USE OF STABLE ISOTOPE ANALYSES TO DESCRIBE TROPHIC DYNAMICS OF AQUATIC ECOSYSTEMS IN GALVESTON BAY, TEXAS

by

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ABSTRACT

USE OF STABLE ISOTOPE ANALYSES TO DESCRIBE TROPHIC DYNAMICS OF AQUATIC ECOSYSTEMS IN GALVESTON BAY, TEXAS

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Food webs in estuarine ecosystems are characterized by omnivory and an abundance of detritivores in addition to seasonal changes in species and physiochemical conditions. Therefore, it is difficult to identify dominant linkages of energy flow in this very complex and dynamic environment. Attempts to construct food webs using stomach content analyses are unsatisfactory because they cannot identify assimilated dietary components. The use of stable isotope analysis, when combined with dietary data, offers a more powerful method for evaluating the trophic classification of an organism. The primary source of productivity is determined through ^{13}C content while the trophic level is determined through ^{15}N. This study used dual stable isotope analyses to identify the primary sources and pathways of nutrition and the trophic level for the main species in

the Galveston Bay Estuary Ecosystem (GBEE) from five different sub-bays; Christmas, East, Galveston, Trinity, and West Bays. Additionally, an analysis on the effects that thawing and utilizing different storage techniques has on stable isotope signatures was conducted. The ^{13}C analysis showed that for the eastern section of the GBEE, the food web supporting the majority of the species was based on a mixture of phytoplankton and epiphytic algae and/or detritus. For the western section of the GBEE, epiphytic algae and/or detritus are very important. Few of the species examined assimilated one basal carbon source exclusively; instead a mixture of sources at each sub-bay appeared to be used. The ^{15}N analysis showed that nutrient cycling in the upper portion of the GBEE is heavily influenced by anthropogenic sources from the Trinity and San Jacinto Rivers whereas other secondary bay communities including Christmas and West Bay are primarily driven by in-situ production from marshes and seagrass beds. When testing the effects that different storage methods and thawing had on the isotopic signatures, it was found that there was no significant difference in storing the samples on ice or flash-freezing them and no significant difference between the control and samples left out to thaw for 1, 3, 5, and 10 days. However, it appeared that the $\delta^{15}N$ values were becoming more enriched the longer the samples were left out to thaw, although this was not statistically significant.

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INTRODUCTION

Estuaries are extremely dynamic habitats along the coasts where freshwater that is discharged from the land meets the sea, producing brackish water of varying salinity. In shallow, temperate estuaries, large variations in chemical, physical, and biological characteristics of the water column occur on the scale of seasons and years (Livingston 1984; Johnson et al. 1990). Such physicochemical variability includes fluctuations in tides, temperature, salinity, turbidity, freshwater inflow, shoreline erosion, and subsidence. Variation in biota occurs due to seasonal changes in assemblages and ontogenetic shifts in trophic structure. These changes in community structure often correspond with more or less predictable seasonal changes in physicochemical conditions (Zimmerman and Minello 1984). Estuarine communities are therefore composed of species that are well adapted to highly unstable, complex habitats.

The Galveston Bay Estuary Ecosystem (GBEE), located in the northeastern portion of the Texas coast, is the largest and most productive estuary in Texas. Approximately one-third of the state's commercial fishing income and over half of the state's expenditures for recreational fishing are related to the bay (McElyea 2003). The GBEE is economically important because it is used as a major nursery and fishery area for commercially important estuarine species (Holland et al. 1973). These nursery areas which include salt marshes and seagrass meadows, aid in the growth and survival of fish and invertebrate species throughout their juvenile life stage, providing refuge from

predation and serving as rich feeding grounds (McTigue and Zimmerman 1998). After members of these species have matured, extensive seasonal migrations including spawning runs occur (Darnell 1958; Montagna and Kalke 1995). In addition, seasonal changes in phytoplankton and zooplankton communities occur in response to changing levels of daylight, freshwater inflow, and resulting turbidity (Johnson et al. 1990). Together these processes can have dramatic impacts on major functional groups in the estuary such as the primary producers, zooplankton, benthos, and nekton communities and their associated food webs (Livingston 1984).

The main types of producers that exist in the GBEE are phytoplankton, benthic algae, and vascular plants (submerged and emergent species). Phytoplankton and algae are both ubiquitous central components of primary production in the GBEE. Sheridan et al. (1989) identified 132 species in upper Galveston Bay and Trinity Bay. The most predominant taxa included diatoms (54 taxa) and green algae (45 taxa). In addition, blue-green algae (14 taxa), dinoflagellates (9 taxa), euglenoids (7 taxa), cryptophytes (2 taxa), and golden-brown algae (1 taxon) were observed. High abundances of planktivorous herbivores such as Gulf menhaden (*Brevoortia patronus)* and striped mullet (*Mugil cephalus*) are found in these waters indicating that a crucial food chain exists from phytoplankton to small fish and large predators (Matlock and Garcia 1983; Patillo et al. 1997). Another important primary producer, benthic algae, grows on submerged materials including vascular plants such as smooth cordgrass (*Spartina alterniflora*) and the shells of mollusks (Akin and Winemiller 2006).

On the periphery of the bay, extensive *Spartina* saltmarshes are dominated by smooth cordgrass in the intertidal zone and saltmeadow cordgrass (*Spartina patens*)

supertidally (Stickney and McGeachin 1978). These *Spartina* saltmarshes are flooded approximately 78% of the year, providing habitat and refuge for smaller species from their predators (Stunz et al. 2010). As the plants mature, they become coated with epiphytes that include algae, bacteria, detritus, diatoms, and microinvertebrates, providing food for the small fishes and invertebrates that reside there (Morgan 1980). Only a very small percentage of vascular plants in the estuary are grazed on directly by aquatic fish and invertebrates, such as pinfish (*Lagodon rhomboides*) (Sheridan et al. 1989). Instead their biomass is transferred into the food chain after death when they are broken down by microorganisms into fine particles of vegetative detritus that are common in estuarine shallows (Créach et al. 1997). In estuaries, Darnell (1961) and Akin and Winemiller (2006) found that detritus was the primary basal resource supporting invertebrate and fish populations in Lake Pontchartrain, Louisiana and Mad Island Marsh, Matagorda Bay, Texas, respectively. Consumption of detritus is not limited to detritivores, but is also ingested by top carnivores inadvertently when they are feeding on the bottom (Jepsen and Winemiller 2002).

Additional predominant functional groups in the GBEE consist of zooplankton, benthos, and nekton communities. Like phytoplankton and algae, zooplankton is ubiquitous within the GBEE. Zooplankton consisting mainly of copepods was the dominant form found by Reid (1955a) in a summer study of East Bay. The second most abundant form of zooplankton found by Sheridan et al. (1989) was barnacle nauplii. These organisms transfer energy and carbon obtained from phytoplankton and detritus up the food web to larger fish and invertebrates (Turner and Tester 1997). Zooplankton is immensely important as a source of nutrition for juvenile fish in aquatic ecosystems, as

well as for the bay anchovy (*Anchoa mitchilli*) that depends on zooplankton throughout its life history (Darnell 1961; Patillo et al. 1997).

Benthic invertebrates are important functional components in estuarine ecosystems because these organisms promote the decomposition of organic matter, recycle nutrients that are used for photosynthesis, and transfer energy to higher consumers in the food web (Gaston et al. 1998). Additionally, benthic organisms are good indicators of pollution because of their direct contact with the sediment and reduced mobility (McElyea 2003). Representative species of benthic invertebrates include polychaete worms, amphipods, and bivalves that are part of the infauna and economically important epibenthic organisms including white and brown shrimp (*Litopenaeus setiferus* and *Farfantepenaeus aztecus*), blue crab (*Callinectes sapidus*), and the Eastern oyster (*Crassostrea virginica*), whose reefs makes up approximately 10% of the bay bottom in the GBEE (Stunz et al. 2010).

Numerous species of nekton feed on these benthic organisms and reside in the GBEE. Specifically, trawling studies conducted by the Texas Parks and Wildlife Department (TPWD) have identified over 150 species of fish in the GBEE (Lester et al. 2002). This total includes some species of freshwater fish in the northern sections of the bay near the mouths of the Trinity and San Jacinto Rivers and marine species that migrate in through the passes from the Gulf of Mexico. The four major fish commercially harvested in the bay are the black drum (*Pogonias cromis*), *M. cephalus*, sheepshead (*Archosargus probatocephalus*), and the southern flounder (*Paralichthys lethostigma*) (Lester et al. 2002). Some of the main sport fish in the bay include the Atlantic croaker

(*Micropogonias undulatus*), sand seatrout (*Cynoscion arenarius*), spotted seatrout (*Cynoscion nebulosus*), and the red drum (*Sciaenops ocellatus*) (Lester et al. 2002).

Currently, many factors are endangering estuarine habitats and their species, such as unsustainable harvesting practices, habitat loss, increased levels of anthropogenic contaminants, and reduced freshwater inflow (Longley 1994; McElyea 2003). Because of the multitude of stressors that exist, single species management approaches have failed to protect many species of finfish. Therefore, an ecosystem management approach that recognizes interactions among species and between species and their environment is needed (Marancik and Hare 2007). Quantifying species and their food webs provides a basis for modeling community dynamics (Winemiller et al. 2007). Ecosystem models that combine this data with species mortality estimates and fishing pressure can assist scientists and ecosystem managers in determining the effects of anthropogenic changes in the ecosystem. Predictive multispecies models that utilize this data include Ecopath with Ecosim (EwE) that examines the energy and biomass among food web functional groups over time and Multispecies Virtual Population Analysis (MSVPA) that can estimate the population and ecosystem status (Christensen and Walters 2004; Marancik and Hare 2007). Therefore, an important prerequisite before developing and using ecosystem models and an ecosystem approach in the management of an estuarine ecosystem is understanding the trophic structure of that ecosystem.

One of the fundamental questions about the properties of an aquatic ecosystem that aids in ecosystem modeling is the interconnectedness of the community's organisms and their subsequent trophic levels (Darnell 1961). Predator-prey relationships have been commonly studied through the use of food webs and food pyramids. Food web studies

provide information needed to form the community structure among matrices of interconnected species. Food pyramid studies combine species into trophic levels to represent the flow of energy and nutrients through ecosystems (Vander Zanden and Rasmussen 1996). Several studies that employed stomach content analyses have been conducted in and around the GBEE to initiate the construction of these dietary interactions in order to understand the interconnectedness of its species (Reid et al. 1956; Diener et al. 1974; Alexander 1983; Divita et al. 1983; Matlock and Garcia 1983; Alexander 1986; McTigue and Zimmerman 1998; Scharf and Schlicht 2000). With this information, preliminary food webs and pyramids can be constructed summarizing the resource-consumer interactions, following the flow of energy in a community. This information can be used to enhance our understanding of ecosystem structure and population dynamics.

Unfortunately, a major downfall of stomach content analysis is that it can only offer a glimpse of the animal's diet and cannot provide any information on the rate of ingestion and assimilation of food (Créach et al. 1997). This method is short term and most likely varies seasonally due to species migration and ontogenetic factors such as size and feeding strategy, making it difficult to assess a species overall diet (Litvin and Weinstein 2003). Furthermore, the trophic structure of salt marsh estuaries are difficult to construct because 1) detrital material lacks descriptive characteristics although it is a dominant dietary item in the food web, 2) opportunistic feeding is prevalent, 3) a variety of primary producers exist that could be supporting the food web at different times of the year, and 4) some organic matter is imported into the system from inland sources (Peterson et al. 1985). A likely solution to this problem is provided through the use of

stable isotopes, which can be used to estimate assimilation of dietary resources over time and space, giving it an advantage over gut content analyses (Thomas and Cahoon 1993; Jepsen and Winemiller 2002).

Isotopes are atoms of an element that possess different numbers of neutrons, but whose number of protons and electrons remain the same. Consequently, when an atom has more neutrons, it is heavier because its atomic mass is greater. The only difference from a normal atom is that because of the isotopes greater mass, it will react slower in a kinetic reaction, a behavior known as fractionation (Fry 2006). In nature, most elements exist as mixtures of different isotopes, occurring in stable and unstable or radioactive forms which release energy as they decay. Stable isotopes are safe isotopes that do not decay and exist in everything, as a product of a species diet and metabolic processes (Holt and Ingall 2000). Stable isotopes provide a natural way to directly follow element cycling in the environment. For this purpose, stable isotopes of hydrogen (^{1}H, ^{2}H), carbon (^{12}C, ^{13}C), nitrogen (^{14}N, ^{15}N), oxygen (^{16}O, ^{17}O, ^{18}O), and sulfur (^{32}S, ^{33}S, ^{34}S, ^{36}S) have been used (Fry 2006).

Carbon isotopes are routinely used to indicate the sources of species nutrition (Cifuentes et al. 1996; Kelley et al. 1998; Yoshii et al. 1999). This can be done because C_4 grasses such as *S. alterniflora* have $\delta^{13}C$ values with an average range from approximately -12 to -14‰ and C_3 terrestrial plants have $\delta^{13}C$ values with an average range from approximately -22 to -29‰ (Teeri and Schoeller 1979; Peterson and Howarth 1987; Deegan and Garritt 1997; Gannes et al. 1997). These isotope distinctions are determined by the biochemistry of either the C_3 (Calvin-Benson) or C_4 (Hatch-Slack) photosynthetic pathways, producing a unique signature for determining the primary

source of nutrition through different carbon isotopic fractionations (Teeri and Schoeller 1979). Likewise, the different sources of CO_2 (air versus water) utilized will produce different mean $\delta^{13}C$ values (Peterson and Howarth 1987). It has been widely documented that ^{13}C exhibits little or no enrichment between trophic levels (< 1.0‰ enrichment per trophic level), but varies at the bottom of the food chain depending on the ultimate source of carbon (Vander Zanden and Rasmussen 1999; Post 2002; Hyndes and Lavery 2005). For example, carbon derived from phytoplankton is assimilated into species that depend on these microorganisms for nutrition. Therefore, if an organism is utilizing a carbon source such as marine phytoplankton ($\delta^{13}C$ values with an average range from approximately -18 to -22‰), then that organism will have a $\delta^{13}C$ value that resembles the source (Kelley et al. 1998).

Stable isotopes can also be used to identify an organism's trophic position (Fry 1988; Gannes et al. 1997). Unlike the ^{13}C isotope, ^{15}N is enriched as the trophic levels increase due to isotopic fractionation. The $\delta^{15}N$ value can be enriched by a factor of 3.0 to 4.0‰ per trophic level (Peterson et al. 1985; Vander Zanden and Rasmussen 1999; Post 2002). Isotopic enrichment occurs at each trophic position because the lighter isotopes (which react faster in a kinetic reaction) are selectively excreted or metabolized, leaving more of the heavier isotope (Holt and Ingall 2000). Consumers have a higher $\delta^{15}N$ value because their protein levels are higher than that of dietary protein due to the removal by the body of ^{14}N-containing urea (Gannes et al. 1997). Therefore, a top predator in the food chain will have a higher $\delta^{15}N$ value that will be heavier (more positive $\delta^{15}N$ values) than that of its prey below it on the food chain (less positive $\delta^{15}N$ values) (Jepsen and Winemiller 2002). For example, in a study done by Yoshii et al.

