from bay to connected ponds to unconnected ponds and from edge to open-water pond habitat.
14. *Study site*. The random effect of study site was incorporated into all models, because we believed stochastic variability among sites significantly contributed to overall variation in mean crab density.

Hypothetically, the effects of water depth, temperature, and so on could be represented by a multitude of variables. For this reason, we incorporated 2-4 variables each into the analyses for water depth, temperature, salinity, and turbidity (Table A2). Variables recorded at trapping locations (*e.g.*, bottom substrate) were presumed to represent small-scale effects regulating microhabitat selection by crabs. Conversely, variables recorded remotely (*e.g.*, wind speed) represented large-scale phenomena affecting the entire estuary and overall abundance of blue crabs. To explore the timing of effects on crab density, we restructured remotely collected data into several forms consisting of computed means for the 1, 7, 14, 21, and 28-day periods including and preceding the day of trapping. In total, 63 different variables represented the 14 hypothesized sources of variation in crab density. Not all variables were included in model-building procedures, however, because preliminary examination revealed that most variable forms were not useful in predicting crab density.

All evaluated models, whether preliminary or otherwise, were generalized linear mixed models (GLMMs), because variation surrounding the mean response of crab density was explained by one or more fixed effects and a random effect (study site). Models were examined for each of four size groups of crabs (1-10 mm, 11-30 mm, 31-50 mm, 51-130 mm). The Poisson distribution with canonical link function (log) was assumed appropriate for the response data, because distributions of response variables were non-normal and zero-inflated. To minimize overdispersion, a value of one was added to each observed response.

Full models, or those incorporated into model-building procedures, contained all 14 effects identified *a priori* but only one variable per effect, because variables representing the same effect were presumed correlated. The only exception was bivariate water temperature, which was included in an interaction with the continuous form of water temperature. Numerous other two- and three-way interactions were also included in full models and were based on *a priori* hypotheses (see above). In total, we examined 40-50 full models of blue crab density for each size group.

We used a manual stepwise selection procedure to select the most important explanatory variables of crab density and made decisions to remove or keep variables based on model fit and Pseudo-AIC_c values (Akaike 1973, Burnham and Anderson 2002). Model dispersion ($\hat{c} = \chi^2/\text{df}$) was an important indicator of model fit. Values of $\hat{c} = 1$ were considered optimal (good model fit), whereas $1 < \hat{c} \leq 4$ indicated slight overdispersion with adequate model structure and $\hat{c} > 4$ indicated poor model structure (inadequate fit; Burnham and Anderson 2002: 67-69). The best fitting models of crab density for each crab size group, along with their hierarchical sub-models, were compiled for comparison.

Results

Fine spatial scale estimates of crab density and biomass.—We collected 915 samples from October 2004-March 2006. Descriptive summaries of crab abundance revealed that inner-marsh habitats had fewer but larger crabs than bay habitat. For instance, mean crab density was 10 times greater in bay (9.5 ± 1.0 crabs/m^2) than any inner-marsh habitat (0.5-1.0 crabs/m^2), but mean biomass was consistent across habitats (2.4-3.3 g/m^2). Extreme right-skewness was prevalent in the size-class distribution of crabs in all habitats but most pronounced in shallow bay, where the majority of crabs were < 10 mm CW (Figure A8). In all interior-marsh habitats, crab density was greatest in the second smallest size-class (11-20 mm). Also, crabs in the interior-marsh were distributed throughout the full range of sizes (1-130 mm) in open water habitats and up to 90 mm in pond edge habitats. In bay habitat, the smallest size class (11-30 mm) contributed the most to biomass; in the inner-marsh pond, the 31-80 mm size class contributed the most to biomass; while in the inner-marsh-open water habitat, the 111-130 mm size class contributed the most to biomass (Figure A9). Examination of temporal patterns revealed that crab densities and biomasses were both generally highest in spring and fall (Figure A10).

Large spatial scale estimates of total crab number and biomass.—As averaged across all sites and sampling periods, total number and standing stock of blue crabs were 9,646 crabs/ha and 11.5 kg/ha, respectively. Patterns in crab numbers and standing stock at the spatial resolution of the marsh were subtly different from those evident at the smaller spatial resolution. More crabs were found in bay (6,890 ± 1,604 crabs/ha) than any other habitat, but connected open water held the second largest total number of crabs (2,319 ± 524 crabs/ha), which was much greater than that of any other interior-marsh habitat (97-225 crabs/ha). Also, in terms of biomass, connected open water habitat contributed more to standing stock (8.1 ± 4.2 kg/ha), on average, than any other habitat, reflecting its larger proportional area and larger average size of crabs.

Sources of variation in crab density.—Of the candidate set of models, two models supported the data relatively well (models 5 and 7, Table A3). Model 5 was the most parsimonious model of the two. Both models noticeably best fit those data originating from PC and from bay habitat, where crabs 1-10 mm were most frequently captured. Predictability of crab density markedly decreased from bay to salt-marsh interior habitats. However, when each observed and predicted values were averaged across sites, densities were better approximated (Figure A11). This was expected, as the study was designed to estimate crab densities by incorporating data from replicate sites.

The most important predictors of crab density were habitat, water column structure type, and structural complexity. Observed and predicted responses of this simple model demonstrated a linear association of 72% ($r = 0.718$), but, when averaged across sites, responses were over 78% associated ($r = 0.785$). Moreover, these variables were the only ones appearing in the best approximating models of crab density that were specific to trapping locations and likely represented the factors most influencing micro-site selection by young juvenile crabs. Other variables included in the best models (salinity, water level, water temperature, wind speed) more generally described conditions within the estuary that influenced such processes as dispersal to and within the salt-marsh, physiological function, and predation rate. In other words, general predictors likely were responsible for determining whether or not young crabs were present within and around the salt-marsh, whereas site-specific variables predicted the magnitude of use by crabs dependent on micro-site (m^2) characteristics.

Results of GLMM analyses highlighted several relationships between crab density and environmental variables that were both statistically and biologically meaningful. Higher densities of crabs were predicted to occur in bay than other habitats, and no significant difference was revealed between connected and unconnected interior ponds. Density was predicted as generally higher in the water column structure type of SAV/algae than either SAV or algae, but mean crab density within each type depended differently on structural complexity. Crab density was highest when complexity was low in algae and medium in SAV/algae but did not vary by complexity level in SAV. Density was positively related to salinity and water level and negatively related to water temperature and wind speed.

The random effect of study site in the model adjusted the predicted values of crab density by the random differences observed among sites; such adjustments were consistent with results of descriptive statistics, which indicated crab density was generally highest at PC.

Model results for crabs 11-30 mm in size were similar to those for crabs 1-10 mm in size. The best approximating model of density included the effects of habitat type, water column structure complexity and type, water level, water salinity, and wind speed in San Antonio Bay, distance to ESV, and interactions between structure complexity and type, and water level and wind speed (model 6, Table A4). A slightly simpler model was achieved by removing the latter interaction (model 5, Table A4). Model fit for both models was good and most clearly illustrated by the linear association of 73% ($r = 0.731$) between raw observed and predicted responses and 94% ($r = 0.943$-0.947) between values averaged across sites (Table A4, Figure A12). Both models predicted crab density would be higher in bay than other habitats and no significant difference in density would be evident between connected and unconnected interior ponds. Crab density was generally highest in SAV versus other water column structure types. Though density did not depend on complexity of SAV, density in each algae and SAV/algae was highest in medium complexity. Density was positively related to salinity and water level and negatively related to wind speed and distance to ESV. The random effect of site adjusted the predicted values of crab density for random differences among sites, which were also observed in descriptive summaries.

Model selection procedures used to explore the density patterns of crabs > 30 mm in size often resulted in non-convergence or excessively large dispersion estimates. Thus, we were unsuccessful in developing an adequate model for predicting density of these crabs. This was unsurprising because as crabs increase in size they become increasingly less common, more mobile, and less dependent on environmental factors.

Conclusions

This study is one of few to sample nekton within habitats of the interior salt marsh and, to our knowledge, the first study to examine patterns of crab abundance in a mature salt marsh where the vegetated interior is dominated by high-marsh halophytes. During this study, we determined that shallow bay clearly provided important nursery habitat for young blue crabs and interior marsh ponds were important habitats for dispersing juvenile and adult blue crabs.

Patterns of crab abundance and size-structure among habitats in this study mirrored the micro-habitat selection of crabs often observed in earlier studies. Findings of previous studies suggest blue crabs and other nekton become increasing independent from cover such as seagrass or due to natural refuge attained by increasing size (Hines and Ruiz 1995). Crabs in non-vegetated mud habitats were shown to be larger in size than those found in adjacent *Spartina* salt marsh fringe; which in turn those in the *Spartina* salt marsh were shown to be larger than those in adjacent seagrass beds (Rozas and Minello 1998, Thomas *et al*. 1990). Such ontogenic changes were revealed at the larger spatial scale of this study, where small crabs were more typically found in SAV and algae-dominated bay waters, larger crabs were found proportionally more often in pond edge habitats, and the largest crabs found refuge in open water pond habitats of the interior-marsh. The connected interior-marsh pond habitat demonstrated considerable importance to crabs, as it encompassed a diversity of structurally distinct habitats (*e.g.*, SAV, *Spartina* fringe, open non-vegetated water). As a result, the widest range of crab sizes was observed in this habitat and it proved to be a significant contributor to total number and standing stock of crabs.

Results of our model-building efforts provided considerable support to descriptive findings. Our models demonstrated an affinity by crabs for bay habitat, relatively high structurally complexity in the water column, close proximity to additional refuge (pond edges), and deeper waters, which are presumed to aid in dispersal and provide additional refuge value.

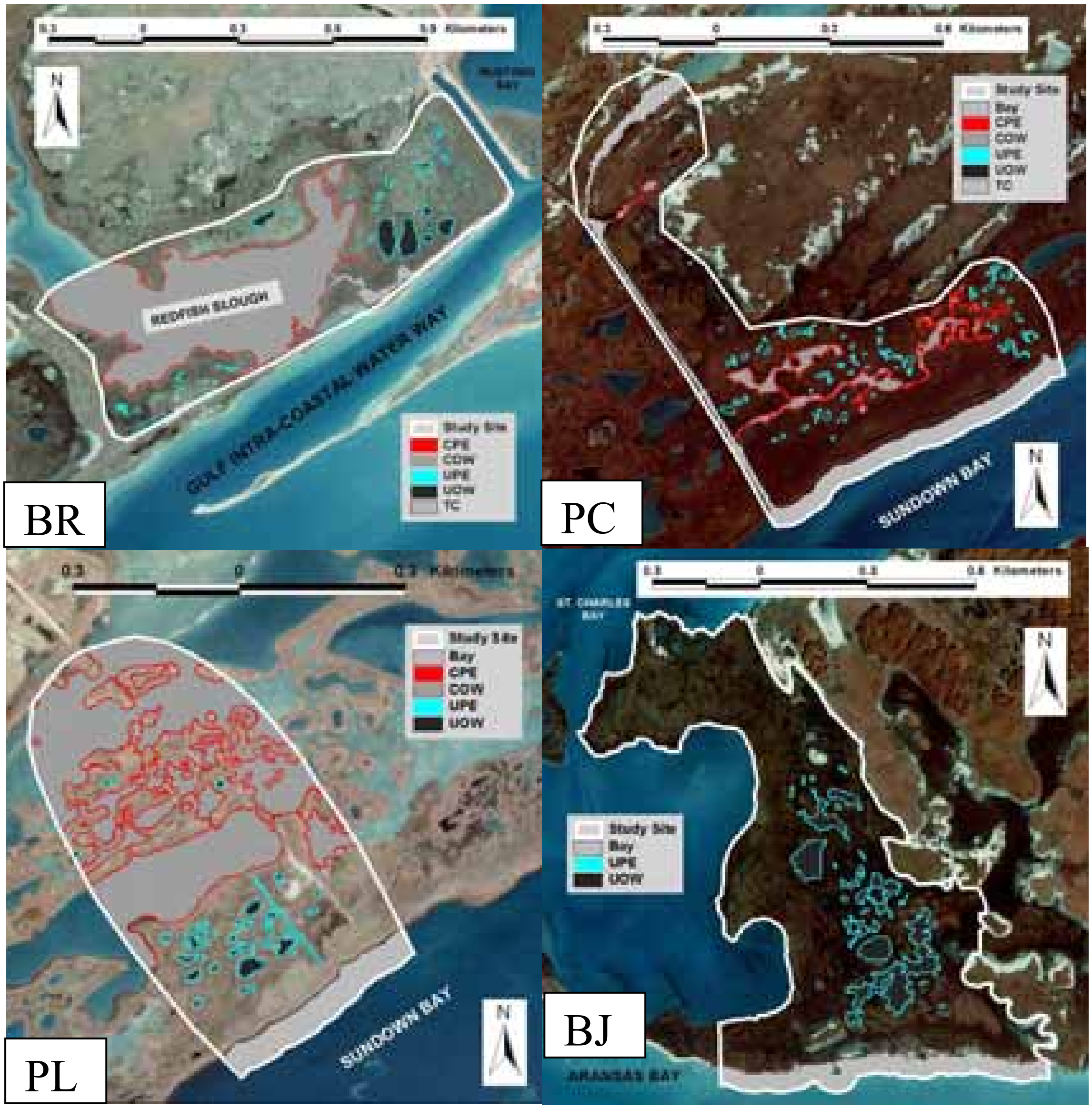


Figure A6. Study sites located along the eastern perimeter of Blackjack Peninsula, Aransas County, Texas. Sites included Boat Ramp (BR), Pump Canal (PC), Pipeline (PL), and Blackjack (BJ), and habitats within sites were identified as bay-marsh interface (bay), tidal creek (TC), connected pond open water (COW) and edge (CPE), unconnected pond open water (UOW) and edge (UPE), and emergent salt-marsh vegetation (no color or pattern).

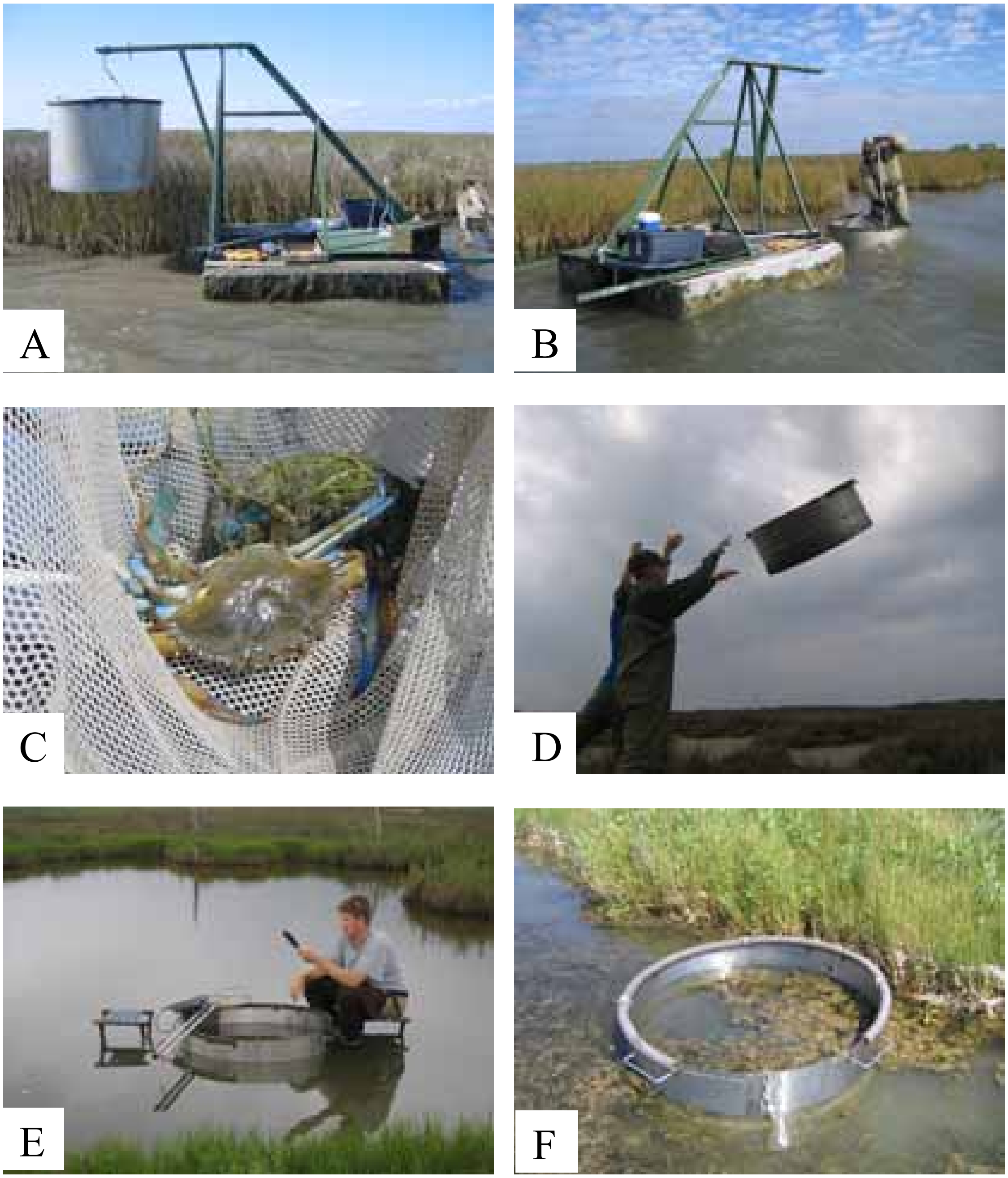


Figure A7. Drop trapping in bay habitat (A-C) and throw trapping (D-F) in the interior salt marsh. Crabs were retrieved from within the trap by sweeping inside the trap with a large dip net (B), followed by sorting through the vegetation, debris, and sediment obtained in the net (middle, left). The throw trap was always thrown by 2 people from elevated ground that supported emergent salt-marsh vegetation and never from within flooded ponds (D). Throw-traps were used in open water (E) and pond edge (F) habitats.

Table A2. Fixed effects and representative explanatory variables included in models of blue crab density (crabs/m^2). Explanatory data were either collected at trapping locations or remotely recorded in San Antonio Bay, on the Guadalupe River, or at ANWR. Model analyses were performed separately for crabs 1-10 mm, 11-30 mm, 31-50 mm, and 51-130 mm.

Effect	Variable	Description of data
Bottom substrate	bsub	Bottom substrate (mud/sand, blocky clay, or shell/oyster) at trapping location.
Structure type	stype	Structure type (none, SAV, algae, SAV/algae) within water column at trapping location.
Structural complexity	scomp	Structural complexity (none, low, medium, high) within water column at trapping location.
Distance to ESV	dist	Shortest distance (m) from trapping location to ESV along pond or bay edge.
Dominant ESV	dom	Dominant ESV (*Spartina alterniflora*, *Batis maritima*, *Distichlis spicata*, mixed high-marsh vegetation, or other) along nearest pond or bay edge.
Presence of water	wpres	Presence or absence (0 or 1) of water at trapping location.
Water depth	wdm	Mean ([max + min]/2) water depth (cm) at trapping location.
	wlmx^1	Moving average of water level during x = 1, 7, 14, 21, or 28 days. (meters)
Water depth variability	wlvx^1	Water level variability ([max-min]/mean) during preceding x = 1, 7, 14, 21, or 28 days.
Water temperature	wts	Surface water temperature (°C) at trapping location.
	wtmx^2	Moving average of water temperature (°C) during x = 1, 7, 14, 21, or 28 days.
	wt15x^2 wt20x^2	Mean water temperature during preceding x = 1, 7, 14, 21, or 28 days, noted as above or below the lower threshold of optimal (15°C or 20°C) water temperature.

Table A2 continued.

Effect	Variable	Description of data
Water salinity	sal	Water salinity (ppt) at trapping location.
	sm$x$[2]	Moving average of daily salinity (ppt) during x = 1, 7, 14, 21, or 28 days.
	rdm$x$[3]	Moving average of daily river discharge (cubic ft/sec) during preceding x = 1, 7, 14, 21, or 28 days; represents inverse effect of water salinity.
	px[4]	Total precipitation (cm) during preceding x = 1, 7, 14, 21, or 28 days.
Water turbidity	ws$x$[1]	Moving average of daily wind speed (km/hr) during x = 1, 7, 14, 21, or 28 days; positively relates to water turbidity.
	wg$x$[1]	Moving average of daily speed (km/hr) of wind gusts during x = 1, 7, 14, 21, or 28 days; positively relates to water turbidity.
Recruitment abundance	meg[5] juv[5]	Relative abundance of crabs during the period of terminal megalopal settlement or post-metamorphosis to the juvenile life stage.
Habitat type	habitat	Habitat (bay, connected pond, unconnected pond) at trapping location; the full range of original habitat categories (bay, connected open water, connected pond edge, unconnected open water, unconnected pond edge) was also considered by omitting the effect of distance to ESV.

[1] Water and meteorological monitoring station no. 031 (Seadrift), Division of Nearshore Research, Texas A&M, Corpus Christi.
[2] Water and meteorological monitoring station no. 127 (GBRA#2), Division of Nearshore Research, Texas A&M, Corpus Christi.
[3] National Water Information System station 08188800 (Guadalupe River near Tivoli), U.S. Geological Survey.
[4] ANWR weather station (refuge headquarters), National Weather Service, National Oceanic and Atmospheric Administration.
[5] Empirical data from intensive study of megalopal settlement and juvenile recruitment patterns (related megalopal settlement study).