(1999) in Lake Baikal, an enrichment factor of 3.3‰ was observed for $\delta^{15}N$ at each trophic transfer.

Unfortunately, additional sources of variability do exist in $\delta^{15}N$ values because the relative abundance of $\delta^{15}N$ is also influenced by the sources of inorganic nitrogen that were utilized by the organism (Holt and Ingall 2000). Inorganic nitrogen leaves septic tanks predominately in the form of ammonium (NH_4^+) (McClelland and Valiela 1998). Some nitrogen is lost due to the volatilization of NH_3, while the remaining ammonium is converted to nitrate by autotrophic bacteria (Valiela et al. 1997a). More nitrogen is then lost through the process of denitrification which is the conversion of nitrate to N_2 gas by anaerobic heterotrophic bacteria (Aravena et al. 1993). Fractionation transformations such as the volatilization of ammonia and denitrification remove ^{14}N at a faster rate than ^{15}N, causing the remaining nitrate from wastewater that enters the estuary to typically have $\delta^{15}N$ values between +10 and +20‰ (McClelland and Valiela 1998). Therefore, anthropogenic nitrogen such as wastewater and septic tank effluent can significantly skew the isotopic composition of the total dissolved inorganic nitrogen (nitrate + nitrite + ammonium) pool delivered to an estuary, causing $\delta^{15}N$ values to increase over the entire estuary (McClelland and Valiela 1998). However, this process can also be used to identify areas artificially enriched by man-made sources of nitrogen.

The dual isotope approach of using carbon and nitrogen provides a powerful tool that depicts nutrient pathways and the trophic relationships in the GBEE. This approach provides significantly more power than using single isotopes only, which cannot be used to determine different food sources for which the isotopic signature of potential sources are similar (Peterson et al. 1985; Thomas and Cahoon 1993). Unlike stomach content

analyses, stable isotope analyses show what dietary items are integrated into an animal's tissues including the relative contribution of detritus, which is poorly quantified by gut content analyses (Pinnegar and Polunin 1999). However, in order to clearly interpret the results, stable isotope analyses should be used in conjunction with direct diet analyses data (Post 2002). Stable isotope analyses are useful for fisheries and natural resource management because there is an immense need to understand food web dynamics within complex trophic systems like estuaries and to maintain the valuable resources that they support (Jepsen and Winemiller 2002).

The use of stable isotopes to study the trophic interactions of aquatic organisms has been used in several estuarine studies around the United States. Litvin and Weinstein (2003) conducted a study within the Delaware Bay estuary to better understand the importance of salt marsh primary production in the flux of nutrients to higher consumers. They found that a greater proportion of the diet of the pelagic fish species, *A. mitchilli* originated in phytoplankton while the demersal species, white perch (*Morone americana*), depended more on benthic microalgae and macrophyte detritus. Another study conducted by Winemiller et al. (2007) continued their stomach content analyses study of Mad Island Marsh through the use of stable isotopes. Primarily, dietary analyses revealed vegetative detritus to be the main component in the food chain but stable isotope analyses concluded that variable mixtures of vegetative detritus and algae were the predominant components in the food chain.

Two previous stable isotope studies have been conducted in the Galveston Bay area. Holt and Ingall (2000) focused on comparing a single species, *C. nebulosus*, and their primary source of nutrition and trophic level in Galveston Bay, with that of Upper

Laguna Madre, an estuary on the southern coast of Texas. In their study, they found that the food web supporting *C. nebulosus* in Galveston Bay is based mainly on phytoplankton and that the nitrogen isotopic composition reflects a greater input of sewage-derived nitrogen into the GBEE. The most recent study done by Fry (2008) utilized C, N, and S isotope tags to investigate whether open bay areas are an additional important nursery habitat for *F. aztecus*. The sulfur isotope tags provided distinctive labeling to separate marsh and bay brown shrimp populations when the C and N tags are similar. The S tags were able to show that both marshes and open bays were important in the life cycle of *F. aztecus*, supporting about $^{1}/_{3}$ and $^{2}/_{3}$ of the total shrimp production, respectively.

Once samples have been collected for stable isotope analyses, differences in the preservation and storage methods may vary and these variations could potentially alter the isotopic signatures enough to lead to incorrect presumptions. In some studies, tissue samples have been collected immediately in the field and sent to the lab for analysis and in others; the tissue samples are not processed immediately but are stored and analyzed at a future time in the lab. Additionally, some samples are initially stored in ice or liquid nitrogen. For example, Jepsen and Winemiller (2002) sealed their samples in aluminum foil before placing them in dry ice in the field whereas Thomas and Cahoon (1993) put their fish samples on ice after they were collected. Arrington and Winemiller (2002) evaluated the effect of salt and formalin-ethanol sample preservation on carbon and nitrogen isotopic signatures of fish muscle tissue. Their results showed statistically significant effects of the tissue preservation technique on both $\delta^{13}C$ and $\delta^{15}N$, but the magnitude of change was small and directionally uniform. Another study conducted by

Feuchtmayr and Grey (2003) compared an immediately processed sample (control) with samples preserved by means of ethanol, methanol, formaldehyde, gluteraldehyde, frozen, and shock frozen methods. They found that ethanol and shock freezing treatments did not significantly alter $\delta^{13}C$ values, but the formalin and freezing treatments deviated most from the control values. For $\delta^{15}N$, all treatments resulted in enrichment relative to control values. Furthermore, there are unfortunate cases in which the samples that have been stored in the freezer, thaw, and are not discovered immediately. Because of the additional time and money it would cost to replace these samples, it is imperative to know how the stable isotope values of these samples are affected by periods of thawing after originally being stored in a freezer.

Dual stable isotope analyses was used to test the hypotheses that (1) $\delta^{13}C$ isotopic values differ among the different sub-bays in the GBEE suggesting different sources of primary production, (2) $\delta^{15}N$ isotope values of similar species from different sub-bays feed at the same trophic level, and (3) $\delta^{15}N$ isotopic values will be higher in the upper estuary near the mouths of the San Jacinto and Trinity rivers than in the lower estuary due to anthropogenic nitrogen loading. The ultimate purpose of this study was to provide information for future ecosystem modeling in the GBEE.

In order to account for any possible variation in stable isotope analytical results due to the influence of sampling and preservation methods, this study also evaluated the effect thawing has on previously frozen samples and the differences between flash freezing samples in liquid nitrogen compared to putting samples on ice in the field. This data tested the hypotheses that (1) flash freezing samples in liquid nitrogen in the field has the least variation in isotopic values compared to storing samples on ice and (2) $\delta^{13}C$

and $\delta^{15}N$ isotope ratios differ the most among samples that were left out to thaw longest. The ultimate purpose of this portion of the study is to be able to provide recommendations on the sampling methods and thawing times that do not significantly alter isotopic values from the control for future isotopic studies.

MATERIALS AND METHODS

Study Location

The Texas coast is approximately 595 km long and includes seven major bay systems, the largest of which is Galveston Bay (approximately 2,020 km^2) (White and Calnan 1990; Clark et al. 2004). Galveston Bay is a bar-built, temperate estuary divided into four main sub-bays, Galveston Bay proper, Trinity Bay, East Bay, and West Bay, and numerous secondary bays that are separated from the Gulf of Mexico (GOM) by Bolivar Peninsula, Galveston Island, and Follet's Island. The bay encompasses roughly 354,000 acres of open water and 118,000 acres of marshes and swamps, making it the seventh largest estuary in the United States (Pulich and White 1991). Seawater flows into the estuary from the GOM through Bolivar Roads, San Luis Pass, and the man-made Rollover Pass. The two major sources of freshwater are the Trinity and San Jacinto Rivers which drain a watershed of approximately 33,000 mi^2 into the GBEE (Lester et al. 2002). The air temperature in this area varies from an average high of approximately 34˚C in the summer to an average low of about 8˚C in the winter and the average annual water temperature is 29.5˚C (White and Calnan 1990; Thronson and Quigg 2008). Like most estuaries on the Texas coast, the depth is relatively shallow, usually not exceeding 3 m in undredged areas and mixed tides that are primarily diurnal with a mean daily range

of 0.3 m (Matlock and Garcia 1983; Stunz et al. 2002). Sediments within the bay mostly consist of clay and silt along with areas of some shell and fine sand (Phleger 1965).

The five bays chosen for this study differ based on their location in the GBEE by the amount of freshwater inflow, salinity regime, and dominant shoreline and submerged vegetation (Figure 1). Trinity Bay is dominated by the turbid, nutrient-rich Trinity River, which has the largest discharge of any coastal Texas river (approximately 5.6 million acre-feet per year) and supplies 78% of the total riverine input and 60% of the freshwater input into the GBEE (LeBlanc and Hodgson 1959; Santschi 1995). Consequently, Trinity Bay exhibits the lowest salinity of all of the bays. Where the Trinity River empties into Trinity Bay, an extensive area of wetlands has developed in which the prominent plants in marsh areas other than *S. alterniflora* include *Alternanthera philoxeroides* (alligator weed), *S. patens, Scirpus californicus* (California bulrush), *Zizaniopsis miliacea* (giant cutgrass), *Cyperus articulates* (flat sedge), *Sesbania* sp. (rattle bush), *Sagittaria* sp. (arrowhead), and *Distichlis spicata* (saltgrass) (Williams 2003). The vast majority of the primary production in the higher, irregularly flooded vegetation zones is not exported, but the lower frequently flushed vegetative zone characterized by the dominant shoreline vegetation, *S. alterniflora*, may contribute about 45% of its net production to the estuarine waters (TDWR 1981). Extending from the mouth of the San Jacinto River to Bolivar Roads, Galveston Bay is the largest Texas bay. The San Jacinto River has a smaller influence on upper Galveston Bay, only discharging about 703,528 acre-feet of freshwater per year. About 80% of the seawater that enters the GBEE enters through Bolivar Roads in the lower part of the bay (LeBlanc and Hodgson 1959; Lester et al. 2002). A large portion of the western shoreline of Galveston Bay is heavily

industrialized, consisting of bulkhead and developed shoreline with significant saltmarshes of *S. alterniflora* only being found in the lower portions of the bay (Santschi 1995). To the southeast is East Bay, which is connected to the GOM by Rollover Pass and receives its greatest inflow of freshwater through Oyster Bayou and Robinson Bayou (Reid 1955a; Reid 1956). An extensive oyster reef (Hanna Reef) acts as a barrier separating East Bay and Galveston Bay proper and the bay is surrounded except

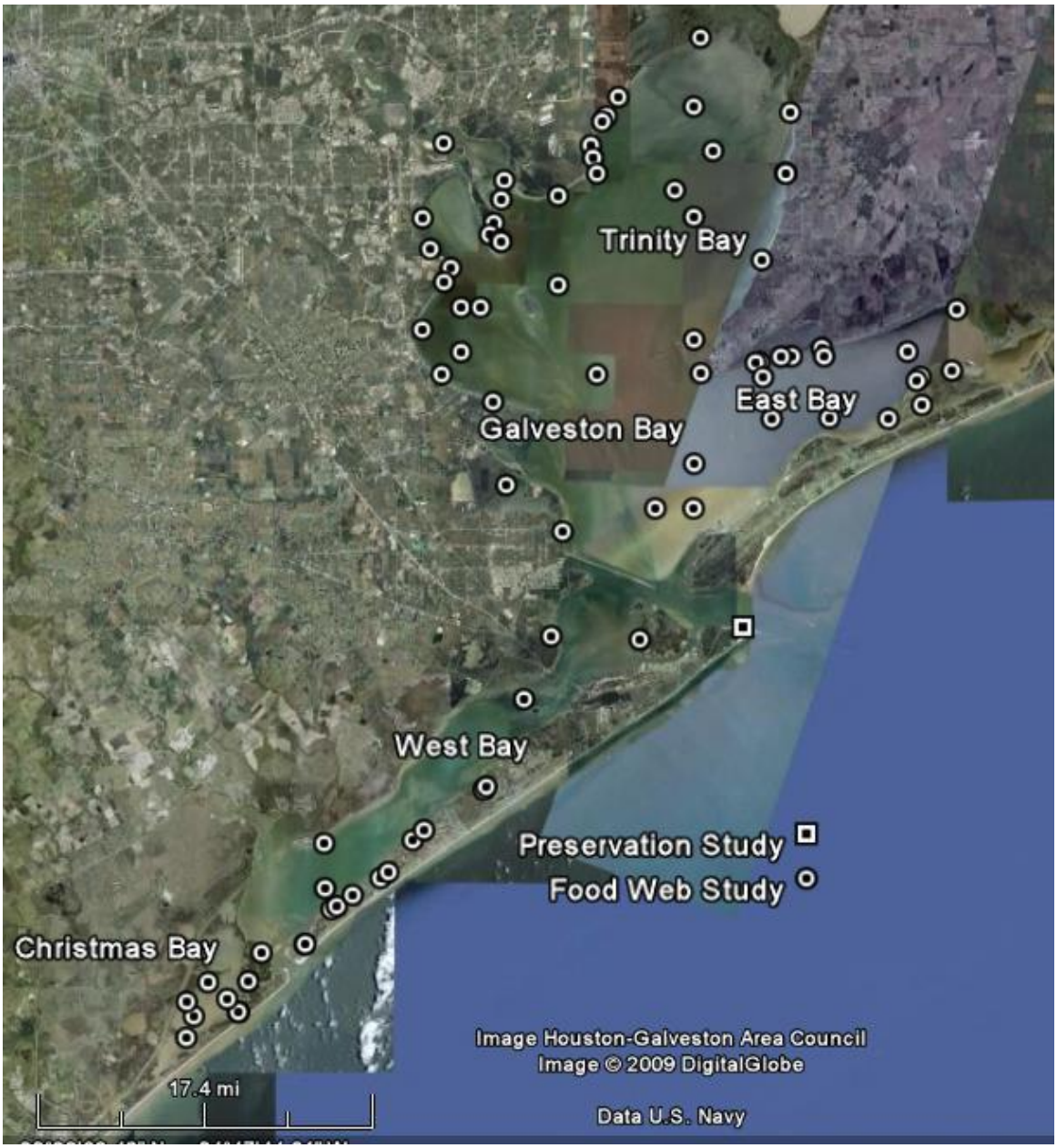

Figure 1. Five sub-bay study sites and sampling locations in the Galveston Bay estuary, Texas.

at its mouth by S. *alterniflora* (Reid 1956; Reid et al. 1956). To the west and mostly separated from the eastern section of the GBEE by the Texas City Dike, West Bay has typically polyhaline waters (salinity range of 15-32 ppt) due to two major inlets off the GOM (Bolivar Roads and San Luis Pass) while freshwater inputs are received from Chocolate Bayou and other small bayous and streams (TDWR 1981; Pulich and White 1991). Extensive saltmarshes of *S. alterniflora* are located on the northern portion of Galveston Island and along the Intracoastal Waterway adjacent to the mainland (Alexander 1983; Rozas et al. 2007). Christmas Bay, a small secondary bay connected to West Bay, is separated from the GOM by Follet's Island and receives saltwater inputs from the San Luis Pass by way of Cold Pass (McFarlane 1991). Extensive saltmarshes are located along the periphery of Christmas Bay and freshwater inputs are received from Bastrop Bayou (McFarlane 1991). Christmas Bay has been designated a coastal preserve and is unique in that it contains the only extensive seagrass meadows including shoalweed, (*Halodule wrightii*), in the GBEE (Pulich and White 1991).

Sampling Design

Sampling took place within a 7 month period (April - October 2008) and also in May 2009 in cooperation with the regular monitoring efforts of the TPWD Coastal Fisheries in Dickenson, Texas. The target taxa selected for this study represented the dominant biomass of the GBEE based on historical TPWD catches. Representative organisms from major habitat types such as open water plankton and nekton, benthic organisms, oyster reefs, and intertidal areas were included in an effort to represent the main trophic levels and groups from the GBEE. Additionally, some fish were divided

into size classes associated with potential life stages during which ontogenetic shifts in diet occur, therefore, possible differences in isotopic composition. At each bay, three replicate samples of each species were collected based on availability.

At each site, temperature (˚C), salinity (ppt), dissolved oxygen (DO) (ppm), and turbidity [Nephelometric Units (NTU)] were measured in addition to the depth (m) of the site based on TPWD protocol (Appendix 1, Appendix 2, and Figure 1). Furthermore, chlorophyll-α (mg/m^3) and pheophytin-α (mg/m^3) surface water samples were collected (Appendix 3). These water samples were immediately filtered using a 0.45 micron glass fiber filter and were frozen immediately after collection (Appendix 3). The filters were ground, extracted in a 90% aqueous acetone solution, and centrifuged before the absorbencies of the acetone extract were measured with a spectrophotometer and then used to calculate chlorophyll-α and pheophytin-α concentrations using the following formulas:

$$\text{Chlorophyll-}\alpha = [26.7\ (664_b - 665_a) \times V_1] / V_2 \times L$$

$$\text{Pheophytin-}\alpha = \{26.7\ [1.7\ (664_a) - 665_b] \times V_1] / V_2 \times L$$

where V_1 = volume of clarified extract (L), V_2 = volume of what was filtered (m^3), L = light path length or width of cuvette (cm), and 664_b and 665_a = the optical densities of 90% acetone extract before and after acidification, respectively (Clesceri et al. 1998).

Concurrent with the water quality measurements, ten biological specimen collection methods were utilized to obtain samples throughout the GBEE (Table 1). In two instances, hook and line were utilized in an attempt to catch larger species of fish without deploying a gill net. Bay trawls (6.1 m) were used to collect species near or on the open bay bottom in water ≥ 1 m deep that was free of obstructions. A bag seine (18.3

m) was pulled parallel to the shoreline for 15.2 m and was used to collect smaller species in nearshore environments. Gill nets (6 to 3 in. mesh) were used to collect larger species nearshore. These nets were set within one hour before sunset and retrieved within four hours after the following sunrise. A dredge was pulled linearly for 30 seconds when collecting species from the oyster reefs (TPWD 2002). A core sampler was utilized for detritus collection off the bay bottom. To collect zooplankton, a plankton net (0.5 m diameter) with a 363 μm mesh and a nonfiltering cod end was towed just under the surface of the water. Phytoplankton were collected by filtering water through Whatman GF/F glass fiber filters (0.7 μm particle retention) and stored in aluminum foil packets (Riera and Richard 1997). A Barnstead International FB1400 muffle furnace (2 h, 450˚C) was used to precombust the glass fiber filters and the aluminum foil packets. Blades of *S. alterniflora* and *H. wrightii* were collected by hand and the macrophyte's softest parts were removed. The plant blades were pre-cleaned to remove epiphytes and attached organisms. Benthic algae samples were collected by scraping the algae off submerged objects including piers, rocks, and oysters.

Table 1. Number of incidents where each gear type was utilized at each sub-bay in the GBEE.

Gear	Christmas	East	Galveston	Trinity	West
Algae scraper	3	2	3	2	2
Bag seine	4	6	6	5	6
Bay trawl	2	4	13	5	1
Chlorophyll filter	2	3	3	2	1
Core sampler	3	3	3	3	3
Dredge	1	2	1	2	0
Gill net	1	6	4	5	9
Hook and line	2	0	0	0	0
Plankton net	1	2	2	2	0
Plant removal	1	1	1	2	1
Total	20	29	36	28	23

Once collected, all specimens were identified to genus or species, measured to the nearest 1 mm total length (TL) or carapace width (CW), and rinsed with deionized (DI)

water thoroughly to remove adhering particles or sediments (Appendix 4). For larger fish species, white muscle tissue was removed from the mid-dorsal region with a fillet knife, whereas whole specimens were collected for smaller individuals (< 65 mm) after removing the bottom lateral section of the fish where most of the organs were contained. White muscle tissue was used because it reflects stable isotopic values with a longer dietary history than tissue with a faster metabolic rate (e.g., red muscle, gonad, liver, and heart) (Pinnegar and Polunin 1999; Bucci et al. 2007). Removal of the stomach is also beneficial in that recently ingested items that might not be assimilated into the tissue will not alter the data (Feuchtmayr and Grey 2003). Additionally, one dead Diamondback terrapin (*Malaclemys terrapin*) was found during sampling and a sample was collected from the neck region of the organism. Invertebrate tissue samples were taken by removing the shell and collecting the muscle tissue underneath because the shells could have had bacteria and algae growing on them that would have affected the isotopic signature of the invertebrate. Due to the small size of some fish and invertebrates such as *A. mitchilli* and grass shrimp (*Palaemonetes* spp.), species were pooled and whole tissues were used to provide enough material for analysis (Hyndes and Lavery 2005). All samples were stored on ice after collection in the field. Upon returning to the TPWD lab, all samples were dissected and placed into 3.5 mL cryogenic vials and placed inside a portable liquid nitrogen vat for temporary storage. After returning to the University of Houston – Clear Lake (UHCL), the samples were transferred to and stored in a -80˚C freezer until they were processed.

The second portion of the study involved evaluating the effects of preservation. For this portion of the study fish were collected by hook and line from Bolivar Roads, a

tidal pass that forms the main entrance to Galveston Bay, on February 27, 2009 between 9:00 and 13:30 (Figure 1). To reduce variability associated with interspecific differences only common hardhead catfish (*Ariopsis felis*) were caught using hook and line while using *L. setiferus* as bait. Once caught, the fish were placed on ice for no more than 4 hours. Five fish specimens were selected and six samples of white muscle tissue were removed from the mid-dorsal region of each fish with a fillet knife. Before placement into 3.5 mL cryogenic vials, all tissue samples were thoroughly rinsed in DI water and placed inside a portable liquid nitrogen vat or an ice chest for temporary storage in the field. The samples were held on ice for no more than 2 hours. After returning to UHCL, the samples were stored in a -80˚C freezer. After the samples had been frozen for three days, different thawing times were applied to some of the samples (Table 2). Following the specified length of thawing time, the samples were placed back into the freezer for at least three days before they were lyophilized.

Table 2. Storage and treatment methods applied to *A. felis* samples.

Sample	Storage method	Thawing period (days)
1	Ice	0
2	Liquid nitrogen	0
3	Liquid nitrogen	1
4	Liquid nitrogen	3
5	Liquid nitrogen	5
6	Liquid nitrogen	10

Stable Isotope Analysis

A freeze-drier (Labconco Inc. Model #7750020) was utilized for lyophilization. All vegetation was lyophilized for approximately 60 hours and all other samples were lyophilized for approximately 48 hours to remove all moisture from the samples. All lyophilized samples were stored in a glass desiccator until the researcher completed

further processing at the Stable Isotope/Soil Biology Laboratory, Institute of Ecology, University of Georgia, Athens. Dried samples were ground into a fine powder using a ball mill (Spex Industries 8000) and then placed into sterile containers. Following this step, the samples were placed in a drying oven at 50°C overnight with the caps resting on top to remove any residual moisture. Subsamples for each tissue sample were weighed to the nearest 10^{-3} mg. At least five milligrams of ground plant tissue and one milligram of ground animal tissue was available for processing (Kang et al. 2003). All crustacean samples were placed in Ultra-Pure 5 x 9 mm pressed silver capsules (Costech) and all other samples were placed in Ultra-Pure 5 x 9 mm pressed tin capsules (Costech). Bosley and Wainright (1999) showed that there was no significant effect caused by the different capsules used, but it was required because tin capsules degrade rapidly in the presence of acid, whereas the more costly silver capsules are more acid resistant. Crustacean samples were acidified with 20% HCl and redried to remove inorganic carbonates. This process was continued until no bubbles appeared in the capsules, indicating the removal of all inorganic carbonates.

The samples were then dry-combusted (micro-Dumas technique) with a Carlo Erba CHN elemental analyzer and the resulting purified gases (CO_2 and N_2) were introduced to a Finnegan Delta C mass spectrometer quantified relative to the standard reference materials. Recalibrant standards (poplar and bovine) were analyzed after every 12 tissue samples in order to calibrate the system and compensate for drift with time (Pinnegar and Polunin 1999). Delta values are not absolute isotope abundances but differences between samples readings and widely used natural abundance standards. The standard reference material for carbon is PeeDee Belemnite limestone (PDB) and the

standard for nitrogen is atmospheric nitrogen (N_2), both of which are assigned a delta (δ) value of 0‰ on their particular scales (Macko et al. 1984; Goering et al. 1990). The data were reported from the lab in atom percent (AP) and delta (Appendix 17). Atom percent gives the absolute number of atoms of a given isotope in 100 atoms of the total element (Fry 2006). The atom percent values were determined by using the formula as follows:

$$AP = F * 100$$

where AP = the atom percent and F = the fractional abundance of the heavy isotope (Fry 2006). The delta values were determined by using the formula as follows:

$$\delta X = [(R_{sample}/R_{standard}) - 1] \times 10^3$$

where X = the heavy isotope (^{13}C or ^{15}N), R = the ratio of the heavy isotope to the light isotope ($^{13}C/^{12}C$ or $^{15}N/^{14}N$), and is defined in parts per thousand or per mil (‰) (Cifuentes et al. 1996; Riera and Richard 1997; Kang et al. 2003). Samples enriched in the heavier isotope (^{13}C and ^{15}N) are more positive and conversely, samples depleted in the heavier isotope are lighter and less positive (Vander Zanden and Rasmussen 1999). Biota tends to have ^{13}C values that are less than PDB and therefore, have negative $\delta^{13}C$ values ranging from 0 to -50‰. On the other hand, relative to N_2, biota tend to have higher $\delta^{15}N$ values (0 to 20‰) (Jepsen and Winemiller 2002). The transformation of atom percent values into delta values is used because the absolute differences between the samples and standards are quite small at natural abundance levels and might appear only in the third or fourth decimal place if atom percent were reported (Fry 2006). Using delta values has its drawbacks, as well, because it does generate very small errors in calculations of fractionation and mixing and when considering enriched samples (Fry 2006).

Data Analysis

Fish and other nekton were further classified based on size distribution prior to conducting analyses by species or primary producer groups and bay systems. Size classes of commonly caught species were calculated based on TPWD catch data by grouping the catches by species from bay trawls, bag seines, and gill nets into percentiles (Martinez-Andrade et al. 2005). The mean and standard error of all isotopic values for each organism and size class were calculated whenever replicate samples were available. The formula used to calculate the trophic position (TP) of each species was:

$$TP = [(\delta^{15}N_{consumer} - \delta^{15}N_{reference})/3.3] + 1$$

where $\delta^{15}N_{consumer}$ is the $^{15}N/^{14}N$ value for the consumer, $\delta^{15}N_{reference}$ is the $\delta^{15}N$ mean of all forms of primary production for each bay system, and 3.3 is the mean estimated trophic enrichment or fractionation value of $\delta^{15}N$ between consumers and their food sources (Yoshii et al. 1999; Winemiller et al. 2007). Isotopic comparisons between potential food sources and consumers were made by subtracting the fractionation value of 3.3‰ for $\delta^{15}N$ per trophic level from the measured isotope values of consumers (Kang et al. 2003).

Scatterplots were used to visually display the data by plotting the $\delta^{13}C$ (x-axis) and $\delta^{15}N$ (y-axis) specie's values from each sub-bay. A one way analysis of variance (ANOVA) was conducted to evaluate differences in water quality variables and isotopic composition for each species between sub-bay systems. Species in which three replicates from each bay were available were used in the ANOVAs. P-values less than or equal to 0.05 were considered significant for all statistical analysis used in this study. When significant differences were found during the ANOVA, a subsequent Tukey's multiple

range test was used to identify categories exhibiting the statistically different values at a comparison wide p-value of < 0.05. To compare primary productivity and for the preservation study, ANOVA's were also used. Additionally, a boxplot was made to show the overlap between different sources of primary productivity. All statistical calculations were performed using Minitab® software version 15 and 16. Furthermore, typical estuarine isotopic values and trophic positions were compiled from the literature to provide estimates that were used for comparison with the values received from the GBEE. In addition, to help interpret isotopic results, dietary data were compiled from the literature, as well.

RESULTS

Hydrology

Total depth in the GBEE ranged from 0.1 m near the shoreline to 3.3 m in the open bay, which was measured in Trinity Bay (Appendix 2). Based on the single depth measurement taken during each bay trawl and oyster dredge collection, Galveston Bay had the deepest average depth (2.2 m), followed by Trinity Bay (2.0 m), East Bay (1.8 m), Christmas Bay (1.2 m), and West Bay (1.1 m) (Appendix 2).

Water Quality

The water temperature from the GBEE ranged from 17.8˚C in April to 33.6˚C in July (Appendix 2). The average water temperature for the GBEE during this study was 27.1˚C (Table 3). Galveston Bay had the highest mean water temperature (28.3˚C) of the five sub-bays and Trinity Bay had the lowest water temperature (25.1˚C) (Table 3 and Figure 2). The ANOVA and Tukey's multiple range test documented significant ($p = 0.072$) differences in water temperatures between Galveston Bay and Trinity Bay (Table 4).

The salinity in the GBEE during the study ranged from 0.2 ppt in Trinity Bay to 36.0 ppt in Christmas Bay (Appendix 2). The average salinity in the GBEE was 18.6 ppt (Table 3). Trinity Bay had the lowest mean salinity (4.7 ppt), while Christmas Bay had the highest mean salinity (30.2 ppt) (Table 3 and Figure 2). The results from the ANOVA

Table 3. GBEE and sub-bay comparisons of 5 mean water quality variables.