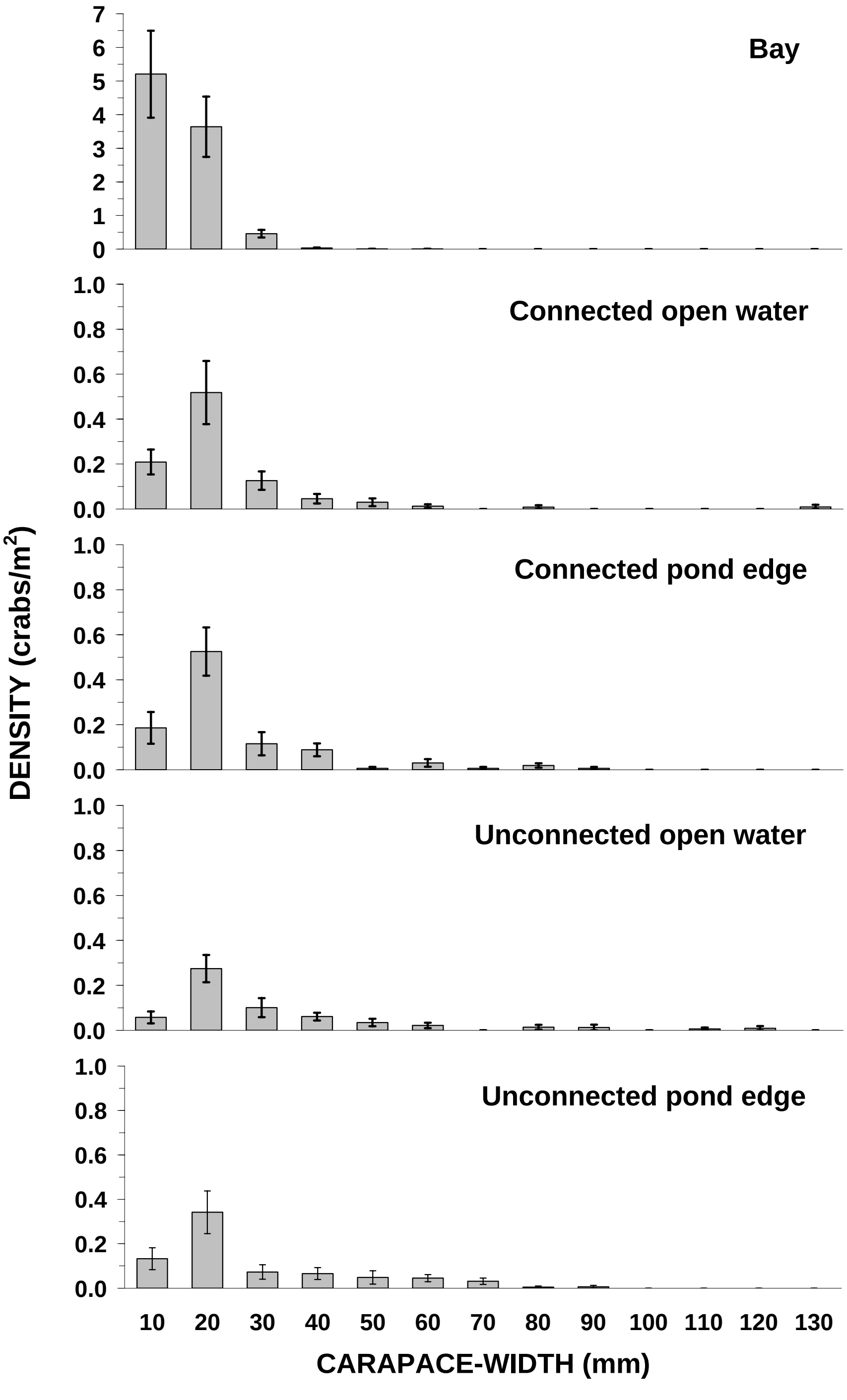


Figure A8. Mean density (crabs/m^2) of blue crabs by carapace width for each habitat, averaged over all months sampled between October 2004-March 2006. Crabs are grouped by increments of 10 mm, the upper bounds of which are noted along the x-axis. Notice the difference in scale along the y-axis between the bay and remaining habitats. Error bars represent variability in densities among months (±1 SE).

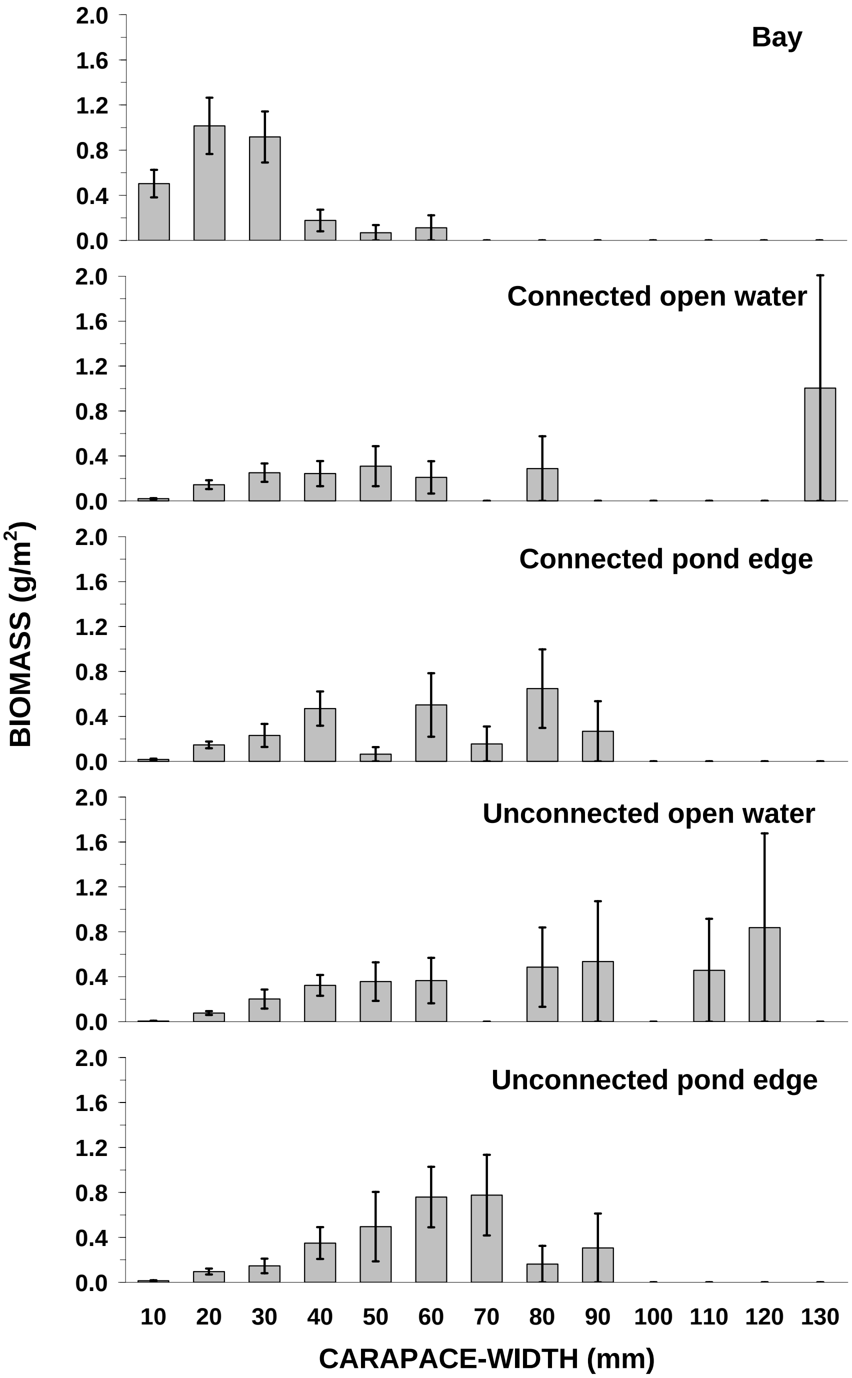


Figure A9. Mean biomass (g/m^2) of crabs by carapace-width for each habitat, averaged over all months sampled between October 2004-March 2006. Crabs are grouped by increments of 10 mm, the upper bounds of which are noted along the x-axis. Error bars represent variability in densities among months (±1 SE).

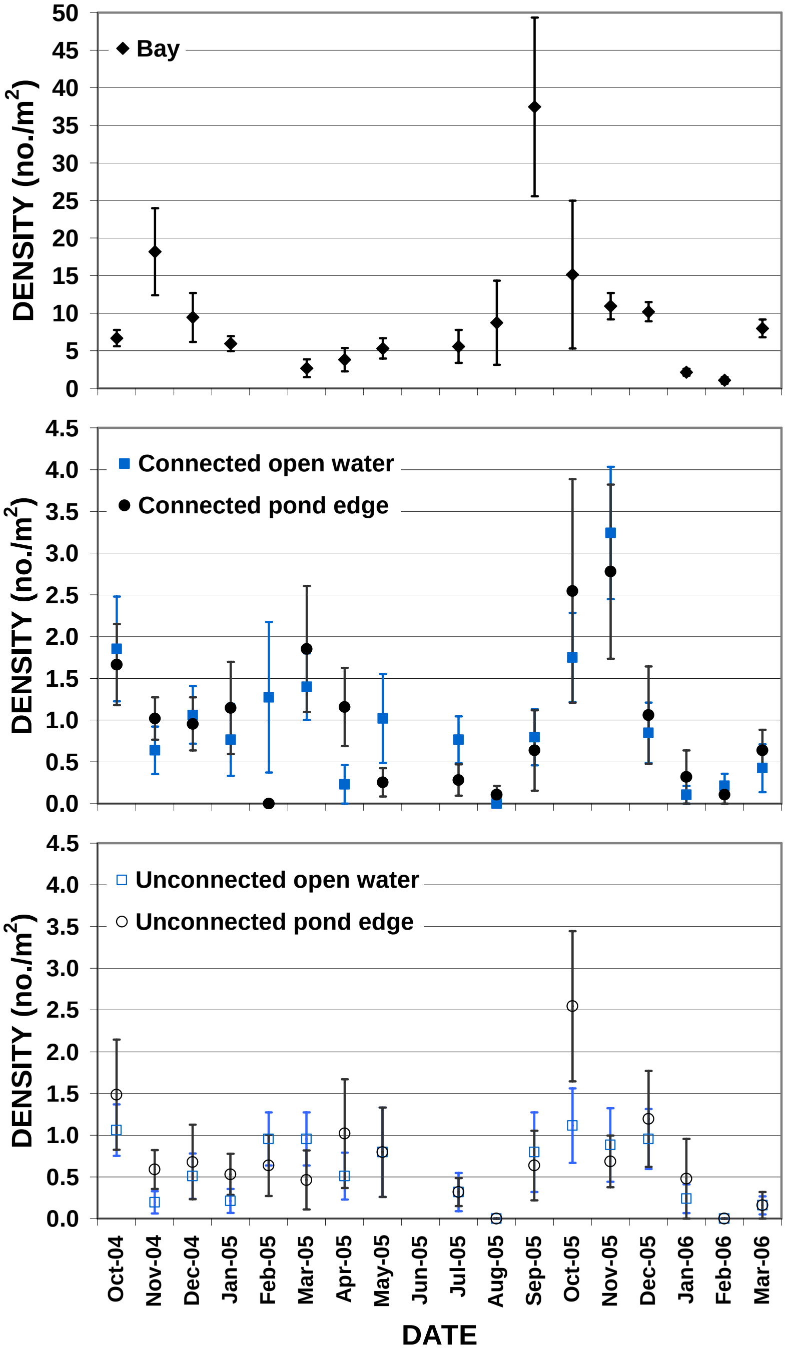


Figure A20. Mean crab density (crabs/m^2) by habitat during October 2004-March 2006. Habitats include bay-marsh interface (top graph), connected open water and pond edge (middle graph), and unconnected open water and pond edge (bottom graph). Notice difference in scale between bay and remaining habitats. Error bars represent variability in densities among sites (±1 SE).

Table A3. The best model (model 7) to approximate the density of crabs 1-10 mm in carapace-width (no. of crabs/m^2), along with hierarchical submodels in order of increasing model fit. Indices of model fit include (1) Pseudo-Akaike's Information Criteria values for small sample sizes (PAIC$_c$), (2) dispersion parameter $\hat{c}$ estimated by χ^2/df, (3) Pearson's product-moment correlation factor (r) describing the linear association between observed and predicted values of crab density, and (4) Pearson's product-moment correlation factor (r_{ave}) describing the linear association between observed and predicted values of crab density averaged across study sites per period.

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
PAIC$_c$	2004.14	1922.42	1906.21	1875.64	1854.11	1849.91	1854.62
$\hat{c}$	0.97	0.83	0.80	0.74	0.71	0.70	0.69
r	0.718	0.807	0.838	0.854	0.861	0.865	0.868
r_{ave}	0.785	0.888	0.924	0.935	0.940	0.952	0.959
--------	-----------------	------------------	-----------------	-----------------	------------------	------------------	-----------------
Fixed Effects	habitat stype scomp stype*scomp	habitat stype scomp stype*scomp sal14	habitat stype scomp stype*scomp sal14 wlm28	habitat stype scomp stype*scomp sal14 wlm28 wt14	habitat stype scomp stype*scomp sal14 wlm28 wt14 ws28	habitat stype scomp stype*scomp sal14 wlm28 wt14 ws28 wlm28*ws28	habitat stype scomp stype*scomp sal14 wlm28 wt14 ws28 wlm28*ws28 sal14*wt14

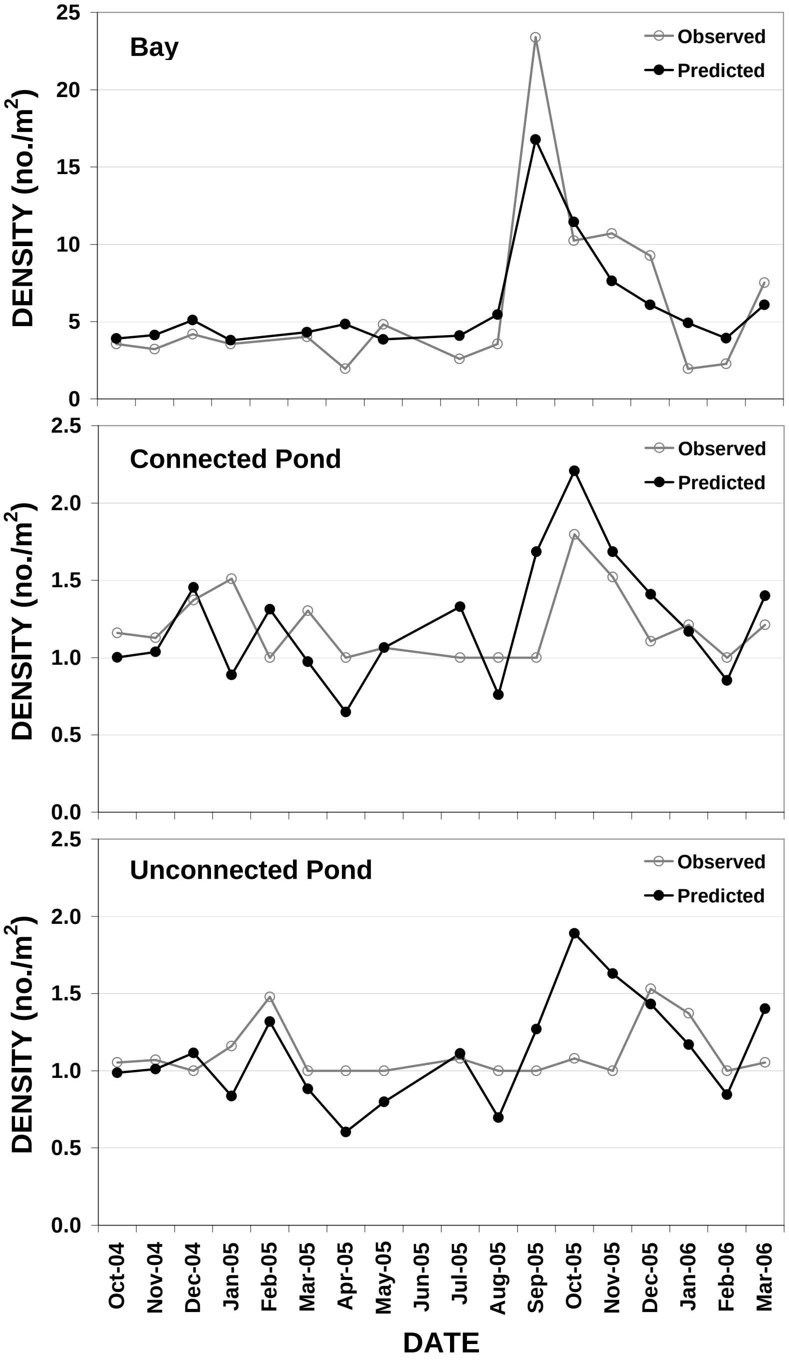


Figure A11. Overlay of mean predicted and observed crab densities (crabs/m^2) for crabs 1-10 mm (carapace-width) in bay, connected pond, and unconnected pond habitats (Boat Ramp, Pump Canal, and Pipeline study sites combined) between October 2004-March 2006. Predicted values were derived from model 5 (Table A3). Notice difference in scale between bay and remaining habitats.

Table A4. The best model (model 6) to approximate the density of crabs 11-30 mm in carapace-width (no. of crabs/m^2), along with hierarchical submodels in order of increasing model fit. Indices of model fit include (1) Pseudo-Akaike's Information Criteria values for small sample sizes (PAIC$_c$), (2) dispersion parameter $\hat{c}$ estimated by χ^2/df, (3) Pearson's product-moment correlation factor (r) describing the linear association between observed and predicted values of crab density, and (4) Pearson's product-moment correlation factor (r_{ave}) describing the linear association between observed and predicted values of crab density averaged across study sites per period.

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
PAIC$_c$	2174.81	2077.00	2048.57	2009.81	2004.10	1995.92
$\hat{c}$	1.37	1.23	1.18	1.12	1.11	1.10
r	0.658	0.690	0.710	0.728	0.731	0.731
r_{ave}	0.859	0.915	0.930	0.942	0.943	0.947
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Fixed Effects	habitat stype scomp stype*scomp	habitat stype scomp stype*scomp wlm28	habitat stype scomp stype*scomp wlm28 sal28	habitat stype scomp stype*scomp wlm28 sal28 distesv	habitat stype scomp stype*scomp wlm28 sal28 distesv ws28	habitat stype scomp stype*scomp wlm28 sal28 distesv ws28 wlm28*ws28

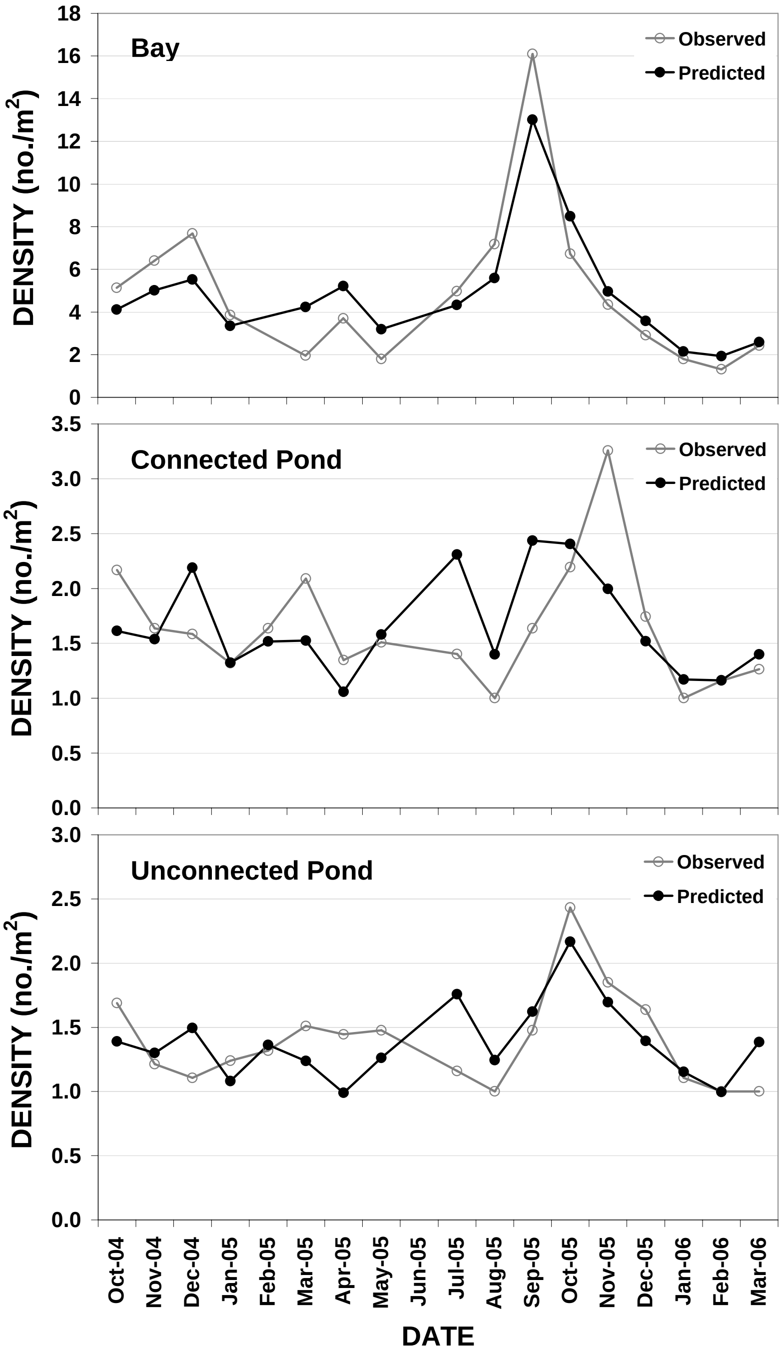


Figure A12. Overlay of mean predicted and observed crab densities (crabs/m^2) for crabs 11-30 mm (carapace-width) in bay, connected pond, and unconnected pond habitats (Boat Ramp, Pump Canal, and Pipeline study sites combined) between October 2004-March 2006. Predicted values were derived by the most parsimonious model of density (model 5, Table A12). Notice difference in scale between bay and remaining habitats.

8. Blue crab settlement and recruitment patterns in shallow habitats of the Texas Gulf Coast

Graduate student project: Danielle Greer – R. Douglas Slack (PhD advisor)

Project Overview
This study was led by D. Greer, a PhD student in the Department of Wildlife & Fisheries Sciences at Texas A&M University

The overall goal for this research was to examine the terminal settlement and recruitment patterns of blue crabs on the Texas Gulf Coast. Efforts were directed to shallow intertidal and subtidal habitats within and adjacent to salt marsh, because these habitats were the most probable locations for terminal settlement and megalopal metamorphosis to first-instar juvenile crab Specific objectives for this research were as follows:

1. Document long-term (2-year) patterns in settlement and recruitment rates at several shallow bay locations immediately adjacent to salt marsh.
2. Investigate the effects of stochasticity and environmental conditions (*e.g.*, freshwater discharge, water temperature, wind speed) on settlement and recruitment of blue crabs in shallow bay.
3. Investigate spatial patterns of megalopal settlement and juvenile recruitment in intertidal and subtidal habitats of the interior salt-marsh.

Methods

To facilitate both the crane and crab portions of our greater study, three of the 19 winter territories (hereafter, study sites) of whooping cranes located within ANWR were used as replicate study sites, including those named Boat Ramp (BR), Pump Canal (PC), and Pipeline (PL; Figure A13). Sampling also occurred within a fourth site, Mustang Bay (MB), which was not specifically associated with any crane territory and was used principally as a reference site. Distances to the nearest source of coastal water (larval supply) increased from MB (49 km) to BR (51 km), PC (56 km), and PL (59 km). Water within each study site was categorized by habitat and included one or more of the following habitat types: (1) bay-marsh interface (bay), (2) tidal creek (TC), (3) connected pond (CP), and (4) unconnected pond (UP). Habitats were not inherently represented at every study site.

Sampling efforts associated with each study objective differed by design. To examine fine-scale temporal trends in rates of megalopal settlement and juvenile recruitment in bay habitat and subsequently evaluate the semi-lunar sampling interval used at BR, PC, and PL for objectives 2 and 3, we sampled daily at four locations within MB during two distinct semi-lunar periods of time (objective 1). To investigate long-term trends in settlement and recruitment rates, we sampled at four locations within the bay habitat of each BR, PC, and PL during 46 semi-lunar periods between September 2003 and October 2005. To determine the spatial extent to which megalopae settled in the salt marsh and individuals were recruited into the crab population (*i.e.*, recently metamorphosed into juveniles), we sampled at four locations within each of the fixed habitats (TC, CP, UP) at each site (BR, PC, PL) during five distinct semi-lunar periods of time. For each objective, mean rates of megalopal settlement and juvenile recruitment were computed per experimental unit (habitat X study site X sampling period) using data acquired from the four sub-sample locations therein.

Our objectives precluded the use of standard collectors (Metcalf *et al.*, 1995) because water depths in bay habitat during low-water periods of the year and in interior-marsh habitats throughout the year were too low for vertically-oriented collectors. Modification of the dimensions and floating orientation of collectors was then essential for this study, as was an increase in the collection interval due to the intensity of data collection (*i.e.*, high spatial coverage and year-round and multi-year sample collection). Collectors were constructed by wrapping ca. 0.38 m^2 of blue hogs-hair furnace filter material (2 halves of 1 50-cm x 76-cm filter) length-wise around PVC piping (3.8-cm [1.5-in] diameter x 1.5-m [5-ft] length) and securing it with cable-ties. Four permanent stands, or collector stations, were installed in each habitat and site sampled. Collectors were secured to stands with rope and floated horizontally in the water column within 5-20 cm below the water's surface by attaching crab pot buoys to the ends of collectors (Figure A14).

Collectors were deployed at the start of collection periods, which began during the new or full moon and lasted one-half the lunar cycle (14-16 days). Sampling for objective 2 comprised a series of 14 daily collection periods during each of two non-adjacent semi-lunar periods, beginning with the full and new moon, respectively. At the end of each collection period, the deployed collectors were retrieved and when the end of one period coincided with the start of the next period, new collectors were deployed in their place. At times of collector deployment and/or retrieval, several environmental variables were measured at each collector station, including water temperature, salinity, and depth. Retrieved collectors were carefully disassembled and thoroughly washed with fresh water to remove all settled organisms and debris (Figure A14). All matter removed from collectors was preserved in formalin (10% formaldehyde) and taken to the lab for processing. In the lab, megalopal and juvenile crabs were identified and enumerated per sample. Juveniles were measured for CW (mm) and classified as either class 1 (1-5 mm, recruits) or class 2 (> 5 mm).

For all objectives, we calculated mean rates of megalopal settlement (number of megalopae/collector) and juvenile recruitment (number of class-1 juveniles/collector) per experimental unit. We also calculated collection rate of larger juveniles (number of class-2 juveniles/collector) for comparison. Differences in subsequent mean settlement and recruitment rates among sites, periods, or habitats were visually inspected rather than analyzed statistically.

We used an information theoretic approach to investigate causes of variability in mean rates of settlement and recruitment and developed *a priori* biological hypotheses concerning such variability. Hypotheses were used as the basis for subsequent development of several GLMMs of settlement rate and recruitment rate. Potential sources of variation included various forms of water salinity, water temperature, water level, and wind, as well as current and previous measures of megalopal settlement and random differentiation among study sites (Tables A5 & A6). Not all variables were included in model-building procedures, however, because preliminary examination revealed that most variables were not useful in predicting megalopal settlement or juvenile recruitment. All evaluated models, whether preliminary or otherwise, were GLMMs, because variation surrounding the mean responses of settlement and recruitment was explained by 1 or more fixed effects and a random effect (study site).

The Poisson distribution with canonical link function (log) was deemed appropriate because distributions of response variables were non-normal and zero-inflated. To minimize overdispersion, a value of one was added to each observed response. We used a manual stepwise selection procedure to select the most important explanatory variables of each settlement and recruitment rate and made decisions to remove or keep variables based on model fit and Pseudo-AICc values (Akaike 1973, Burnham and Anderson 2002). Model dispersion ($\hat{c} = \chi^2/\mathrm{df}$) was an important indicator of model fit. Values of $\hat{c} = 1$ were considered optimal (good model fit), whereas $1 < \hat{c} \leq 4$ indicated slight overdispersion with adequate model structure and $\hat{c} > 4$ indicated poor model structure (inadequate fit; Burnham and Anderson 2002: 67-69). The best fitting model of each settlement and recruitment rate, along with its hierarchical sub-models, were compiled for comparison.

Results

Efficacy of field methods.—The horizontal orientation and shallow draft of our modified collectors allowed collectors to float in all water depths observed during this study (14-103 cm). Furthermore, we were successful in deploying and retrieving collectors for every period attempted and in all habitats sampled. Of the total 718 samples collected during this study, 605 samples were collected in bay habitat and 113 samples were collected in tidal creek, connected pond, and unconnected pond combined.

Fine-scale temporal patterns in settlement and recruitment.— When collectors were exchanged daily during two series of 14 collection periods (7-21 March and 14-28 October 2004), two fine-scale patterns of settlement and recruitment were observed at MB: episodic and evenly distributed. During the first series, megalopal settlement was episodic, with over 90% of all settlers for the series collected in one day. Settlement during the second series occurred more frequently and at much lower levels. Mean settlement (± SD) during days of occurrence only was 14.63 ± 17.15 and 0.55 ± 0.41 megalopae/collector in March and October, respectively. Frequency of recruitment events was much less in March than October, but neither series was associated with high numbers of recruits (0.25 and 1.10 ± 0.77 class-1 juveniles/collector, respectively). Collection of class-2 juveniles occurred during all 14 collection periods (days) and was non-episodic for both series, but numbers of class-2 juveniles collected in March (0.98 ± 0.66 class-2 juveniles/collector) were lower and more evenly distributed across days than those of October (5.16 ± 4.56).

Long-term patterns in settlement and recruitment.—Megalopal settlement occurred throughout March-November, and recruitment occurred throughout most of the year, infrequently in January and March and never in February. Peak rates of settlement and recruitment generally occurred in spring (March-June) and fall (August-October). Mean settlement rate, variability surrounding the mean rate, and frequency of settlement events all decreased from BR to PC to PL (Figure A15). Specifically, the range of mean settlement rates among collection periods decreased from BR (0-55) to PC (0-8.8) to PL (0-1.5), and the percentage of all sampling periods resulting in at least one or more megalopae collected also decreased from BR (33.3%) to PC (28.9%) to PL (11.1%). Mean recruitment rate, variability surrounding the mean, and frequency of recruitment events were also higher at PC than PL but were lowest at BR. Specifically, the range of mean recruitment rates among collection periods decreased from PC (0-29) to PL (0-21) to BR (0-12), and frequency of recruitment events decreased from 56.8% at PC to 43.2% at PL and 26.8% at BR. Despite these latter findings, the proportion of settling individuals having recently metamorphosed from megalopa to juvenile dramatically increased from BR (27%) to PL (93%), indicating that megalopae were developmentally advanced by the time they reached our study sites, particularly PL. Class-2 juveniles ranged 6-60 mm in size and were collected during all periods of the study, except the first. Overall mean collection rates varied minimally across sites, but variability surrounding the mean rate per period increased from BR (0-12) to PC (0-17) to PL (0-26).

Prediction of settlement and recruitment rates.—
Of the candidate set of models, two models supported the data relatively well (models 5 and 6, Table A8). Model 5 was the most parsimonious model of the two and predicted the response relatively well (Figure A16). Predictors of settlement rate originated from several points during the recruitment process, including the probable periods of spawning and larva development (see Tables A5 & A6). The most important predictors of settlement rate, however, originated from the period of spawning and included the continuous form of water temperature, bivariate water temperature, and their interaction. Both water temperature and water level were positively related to settlement rate, but the exact nature of their relationships depended on whether temperature was above or at/below 20°C. The interacting effects of wind speed and direction were important in the model, because settlement increased with wind speed when winds were northerly but slightly decreased when winds were southeasterly. River discharge was negatively related to settlement and likely functioned as the inverse effect of salinity. The random effect of site in the model adjusted the predicted values of settlement rate for random differences among sites; such adjustments were consistent with results of descriptive statistics, which indicated mean settlement rate progressively decreased from BR to PC to PL.

Of the candidate set of models, two models supported the juvenile recruitment data (Models 4 and 6, Table A8). The strength of linear association between observed and predicted responses for model 6 was extremely high ($r = 0.902$) (Figure A17). Precipitation was the most important predictor of recruitment rate, demonstrating the lowest PAICc value and highest model fit of any single-fixed effect model. Moreover, correlation of observed and predicted responses from this model revealed strength of linear association at 56% ($r = 0.557$) (Figure A17). Recruitment rate was positively related to both precipitation and water level. The interaction of wind speed and direction revealed that recruitment increased with wind speed but the effect of increasing wind speed from the north was considerably greater than from the southeast. As with models of settlement, random effect estimates used to adjust recruitment predictions at each site mirrored descriptive results presented earlier, which indicated recruitment rate decreased from PC to PL to BR.

Spatial patterns in settlement and recruitment.—The spatial extent to which crabs were found in salt-marsh was related to stage of development. Megalopal crabs were collected in tidal creek habitat during two of four collection periods and were never found in either connected or unconnected pond habitats. Collection of class-1 juveniles (recruits) occurred in tidal creek habitat during all four periods sampled and connected pond habitat during two of four sample periods; recruits were never found in unconnected ponds (Figure A18). Class-2 juveniles were collected in nearly every habitat and time period combination sampled (Figure A18). Thus, the extent to which young crabs infiltrated the salt marsh increased with age and mobility associated with advancements in development.

Conclusions

The field methods used in this study, particularly the horizontal orientation and shallow draft of our modified settlement collectors, proved highly effective for estimating and monitoring relative rates of nekton settlement in extremely shallow estuarine habitats. Observed high rates of metamorphosis from megalopa to juvenile crab and gradual, age-dependent infiltration of crabs into adjacent salt marsh suggest that our study sites were not only representative of terminal settlement habitat but also critical nursery habitat. Our model-building efforts indicated that developing crabs are influenced by numerous abiotic factors that act like filters along the pathway from spawned egg to terminal settlement site. Most importantly, our study revealed that water temperature during the period of spawning and larval export may be the most significant predictor of megalopal settlement, which in turn determines juvenile recruitment.

Figure A13**.** Study sites located along the eastern perimeter of Blackjack Peninsula, Aransas County, Texas. From north to south, Boat Ramp (top), Pump Canal (middle), and Pipeline (bottom).

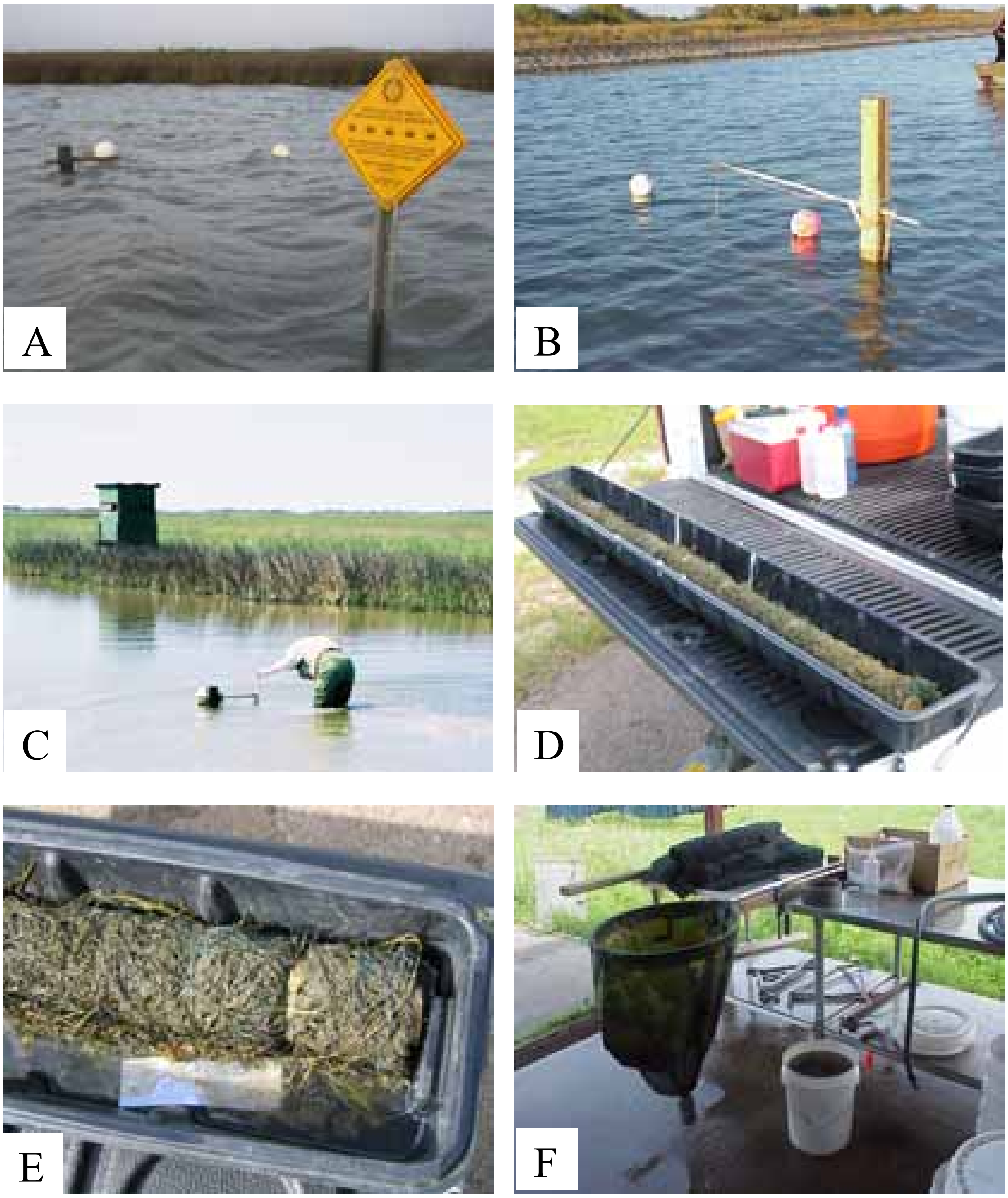


Figure A14. Megalopae collector stations and the post-deployment process. Bay stations included reinforced wooden (A) or galvanized steel (B) stands, rope, the collector (*i.e.*, artificial habitat), and two crabpot buoys. Stations in interior salt-marsh habitats did not require reinforcement, and only small stringer floats were used. Upon collector retrieval, environmental characteristics were recorded (C), and collectors were placed into trays and transported to land (D and E). Filters were removed from PVC piping, placed in buckets filled with freshwater, and thoroughly washed to remove all organisms (F).

Table A5. Fixed effects included in global models of blue crab megalopal settlement. Descriptive measures of each water temperature, salinity, water level, and wind corresponded to the period of spawning and larval export (S) or period of larval and post-larval development and estuary invasion (D). Period S was represented by the string of x = 7, 14, 21, or 28 days ending y = 28, 35, 42, or 49 days ago. Period D was the x = 1, 7, 14, 21, 28, or 35 days immediately prior to and including the date of collector retrieval.

Variable	Description
Water temperature	
wtm	Mean water temperature (°C).
wt$x.y$[1]	Mean water temperature during S.
wt$x$[1]	Mean water temperature during D.
wt$z.x.y$[1]	Binomial random variable indicating water temperature during S was either $\leq z$ or $> z$ where z = 15°C or 20°C.
wt$z.x$[1]	Binomial random variable, indicating water temperature during D was either $\leq z$ or $> z$ where z = 15°C or 20°C.
Water salinity	
sm	Mean water salinity (ppt) recorded per experimental unit.
rd$x.y$[2]	Mean river discharge (cubic ft/sec) during S.
rdm$x$[2]	Mean river discharge during D.
rdv$x$[2]	Variability in river discharge ([max-min]/mean) during D.
px[3]	Total precipitation (cm) during D.
Water level	
wpm	Mean water depth (cm) recorded per experimental unit.
wl$x.y$[1]	Mean water level (m above reference datum) during S.
wlm$x$[1]	Mean water level during D.
wlv$x$[1]	Variability in water level ([max-min]/mean) during D.
Wind	
ws$x$[1]	Mean wind speed (km/hr) during D.
wg$x$[1]	Mean gust speed (km/hr) during D.
wd$x$[1]	Modal wind direction (N, NE, E, SE, S, SW, W, NW) during D.

[1] Data recorded at Seadrift (031) by the Division of Nearshore Research, Texas A&M, Corpus Christi.

[2] Data recorded at station Guadalupe River near Tivoli (08188800) by the U.S. Geological Survey.

[3] Data recorded at ANWR weather station as part of the National Weather Service, NOAA.

Table A6. Fixed effects included in global models of blue crab juvenile recruitment. Descriptive measures of each water temperature, salinity, water level, and wind corresponded to the $x = 1$, 7, or 14 consecutive days preceding and including the date of collector retrieval. Such timing represented the period occurring immediately prior to and following metamorphosis from megalopa to juvenile crab (M).

Variable	Description
Water temperature	
wtm	Mean water temperature (°C) recorded.
wtx^1	Mean water temperature during M.
wt$y.x^1$	Binomial random variable indicating water temperature during M was either $\leq y$ or $> y$ where $y = 15$°C or 20°C.
Water salinity	
sm	Mean water salinity (ppt) recorded.
rdmx^2	Mean river discharge (cu ft/sec) during M.
rdvx^2	Variability in river discharge ([max-min]/mean) during M.
px^3	Total precipitation (cm) during M.
Water level	
wpm	Mean water depth (cm) recorded.
wlmx^1	Mean water level (m above reference datum) during M.
wlvx^1	Variability in water level ([max-min]/mean) during M.
Wind	
wsx^1	Mean wind speed (km/hr) during M.
wgx^1	Mean gust speed (km/hr) during M.
wdx^1	Modal wind direction (N, NE, E, SE, S, SW, W, NW) during M.

[1] Data recorded at Seadrift (031) by the Division of Nearshore Research, Texas A&M, Corpus Christi.
[2] Data recorded at station Guadalupe River near Tivoli (08188800) by the U.S. Geological Survey.
[3] Data recorded at ANWR weather station as part of the National Weather Service, NOAA.

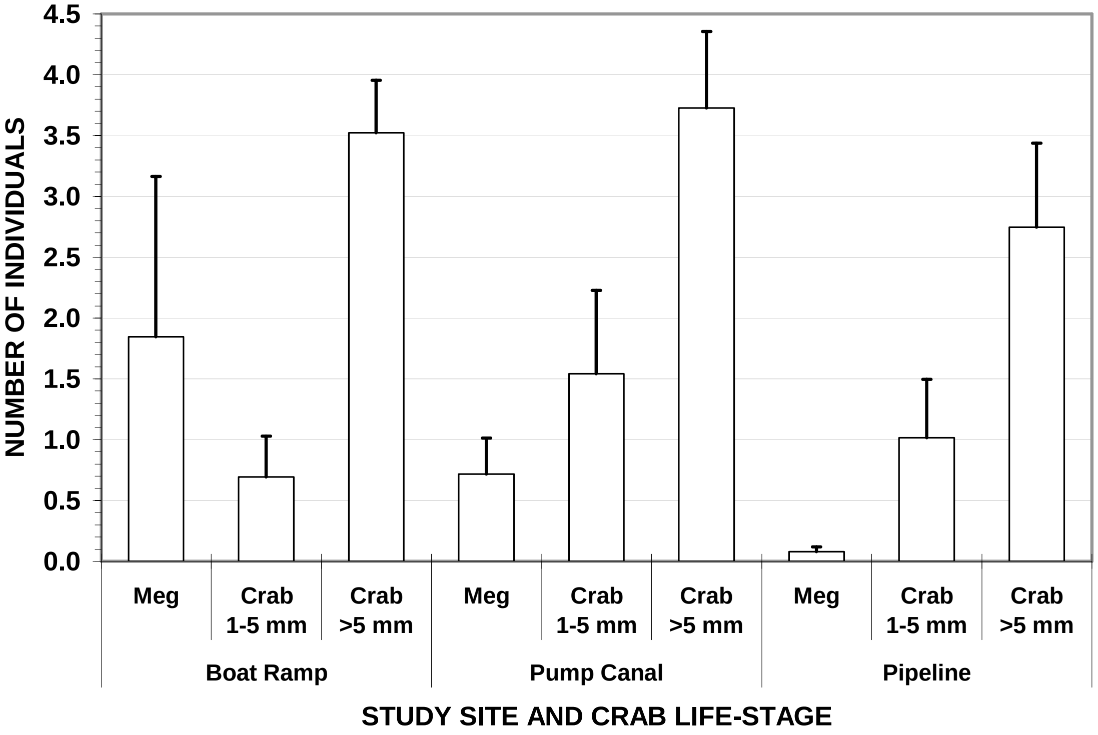


Figure A15. Mean number of blue crab megalopae (*Meg*), class-1 juveniles (crabs 1-5 mm), and class-2 juveniles (crabs >5 mm) settled per collector in the bay habitat of each study site for all collection periods combined (25 Sep 2003-18 Sep 2005).