Water quality parameter	GBEE	Christmas	East	Galveston	Trinity	West
Temperature (˚C)	27.1	27.2	27.7	28.3	25.1	27.2
Salinity (ppt)	18.6	30.2	15.0	16.9	4.7	26.3
Dissolved oxygen (ppm)	6.3	5.8	6.2	6.3	7.7	5.7
Turbidity (NTU)	44.3	35.7	66.9	35.3	53.6	30.1
Chlorophyll-α (mg/m^3)	7.8	3.3	7.1	11.4	5.0	12.3

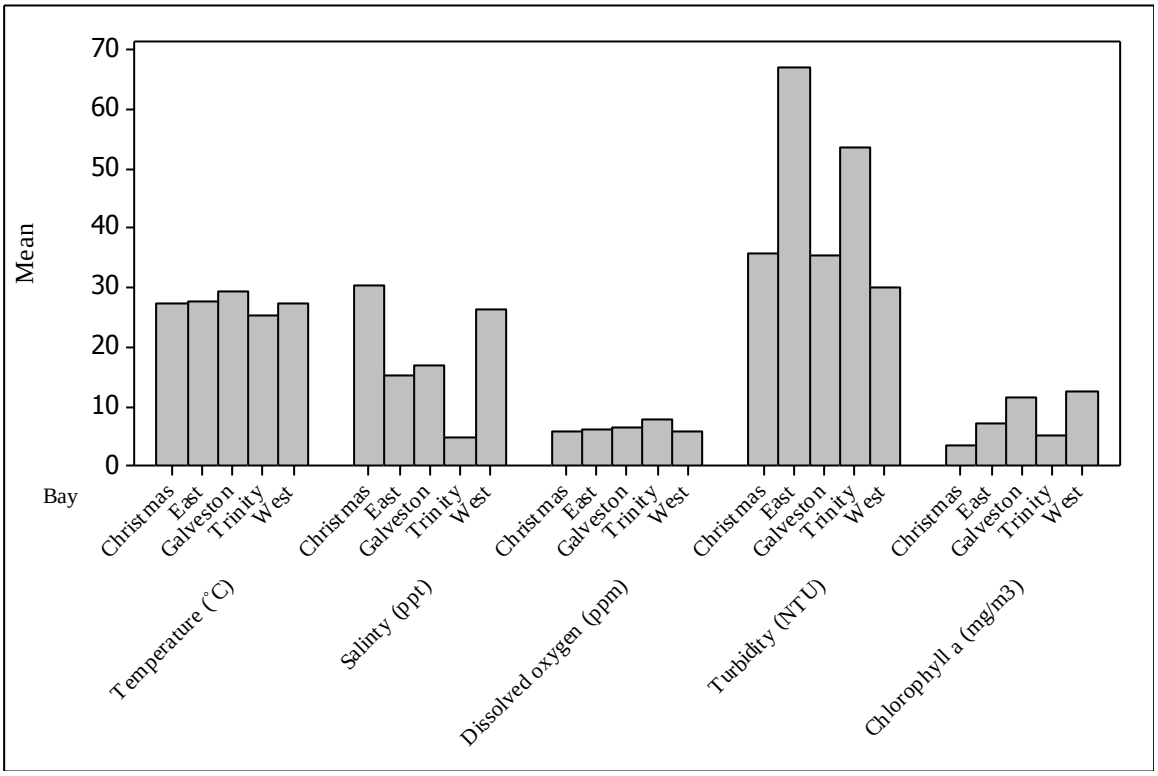

Figure 2. Mean values of five water quality parameters taken from the five sub-bays of the GBEE.

Table 4. Results of Tukey's multiple range test for significant ($p < 0.05$) ANOVA tests comparing each water quality parameter between the 5-sub bays of the GBEE. Values in cells refer to bays which are significantly different, (East Bay = E, Galveston Bay = G, Trinity Bay = T, and West Bay = W).

Water quality parameter	P-value	Christmas	East	Galveston	Trinity
Temp (˚C)	0.072			T	
Salinity (ppt)	0.000	E,G,T	T,W	T,W	W
DO (ppm)	0.000	T	T	T	W
Turbidity (NTU)	0.151				
Chlorophyll-α (mg/m^3)	0.295				

and Tukey's multiple range test showed that Christmas Bay salinity was significantly different ($p < 0.000$) from all of the sub-bays except West Bay and vice versa. East Bay and Galveston Bay salinities were significantly different from all sub-bays except each other and Trinity Bay, which was also significantly different from all sub-bays (Table 4).

During the study, DO within the GBEE ranged from 2.9 ppm (West Bay) – 9.5 ppm (Trinity Bay), with the average value of 6.3 ppm (Appendix 2 and Table 3). Based on the mean water quality data from the sub-bays, West Bay had the lowest mean DO value (5.7 ppm) and Trinity Bay had the highest mean DO value (7.7 ppm) (Table 3 and Figure 2). Trinity Bay's DO levels were significantly different from all of the other sub-bays based on results of the one-way ANOVA ($p \leq 0.000$) and Tukey's multiple range test (Table 4). All of the data for DO obtained from the last five samples taken from May 2009 were not used in our statistical analysis. These values which ranged from 15.0 – 23.5 ppm were the result of an instrument malfunction and were far above the normal DO saturation level for the temperature and salinity (Colt 1984).

Turbidity in the GBEE ranged from 2 NTU measured in Trinity Bay to 252 NTU observed in East Bay (Appendix 2). The average turbidity from the GBEE was 44.3 NTU (Table 3). The highest mean turbidity value came from East Bay (66.9 NTU), while the lowest mean value came from West Bay (30.1 NTU) (Table 3 and Figure 2). However, none of the sub-bays were found to be significantly different from each other ($p = 0.151$) (Table 4).

For chlorophyll-α, only 11 samples were taken during this study. The chlorophyll-α values ranged from 1.1 mg/m^3 in West Bay to 17.0 mg/m^3 sampled in Galveston Bay (Appendix 3). The average chlorophyll-α value for the GBEE was 7.8 mg/m^3 (Table 3).

Christmas Bay had the lowest mean chlorophyll-α value (3.3 mg/m^3) and the highest value was found in West Bay (12.3 mg/m^3) where only one filter was processed (Table 3 and Figure 2). Chlorophyll-α (p-value = 0.295) values were never significantly different between the sub-bays (Table 4).

During the study, a total of 623 samples comprising 49 species from 32 families were collected for $\delta^{13}C$ and $\delta^{15}N$ analysis at 90 different sites in the GBEE (Appendix 1 and 4). A total of 593 samples were taken from five different sub-bays in the GBEE as part of the study focused on the $\delta^{13}C$ and $\delta^{15}N$ isotopic values of the main species comprising this system (Table 5 and Appendices 5-9). Of the 593 samples, 14.33% represent species of primary production, 20.91% represent benthic invertebrates, and 64.76% represent all other types of nekton sampled (Table 5). In Table 6, all of the species collected during this study were identified by their scientific name, common name, and the code used to identify them in graphs. For the additional storage and preservation analysis portion of this study, another 30 samples were collected from *A. felis* from Bolivar Roads (Figure 1, Appendix 17).

Table 5. Total number of samples from each group taken at each sub-bay in the GBEE.

Group	Christmas	East	Galveston	Trinity	West	Total	%
Primary producers	18	16	17	13	21	85	14.33
Benthic invertebrates	18	24	28	32	22	124	20.91
Nekton	66	81	78	65	94	384	64.76
Total	102	121	123	110	137	593	100.00

Table 6. Scientific name, common name, size class, and code for species captured in the GBEE.

Scientific name	Common name & size class	Code	Scientific name	Common name & size class	Code
Primary Producers			Vertebrates cont.		
	Vegetative detritus	D	*Dorosoma cepedianum*	Gizzard shad	Dc
	Suspended particulate matter	SPM	*Anchoa mitchilli*	Bay anchovy	Am
	Epiphytes	E	*Ictalurus furcatus*	Blue catfish	If
	Benthic algae	B	*Ariopsis felis*	Hardhead catfish (≤ 155)	Afs
	Filamentous algae	F		Hardhead catfish (> 155)	Afl
Sargassum fluitans	Fatleaf sargassum	Sf	*Bagre marinus*	Gafftopsail catfish (≤ 339)	Bms
Sargassum natans	Narrowleaf sargassum	Sn		Gafftopsail catfish (> 339)	Bml
Spartina alterniflora	Smooth cordgrass	Sa	*Mugil cephalus*	Striped mullet (≤ 233)	Mces
Halodule wrightii	Shoalweed	Hw		Striped mullet (> 233)	Mcel
Invertebrates			*Mugil curema*	White mullet (≤ 233)	Mcus
Beroe ovata	Comb jelly	Bo		White mullet (> 233)	Mcul
Chrysaora quinquecirrha	Sea nettle	Cq	*Fundulus grandis*	Gulf killifish	Fg
Aurelia aurita	Moon jelly	Aa	*Fundulus similis*	Longnose killifish	Fs
Stomolophus meleagris	Cannonball jelly	Sme	*Cyprinodon variegatus*	Sheepshead minnow	Cva
Cymothoa exigua	Tongue-eating isopod	Ce	*Menidia beryllina*	Inland silverside	Mb
Menippe adina	Gulf stone crab	Ma	*Archosargus probatocephalus*	Sheepshead	Ap
Palaemonetes spp.	Grass shrimp	Ps	*Lagodon rhomboides*	Pinfish	Lr
Macrobrachium ohione	Ohio River shrimp	Mo	*Cynoscion arenarius*	Sand seatrout (≤ 99)	Cas
Rhithropanopeus harrisii	Mud crab	Rh		Sand seatrout (100-198)	Cam
Farfantepenaeus aztecus	Brown shrimp (≤ 75)	Fas		Sand seatrout (≥ 199)	Cal
	Brown shrimp (> 75)	Fal	*Cynoscion nebulosus*	Spotted seatrout (≤ 216)	Cns
Litopenaeus setiferus	White shrimp (≤ 75)	Lss		Spotted seatrout (217-380)	Cnm
	White shrimp (> 75)	Lsl		Spotted seatrout (≥ 381)	Cnl
Callinectes sapidus	Blue crab (≤ 109)	Csas	*Leiostomus xanthurus*	Spot croaker (≤ 136)	Lxs
	Blue crab (> 109)	Csal		Spot croaker (> 136)	Lxl
Callinectes similis	Lesser blue crab	Csi	*Micropogonias undulatus*	Atlantic croaker (≤ 136)	Mus
Rangia cuneata	Common rangia	Rc		Atlantic croaker (137-226)	Mum
Crassostrea virginica	Eastern oyster	Cvi		Atlantic croaker (≥ 227)	Mul
Lolliguncula brevis	Atlantic brief squid	Lb	*Pogonias cromis*	Black drum (≤ 198)	Pcs
Vertebrates				Black drum (199-318)	Pcm
Carcharhinus leucas	Bull shark	Cle		Black drum (≥ 319)	Pcl
Carcharhinus limbatus	Blacktip shark	Cli	*Sciaenops ocellatus*	Red drum (≤ 276)	Sos
Rhizoprionodon terraenovae	Atlantic sharpnose shark	Rt		Red drum (277-518)	Som
Dasyatis sabina	Atlantic stingray	Ds		Red drum (≥ 519)	Sol
Atractosteus spatula	Alligator gar	As	*Scomberomorus maculatus*	Spanish mackerel	Sma
Lepisosteus oculatus	Spotted gar	Lo	*Paralichthys lethostigma*	Southern flounder	Pl
Brevoortia patronus	Gulf menhaden (≤ 152)	Bps	*Malaclemys terrapin*	Diamondback terrapin	Mt
	Gulf menhaden (> 152)	Bpl			

Basal Carbon Sources

Several different sources of primary productivity were sampled in the GBEE, such as *S. alterniflora*, *H. wrightii*, epiphytes from *S. alterniflora* stems, benthic algae, filamentous algae, phytoplankton or suspended particulate matter (SPM), and detritus.

The primary producer with the most depleted mean value of $\delta^{13}C$ from all five sub-bays was SPM (-23.64 ± 0.39), while the most enriched mean $\delta^{13}C$ value belonged to benthic algae (-11.44 ± 0.45) (Figure 3). Among the five different sub-bays, SPM $\delta^{13}C$ values were the most depleted from Trinity Bay (-24.97 ± 0.76) and the most enriched from West Bay (-22.01 ± 0.18). Additionally, Trinity Bay had the most depleted $\delta^{13}C$ values for epiphytes (-19.56 ± 0.00) and for *S. alterniflora* (-18.27 ± 2.96). The most depleted $\delta^{13}C$ values for vegetative detritus came from Christmas Bay (-17.65 ± 0.71), while the most enriched vegetative detritus samples came from West Bay (-15.29 ± 0.39). Galveston Bay had the most enriched epiphyte values (-15.81 ± 1.29) and *S. alterniflora* values (-12.87 ± 0.14).

Occassionally, the range of $\delta^{13}C$ values from one or more primary producers overlapped with each other. Specifically, the range of $\delta^{13}C$ values for *S. alterniflora* overlapped with *H. wrightii* (Figure 3). Also, detritus, epiphytes, and filamentous algae had roughly similar medians and $\delta^{13}C$ values that overlapped each other. Detritus and SPM had the most variability, with interquartile ranges of 2.79 and 2.985, respectively. *S. alterniflora* had the smallest interquartile range (0.53) and had two outliers (-21.19 and -21.27). SPM had the lowest median and had $\delta^{13}C$ values that did not overlap with any other producer, while benthic algae had the highest median (-11.48). An ANOVA was

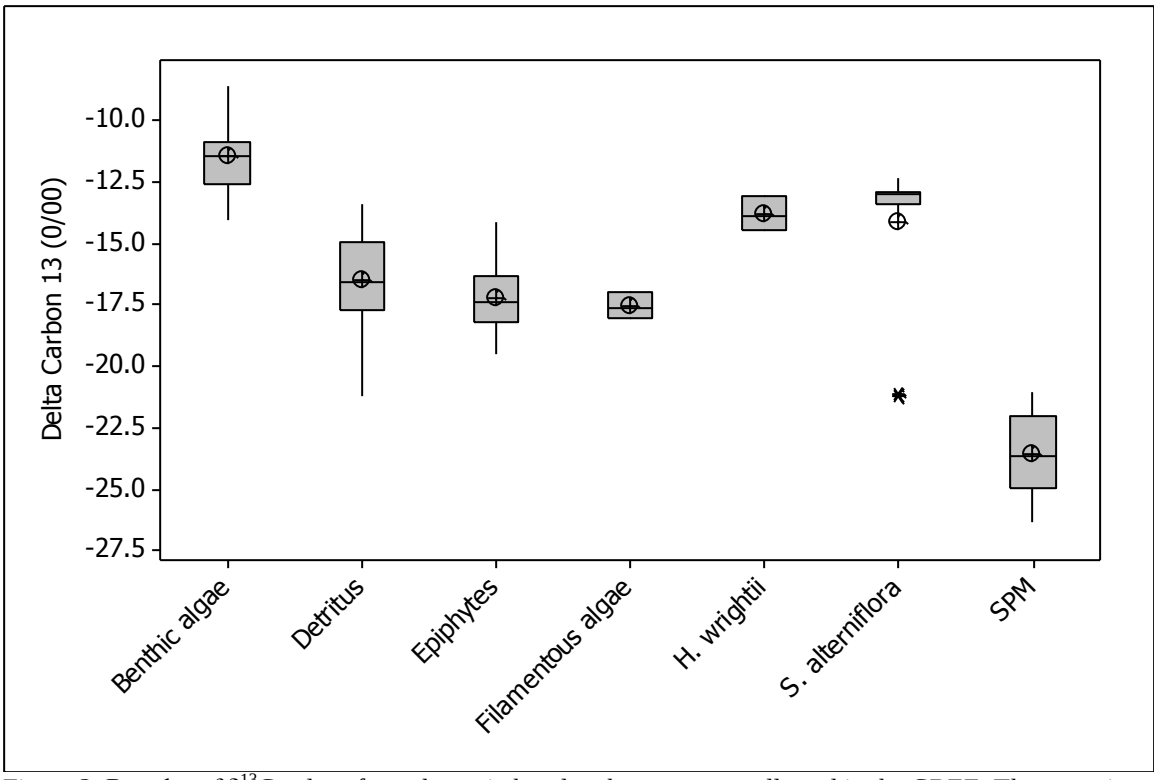

Figure 3. Boxplot of $\delta^{13}C$ values from the main basal carbon sources collected in the GBEE. The mean is denoted by the circle and the median is indicated by the horizontal line inside the rectangular box that represents the middle 50% of the data. The whiskers extending from the box represent the upper and lower 25% of the distribution and exclude outliers which are indicated with asterisks.