Table A7. The best approximating model (model 6) of megalopal settlement rate (no. of megalopae/collector) with hierarchical submodels in order of increasing model fit. Indices of model fit include (1) Pseudo-Akaike's Information Criteria values for small sample sizes (PAIC$_c$), (2) dispersion parameter $\hat{c}$ estimated by χ^2/df, (3) Pearson's product-moment correlation factor (*r*) describing the correlation between observed and predicted values of megalopal settlement, and (4) Pearson's product-moment correlation factor (r_{ave}) describing the correlation between observed and predicted values of megalopal settlement averaged across study sites per period.

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
PAIC$_c$	572.50	411.53	399.62	382.33	366.90	345.77
$\hat{c}$	2.75	1.45	1.22	1.16	1.10	1.03
r	0.467	0.765	0.798	0.821	0.825	0.824
r_{ave}	0.575	0.922	0.964	0.979	0.985	0.992
Fixed Effects	wt42.28 wt49.28.20 wt42.28*wt49.28.20	wt42.28 wt20.49.28 wt42.28*wt20.49.28 ws35 wd35 ws35*wd35	wt42.28 wt20.49.28 wt42.28*wt20.49.28 ws35 wd35 ws35*wd35 rm35.07	wt42.28 wt20.49.28 wt42.28*wt20.49.28 ws35 wd35 ws35*wd35 rm35.07 wl35.07 wl35.07*wt20.49.28	wt42.28 wt20.49.28 wt42.28*wt20.49.28 ws35 wd35 ws35*wd35 rd35.07 wl35.07 wl35.07*wt20.49.28 wlm21 wlm21*wt20.49.28	wt42.28 wt20.49.28 wt42.28*wt20.49.28 ws35 wd35 ws35*wd35 rd35.07 wl35.07 wl35.07*wt20.49.28 wlm21 wlm21*wt20.49.28 wlv21 wlm21*wlv21 wlv21*wt20.49.28 wlm21*wlv21*wt20.49.28

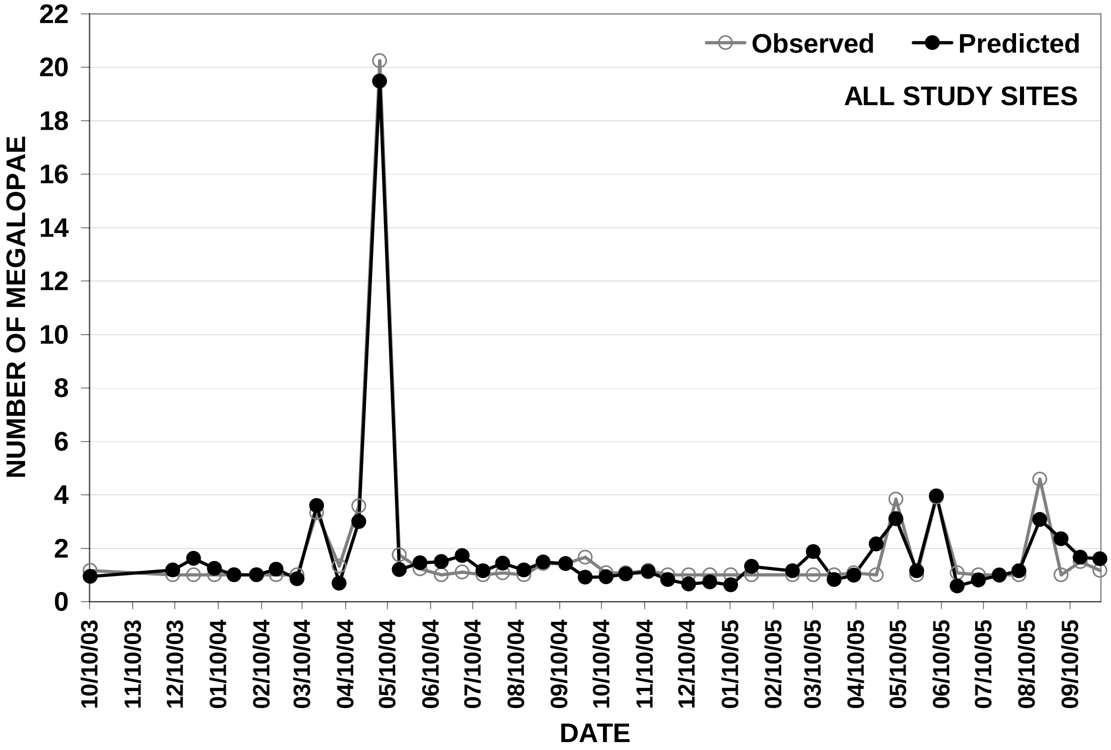


Figure A16. Overlay of observed and predicted values of megalopal settlement rate (no. of megalopae/collector) averaged as across study sites per period. Predicted values were derived using model 5 (Table A7).

Table A8. The best approximating model (model 6) of juvenile recruitment rate (no. of class-1 [1-5 mm] juveniles/collector) with hierarchical submodels, in order of increasing model fit. Indices of model fit include (1) Pseudo-Akaike's Information Criteria values for small sample sizes ($PAIC_c$), (2) dispersion parameter $\hat{c}$ estimated by χ^2/df, (3) Pearson's product-moment correlation factor (r) describing the correlation between observed and predicted values of megalopal settlement per experimental unit, and (4) Pearson's product-moment correlation factor (r_{ave}) describing the correlation between observed and predicted values of megalopal settlement averaged across study sites per period.

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
$PAIC_c$	409.48	386.27	334.47	328.00	303.10	300.62
$\hat{c}$	1.75	1.53	1.15	1.06	0.78	0.72
r	0.557	0.694	0.837	0.855	0.883	0.902
r_{ave}	0.557	0.728	0.881	0.898	0.903	0.924
--------	-------------	-------------	-------------	-------------	-------------	-------------
Fixed Effects	pp14	pp14 wlm14	pp14 wlm14 wd1	pp14 wlm14 ws1 wd1 ws1*wd1	pp14 wlm14 ws1 meg	pp14 wlm14 ws1 wd1 ws1*wd1 meg

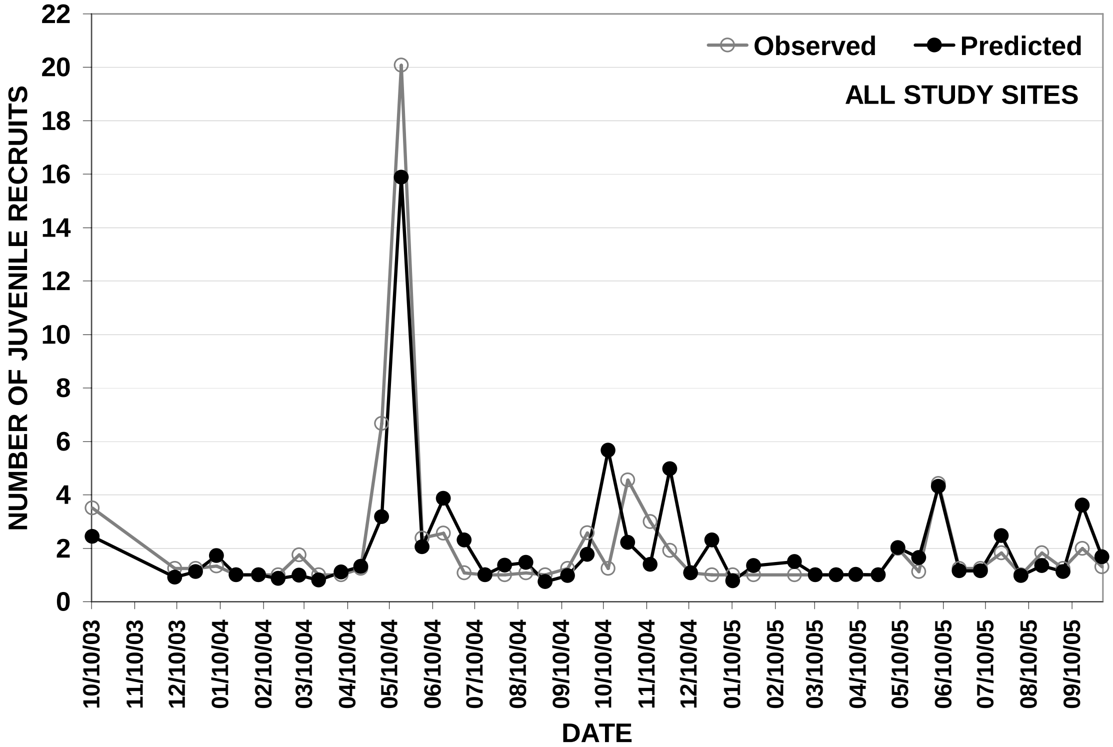


Figure A17. Overlay of observed and predicted values of juvenile recruitment rate (no. of juvenile recruits/collector) averaged across study sites per period. Predicted values were derived model 4 (Table A8).

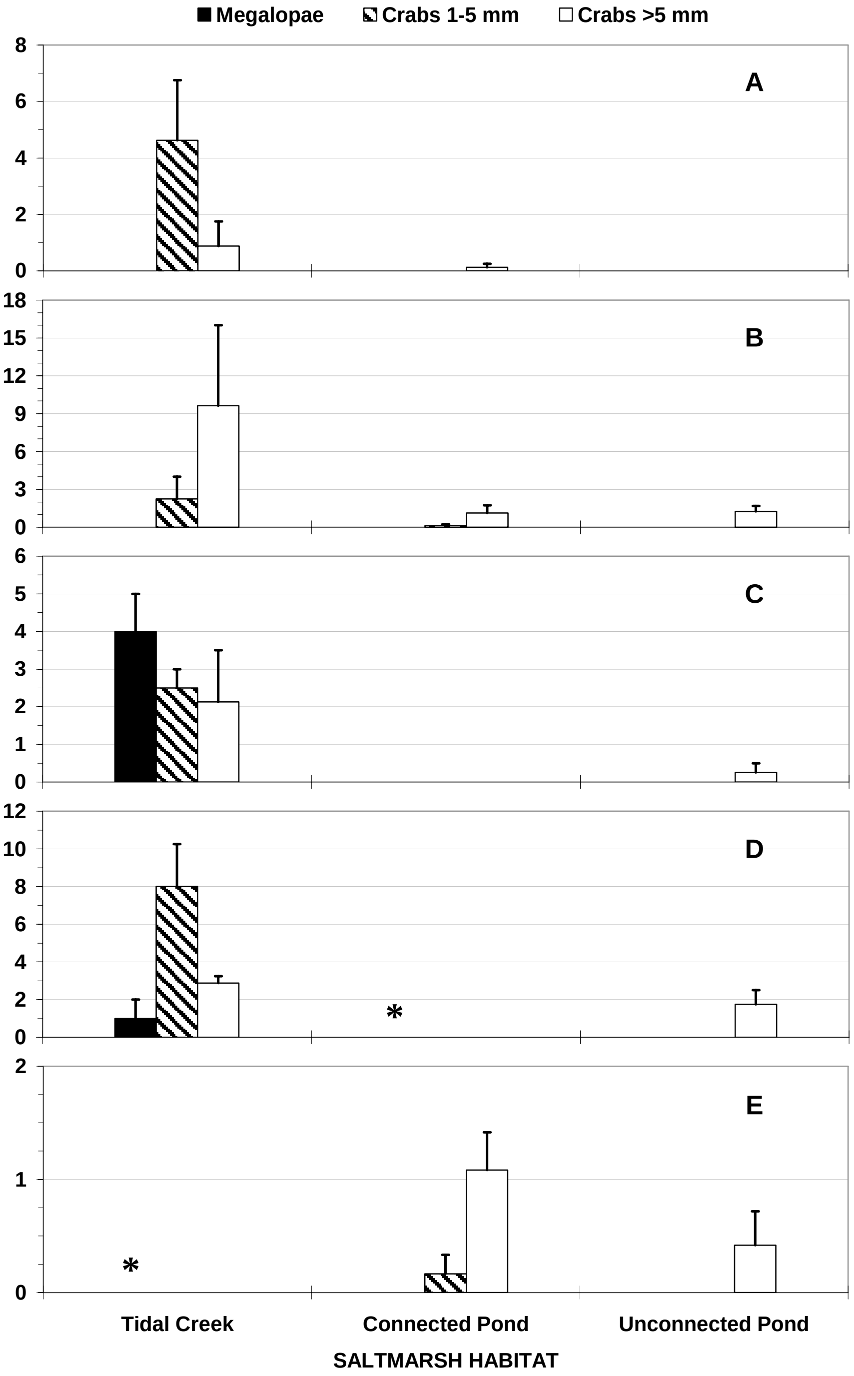


Figure A18. Mean number of blue crab megalopae, class-1 juveniles (crabs 1-5 mm), and class-2 juveniles (crabs >5 mm) settled per collector in each interior salt marsh habitat sampled for all study sites combined during each of 5 collection periods: (A) 25 September-10 October 2003, (B) 18 May-2 June 2004, (C) 28 September-13 October 2004, (D) 13-27 October 2004, and (E) 17 September-1 October 2005.

9. Whooping crane foraging ecology: Gains, costs, and efficiency of foraging during winter

Graduate student project: Danielle Greer – R. Douglas Slack (PhD advisor)

Project overview

This study was led by D. Greer, a PhD student in the Department of Wildlife & Fisheries Sciences at Texas A&M University

Our overall goal for this research was to determine the winter foods of greatest value to adult whooping cranes at ANWR. Our approach was to quantify the contribution of foods to the crane's diet, as well as the gains, costs, and overall benefits achieved by cranes when foraging for foods. Specific objectives were as follows:

1. Document temporal (within and across winters) and spatial (within and across crane territories) variability in proportional use of foods by cranes.
2. Document temporal and spatial variability in foraging gains, represented by numeric (frequency), dry mass, lipid, energy, and protein intake rates.
3. Quantify the effort required to search for and handle foods (*e.g.*, steps, probes, food manipulations), representing the costs of foraging.
4. Quantify the optimality of foraging for foods by calculating indices of foraging efficiency (*i.e.*, ratios of gains : costs).

Methods

We studied four of 19 winter territories of whooping cranes located on the Blackjack Peninsula of ANWR during November-March of winters 2004-2005 (winter 1) and 2005-2006 (winter 2). Three territories, named Boat Ramp (BR), Pump Canal (PC), and Pipeline (PL), were selected based on ease of inland access (*e.g.*, road, levee or mowed trail) to ensure sites could be visited when boating conditions were sub-optimal (Figure A6). The fourth territory, Blackjack (BJ), was located directly across St. Charles Bay from Goose Island State Park and therefore most easily accessed by boat, but it was specifically selected to increase spatial distribution of study sites on Blackjack Peninsula. All sites were considered fully representative of the contiguous salt marsh and adjacent bay habitat in which they were located.

To collect data on food consumption (*i.e.*, foraging gains) and foraging effort (*i.e.*, costs of foraging), we observed whooping cranes from observation blinds that were permanently situated along the perimeter of crane territories (Figure A19). We video-recorded cranes for approximately 25 minutes of foraging behavior and later watched videos to transcribe data. Only one observation session was conducted per daylight hour-block (*e.g.*, 0700, 0800, 0900,… 1700) on any one day. Recordings were made using a digital camcorder, but close-up views of the cranes were made possible with attachment of a 2000-mm telescope lens and spy camera (Figure A19). During video-recording, we selected only adult cranes for observation and tracked one crane at a time. Sessions were less than 25 minutes when both adult birds either walked or flew out of view for the remainder of the hour block. Foraging behavior did not differ among hour-blocks, so data from each combination of winter, month, and territory were compiled to define experimental units.

When watching videos, we recorded several random variables, including total length of time spent foraging by the focal crane, total number of items consumed per food type, and total numbers of steps, probes, and food manipulations (*e.g.*, jabs, violent head-shaking, nibbling) per observation session. Because blue crab was a food previously identified as important to whooping cranes, we identified *a priori* three categories within which to tally the number of blue crab consumed: (1) small blue crab, i.e., crab CW ≤ 25% of the crane's bill length, (2) medium blue crab, i.e., CW > 25% and ≤ 50% of bill, and (3) large blue crab, *i.e.*, CW > 50% of bill. When food items were not identifiable by sight, food type was either inferred from crane behavior (seen previously with confirmed foods) or deemed unknown.

To examine the proportional use of foods by cranes, we calculated per observation session the percentage of total dry mass in the diet comprised by each food type. To examine foraging gains, we calculated the rate of numeric intake per food type and subsequently derived dry mass (g/min), energy (kJ/min), protein (mg/min), and lipid (mg/min) intake rates using the appropriate conversion factors or coefficients for dry mass and nutritive contents in food. To examine the costs of foraging, we calculated rates of stepping (number of steps/minute), probing (number of probes/min), and handling (number of food manipulations/min) and considered these to be indices of foraging effort. We summarized each computed variable per month and per season for each territory and overall. Temporal and spatial variability in diet were further examined using Pearson's chi-square statistic and the Breslow-Day test of homogeneity of odds ratios; intake rates and measures of foraging effort did not undergo statistical testing.

Findings related to the gains and costs of foraging were integrated to explore the efficiency of crane foraging. Efficiency was defined as the ratio of mean total numeric, dry mass, energy, protein, or lipid intake rate to total foraging effort (total number of foraging movements/min). Because steps, probes, and food manipulations were not always counted within the same observation session (at the sub-sample level), total foraging effort was determined by adding together the mean rates of stepping, probing, and handling at the level of the experimental unit. For each type of efficiency (*i.e.*, numeric, mass, energy, protein, lipid), we compared efficiency values among foods to demonstrate variability in optimality associated with foraging for foods. Values were $ln(x+1)$ transformed due to non-normal distributions and then analyzed using ANOVA. Multiple comparisons were performed using the Waller-Duncan method (alpha = 0.05) to identify specific differences among foods.

Results

During winters 1 and 2, respectively, 105 and 120 observation sessions were successfully conducted from over 300 and 400 hours attempted.

Composition and proportional use of foods in the crane diet.—The whooping crane diet comprised wolfberry fruit, blue crab, razor clam, periwinkle snail, unknown insect, fiddler crab, and unknown snake and fish. With the exception of wolfberry fruit, the overall mean proportional use of foods in the diet differed considerably between winter 1 and winter 2. Percent of the diet containing blue crab (all sizes combined) declined by over 80% from winter 1 to winter 2, clam and blue crab-or-clam combined (hereafter, clam) nearly doubled, and snail, insect and snail-or-insect combined (hereafter, snail-and-insect) tripled from winter 1 to 2. Percent diet of all other foods combined was consistent between winters (< 2%).

Wolfberry fruit was a principal food of territorial cranes in November of winter 1 (100%) and in November (47%) and December (90%) of winter 2. In winter 1, proportional use of blue crab was highest in December (90%) and subsequently decreased (to 28%); medium blue crab made up 50-91% of all blue crab consumed. During winter 2, blue crab made up 20% of the diet in November but was minimally used thereafter (0-7%). Of all blue crab consumed in winter 2, 71-80% were large crabs. The odds of cranes consuming small blue crab during either winter were near or equal to zero. Clam was a significant food for cranes during January-March of winter 1 (32-44%) and in all months except December in winter 2 (15-88%). Peak use of clam occurred in January in both winters. The discontinuation of wolfberry fruit and gradual decrease of blue crabs and clams in the cranes' diet was offset by a marked increase in use of snail-and-insect during both winter 1 (max 34%) and winter 2 (max 78%).

The winter diets of whooping cranes observed in this study were somewhat distinctive among territories. For instance, clam was consumed in greater proportion and more consistently across months at BR than in any other territory during both winters. Percent diet of wolfberry fruits and blue crabs at PC and PL was generally more than observed at BR.

Foraging gains.—Foraging gains incurred by whooping cranes, as measured by numeric, dry mass, energy, protein, and lipid intake rates, were over twice as much in winter 2 as winter 1. Intake of wolfberry fruit increased 3.7-fold from winter 1 to 2, despite concurrent findings of equivalent proportional use. Dry mass intake of blue crab (all sizes combined) declined 70%, and medium and large blue crabs intake decreased by 90% and 43%, respectively, from winter 1 to 2. Consumption of blue crab was predominantly of medium crabs in winter 1 (1.5 times that of large crabs) and large crabs in winter 2 (over four times that of medium crabs). Small blue crabs were rarely consumed and comprised less than 2% of all blue crabs consumed in either winter. Intake of clam was consistent between winters. Snails and insects were consumed in quantities 8.5 times greater in winter 2 than 1, and all other foods combined comprised less than 1% of total intake.

Whooping cranes consumed wolfberry fruits at overall mean rates of numeric intake greater than any other foods during both winters. The next most frequently consumed foods, snails and insects and clams, were respectively consumed at rates 35-52% and 4-15% that of wolfberry fruits. The highest overall mean rates of dry mass intake were achieved by cranes when feeding for either clams or snails and insects, whereas snails and insects was consumed at overall mean rates of energy and lipid intake equal to or greater than all other foods combined. Overall mean rates of protein intake for snails and insects and blue crabs were similar to each other and 2.5 times greater than clams in winter 1. In winter 2, intake of snails and insects contributed 84% to the total rate of protein intake and was 12, 15, and 23 times that of clams, blue crabs, and wolfberry fruits, respectively.

All measures of intake rate, except frequency, were highest for whooping cranes in late winter (February-March) when snails and insects were the major food group targeted (Figures A20 & A21). Numeric intake was alternatively highest during early winter (November-December), when wolfberry fruits were actively consumed, and secondarily highest in late winter. It was lowest in January, when foods consumed by cranes were principally clams. Conversely, dry mass intake generally increased from November to March, as the crane diet increasingly incorporated more profitable foods, such as clams and snails and insects. In addition to snails and insects as a major source of protein for cranes, total protein intake was also high during December-January of winter 1 when the diet principally comprised blue crabs. Intake rates during December-January of winter 2 were considerably lower than those of winter 1, as blue crabs entered the diet minimally.

Foraging costs.—Cranes exhibited relatively distinct levels of foraging effort for specific food types (Table A9). Effort required to forage for wolfberry fruits was less than any other food in the crane's diet and involved only stepping. Snails and insects required only slightly more effort, principally through stepping and low levels of probing. Blue crabs were the next most "expensive" food, requiring relatively high levels of stepping, low levels of probing, and high levels of handling. When foraging for clams, cranes stepped and handled food relatively infrequently but probed at higher and more variable rates than for any other food type. Effort required to search for, capture, and consume fiddler crabs was somewhat similar to that for blue crabs, only more variable and costly in each component of foraging (stepping, probing, handling).