Table 7. Results of Tukey's multiple range tests for significant ($p < 0.05$) ANOVA tests comparing $\delta^{13}C$ values from producers of the GBEE. The x's signify paired primary producer sources with significantly different $\delta^{13}C$ values; ($p = 0.000$).

Carbon source	Benthic algae	Detritus	Epiphytes	Filamentous algae	*H. wrightii*	*S. alterniflora*	SPM
Benthic algae		x	x	x		x	x
Detritus	x					x	x
Epiphytes	x					x	x
Filamentous algae	x						x
H. wrightii							x
S. alterniflora	x	x	x				x
SPM	x	x	x	x	x	x	

conducted in addition to the box plot (Table 7). The results of the ANOVA showed that SPM had significantly different $\delta^{13}C$ values from all other basal carbon sources. Benthic algae $\delta^{13}C$ values were significantly different from all other basal carbon sources except *H. wrightii* and detritus and epiphytes were significantly different from *S. alterniflora*.

Isotopic Comparison of Sub-bay Assemblages

The mean isotopic values were compared from the 22 species that were collected from all 5 sub-bays (Figure 4; Appendices 5-9). Trinity Bay had the most depleted $\delta^{13}C$ values of any of the sub-bays. Galveston Bay was the next most depleted in $\delta^{13}C$,

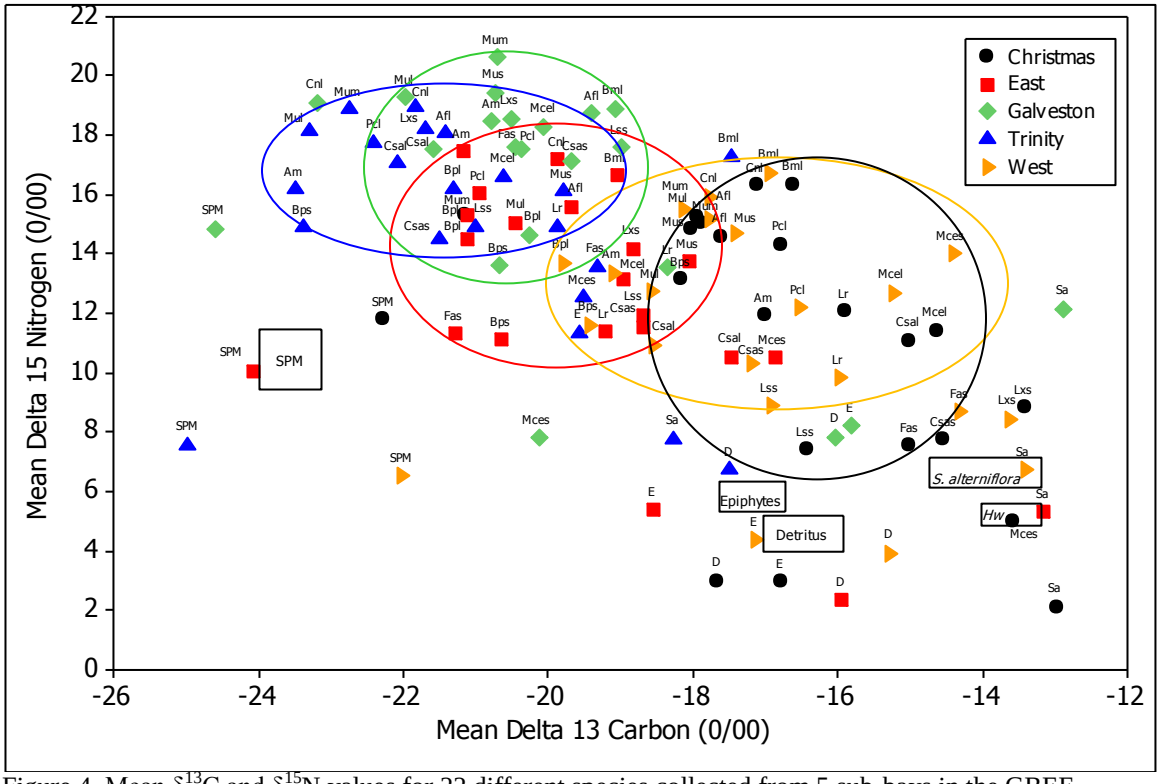

Figure 4. Mean $\delta^{13}C$ and $\delta^{15}N$ values for 22 different species collected from 5 sub-bays in the GBEE. Boxes encapsulate the range of values for different groups of primary producers and circles group together large clusters taken from each sub-bay.

followed by East Bay, West Bay, and Christmas Bay. When comparing $\delta^{15}N$ values, Galveston Bay was the most enriched followed by Trinity Bay, East Bay, West Bay, and Christmas Bay. East Bay's isotopic values were the most intermediate of the five sub-bays. ANOVA's were conducted comparing the $\delta^{13}C$ and $\delta^{15}N$ values of the 22 species that were captured from all five sub-bays (Table 8 and 9). When comparing the $\delta^{13}C$ values, detritus, epiphytes, *S. alterniflora*, *L. setiferus* (≤ 75 mm TL), *B. patronus* (> 152 mm TL), gafftopsail catfish (*Bagre marinus*) (> 339 mm TL), *M. cephalus* (≤ 233 mm TL), and *L. rhomboids* were never significantly different from each other (Table 8). For species such as *F. aztecus* (≤ 75 mm TL), Christmas Bay $\delta^{13}C$ values significantly differed from East Bay, Galveston Bay, and Trinity Bay while East Bay, Galveston Bay, and Trinity Bay all significantly differed from West Bay. In total, Christmas Bay never

Table 8. Results of Tukey's multiple range tests for significant ($p < 0.05$) ANOVA tests comparing $\delta^{13}C$ values from 22 species between the 5 sub-bays of the GBEE. Values in cells refer to bays which are significantly different, (East Bay = E, Galveston Bay = G, Trinity Bay = T, and West Bay = W).

Species	P-value	Christmas	East	Galveston	Trinity
Vegetative detritus	0.637				
SPM	0.019				W
Epiphytes	0.104				
S. alterniflora	0.071				
F. aztecus (≤ 75)	0.000	E,G,T	W	W	W
L. setiferus (≤ 75)	0.053				
C. sapidus (≤ 109)	0.003	G,T			W
C. sapidus (> 109)	0.010	G,T			
B. patronus (≤ 152)	0.000	E,G,T	T,W	T	W
B. patronus (> 152)	0.247				
A. mitchilli	0.009	T			
A. felis (> 155)	0.000	E,G,T	T,W	T,W	W
B. marinus (> 339)	0.097				
M. cephalus (≤ 233)	0.038				
M. cephalus (> 233)	0.000	E,G,T	W	W	W
L. rhomboides	0.030				
C. nebulosus (≥ 381)	0.000	E,G,T	G,W	W	W
L. xanthurus (≤ 136)	0.000	E,G,T	G	W	W
M. undulatus (≤ 136)	0.001	G,T	G	W	W
M. undulatus (137-226)	0.002	E,T			W
M. undulatus (≥ 227)	0.003	G,T			W
P. cromis (≥ 319)	0.000	E,G,T	W	T,W	W

significantly differed from West Bay, but was significantly different than East, Galveston, and Trinity Bays for 8, 11, and 13 species, respectively. Therefore, Trinity Bay's $\delta^{13}C$ values were the most different from $\delta^{13}C$ values from Christmas Bay. Galveston Bay and East Bay also differed from Christmas Bay more than any other bays, while West Bay differed most from Trinity Bay. Furthermore, East Bay only significantly differed from Trinity Bay when comparing *B. patronus* (≤ 152 mm TL) and *A. felis* (>155 mm TL) and Galveston Bay only differed from Trinity Bay significantly when comparing those two species and *P. cromis* (≥ 319 mm TL).

When comparing $\delta^{15}N$ values, SPM, *B. marinus* (> 339 mm TL), *M. cephalus* (>233 mm TL), and *C. nebulosus* (≥ 381 mm TL) were never significantly different from each other among the five sub-bays (Table 9). The isotopic signature of 14 species

Table 9. Results of Tukey's multiple range tests for significant ($p < 0.05$) ANOVA tests comparing $\delta^{15}N$ values from 22 species between the 5 sub-bays of the GBEE. Values in cells refer to bays which are significantly different, (East Bay = E, Galveston Bay = G, Trinity Bay = T, and West Bay = W).

Species	P-value	Christmas	East	Galveston	Trinity
Vegetative detritus	0.000	G,T	G,T	W	W
SPM	0.055				
Epiphytes	0.000	G,T	G,T	W	W
S. alterniflora	0.000	E,G,T,W	G,T	T,W	
F. aztecus (≤ 75)	0.000	G,T	G	T,W	W
L. setiferus (≤ 75)	0.002	G,T		W	
C. sapidus (≤ 109)	0.009	G,T			
C. sapidus (> 109)	0.000	G,T	G,T	W	W
B. patronus (≤ 152)	0.000	E,T,W	G,T	W	W
B. patronus (> 152)	0.017				W
A. mitchilli	0.006	E,G		W	
A. felis (> 155)	0.000	G,T	G,T	W	W
B. marinus (> 339)	0.435				
M. cephalus (≤ 233)	0.004	T,W		T,W	
M. cephalus (> 233)	0.144				
L. rhomboides	0.015				W
C. nebulosus (≥ 381)	0.025				
L. xanthurus (≤ 136)	0.000	E,G,T	W	W	W
M. undulatus (≤ 136)	0.000	G	G,T	T,W	
M. undulatus (137-226)	0.001	G,T	G	W	
M. undulatus (≥ 227)	0.000	G,T	G,T	W	W
P. cromis (≥ 319)	0.001	G,T	W	W	W

collected in Christmas Bay significantly differed from specimens collected in Galveston Bay and Trinity Bay. However, only 4 and 3 species collected in Christmas Bay differed significantly from East and West Bays, respectively. The isotopic signatures in East Bay significantly differed from 10 species collected in Galveston Bay, 8 species collected in Trinity Bay, and 2 species collected in West Bay. The isotopic signature of 15 species collected in Galveston Bay significantly differed from specimens collected in West Bay more than any other bay. However, only 4 species collected in Galveston Bay differed significantly from Trinity Bay. Finally, the isotopic signature of 11 species collected in Trinity Bay significantly differed from specimens collected in West Bay.

To further visualize the differences between each sub-bay and the isotopic values of the species, five additional scatterplots were constructed that separated the species into five functional groups that consisted of primary producers, invertebrates, primary consumer fish, omnivorous fish, and predators (Figure 5 – Figure 9). In Figure 5, the four primary producers that were collected from the five sub-bays reiterate what was shown in Figure 3 for the $\delta^{13}C$ values and in Figure 4 for $\delta^{15}N$ values. When the only the invertebrates are separated, there are distinct groupings for the $\delta^{15}N$ values. The Galveston Bay invertebrates have the highest $\delta^{15}N$ values followed by Trinity Bay, East Bay, West Bay, and then Christmas Bay (Figure 6). The same order of $\delta^{15}N$ value groupings occur again with the omnivorous fish (Figure 8). For fished grouped in the primary consumer category, Christmas Bay $\delta^{15}N$ values were located more towards the center, while East and Galveston Bay had the lowest $\delta^{15}N$ values (Figure 7). For the predatory fish graph, West Bay had the lowest $\delta^{15}N$ values, but the groupings followed the same order as before (Figure 9).

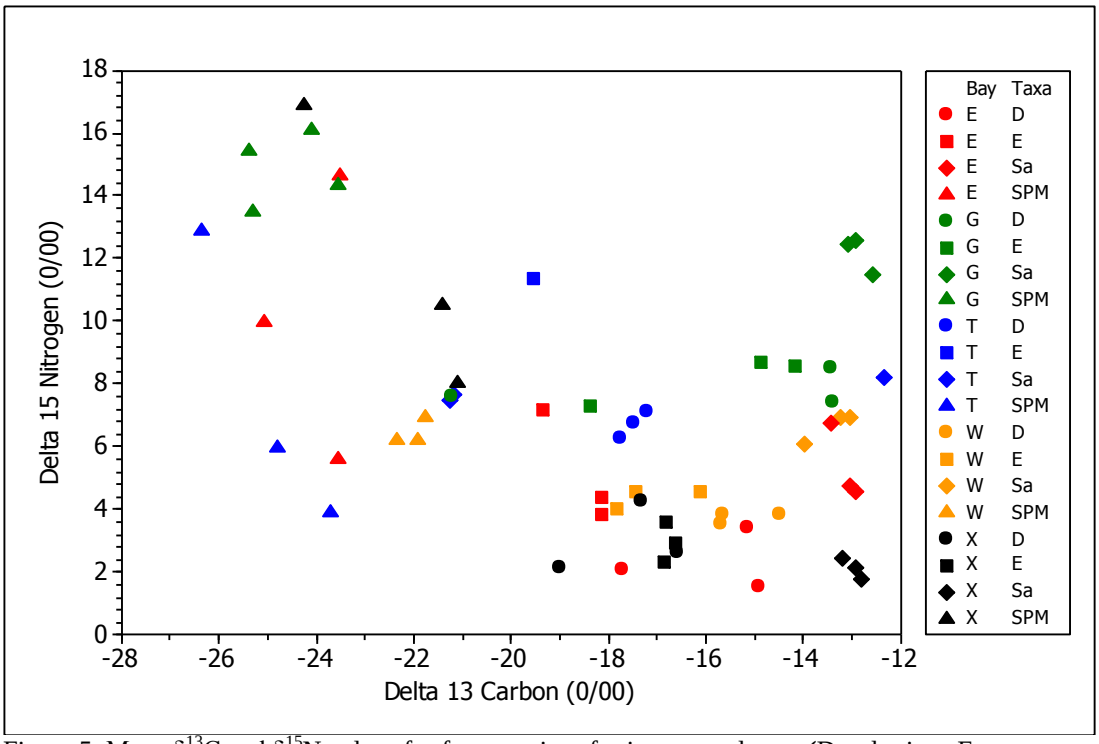

Figure 5. Mean $\delta^{13}C$ and $\delta^{15}N$ values for four species of primary producers **(**D = detritus, E = epiphytes, Sa = *S. alterniflora*, and SPM = suspended particulate matter) collected from 5 sub-bays (E = East Bay, G = Galveston Bay, T = Trinity Bay, W = West Bay, and X = Christmas Bay) in the GBEE.

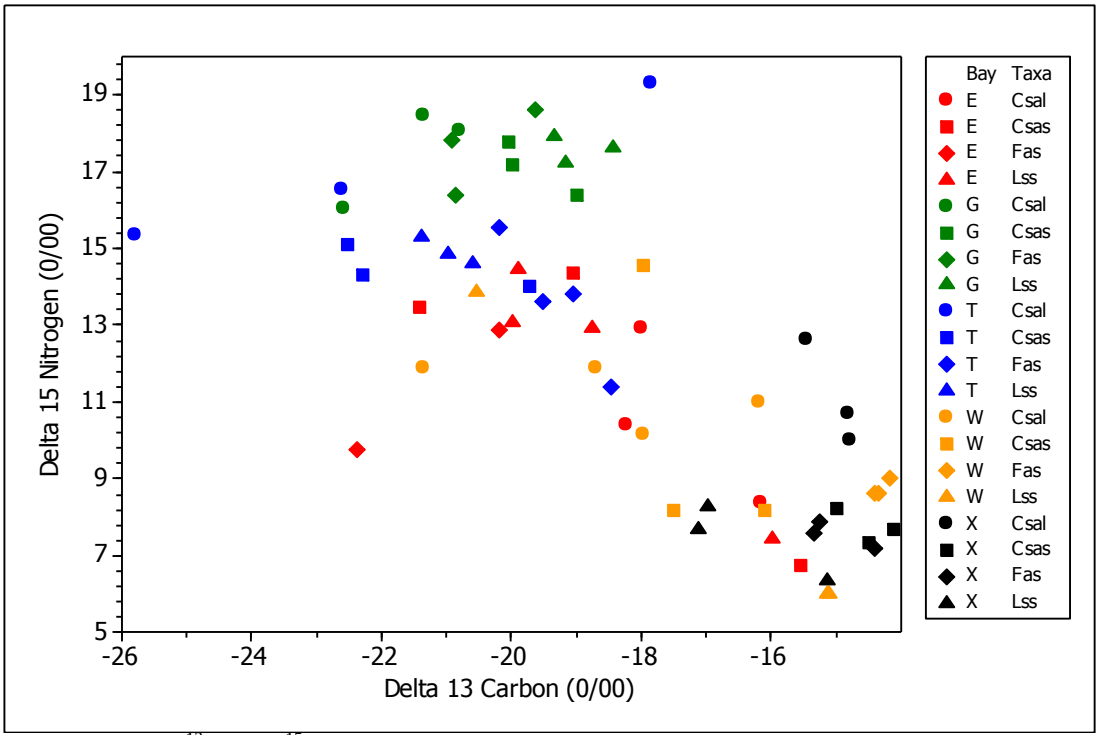

Figure 6. Mean $\delta^{13}C$ and $\delta^{15}N$ values for four species of invertebrates (Csal = large *C. sapidus*, Csas = small *C. sapidus*, Fas = small *F. aztecus*, and Lss = small *L. setiferus*) collected from 5 sub-bays (E = East Bay, G = Galveston Bay, T = Trinity Bay, W = West Bay, and X = Christmas Bay) in the GBEE.

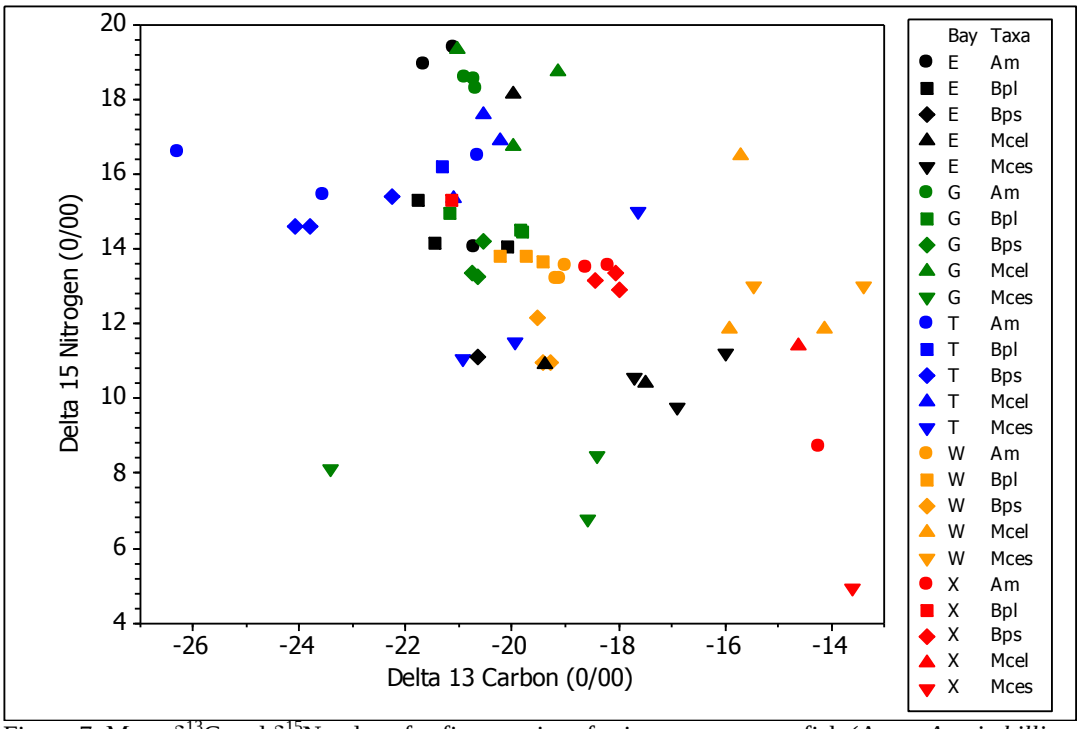

Figure 7. Mean $\delta^{13}C$ and $\delta^{15}N$ values for five species of primary consumer fish (Am = *A. mitchilli*, Bpl = large *B. patronus*, Bps = small *B. patronus*, Mcel = large *M. cephalus*, and Mces = small *M. cephalus*) collected from 5 sub-bays (E = East Bay, G = Galveston Bay, T = Trinity Bay, W = West Bay, and X = Christmas Bay) in the GBEE.

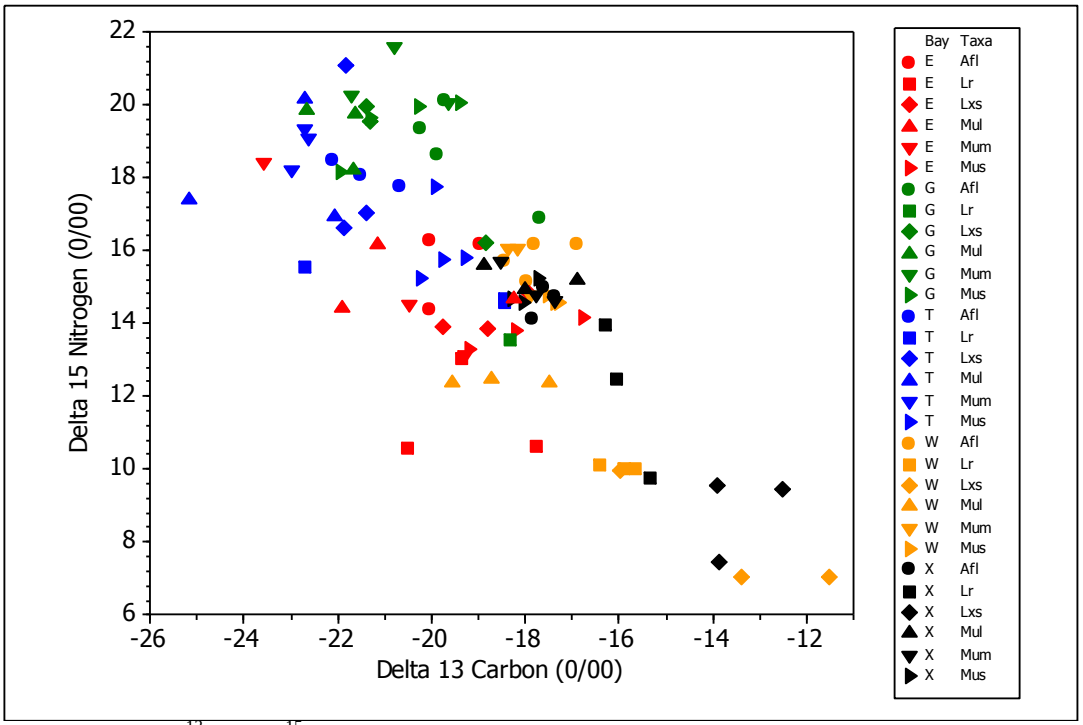

Figure 8. Mean $\delta^{13}C$ and $\delta^{15}N$ values for six species of omnivorous fish (Afl = large *A. felis*, Lr = *L. rhomboides*, Lxs = small *L. xanthurus*, Mul = large *M. undulatus*, Mum = medium *M. undulatus*, and Mus = small *M. undulatus*) collected from 5 sub-bays (E = East Bay, G = Galveston Bay, T = Trinity Bay, W = West Bay, and X = Christmas Bay) in the GBEE.

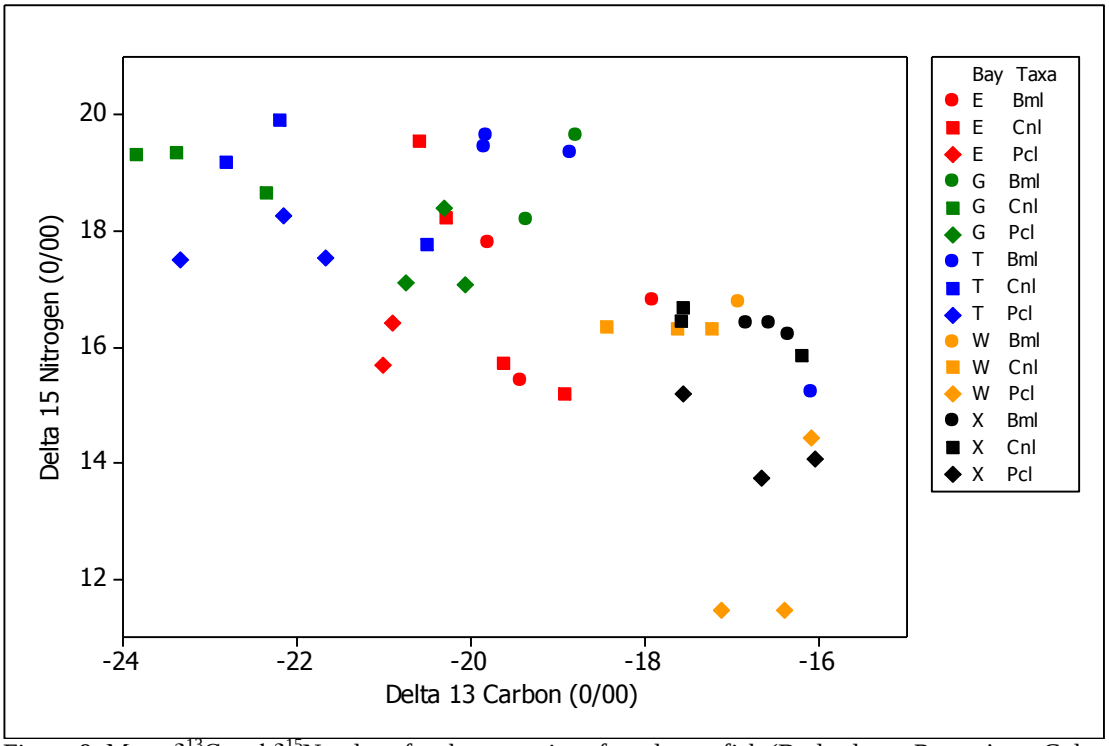

Figure 9. Mean $\delta^{13}C$ and $\delta^{15}N$ values for three species of predatory fish (Bml = large *B. marinus*, Cnl = large *C. nebulosus*, and Pcl = large *P. cromis*) collected from 5 sub-bays (E = East Bay, G = Galveston Bay, T = Trinity Bay, W = West Bay, and X = Christmas Bay) in the GBEE.

When the isotopic values of the species sampled from each individual bay were compared, Christmas Bay had mean $\delta^{13}C$ values that ranged from -22.26 to -11.97$^{0}/_{00}$ with the majority of values between -18 to -12$^{0}/_{00}$ (Appendix 5 and Figure 10). The mean $\delta^{15}N$ values ranged from 0.31 to 17.35$^{0}/_{00}$ with the majority of values falling between 7 to 17$^{0}/_{00}$ (Figure 10). The most depleted samples of $\delta^{13}C$ came from SPM (-22.26 ± 1.00), large *B. patronus* (-21.14 ± 0.00), *C. virginica* (-19.90 ± 0.44), and medium *P. cromis* (-19.26 ±1.07). The most enriched samples came from benthic algae (-11.97 ± 0.67), sheepshead minnow (*Cyprinodon variegatus*) (-12.21 ± 0.23), small white mullet (*Mugil curema*) (-12.68 ± 0.53), and *S. alterniflora* (-12.98 ± 0.11). For $\delta^{15}N$, the most depleted values occurred in benthic algae (0.31 ± 0.20), *S. alterniflora* (2.12 ± 0.18), epiphytes (2.94 ± 0.36), and vegetative detritus (2.99 ± 0.64). The most enriched values of $\delta^{15}N$

came from large *C. arenarius* (17.35 ± 0.00), large *B. marinus* (16.34 ± 0.07), large *C. nebulosus* (16.32 ± 0.25), and medium *C. nebulosus* (15.83 ± 0.33).