Foraging efficiency.—Whooping cranes foraged 3-7 times more efficiently during winter 2 than 1, as determined by all five types of foraging efficiency. During both winters, efficiency was highest early (November and/or December) and late (February and/or March) in winter and lowest in January (Table A10). Early winter peaks in efficiency corresponded with peak use of wolfberry fruits in nearly all cases, and late winter peaks corresponded perfectly with peak consumption of snail-and-insect. Low efficiency in January paralleled peak use of clams. Foraging efficiency varied among cranes of different territories. Those at PC generally exhibited the highest levels of efficiency during both winters; whereas cranes in PL and BR experienced the lowest levels of efficiency during winters 1 and 2, respectively.

Other important discoveries were made by comparing the efficiency of foraging among foods. First, the most optimal foods for whooping cranes varied by efficiency type, depending on the specific resource gained (*e.g.*, number of food items vs. energy gain). Wolfberry fruits and snails and insects were the most optimal foods according to numeric, lipid, and energy efficiencies, but cranes foraging for mass were most efficient when feeding on snails and insects and clams. In addition, optimal foraging for protein was achieved when cranes targeted snails and insects and large blue crabs. We were also able to quantify the optimality of foraging for blue crabs of different size. Foraging for small blue crabs was more efficient than foraging for either medium or large blue crabs when number of food items consumed mattered. However, small blue crabs never significantly contributed to dry mass, energy, protein, or lipid intake and, consequently, were assumed to be the least optimal of the three crab sizes. In all cases other than numeric efficiency, foraging for large blue crabs was more efficient than foraging medium blue crabs.

Conclusions

The whooping crane diet incorporated wolfberry fruits, blue crabs, clams, snails and insects, fiddler crabs, snakes, and fish. Overall benefit achieved from foraging differed among foods, depending on the foraging currency used (*e.g.*, intake rate, effort, efficiency), resource gained or conserved (*e.g.*, number of food items, biomass, energy, protein), and temporal patterns of food availability during winter. Wolfberry fruits and snails and insects were consumed in the highest quantities, required the least effort during foraging, and generally were associated with the most efficient foraging behavior. However, blue crabs were the most optimal food when foraging for protein, and clams were a significant source of biomass.

Figure A19. Observation blind (top) and video-recording system (bottom) used to collect diet and foraging behavior data from whooping cranes at ANWR during winters 2004-2005 and 2005-2006.

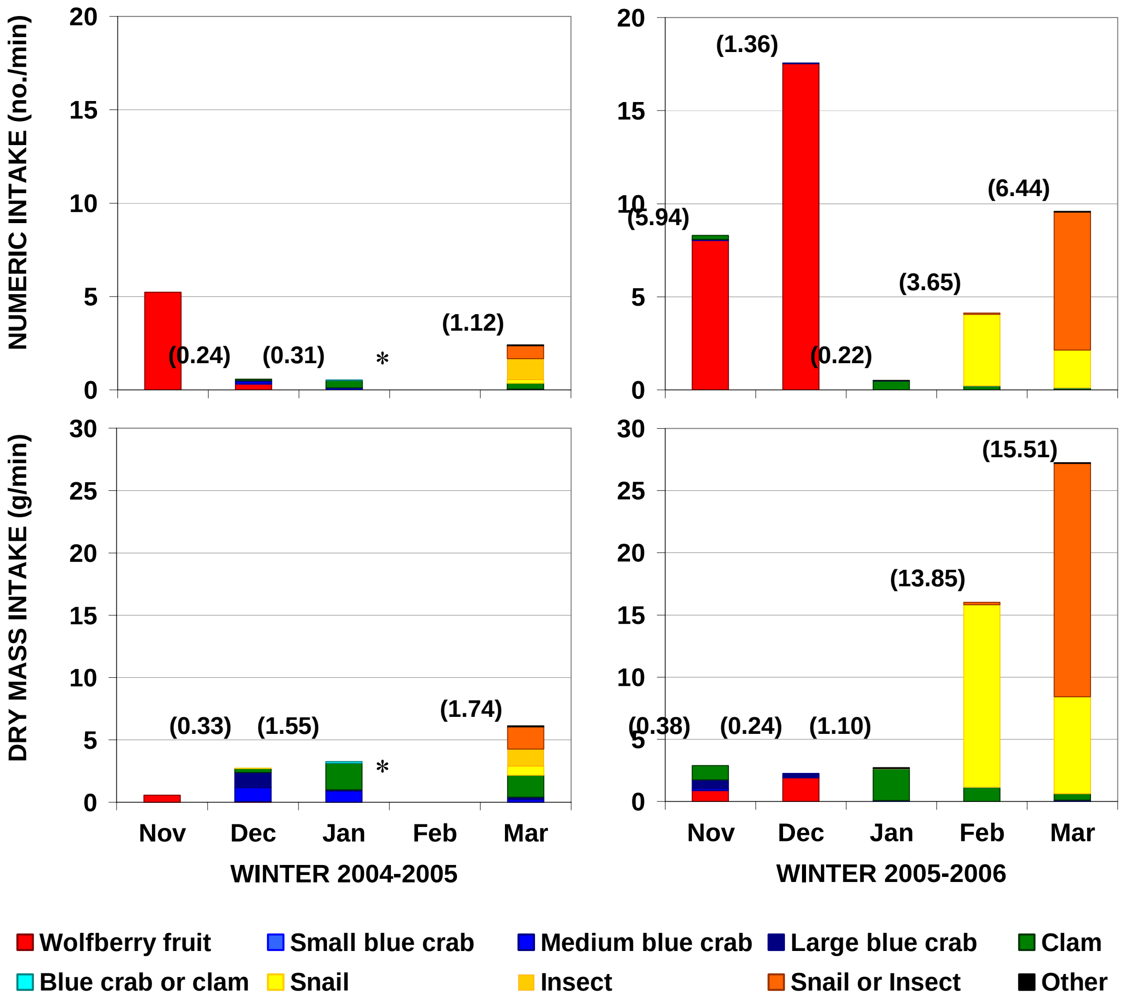


Figure A20. Contribution of foods to mean numeric and dry mass intake rates for whooping cranes during each month of winters 2004-2005 and 2005-2006. Standard errors (in parentheses) represent variability among territories (*n* = 3 territories for all months, except *n* = 1 territory in Nov 2004). No data were collected in February 2005 (*).

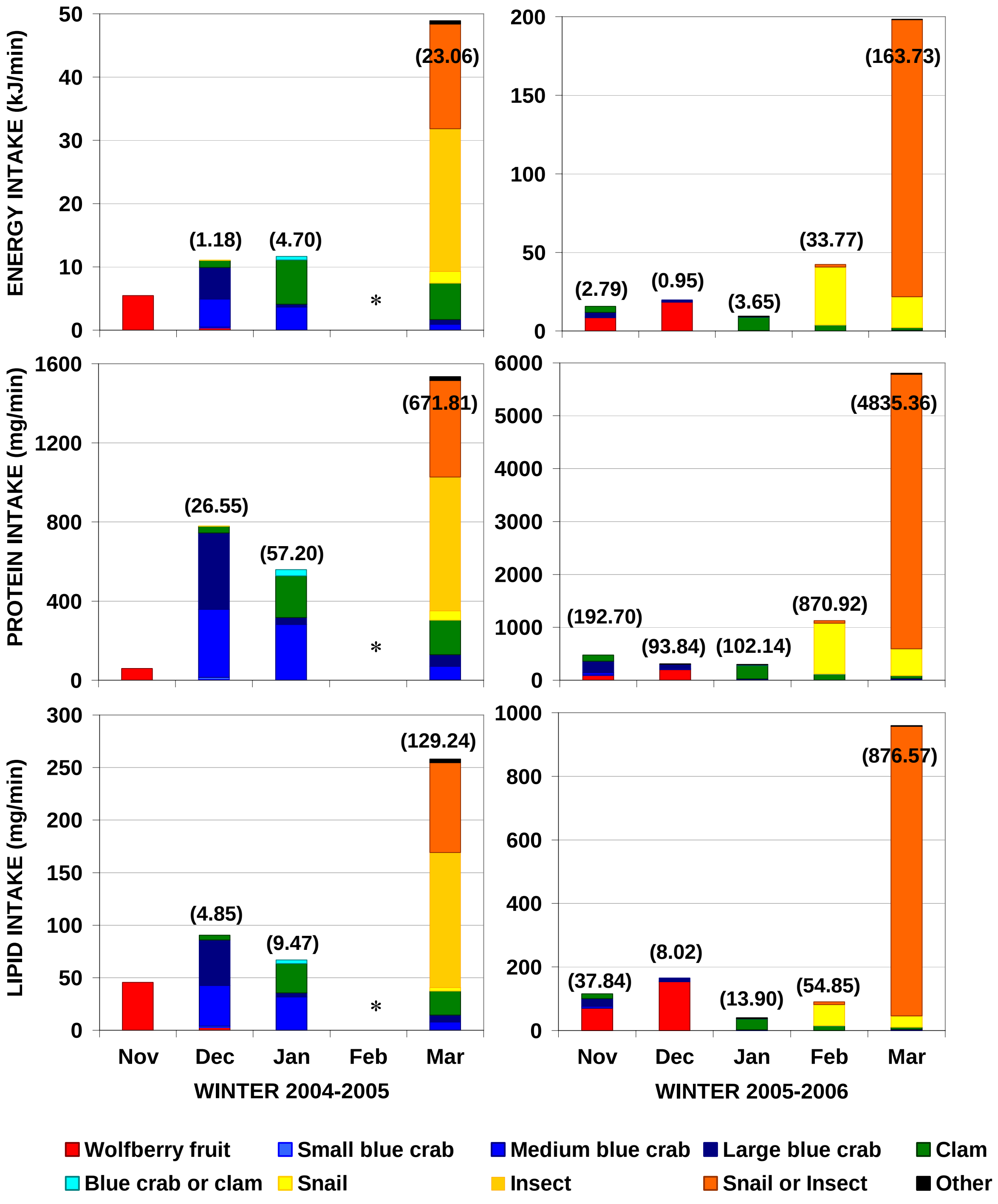


Figure A21. Contribution of foods to mean energy, protein, and lipid intake rates for whooping cranes during each month of winters 2004-2005 and 2005-2006. Standard errors (in parentheses) represent variability among territories (*n* = 3 territories for all months, except *n* = 1 territory in Nov 2004). No data were collected in February 2005 (*). Note large differences in scales of y-axis between winters.

Table A9. Foraging effort exhibited by whooping cranes when targeting foods during winters 2004-2005 and 2005-2006. Indices of foraging effort include rates of stepping (no. steps/min), probing (no. probes/min), handling (no. food manipulations/min), and total effort (no. foraging movements/min). Food types are listed from least to most costly (top to bottom).

	Index of foraging effort			
Food type	Stepping rate	Probing rate	Handling rate	Total effort
Wolfberry fruit	10-15	0	0	10-15
Snail-and-insect	15-30	0-15	0	15-40
Blue crab	20-23	3-11	11-19	40-45
Clam	10-22	27-88	1-8	50-100
Fiddler crab	21-40	3-13	5-58	59-82

Table A10**.** Temporal patterns in foraging efficiency (*i.e.*, gain : cost) demonstrated by actively foraging whooping cranes during winters 2004-2005 and 2005-2006. Indices of foraging efficiency, mean ± SE (coefficient of variation), were derived by dividing numeric (no. of food items/min), dry mass (g of food/min), energy (kJ of energy/min), protein (mg of protein/min) or lipid (mg of lipids/min) intake rate by total foraging effort (total no. of foraging movements [steps, probes, food manipulations]/min). Measures of variability are not listed for those months where adequate data were obtained from only one territory (*n* = 1).

	Index of foraging efficiency				
Winter / Month	Numeric	Dry mass	Energy	Protein	Lipid
Winter 2004-2005					
November	0.475 (*n* = 1)	0.052 (*n* = 1)	0.498 (*n* = 1)	5.39 (*n* = 1)	4.17 (*n* = 1)
December	0.014 ± 0.006 (73.4)	0.062 ± 0.009 (22.9)	0.250 ± 0.030 (20.4)	17.53 ± 0.77 (7.6)	2.04 ± 0.13 (11.1)
January	0.007 ± 0.003 (62.7)	0.045 ± 0.012 (45.0)	0.166 ± 0.037 (38.0)	9.33 ± 2.79 (51.7)	1.10 ± 0.30 (46.4)
March	0.049 ± 0.032 (114.0)	0.107 ± 0.046 (73.6)	0.981 ± 0.641 (113.3)	30.47 ± 19.39 (110.3)	5.28 ± 3.61 (118.5)
Mean	0.136 ± 0.114	0.067 ± 0.014	0.474 ± 0.184	15.68 ± 5.54	3.15 ± 0.96
Winter 2005-2006					
November	0.338 ± 0.285 (146.1)	0.070 ± 0.018 (43.5)	0.475 ± 0.245 (89.5)	11.44 ± 4.79 (72.5)	3.81 ± 2.18 (99.1)
December	1.136 ± 0.278 (42.4)	0.141 ± 0.023 (27.9)	1.258 ± 0.253 (34.8)	18.08 ± 3.71 (35.6)	10.54 ± 2.10 (34.4)
January	0.010 ± 0.005 (79.6)	0.052 ± 0.023 (75.2)	0.178 ± 0.075 (72.8)	5.71 ± 2.12 (64.3)	0.78 ± 0.29 (64.9)
February	0.116 ± 0.106 (157.0)	0.448 ± 0.401 (154.9)	1.177 ± 0.982 (144.4)	31.16 ± 25.38 (141.1)	2.46 ± 1.64 (115.6)
March	0.556 ± 0.470 (146.4)	1.484 ± 1.157 (135.2)	12.397 ± 11.515 (160.9)	363.65 ± 339.79 (161.9)	62.28 ± 60.40 (168.0)
Mean	0.431 ± 0.200	0.439 ± 0.271	3.097 ± 2.335	86.01 ± 69.54	15.97 ± 11.70

10. Spatial and temporal winter territory use and behavioral responses of whooping cranes to human activities

Graduate Student Project: Kristin E. LaFever – R. Douglas Slack (thesis advisor)

Project overview
This study was led by K. LaFever, a M.S. student in the Department of Wildlife & Fisheries Sciences at Texas A&M University

Habitat use and behavioral patterns of whooping cranes wintering at ANWR were examined for two primary purposes. The first purpose was to provide baseline data on territorial crane behavior during winter. These data will be increasingly important as the crane population continues to grow and will allow for future comparisons of behavior, territory size, and effect of human activities. The second purpose was to understand the utilization of territories spatially and temporally on Blackjack Peninsula, the area of the wintering grounds with the smallest winter territories. These data can be used to estimate minimum territory size and further predict progress toward habitat saturation. Specific objectives for this study were as follows:

1. to develop a time-activity budget for whooping cranes wintering on the Blackjack Peninsula at ANWR,
2. to document spatial and temporal use of habitats by whooping cranes within respective winter territories,
3. to document the behavioral responses of whooping cranes to human activities on the wintering grounds,

Methods

Whooping crane behavioral activities and use of habitat within five winter territories were examined during December 2003-April 2004 and October 2004-April 2005. Territories were relatively evenly distributed from the northern to southern extents of the Blackjack Peninsula portion of ANWR. From north to south, territories included Boat Ramp (BR), Pump Canal (PC), Pipeline (PL), Lobstick (LS), and Blackjack (BJ) (Figure A6). Observations occurred during four distinct periods of daylight, including early morning, late morning, early afternoon, and late afternoon. For each day in the field, one territory was randomly observed per period with the provision that no territory was observed more than once per day. During each observation period (period of day), cranes were observed during one or more 30-minute sessions with minimum 10-minute breaks between sessions. In total, cranes at each territory were observed at least once per combination of period and winter month, and 276 total hours of observation were conducted.

Time-activity budgets.—Time-activity data were collected using 10X binoculars, a 20-60X spotting scope, and methods of instantaneous scan sampling. During each observation session, a scan of the crane pair or family was performed, and instantaneous behavior was recorded every 30 seconds. Behaviors were categorized as one of four activities: foraging (searching or feeding), alert, comfort (preening, loafing or resting), or movement (flying or walking). The proportion of time spent in any one activity was calculated per observation session by dividing the number of records per activity by the total number of records in the session. Time-activity data were examined using ANOVA. Month category and period of day were fixed factors, and territory was included as a random effect to account for correlation of behaviors within each territory. Prior to statistical analyses, proportions were transformed using an arcsine square-root function. Following analyses, multiple contrasts were performed to determine differences among levels within factors.

Spatial and temporal use of territories.—During each observation period, the distance and bearing to each focal bird were recorded every five minutes using a rangefinder and compass, respectively. Distance and bearing data were also recorded when cranes flew to new locations within the territory. Data were subsequently uploaded into ArcView 3.3 and ArcMap 9.0, and discrete five-minute locations, movement paths, mean movement velocity (m/min), mean flight distance (m/flight event), and percent flight occurrence (measured as the percent of sessions with flight) were determined for each combination of territory and month category. Kruskal-Wallis and Mann-Whitney U tests were used to identify differences in movement velocity and flight distance among territories and month categories. Using derived location points within each month category, territories were delineated based on methods of Minimum Convex Polygon and Kernel Home Range probabilities. Within each configured territory, habitat was classified as open water, land, or edge. To test for habitat selection, the observed number of location points within the each habitat was compared to the expected number, which was based on the territory proportion within each habitat and the total number of location points collected in each month category. The ratio of observed to expected location points was referred to as the selection ratio. Selection ratios < 1 indicated cranes used a habitat less than expected, whereas ratios > 1 indicated cranes selected for a habitat. To additionally test for habitat selection, the percentage of each habitat within the movement paths of cranes was calculated for each territory X month category combination and compared to the total percentage of each habitat type available within the territory.

Crane response to human activity.—All human activities or “stimuli” visible from and occurring within 750 m of territories were recorded during observation sessions. Several types of human stimuli were recorded, including motor boats, airboats, tour boats, sail boats, shrimp boats, barges, barge tugboats, helicopters, airplanes, motor vehicles, and humans on foot. During each stimulus event, the type, proximity, duration, travel direction, and intensity of the stimulus were recorded. Intensity was classified as low, medium, or high. Stimulus frequency, duration, and intensity were summarized overall or by territory or territory x month category to examine patterns of human stimuli. Measures of stimulus duration at each territory were log-transformed and then compared using one-way ANOVA. Measures of frequency were compared among territories using the Kruskal-Wallis test, and specific differences between territories were determined post-hoc using the Mann-Whitney U test. Patterns of crane response to human stimuli were examined in two ways. First, crane time-activities (foraging, alert, comfort, and movement) were compared between sessions in which no stimuli were evident and sessions in which one or more stimuli were recorded. A second method of evaluating crane response to stimuli included comparing time-activities before, during, and after high intensity stimuli occurred; only high intensity stimuli lasting at least two minutes were used in the analysis. In all cases, the Kruskal-Wallis test was used to determine if significant differences existed among groups, and the Mann-Whitney test was used to identify specifically which groups differed.

Results

Time-activity budgets.—Adult and juvenile cranes each spent 65% of the day foraging for food. Alert behavior was also similar between adults and juveniles, comprising 14% and 16% of the overall time-activity budget, respectively. Comfort and movement behaviors each constituted 7% of the overall time-activity budget and again did not differ between age groups. Agonistic, vocalization, and courtship behaviors were rarely seen. Adult foraging, alert, and comfort behaviors were not found to differ among month categories or periods of day. However, movement in November-December was significantly higher than in January-February and slightly higher than in March-April. Juvenile behavior alone did not differ among periods of day or month categories for any activity category. Adults were more alert than juveniles in January-February, but the proportion of time spent in other behaviors or spent alert during other periods of winter did not differ by age.

Spatial and temporal use of territories.—Over-winter use of territories varied spatially and temporally. Both flight occurrence and movement velocity were highest in November-December. Several families exhibited disproportionately greater use of land habitat in November-December. Edge habitat was also used disproportionately greater than its availability throughout winter. Several families used open water greater than available and land habitat less than available. Substantial variation in both temporal and spatial use of habitats among territories was cause for difficulty in generalizing about the minimum territory requirements for wintering whooping cranes.

Crane response to human activity.—The most common type of human stimulus was motor boats, representing 50% of all stimuli that occurred during the study. Barges were the second most frequent stimuli (18%), and other common types of stimuli included shrimp boats, air boats, tour boats, airplanes, and helicopters. Other sources of stimuli rarely observed were barge tugs, sailboats, motor vehicles, and humans on foot (each less than 1%). Duration and frequency of stimuli differed significantly among territories for most types of stimuli. Intensity of stimuli tended to be similar among most territories, with the exception of LS. Low intensity stimuli made up 82-86% of all stimuli occurring at each BR, PC, PL and BJ but only 8.2% of stimuli at LS. Behavioral responses of whooping cranes to varying frequency and intensity of human stimuli were evaluated, but most stimuli did not elicit a response or change in activity. Mixed responses of territorial crane families to varying levels of human stimuli were observed. For instance, during periods of high-intensity stimuli, two crane families decreased the proportion of time spent foraging during periods of high-intensity stimuli, whereas cranes of other families increased time spent foraging or increased movement during such times.

Conclusions

Both adult and juvenile time-activity budgets were relatively consistent across winter months, with the greatest proportion of daylight hours allocated to foraging (65% of the day). Adult cranes moved around within their actively-defended territories at frequencies that were highest in early winter when wolfberry fruits and blue crabs were typical target foods and lowest in mid winter when overall food abundance was presumably low and razor clams were ubiquitously targeted.

Frequency of flights and movement velocity were highest for whooping cranes in early winter (November-December), coinciding with the active defense and establishment of territorial boundaries that typically occur upon arrival to the Texas coast. Crane use of habitats (land, open water, pond edge) within territories was seemingly related to abundances of targeted foods throughout winter (*e.g.*, greater land use in November-December when consuming primarily wolfberry fruits). This emphasizes the importance of multiple habitats for cranes and brings to question the optimal composition and spatial heterogeneity of habitats for wintering whooping cranes.

A large diversity of human activities occurred in the vicinity of crane territories. Although these activities were previously perceived as potential stimuli for behavioral response and disturbance stress of cranes, ‘stimuli’ were typically qualified as low intensity and did not elicit observable responses. The highly variable influence of human activities on whooping crane behavior in combination with high crane productivity indicates that human activities in and around ANWR are not detrimentally impacting crane fitness.

11. Projecting population dynamics of the endangered whooping crane

Graduate Student Project: Karine Gil – William E. Grant (PhD advisor)

Project overview
This study was led by K. Gil, a PhD. student in the Department of Wildlife & Fisheries Sciences at Texas A&M University

The only free-living, non-experimental, population of whooping cranes (*Grus americana*) has increased from 18 individuals in 1938 to 266 individuals in the winter of 2007-2008. The population winters, October through March, at ANWR and adjacent areas along the Gulf of Mexico in Texas, U.S.A., and breeds and spends the summer, late April through mid September, at Wood Buffalo National Park (WBNP) and adjacent areas in northwestern Canada. It migrates in late September and early to mid April. The population uses areas in southern Saskatchewan, the central portion of the Platte River in Nebraska, and the Quivira National Wildlife Refuge in Kansas as stopover sites (Lewis 1995 and Chavez-Ramirez pers. com). Both USFWS and the Canadian Wildlife Service (CWS) currently list the whooping crane as an endangered species, but hope to down-list the species from “endangered” to “threatened” by the year 2035 (CWS and USFWS 2005). One criterion for down-listing is attainment of a population size of 1,000 individuals; thus, projections of population levels are of great interest.

Whooping crane population trends have been projected several times within the context of population viability analysis (PVA) using a variety of commercially-available PVA programs (Mirande *et al.* 1997; Brook *et al.* 1999; Brook *et al.* 2000; Tischendorf, 2004). All of these analyses were based primarily on information reported by Binkley and Miller (1983), although different assumptions necessarily were made to satisfy the specific input requirements of each program. Specific projections from the various programs differed noticeably, but all projected continued exponential growth (Brook *et al.*, 1999).

In this study, a simulation model, designed specifically to describe the historical, and projected future trends for the ANWR–WBNP whooping crane population, is presented. The model draws upon previously-reported demographic information (Binkley and Miller, 1983), but also includes results of newly-available demographic analyses of the ANWR–WPNP population based on data from well over 100 marked birds from 12 different cohorts that have been monitored for the last three decades.

The model was formulated as a compartment model based on difference equations ($\Delta t = 1$ day) and programmed the model using STELLA® 7 (High Performance Systems, Inc.). The model maintains the identity of daily cohorts of individuals from eggs (for 30 days) (Kuyt 1981), chicks (for 10 days) (Kuyt 1981), juveniles at WBNP (123 days), juveniles in fall migration (35 days), juveniles on wintering ground (155 days), and juveniles during spring migration (22 days). The model assumed that all eggs were laid on May 15, which was near the end of the egg laying season (CWS unpublished data, Lewis 1995) and that all individuals were on the breeding grounds in Canada from April 16 to September 15, in fall migration for 35 days, on the wintering grounds in Texas from day-of-year 294 (October 21) to day-of-year 83 (March 24), and in spring migration for 22 days (Chavez-Ramirez 2004).

To estimate model parameters, demographic data reported by Binkley and Miller (1983) and also newly-available demographic data from the ANWR–WBNP population were used. Data from WBNP were provided by the CWS (Lea Craig-Moore and Brian Johns, CWS unpublished data, provided in 2005). These data were collected from aerial and ground surveys each May and June from 1967 to 2004. Each survey consisted of approximately 25 hours of observations over approximately 927 km^2 of WBNP and adjacent areas. Data include estimates of number of nests, number of eggs per nest, and number of chicks fledged per nest. During the ground surveys from 1977 through 1988, CWS banded 134 juvenile birds.

Data from ANWR were provided by USFWS (Stehn 2004). These data were collected from ground and/or aerial surveys conducted weekly from mid-October through April from 1977 to 2004. Each aerial survey consisted of a single, approximately 7-hour flight along the approximately 56 kilometers extent of coastal salt marsh, adjacent uplands of ANWR, and surrounding area. Data include censuses of juveniles, sub-adults, and adults, observations of banded birds, and reports of mortality, with the latter usually inferred from the disappearance of an individual from its territory (Stehn 2004).

To parameterize the model for the period prior to 1977, the age-specific natality and mortality rates reported by Binkley and Miller (1983) were used. The model was initialized with a population size of 18 individuals, which was the observed population size in 1938, and distributed these individuals according to the stable age-class distribution calculated from the age-specific rates reported by Binkley and Miller (1983). To calibrate the model for this period, the age of first reproduction was assumed to be four years, rather than the estimate of five years used by Binkley and Miller (1983), and adjusted the proportion of four year olds that were reproductively mature such that simulated population growth corresponded to that observed from 1938 to 1976.

To parameterize the model for the period beginning in 1977, age-specific survivorship (l_x) was estimated from the newly-available survival data on 132 banded birds (information on sex of two birds was not available) using the Kaplan-Meier method (Kaplan and Meier 1958, Kleinbaum and Klein 2005) programmed in STATA v.7 (STATA Corp., College Station, Texas). The number of individuals at age 0 in each cohort was established as the number of eggs laid in nests in which banded individuals hatched. Thus, estimates of l_0 accounted for egg, chick, and juvenile mortality. The Kaplan-Meier method adjusts l_x estimates to account for marked individuals whose fate is unknown. In this case, banded individuals that were still alive were "censored" from age classes which they had not yet had enough time to reach. For example, individuals from the 1988 cohort that were still alive in 2004, at age 16, were censored from age classes >16; individuals from the 1987 cohort that were still alive in 2004, at age 17, were censored from age classes >17; and so on. We estimated age-specific fecundity (b_x) for ages $x \leq 19$ directly from data on 33 banded females. We estimated values of b_x for $x > 19$ by extrapolating the linear regression of b_x on x for $14 \leq x \leq 19$ ($b_x = 1.46 - 0.03*x$, $r^2 = 0.96$), since each of these older age classes was represented by only 1 or 2 females. To calibrate the model for this period, we adjusted the proportion of successfully reproducing females such that simulated population growth corresponded to that observed from 1977 to 2008.

The model simulated the general historical trend in population growth quite accurately with the proportion of four-year olds that were reproductively mature for the period prior to 1977 adjusted to 0.35 and the proportion of successfully reproducing females for the period beginning in 1977 adjusted to 0.55. Data from banded females suggest that some females do reproduce at four years of age, and although an empirical estimate of the proportion of four year olds that are capable of reproducing is not available, 35% appears to be a reasonable estimate (Brian Johns, pers. comm.). An empirical estimate of the proportion of successfully reproducing females for the period beginning in 1977 is not available. However, Brook *et al.* (1999) estimated that an average of 47% of the females were successful in producing broods each year, thus 55% appears to be a reasonable estimate.

Future population trends projected by the model suggest that population size will surpass the estimated carrying capacity of the area currently occupied by whooping cranes (511 individuals, Stehn and Prieto, 2008) by the year 2024 and will reach 602 individuals by the year 2028 (Fig. A22).

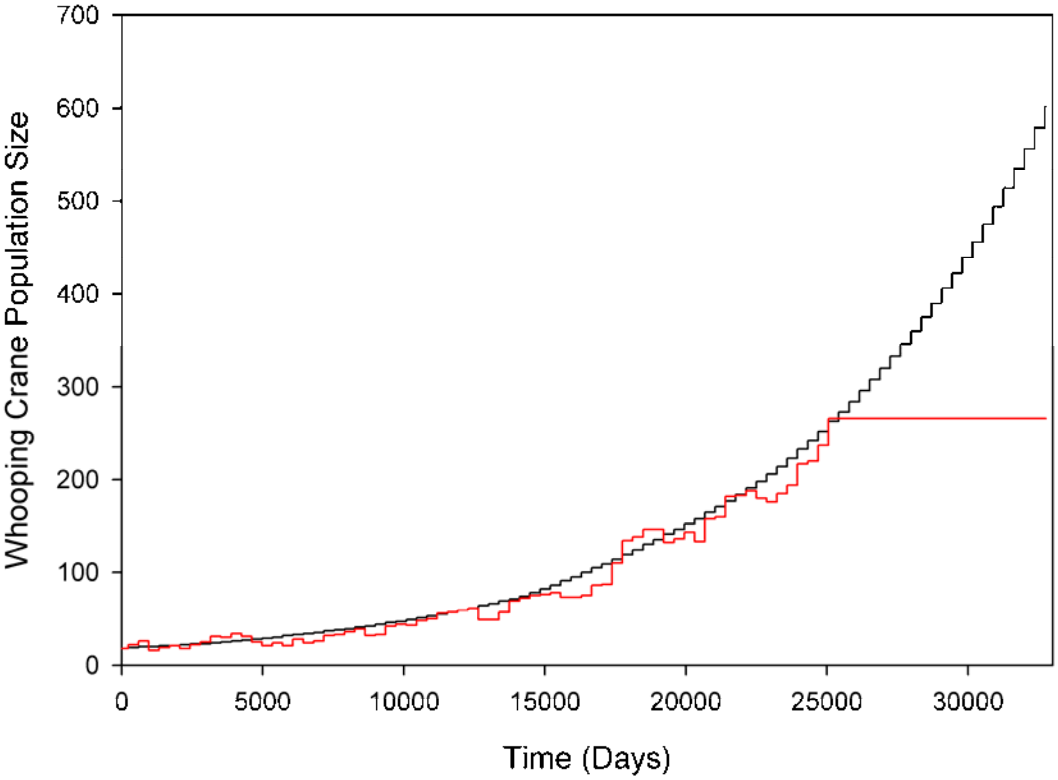


Figure A22. Simulated (black line) and actual (red line) whooping crane population sizes projected from 1938 to 2028. At the time of this manuscript, data were not available after so the actual population size remained constant after 2007 and simulated population is projected through 2028.

12. Modeling hydrological connectivity in salt marsh ecosystems

Research Project Participants: Todd M. Swannack and William E. Grant

Project Overview

This project was led by T. Swannack and W. Grant., a post-doc and professor in the Department of Wildlife and Fisheries Sciences at Texas A & M University, College Station, Texas.

The objective of this project was to develop a dynamic model that simulated water-level changes and hydrological connectivity in marsh ecosystem using LIDAR and water-level data from the Seadrift gauge station.

We developed a spatially-explicit, grid-based model that simulates marsh inundation and records the water level at which each area first becomes inundated. Simulated areas are not inundated based exclusively on their elevation, but rather based on their sea-level connection, which we defined as the water level at which water can first find its way into the area. Thus, as simulated water levels rise, some areas of lower elevation will flood later than some areas of higher elevation if water must breach a dike of sorts to reach the lower area.

We programmed the model in VB.NET (Microsoft, 2003), and used ArcGIS v9.1 (ESRI, Redlands, California) to manipulate geo-referenced elevation data and to spatially interpret and evaluate simulation results. We obtained geo-referenced elevation data LIDAR images (1.4m x 1.4m cells, projected in the NAVD 88 geodetic vertical datum) of Calhoun and Aransas Counties, Texas (http://www.tnris.state.tx.us/lidar.aspx), from which we extracted three grids representing the BR, PC, and SB territories. The availability of LIDAR represents a considerable advancement in digital elevation mapping (DEM) technology. LIDAR data decrease the spatial resolution of elevation data by orders of magnitude compared to previously available DEMs (*e.g.*, previous DEMs mapped elevations in 30m x 30m cells, compared to the 1.4m x1.4m cells of LIDAR). Due to practical limitations related to computing-time requirements of the simulation model, we further extracted three smaller, topographically representative, sample grids, each containing the geo-referenced location of a water-level gauge used in the field study (Figure A23). Grids were composed of 47,607; 52,342; and 12,016 cells (cell area: 1.96m^2) for BR, PC, and SB, respectively. Elevations for each 1.4 x 1.4 m LIDAR cell within these sample grids were assigned to a corresponding habitat cell in the simulation model (elevation, X and Y coordinates, as well as sea-level connection, were represented as *attributes* of a *habitat class*, where each *instance* of that class represented a particular LIDAR m^2 cell).

With the model parameterized to represent the topography of each sample grid, we simulated a hypothetical inundation by initializing the model with water only in cells within tidal creeks and then raising water levels within these cells incrementally, 1 cm at a time. After each incremental rise, the simulated water sought its own level. That is, if the current water level in an adjacent cell was lower, water moved into that cell. This resulted in a virtual seiche, which continued until all changes in water level within the system were < 0.1 cm, at which time the current water level was recorded as the sea-level connection for all newly-flooded cells, water level in the tidal creek cells was raised by 1 cm, and the entire procedure was repeated until a sea-level connection had been recorded for each cell.

After establishing the sea-level connection for each cell, we then simulated a 10-year historical inundation regime on each sample grid. Daily water-level changes were driven with data from the Seadrift gauge. Tidal creek water levels were calculated based on correlative relationships between Seadrift and the respective water-level recorder (data were recorded continuously from 2003-2004) (Figure A24, Eqs: A1-A3).

$BR_t = 0.209 + 0.737*Sd_t$, ($r^2 = 0.75$, n=8132) (A1)
$PC_t = 0.0571 + 0.744*Sd_t$, ($r^2 = 0.79$, n=8132) (A2)
$SB_t = 0.0301 + 0.749*Sd_t$, ($r^2 = 0.83$, n=8132) (A3)

Daily water levels of each cell were recorded and when simulated water level in the tidal creek receded below the sea level connection of an inundated cell, we calculated daily water loss from that cell due to evapotranspiration (ET_t, mm day^{-1}) using the Hargreaves equation (Allen *et al.*, 1998; Allen *et al.*, 2005):

$ET_t = 0.0023 * (((MaxT_t+MinT_t)/2)*((MaxT_t - MinT_t)\hat{}0.5))) * Ra$ (A4)

where $MaxT_t$ and $MinT_t$ represent daily maximum and minimum temperatures (°C), respectively, and *Ra* represents mean daily extraterrestrial radiation (MJ m^{-2}day^{-2}) at the ANWR gauge (www.ncdc.noaa.gov, latitude ≈ 24°N) (Hargreaves *et al.*, 1985). *Ra* values for the 15th of each month were used, which provide good estimates (<1.0% error) of *Ra* averaged over all the days within a month (Allen *et al.*, 1998). Precipitation events during the study period did not have a noticeable effect on the water balance in the system, so it was not included (Miller et. al., *in press*). We did not estimate percolation, since coastal water tables are relatively high and sandy clay soils, which are typical of ANWR, have very low percolation rates (Rawls *et al.*, 1992). We summarized landscape-level patterns by monitoring the total length of time (days) each cell was flooded or dry and connected or unconnected to the tidal creek (sea-level connection).

We evaluated the performance of the model by comparing simulated daily water-level changes in the tidal creeks of each territory over a the thirteen month period (2003-2004), to observed patterns in water level collected during the same period. We further compared simulated water-level dynamics in ponds to those observed in the field at the corresponding geo-referenced points. Simulated and observed daily water-level fluctuations in all three tidal creeks were quite similar (Figure A25), as were simulated and observed pond water levels in the PC and SB territories (Figure A26B & C), whereas simulated pond water levels in the Boat Ramp territory were consistently overestimated by about 0.4 m (Figure A26). Simulated sea-level connections compared well to actual connection events (as reported by Miller *et al.*, *in press*). Simulated and observed sea-level connections, indicated by portions of the plots in Figure A27 where pond water levels paralleled tidal creek fluctuations, were 61 versus 71.3 cm, 64 versus 71.3 cm, and 71 versus 61.6 cm above sea level, respectively, for the gauged ponds in BR, PC, and SB (actual connection events noted by Miller *et al.*, *in press*). The differences of simulated and observed relationships between tidal creek and pond water levels within the BR territory remain enigmatic.

Simulation results indicated that the majority of the cells were inundated less than approximately one-fifth of the time (Figure A28). We defined this more precisely based on frequency distributions of the percentages of time that cells were inundated, which we generated using the “natural breaks” algorithm in ArcGIS v9.1 (ESRI, Redlands California). A natural break fell close to one-fifth for each sample grid: 21.5%, 18.6%, and 18% of the time in BR, PC, and SB, respectively (Figure A28).

The results from this study indicated that this model has considerable potential for modeling hydrological dynamics in a salt-marsh ecosystem. We attempted to develop the most parsimonious model possible (*i.e.*, fewest number of parameters and equations), and using just elevation, water-level (at Seadrift) and evapotranspiration, we were able to simulate the dynamic pattern of water level changes at ANWR (Figures A25 & A26). However, time periods when the simulated dynamics did not capture the dynamics observed at ANWR did occur (Figure A26). This lack of fit between simulated and observed patterns could be a result of ecological processes occurring in the marsh that were not parameterized in the model (*e.g.*, wind effects) or error in the elevation recorded by the LIDAR projections.

Future research resulting from this project will need to focus on incorporating other ecological processes, such as wind effects, into the model and ascertaining the limitations and associated errors of LIDAR data.

Figure A23. Left: Satellite images of (A) BR, (B) PC and (C) SB. Yellow circles represent water sampling platforms, purple triangles represent pond water-level recorders, and shaded boxes represent approximate areas chosen as representative samples of each territory. Right: LIDAR images of topographically representative samples of each territory. Green squares represent geo-referenced location of water-level gauges used during the field studies, darker browns represent lower elevations.

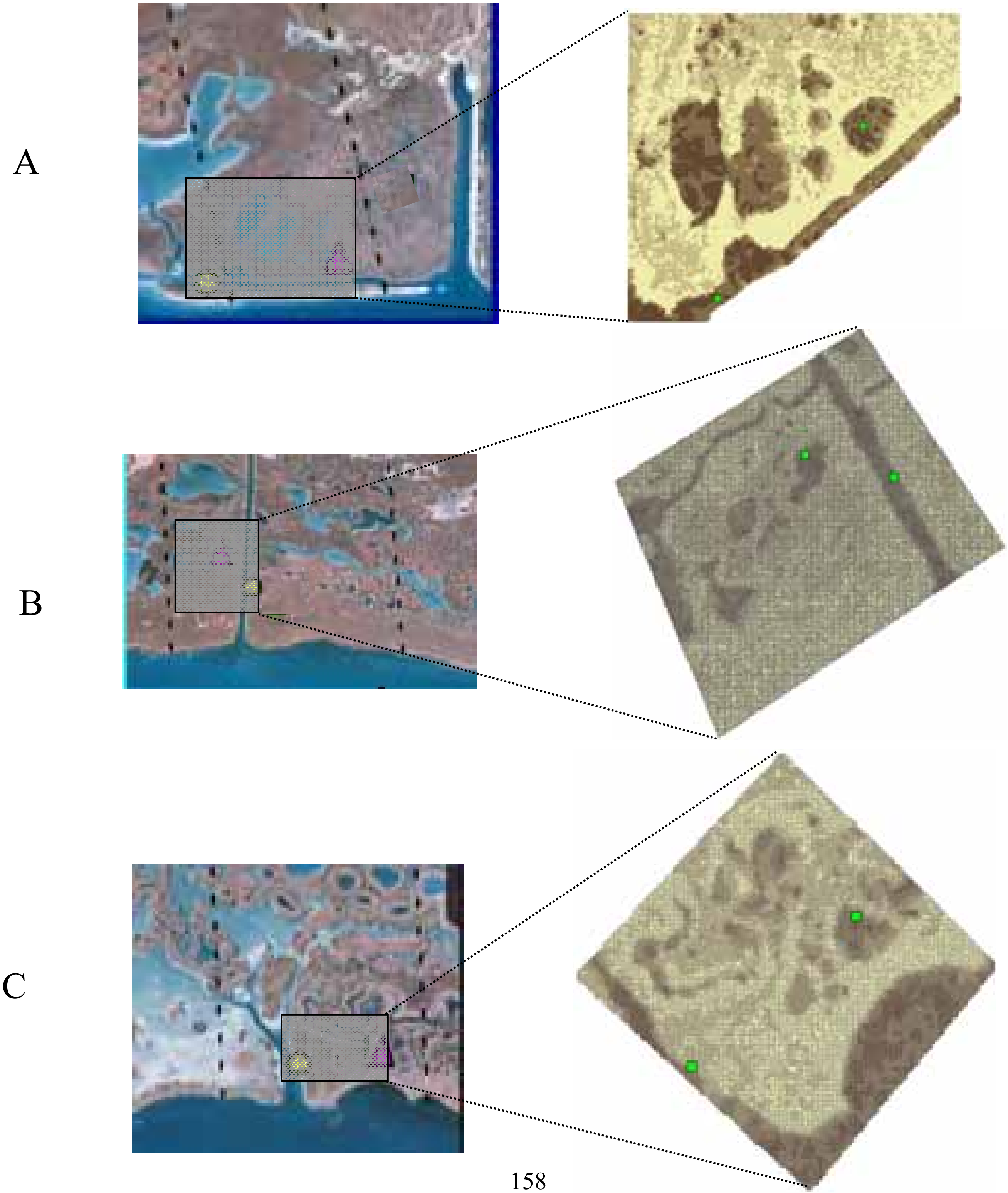


Figure A24. Relationships between hourly water levels at the Seadrift gauge and the water levels in the tidal creeks of (A) BR, (B) PC and (C) SB. Solid black line was generated using linear regression (n=8132 for all territories, associated r^2 values listed on each plot). Black dashed and red dotted lines represents 95% mean confidence and individual prediction intervals, respectively. Data were collected from 27 June 2003 to 29 June 2004.