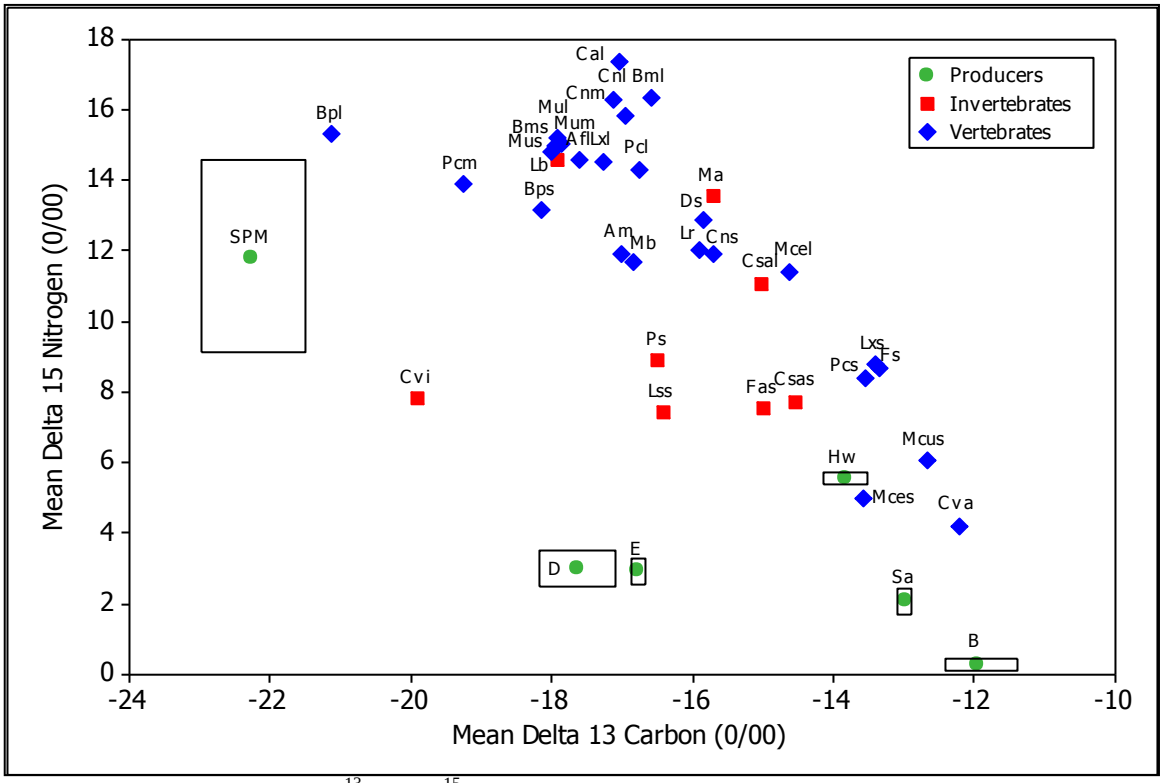

Figure 10. Scatterplot of mean $\delta^{13}C$ and $\delta^{15}N$ values for all flora and fauna collected from Christmas Bay. Boxes encapsulate the range of values for different groups of primary producers. Standard error values are located in Appendix 5.

East Bay's mean $\delta^{13}C$ values ranged from -24.06 to -9.69 $^{0}/_{00}$ and the majority of the values were between -18 and -21 $^{0}/_{00}$ (Appendix 6 and Figure 11). The most depleted $\delta^{13}C$ values belong to SPM (-24.06 ± 0.51), large spot croaker (*Leiostomus xanthurus*) (-23.78 ± 0.68), common rangia (*Rangia cuneata*) (-23.56 ± 0.00), and *C. virginica* (-21.65 ± 0.09). The most enriched $\delta^{13}C$ values belonged to benthic algae (-9.69 ± 0.88), bull shark (*Carcharhinus leucas*) (-11.99 ± 0.00), *S. alterniflora* (-13.15 ± 0.15), and small *P. cromis* (-14.65 $^{\pm}$ 1.98). In terms of mean $\delta^{15}N$, the values ranged from 2.35 to 18.47 $^{0}/_{00}$ with the majority falling in between 11 to 17 $^{0}/_{00}$. The most enriched $\delta^{15}N$ values belonged to large *C. arenarius* (18.47 ± 0.00), large *L. xanthurus* (18.21 ± 0.51), *A. mitchilli* (17.47

± 1.69), and sea nettle (*Chrysaora quinquecirrha*) (17.39 ± 0.57). The most depleted in $\delta^{15}N$ consisted of three primary producers, vegetative detritus (2.35 ± 0.57), *S. alterniflora* (5.34 ± 0.70), and epiphytes (5.41 ± 1.04), in addition to *C. variegatus* (5.33 ± 0.00).

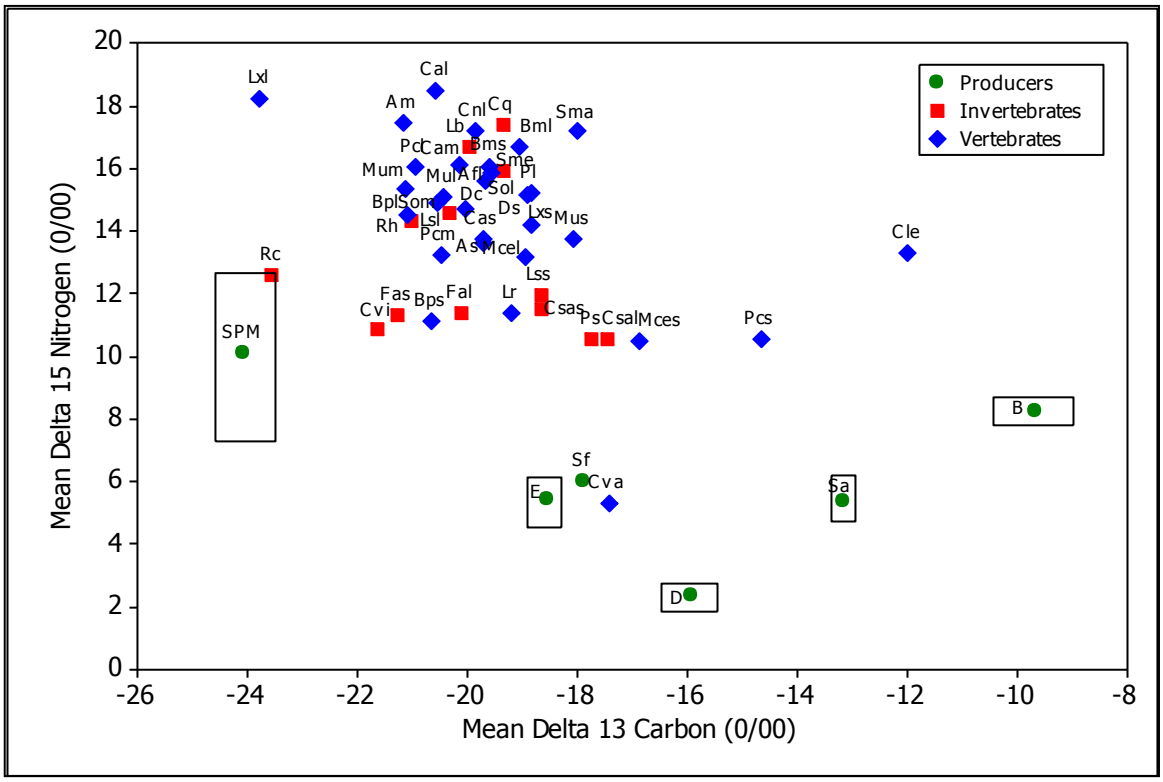

Figure 11. Scatterplot of mean $\delta^{13}C$ and $\delta^{15}N$ values for all flora and fauna collected from East Bay. Boxes encapsulate the range of values for different groups of primary producers. Standard error values are located in Appendix 6.

The mean $\delta^{13}C$ isotopic values for taxa collected from Galveston Bay ranged from -24.60 to -12.87$^{0}/_{00}$ with most species falling in between -21 to -18$^{0}/_{00}$ while the mean $\delta^{15}N$ values ranged from 7.85 to 20.64$^{0}/_{00}$ with the majority of the species falling between 16 to 20$^{0}/_{00}$ (Appendix 7 and Figure 12). The species most depleted in $\delta^{13}C$ were SPM (-24.60 ± 0.45), *C. virginica* (-24.28 ± 0.28), large *C. nebulosus* (-23.19 ± 0.44), and *R. cuneata* (-22.70 ± 0.10). The most enriched species in $\delta^{13}C$ were four sources of primary productivity; *S. alterniflora* (-12.87 ± 0.14), fat leaf sargassum (*Sargassum fluitans*) (-

15.63 ± 0.00), epiphytes (-15.81 ± 1.29), and vegetative detritus (-16.02 ± 2.60). These four producers also have the most depleted $\delta^{15}N$ values (12.18 ± 0.34, 9.70 ± 0.00, 8.20 ± 0.45, and 7.85 ± 0.33, respectively). The $\delta^{15}N$ that were the most enriched belonged to medium *M. undulatus* (20.64 ± 0.49), tongue-eating isopod (*Cymothoa exigua*), (20.20 ± 0.00), *C. quinquecirrha* (20.00 ± 0.00), and *C. leucas* (19.85 ± 0.00).

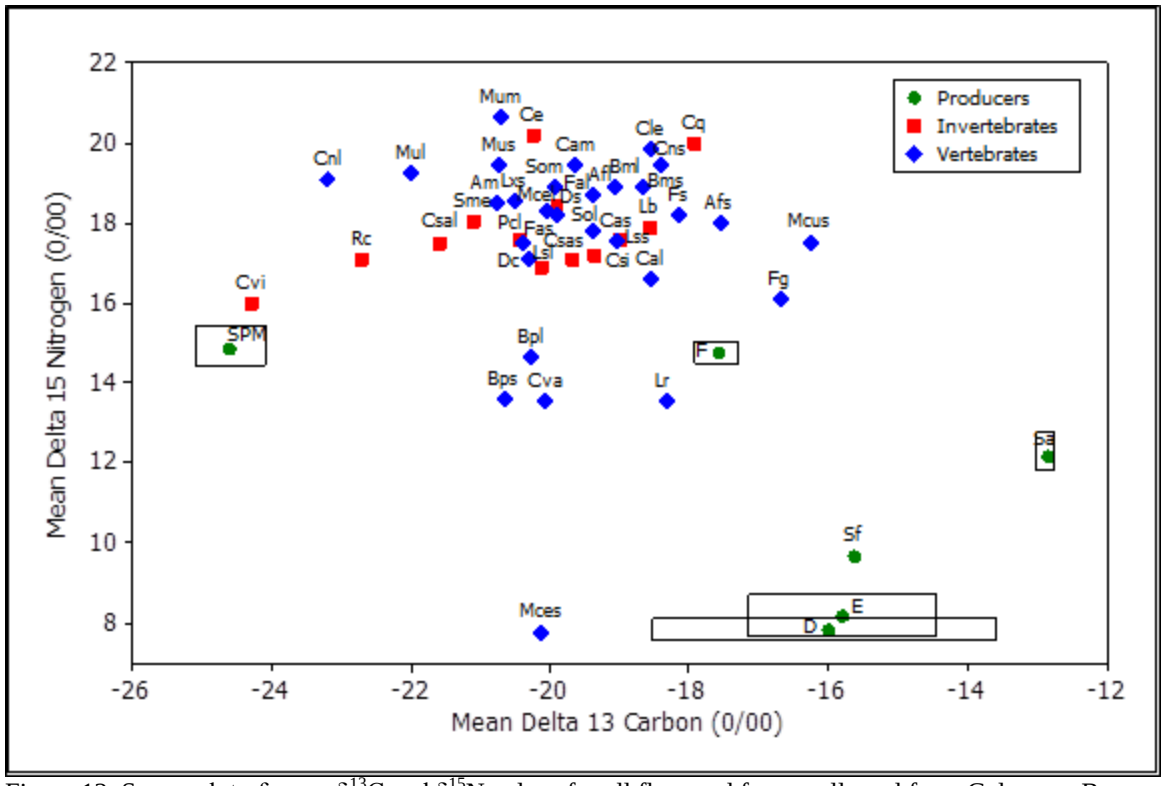

Figure 12. Scatterplot of mean $\delta^{13}C$ and $\delta^{15}N$ values for all flora and fauna collected from Galveston Bay. Boxes encapsulate the range of values for different groups of primary producers. Standard error values are located in Appendix 7.

Trinity Bay's mean $\delta^{13}C$ values ranged from -28.19 to -11.92$^{0}/_{00}$, the greatest $\delta^{13}C$ range of all of the sub-bays (16.27$^{0}/_{00}$), with the majority of the species having values that were between -24 to -19$^{0}/_{00}$ (Appendix 8 and Figure 13). The Ohio River shrimp (*Macrobrachium ohione*) had a $\delta^{13}C$ value that was more depleted than the values from any other sub-bay. The other most depleted $\delta^{13}C$ values from Trinity Bay included the spotted gar (*Lepisosteus oculatus*) (-25.84 ± 0.00), SPM (-24.97 ± 0.76), and *C. virginica*

(-24.73 ± 0.00). The most enriched $\delta^{13}C$ values belonged to benthic algae (-11.92 ± 0.52), small *M. curema* (-17.21 ± 0.43), large *B. marinus* (-17.48 ± 1.38), and vegetative detritus (-17.49 ± 0.16). The range of the mean $\delta^{15}N$ values for the species collected from Trinity Bay was from -0.31 to 19.93$^{0}/_{00}$, the greatest $\delta^{15}N$ range of all of the sub-bays (20.24$^{0}/_{00}$), with most of the species values occurring between 16 to 19$^{0}/_{00}$. The most depleted $\delta^{15}N$ values belonged to four primary producers; benthic algae (-0.31 ± 0.14), vegetative detritus (6.72 ± 0.24), SPM (7.59 ± 2.72), and *S. alterniflora* (7.79 ± 0.21). The most enriched $\delta^{15}N$ values belonged to medium *C. nebulosus* (19.93 ± 0.00), gizzard shad (*Dorosoma cepedianum* (19.20 ± 1.61), large *C. nebulosus* (18.96 ± 0.63), and medium *M. undulatus* (18.88 ± 0.35).

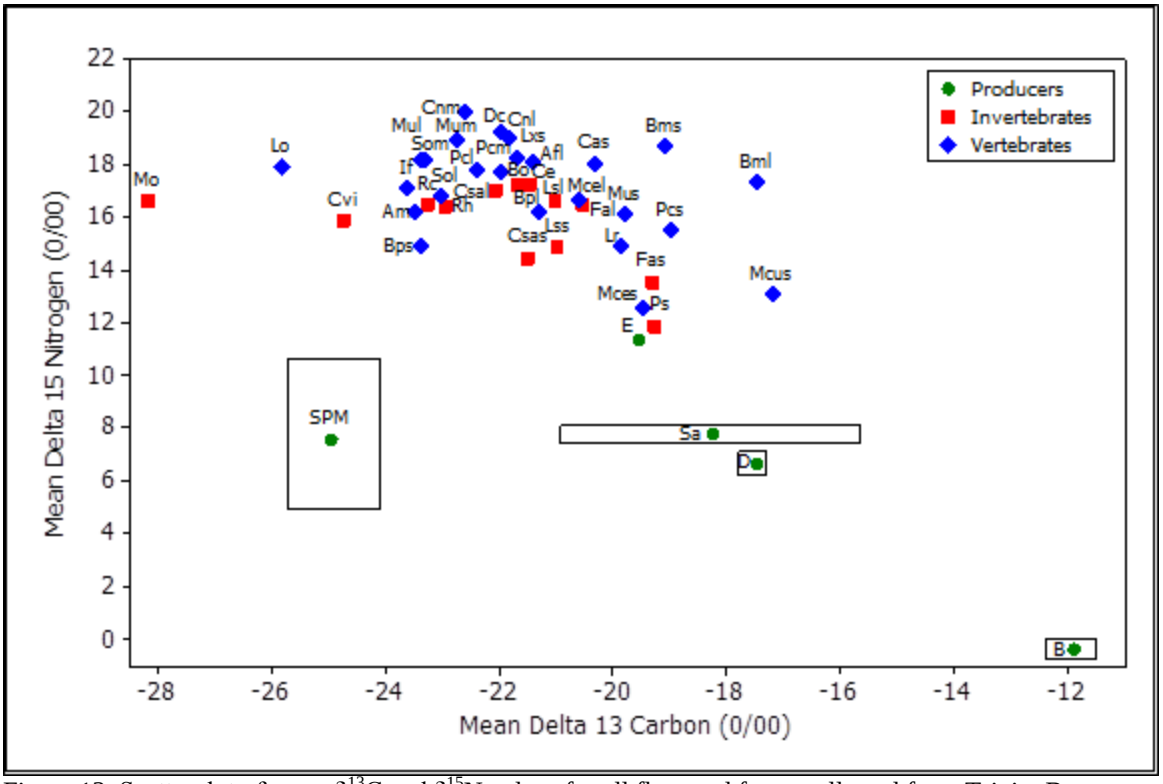

Figure 13. Scatterplot of mean $\delta^{13}C$ and $\delta^{15}N$ values for all flora and fauna collected from Trinity Bay. Boxes encapsulate the range of values for different groups of primary producers. Standard error values are located in Appendix 8.