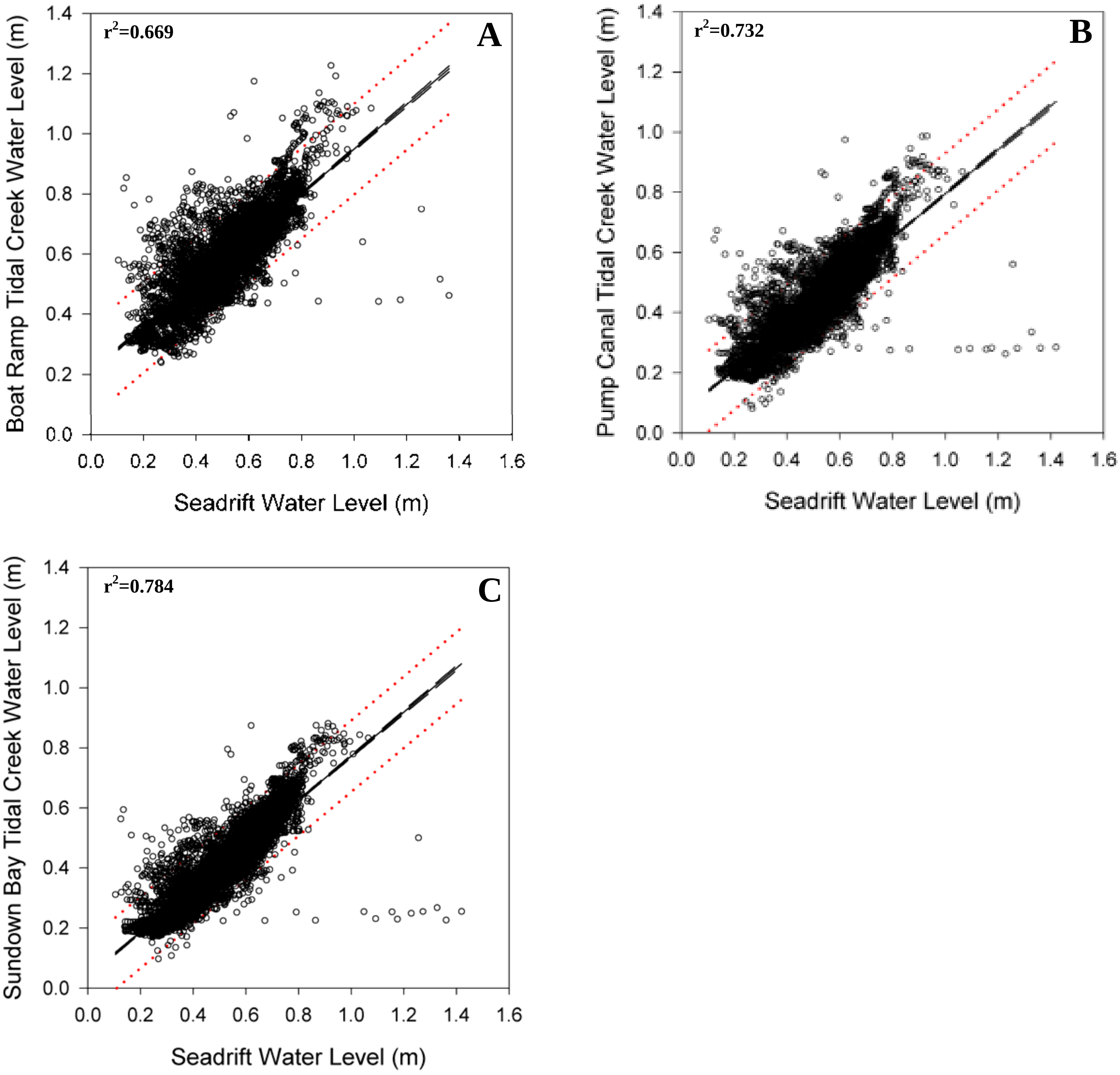


Figure A25. Comparison of simulated (red) to observed (black) daily water-levels in the tidal creeks of (A) BR, (B) PC and (C) SB. Observed values were collected during a 13 month period from 2003 – 2004.

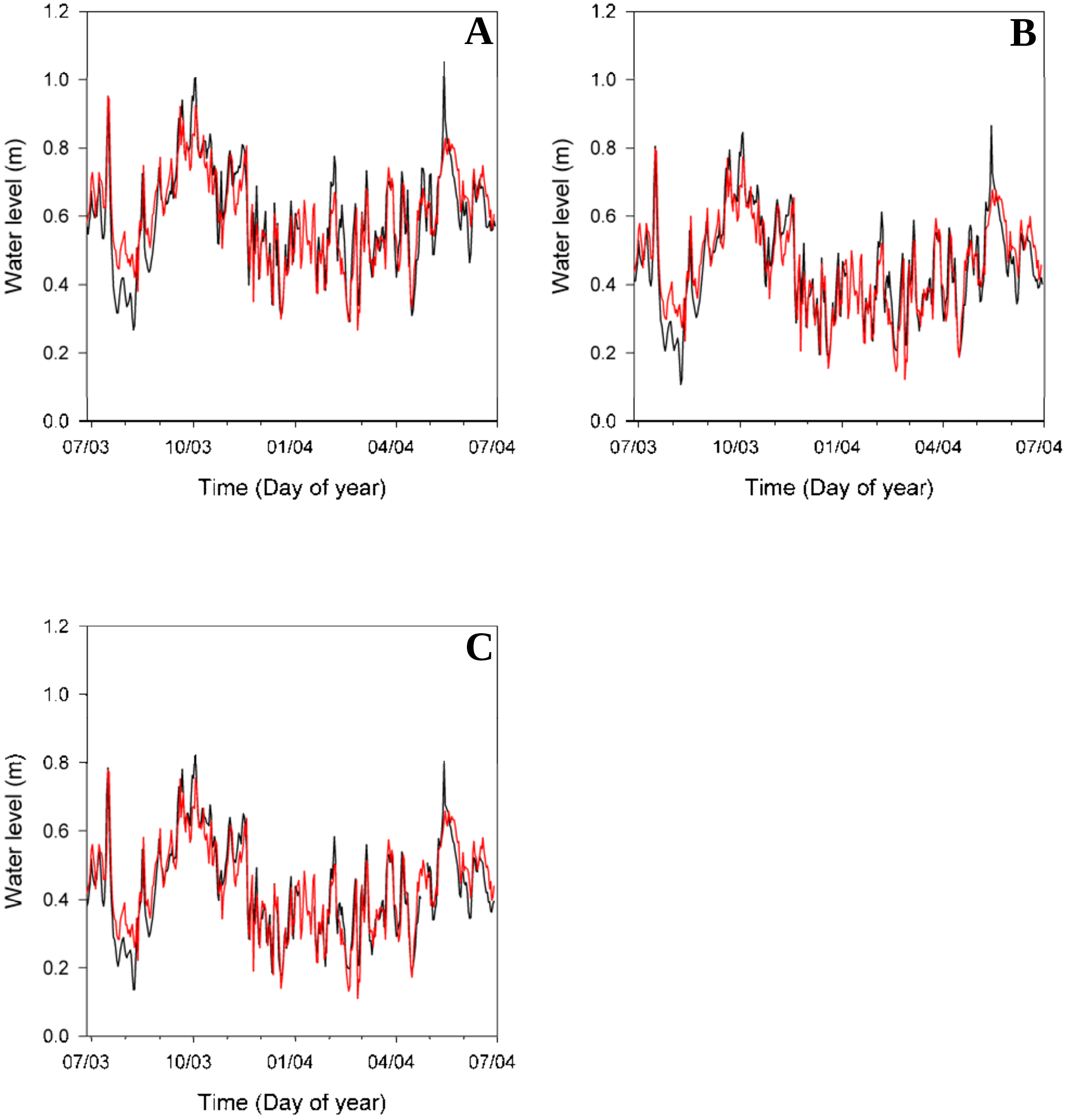


Figure A26. Comparison of simulated (red) to observed (black) water-level changes in the ponds of (A) BR, (B) PC and (C) SB. Observed values were collected from 27 June 2003 – 4 July 2004.

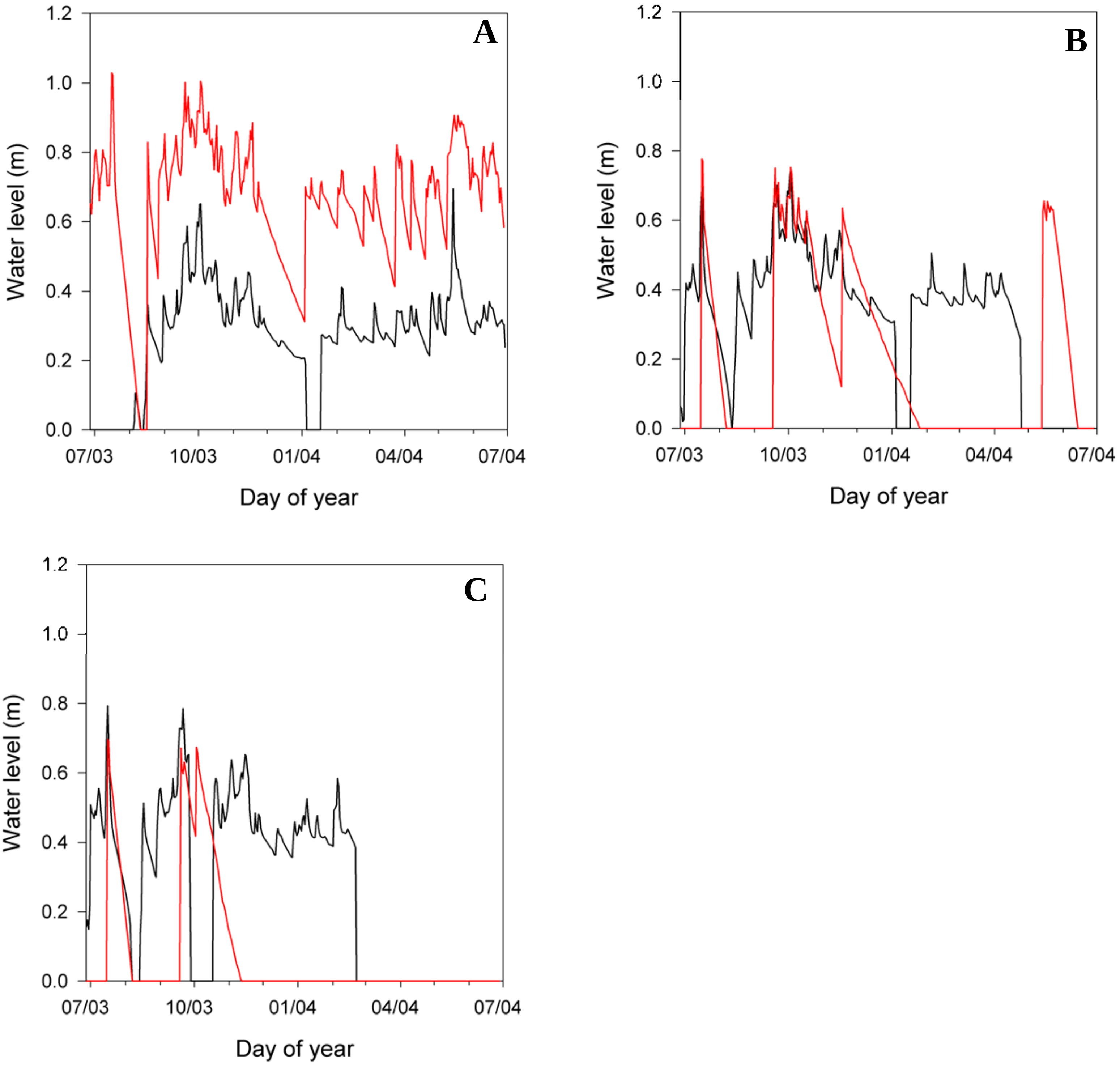


Figure A27. Comparison of simulated (white) to observed (black) water-level changes in the study ponds and tidal creeks of (A) BR, (B) PC and (C) SB. Observed values were collected from 27 June 2003 – 4 July 2004.

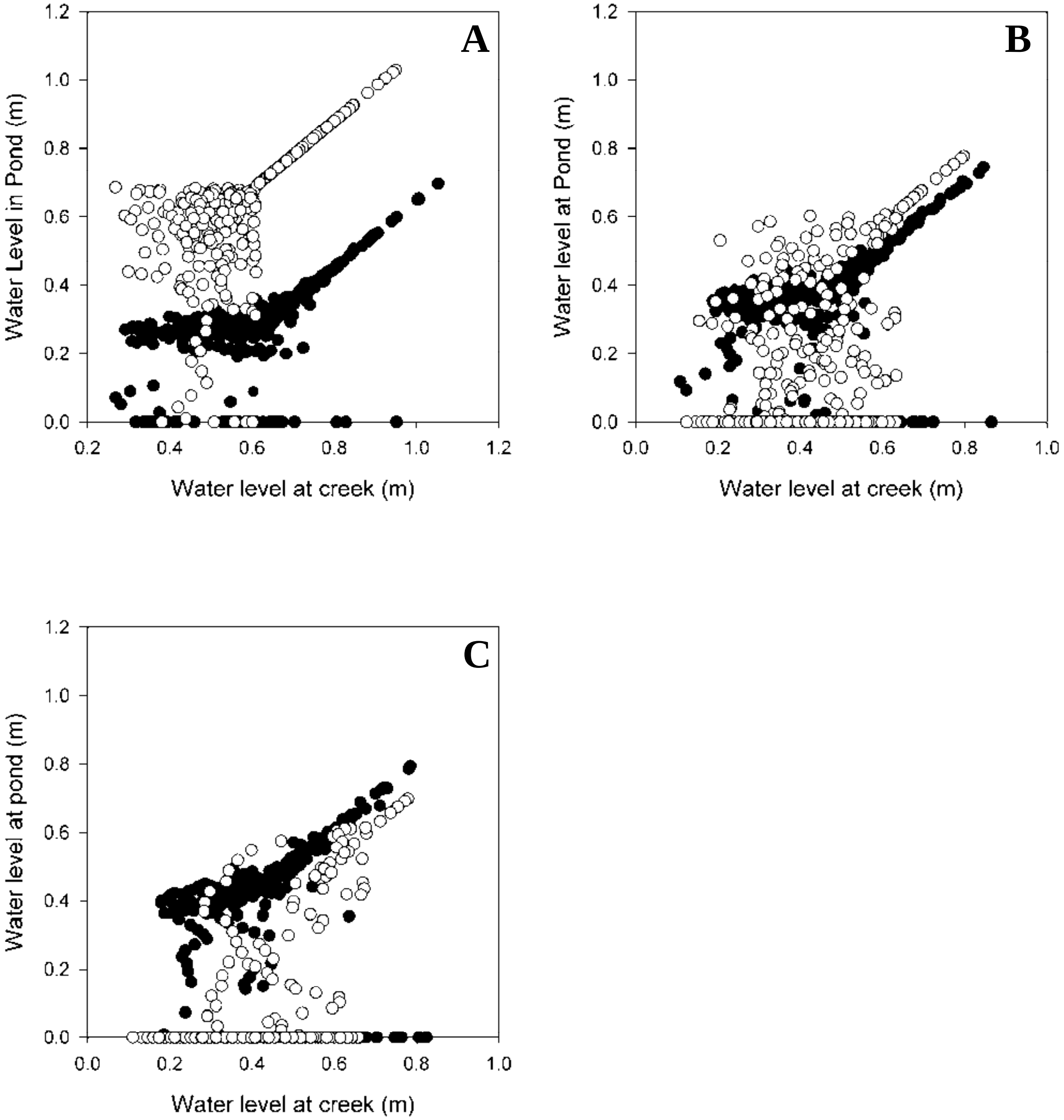
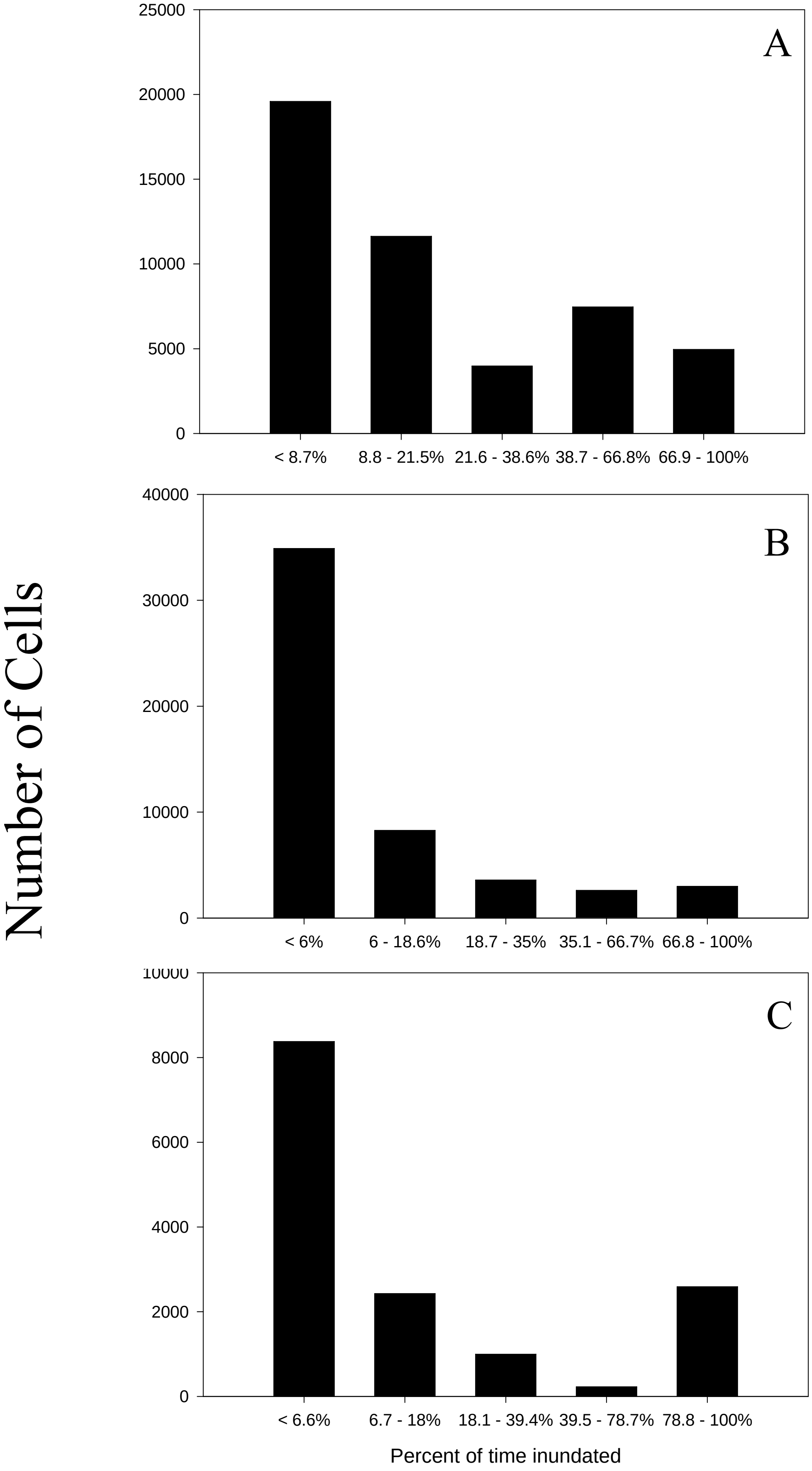


Figure A28. Frequency distribution of the percentage of time cells within each of three whooping crane territories were inundated during a 10-year hydrological simulation. (A) BR, (B) PC and (C) SB.



Complementary Studies

13. Bridging the gap between plankton dynamics and spatial variability in water quality in the Guadalupe Estuary (Texas): The importance of freshwater pulses

Research Project Participants: Stephen Davis, Daniel Roelke, Carrie Miller, George Gable, Hsiu Ping Li, and Kung Jen Liu

Project Overview
This was a three-year study (2004-2006) funded by USGS through the National Institutes of Water Resources National Competitive Grants Program. This work and all sample analyses were conducted at Texas A&M University and led by Drs. Stephen Davis and Daniel Roelke. The study was centered on the San Antonio Bay Estuary (Figure A29) and sought to characterize water quality and quantify water column productivity across the entire estuary during different inflow conditions on a monthly basis. The synthesis of information collected from this study and concurrent studies in the Galveston Bay Estuary also by Davis and Roelke helped to provide a more comprehensive understanding of the relationships between the nature of pulsed inflow events and estuarine ecosystem health along the Texas Gulf Coast.

Inflows to the estuary varied considerably over the course of the study. At the beginning of 2005, inflows were high and tapered off through the summer. The region has been experiencing a lengthy drought which continued through 2005 and was followed by a series of smaller pulses in early 2006. Low inflows then prevailed for the remainder of the study. Winds in this system are predominantly out of the SE and E—especially during the summer months—and represent a significant force in estuarine hydrodynamics.

As part of this work, we established a refrigerated water sampler at the USGS gauge at Tivoli, Texas along the lower Guadalupe River (*i.e.*, Station 8) at GBRA's saltwater barrier. We ran a water sampling program at this site that collected tri-daily, composite water samples. These samples were retrieved every two weeks, processed, and taken to the laboratory for nutrient analyses. Technical problems with the sampler precluded us from generating a continuous record of inflows. However, we have sporadic concentration data for total suspended solids (TSS), dissolved inorganic N ($NO_3^- + NO_2^-$ and NH_4^+) and P (orthophosphate or PO_4^{3-}), dissolved organic carbon (DOC), total nitrogen (TN), and total phosphorus (TP; see Figure A30).

The Guadalupe River sample data from this period indicates positive correlation between flow magnitude and concentration for most all parameters measured (Figure 2). We saw very high inflows in late 2004, and most constituents were declining towards the end of this massive pulse. However, smaller but significant, pulses later in the study resulted in noticeable increases in concentrations of most nutrients—especially nitrogen and TSS. DOC and TSS concentrations were reflective of particulate and organic matter loadings to the estuary and often increase under high flows. Concentrations of TN and TP were often associated with these organic and inorganic constituents and show similar patterns relative to flow magnitude. In terms of dissolved inorganic nitrogen and phosphorus, phosphate, ammonium, and nitrate + nitrite concentrations in the lower river, these constituents were sensitive to flow magnitude. However, a longer continuous record is needed in order to understand the seasonal dynamics as well as response to flow conditions exhibited by these water column constituents.

The bulk of this study involved monthly measurements of water quality and water column productivity at fixed stations along estuarine salinity axis. In addition to Station 8 (*i.e.*, the saltwater barrier), seven fixed stations were selected to represent the range of salinity/inflow conditions across San Antonio Bay (Figure A1; Table A1). Station 1 was located nearest the Gulf of Mexico in Espiritu Santo Bay and represented our saline end-member. Stations 2 and 3 were located in lower San Antonio Bay. Stations 4 and 5 represented mid-estuary sites. Station 6 was in Hynes Bay, and Station 7 represented the freshwater end-member near the mouth of the Guadalupe River (Figure A29; Table A11). Our results showed strong relationships between nutrient concentrations and location along the estuarine with nutrient concentrations and particulate measures highest near the mouth of the river.

Water quality data from the fixed bay stations reflected the relative importance of Gulf of Mexico versus river influence. Salinity was always lowest in the upper estuary, especially at Station 7 near the Guadalupe River outfall. This was followed by Stations 6, 5, 4, 3, and 2. Station 1 always had the highest salinity. Light attenuation across stations was similar, although Station 1 typically had the lowest attenuation. This site was most influenced by relatively clear waters, but also showed a strong influence of wind mixing. Throughout the bay, light attenuation was largely driven by wind forcing and river inflows.

In general, concentrations of dissolved inorganic nitrogen and phosphorus were lowest in the lower estuarine areas. This reflects the paucity of nutrients in the Gulf of Mexico relative to river sources. Whereas, inorganic constituents near the river mouth tended to be highest during high inflow periods. Concentrations of TN and TP showed a similar spatial pattern of river discharge influence and disproportionately higher concentrations near the mouth of the river. However, these constituents were more conservative across the estuarine salinity axis than dissolved inorganic N and P. This is likely due to the fact that TN and TP concentrations across the bay are likely affected by wind-driven re-suspension. Gross productivity in the water column at these fixed stations often exceeded respiration, resulting in consistent, positive net productivity. Overall, rates of these water column processes indicated more of a seasonal than inflow-related pattern.

We also conducted in-lab experiments to determine the role of a pulsed hydrology in affecting phytoplankton community dynamics and the transfer efficiency of energy to zooplankton. Our microcosm experiments were novel as they utilized natural plankton communities from San Antonio Bay, thereby allowing the simultaneous interaction between hydrology, resource availability, and grazing. Results showed differences in microcosms according to magnitude and frequency of flushing. For example, copepod population density was greatest at the average annual inflow magnitude from the Guadalupe River. At half the mean annual inflow, a decline in prey quality likely resulted in poorer grazer performance, and at double the mean annual inflow magnitude increased flushing losses prevented the incidence of higher copepod densities. Similarly, pulsed inflows resulted in greater copepod population densities, higher overall phytoplankton biomass, and dominance of centric diatoms (known to be faster growing and more edible). Before implications for management can be discerned from these findings, however, larger scale experiments are should be focused on the roles of inflow magnitude and frequency. The recent paper by Miller *et al.* (2008) provides the best description of the results of this set of experiments.

Table A11: Latitude and longitude of fixed sampling stations in San Antonio Bay.

Station	Latitude	Longitude
1	28°19.00'	93°36.00'
2	28°16.00'	96°41.00'
3	28°14.00'	96°44.00'
4	28°18.00'	96°45.00'
5	28°21.00'	96°44.00'
6	28°23.00'	96°48.00'
7	28°26.00'	96°46.00'

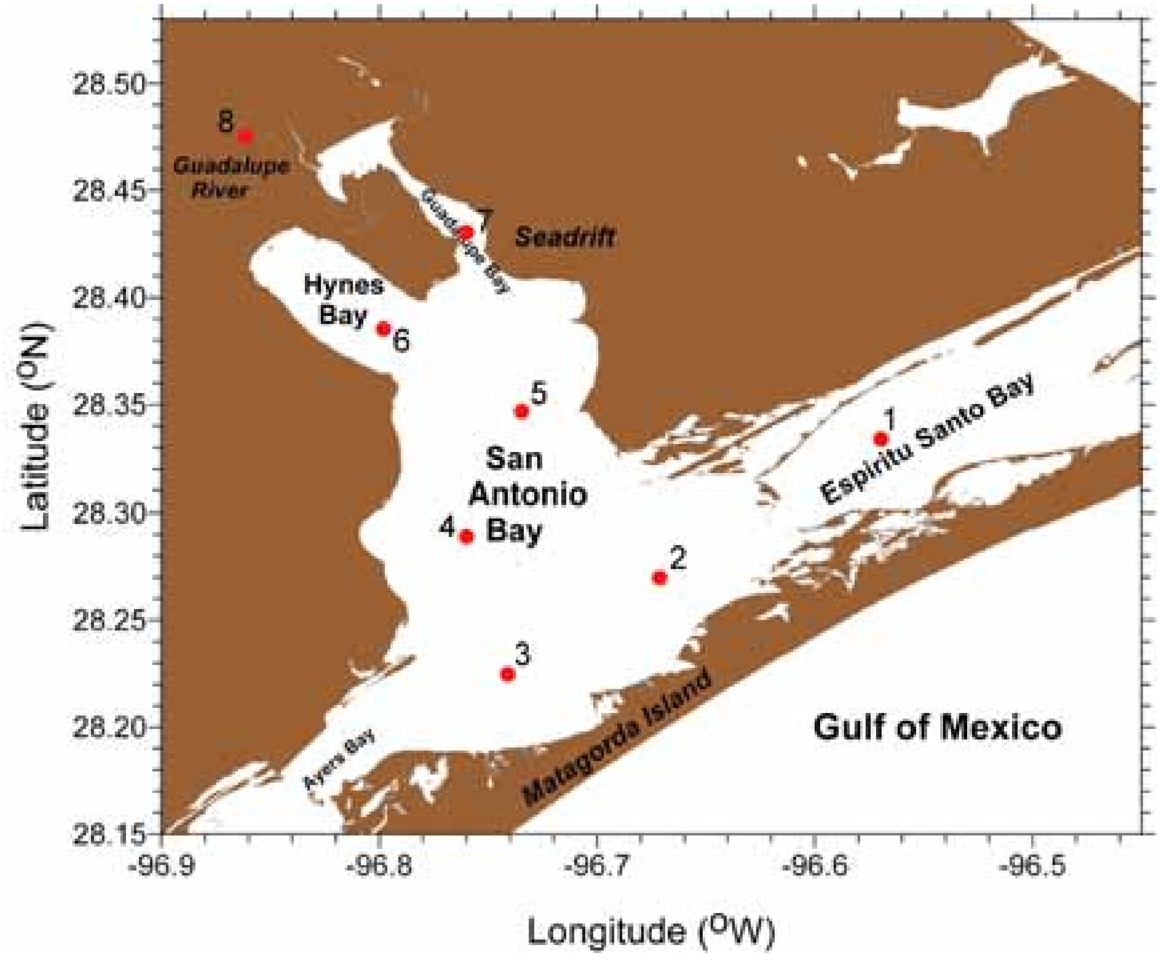


Figure A29: Map of San Antonio Bay/Guadalupe River Estuary and identification of fixed sampling stations.

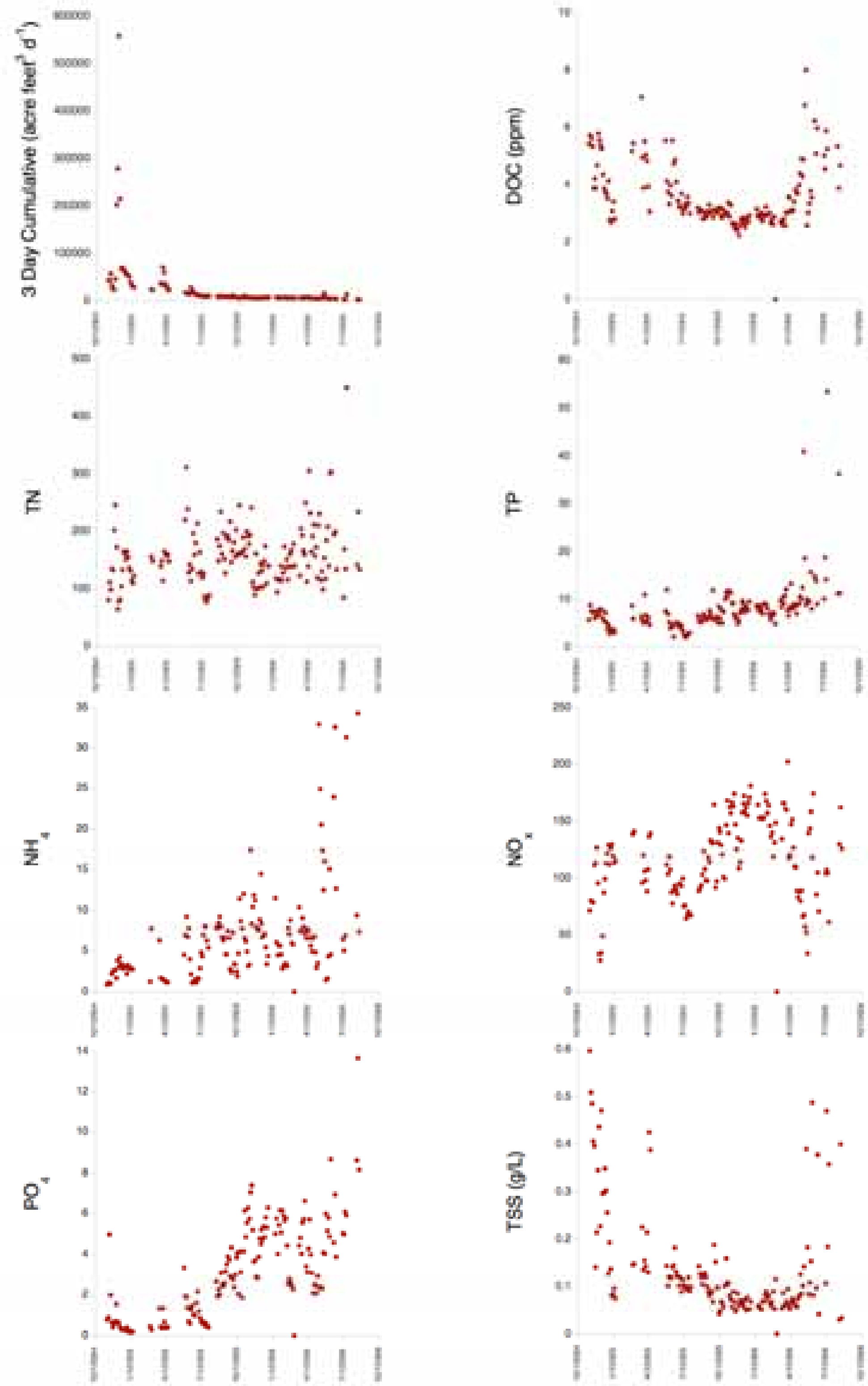


Figure A30: Combined river discharge estimate (upper left) and constituent concentrations (micro-Molar (µM), unless indicated otherwise) measured at Station 8 (lower Guadalupe River) throughout the project duration.

14. Reduced freshwater inflows and productivity in the Guadalupe Estuary: Use of high-resolution spatial mapping

Research participants: Stephen Davis, Daniel Roelke, Carrie Miller, George Gable, Hsiu Ping Li, and Kung Jen Liu

Project Overview

This was a two-year study (2005-2006) funded by Texas Sea Grant that was centered on the San Antonio Bay Estuary. This work and all analyses were conducted at Texas A&M University and led by Drs. Stephen Davis and Daniel Roelke. The primary goal of this study was to characterize and map water quality at a high degree of spatial resolution across the entire Guadalupe Estuary during different inflow conditions on a monthly basis. The synthesis of information collected from this study helped to provide a more comprehensive understanding of the relationships between the nature of pulsed inflow events and estuarine ecosystem health along the Texas Gulf Coast.

Inflows to the estuary varied considerably over the course of the study. At the beginning of 2005, inflows were high and tapered off through the summer, and were followed by a series of smaller pulses in early 2006. Low inflows then prevailed for the remainder of the study. Winds in this system are predominantly out of the SE and E—especially during the summer months and represent a significant force in estuarine hydrodynamics.

Spatial patterns of water quality in the Guadalupe Estuary were measured with Dataflow, a high-speed, flow-through measurement apparatus developed for mapping physicochemical parameters in shallow aquatic systems (Madden and Day 1992; see images in Figure A31). This integrated instrument system was used to concurrently measure water temperature, salinity, beam transmittance (*i.e.*, water clarity), chlorophyll *a* (*in situ* fluorescence), and colored dissolved organic matter (CDOM; *in situ* fluorescence) from a boat, running tightly gridded transects across the estuary. Water quality measurements were taken at 4-second intervals from about 30 cm below the surface. An integrated GPS was used to simultaneously plot sample positions, allowing geo-referencing of all measurements for each variable. Downloaded GPS and Dataflow information were then entered into the Surfer software program to interpolate across sampling points and the estuarine boundaries to create highly detailed contour maps of water quality parameters in relation to physiographic features.

In all, we conducted 19 monthly Dataflow samplings as a result of the project funding (Table A12). Due to equipment problems, we did not start Dataflow sampling in the the entire estuary until January 2005. Dataflow samplings in the Guadalupe River estuary were conducted monthly, weather and equipment permitting, and required at least one day to complete. During each of these samplings, we stopped at all fixed stations to collect water samples for nutrient analysis, TSS, HPLC pigments, and chlorophyll *a*. Dataflow maps were generated for each sampling described in Table A11. These maps provide a powerful illustration of the influence of river inflow relative to marine exchange and even serve to identify general circulation and exchange patterns. These maps can also help identify areas of management concern (*e.g.*, areas of wetland loss, urban development, pollutant loading).

This in situ, water quality mapping technology provides scientists an alternative to remote sensing for data collection in shallow water environments. In addition, this technology is much more accurate and reliable than remote sensing because of the uncertainties associated with remote sensing algorithms targeting shallow type II waters. Our data was made readily available to other scientists, resource managers, and lay people. We developed a web-based system where users can quickly access the data. The fixed station data is in two formats. The first format shows the data with emphasis on spatial trends, and the second format with emphasis on temporal trends. The URL address for these data web pages is http://wfsc.tamu.edu/roelkelab/inflows.html.

Table A12: List of Dataflow sampling dates and parameters measured in San Antonio Bay. *The September 2005 sampling was delayed into early October as a result of Hurricane Rita.

Dates	**Parameters**
January 25, 2005	transmissivity, chl *a*, DOM, temperature
February 28, 2005	transmissivity, chl *a*, DOM, temperature
March 29, 2005	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
April 26, 2005	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
May 24, 2005	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
June 24, 2005	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
July 24, 2005	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
August 29, 2005	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
October 4, 2005*	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
October 27, 2005	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
November 19, 20, 2005	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
December 20, 2005	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
January 26, 2006	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
February 22, 2006	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
April 21, 2006	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
May 22, 2006	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
June 23, 2006	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
July 30, 2006	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
August 28, 2006	transmissivity, chl *a*, DOM, temperature, salinity/conductivity

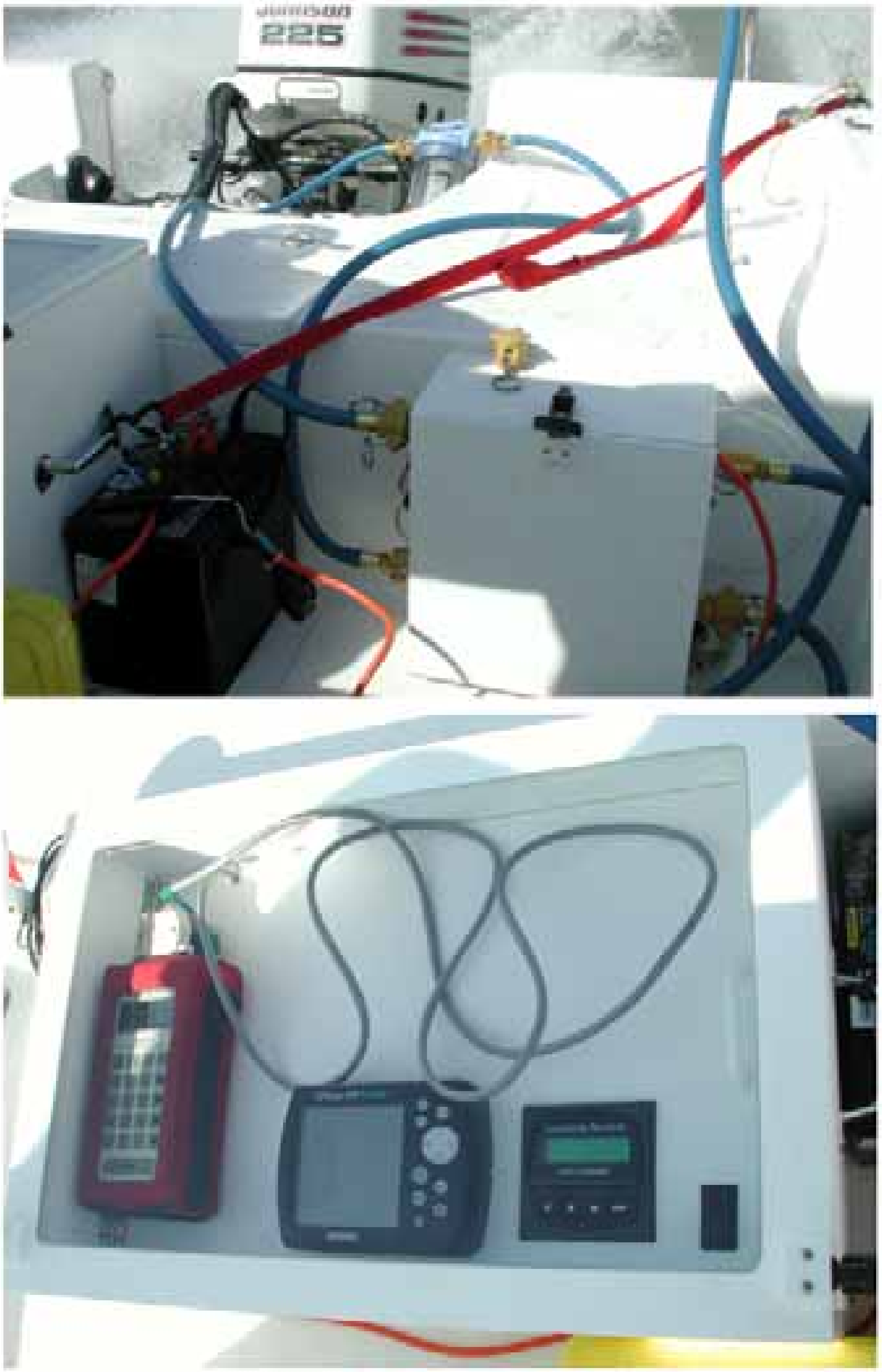


Figure A31: Photos of Dataflow operation in San Antonio Bay. The upper image shows the regulator pump box attached to the intake ram (right), the de-bubbler (near engine), and inflow pump to the Dataflow box (left). The bottom image shows the GPS, temperature, and conductivity displays as well as the datalogger (on left). All other sensors are in the lower level of the box.

Non-SAGES ANWR studies

15. Community structure and foodweb dynamics in created and natural wetlands along Aransas National Wildlife Refuge

16. Diet and trophic position of blue crabs relative to size in ANWR marsh

17. Importance of connectivity in shaping aquatic food webs in ANWR marsh

Research Participants: Stephen Davis, Jeff Wozniak, Steven Zeug, Virginia Shervette, David Hoeinghaus and Katherine Roach

Project Overview

This was a set of studies conducted in 2004 and led by S. Zeug, V. Shervette, and D. Hoeinghaus, all PhD students in WFSC at Texas A&M University. Dr. Stephen Davis served as a committee member for each student but was not a primary advisor. These studies were conducted to further define the coastal marshes. SAGES resources were not used to support this research, but access was provided through SAGES-funded projects. This work involved a series of studies that sought to understand: 1) the functional equivalency of created and natural *Spartina* marshes along ANWR, 2) the size-specific trophic dynamics of blue crabs across ANWR salt marsh, and 3) the foodweb structure of the ANWR marsh faunal community across gradients of hydrologic connectivity. Specifically, each project is described below in abstract form. K. Roach (a PhD student) and J. Wozniak have also taken a recent interest and are collaborating on a paper that will come from the third study.

15. Functional equivalency study: Natural and created *Spartina* marsh habitats in the Guadalupe Estuary, adjacent to ANWR were surveyed during spring, summer, and fall 2004 to evaluate the equivalence of nekton assemblages in an old (> 30 years) created marsh. During each season, six replicate samples were collected in each marsh type using a 1m^2 drop sampler. Multivariate analysis revealed significant differences in nekton assemblage structure among marsh type, both within and across seasons. Species richness was significantly higher in the natural marsh, and several species that were dominant in the natural marsh, but rare or absent in created marsh, had strong correlations with the presence of oyster substrate that was only encountered in natural marsh samples. Although cumulative richness was greater in the natural marsh, eight species were collected only from the created marsh. Aggregate crab biomass was similar in both marsh types, however, shrimp and fish biomass was significantly higher in natural marsh. Analysis of the density, biomass, and size structure of three commercially important crustaceans indicated that the created marsh supported similar biomass of some species (*e.g.*, white shrimp, blue crab), however, the size structure of some populations were variable among marshes (*e.g.*, blue crab, brown shrimp). We conclude that lower substrate complexity (specifically oyster) and soil organic content in the created marsh reduced measures of nekton similarity, and we recommend that these features be addressed in future restorations.

16. Blue crab study: Analyses of stable C and N isotopes were used to examine trophic characteristics of blue crabs in relation to body size (15 – 165 mm carapace width) within salt-marsh habitats of ANWR. Blue crab trophic position did not change with increasing body size, and all size-classes appear to consume primary consumers and primary producers in relatively equal proportions. However, blue crab $\delta^{13}C$ values increased significantly with increasing body size. As body size increased, blue crabs assimilated greater proportions of carbon ultimately derived from *Spartina alterniflora*. Individuals of approximately 35 mm CW assimilated carbon almost exclusively derived from C3 plants and benthic algae, whereas, larger individuals (125 mm CW) assimilated carbon derived from benthic algae and *Spartina alterniflora* derived detritus in equal proportions. Given the complex nature of salt marsh food webs and the omnivorous diet of blue crabs, the observed size-based trends have important management and conservation applications.

17. Foodweb/connectivity study (in prep): We utilized carbon ($\delta^{13}C$) stable isotope signatures to elucidate the variation in the origin of consumer basal production sources, as a result of habitat variation along the estuarine coast of ANWR. The objective was to determine if consumers assimilated local, basal carbon sources from the surrounding habitat. Allochthonous basal sources of organic matter were sampled from estuarine salt marsh sites and autochthonous basal sources of organic matter from isolated pond, connected pond, and tidal creek sites along the same estuarine gradient at two marsh locations (BR and SB). Variation in $\delta^{13}C$ signatures at study sites along the ANWR coast and the varied degree of hydrologic connectivity between the three sampled habitat types (tidal creeks, connected ponds, and isolated lagoons) would illustrate the role of varied water level, nutrient sources, and hydrologic connectivity in habitat and food web variation. The results of this study will further our understanding of the flux of carbon across the landscape and the overall importance of carbon sources found in the main aquatic habitat types along the coastal marshes of ANWR. These findings will also aid habitat managers at ANWR in understanding the combined effects of marsh water-level variation, habitat connectedness, and coastal marsh habitat quality.

See papers by:

Zeug *et al.*, 2007; Hoeinghaus and Davis, 2007; and Roach *et al.*, *in progress*.