For West Bay, the mean $\delta^{13}C$ values ranged from -22.01 to $-12.19^{0}/_{00}$ with the majority of the mean $\delta^{13}C$ values falling between -20 and $-15^{0}/_{00}$ (Appendix 9 and Figure 14). The most depleted source of $\delta^{13}C$ belonged to SPM (-22.01 ± 0.18), *C. exigua.* (-19.93 ± 0.00), large *B. patronus* (-19.80 ± 0.23), and *A. probatocephalus* (-19.47 ± 0.88). The most enriched values of $\delta^{13}C$ included benthic algae (-12.19 ± 0.95), small *M. curema* (-13.13 ± 0.43), *C. variegatus* (-13.39 ± 0.69), and *S. alterniflora* (-13.42 ± 0.28). The mean $\delta^{15}N$ values from West Bay ranged from 3.93 to $17.49^{0}/_{00}$, with most values falling in between 8 to $16^{0}/_{00}$. Vegetative detritus (3.93 ± 0.26), epiphytes (4.36 ± 0.17), *C. variegatus* (4.43 ± 0.64), and benthic algae (4.44 ± 0.87) were the most depleted species of $\delta^{15}N$. The species that were the most enriched in $\delta^{15}N$ included large *C. arenarius* (17.49 ± 0.51), one *M. terrapin* (16.99), a single large *B. marinus* (16.76), and

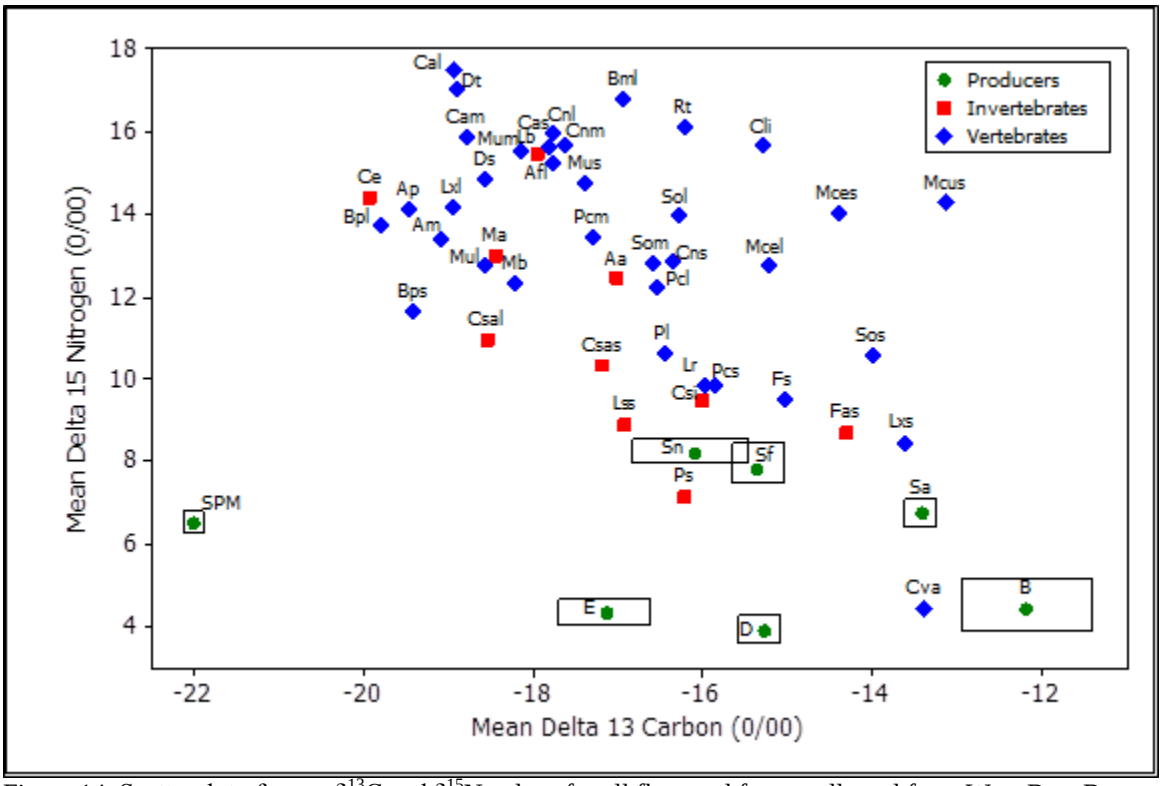

Figure 14. Scatterplot of mean $\delta^{13}C$ and $\delta^{15}N$ values for all flora and fauna collected from West Bay. Boxes encapsulate the range of values for different groups of primary producers. Standard error values are located in Appendix 9.

Atlantic sharpnose shark (*Rhizoprionodon terraenovae*) (16.07 ± 0.00).

Sub-bay Trophic Levels

The trophic position (TP) for the species collected from each sub-bay was determined after calculating each bay's reference value (Appendix 5-9). For Christmas Bay, the reference value used to calculate the trophic position of the fauna was 4.28 (Appendix 5 and Figure 15). When calculated, all sources of primary productivity had the lowest trophic positions except for *H. wrightii* (TP = 1.38) and SPM (TP = 3.28). *H. wrightii* had a higher trophic position than small *M. cephalus* and *C. variegatus*. SPM had a TP higher than 13 other consumers and was the highest TP for SPM for all five sub-bays. Following small *M. cephalus*, the next major grouping (TP = 1.95 - 2.41) consisted

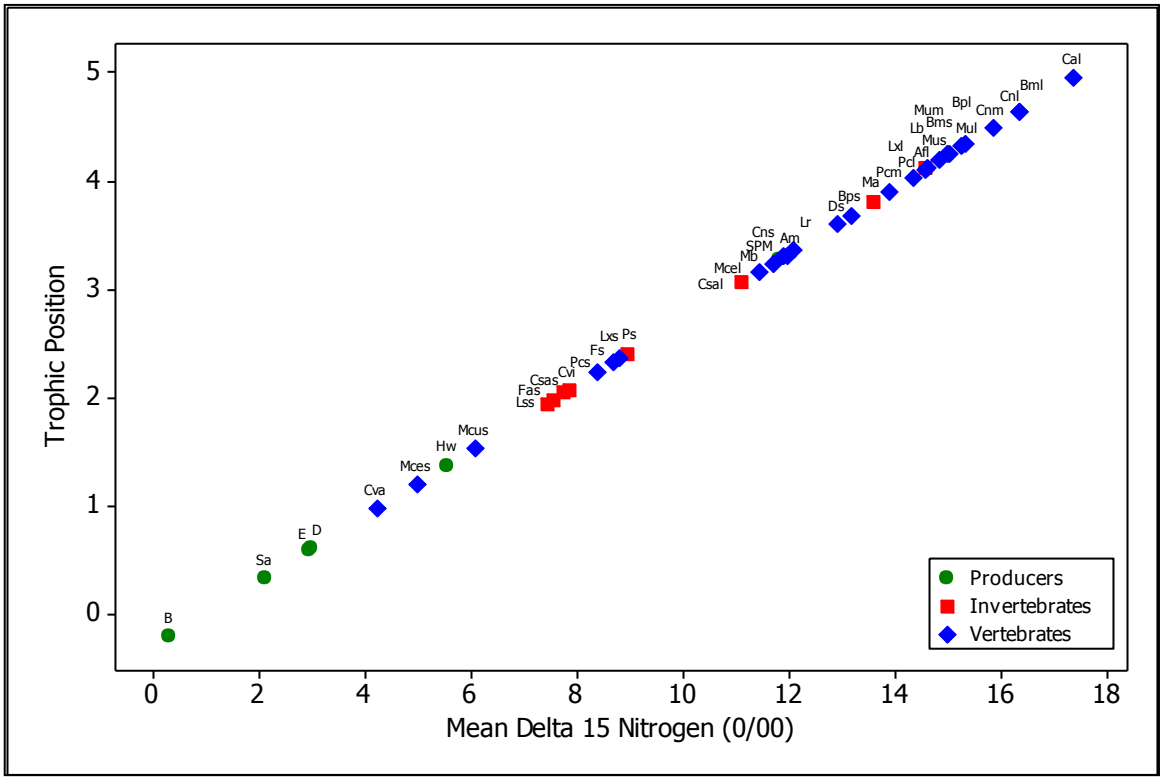

Figure 15. Scatterplot of mean $\delta^{15}N$ values and trophic position for species from Christmas Bay. Trophic positions were determined from the formula $TP = [(\delta^{15}N_{consumer} - \delta^{15}N_{reference})/3.3] + 1$.

predominately of juvenile fish and invertebrate species (*L. setiferus*, *F. aztecus*, *C. sapidus*, *C. virginica*, *P. cromis*, *L. xanthurus*, and *Palaemonetes spp.*) and one small fish species, longnose killifish (*Fundulus similis*). The highest trophic position of an invertebrate from Christmas Bay was *Menippe adina* (Gulf stone crab) (TP = 3.82). The highest trophic position was held by large *C. arenarius* (TP = 4.96). Other high trophic positions included large *C. nebulosus* (TP = 4.65), large *B. marinus* (TP = 4.65), and medium *C. nebulosus* (TP = 4.50).

For East Bay, the reference value used to calculate the trophic position of the species was 6.22 (Appendix 6 and Figure 16). Only one species, vegetative detritus (TP = -0.17), had a trophic position below zero in this bay. All sources of primary production were found above this value through SPM (TP = 2.17) with the exception of *C. variegatus* (TP = 0.73). From small *M. cephalus* (TP = 2.30), the majority of crustaceans

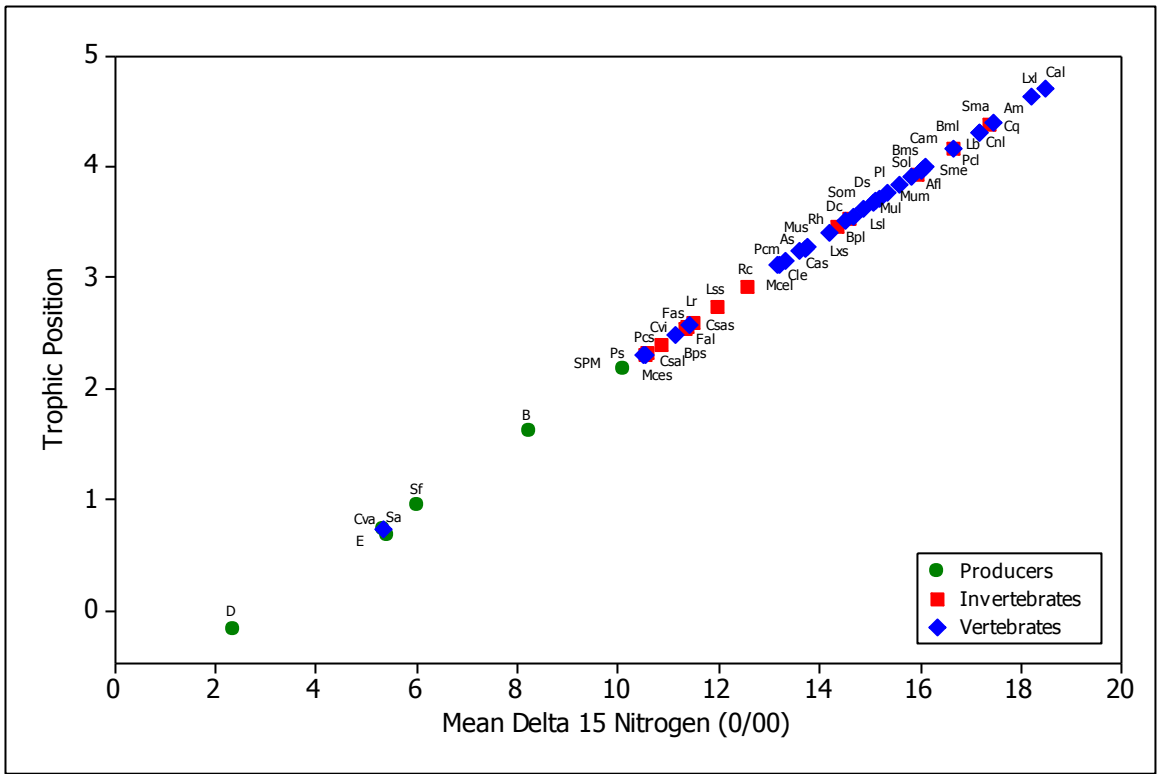

Figure 16. Scatterplot of mean $\delta^{15}N$ values and trophic position for species from East Bay. Trophic positions were determined from the formula $TP = [(\delta^{15}N_{consumer} - \delta^{15}N_{reference})/3.3] + 1$.

and small nekton followed up to larger nekton species such as large *C. arenarius* (TP = 4.71), which had the highest TP in East Bay. Other species that exhibited high trophic positions in East Bay included *L. xanthurus* (TP = 4.63), *A. mitchilli* (TP = 4.41), and the jellyfish, *C. quinquecirrha* (TP = 4.39), which held the highest trophic position for an invertebrate.

The reference value used to estimate the trophic position of the flora and fauna in Galveston Bay was 11.66, the highest reference value for any bay system (Appendix 7 and Figure 17). This reference values was almost twice the magnitude of the next highest reference value in from the GBEE. In Galveston Bay, three species had trophic positions below zero, small *M. cephalus* (TP = -0.17), vegetative detritus (TP = -0.15), and epiphytes (TP = -0.05). *S. fluitans* (TP = 0.41) was the next species, followed by *S. alterniflora* (TP = 1.16). Then three fish species (*C. variegatus*, *L. rhomboids*, and small

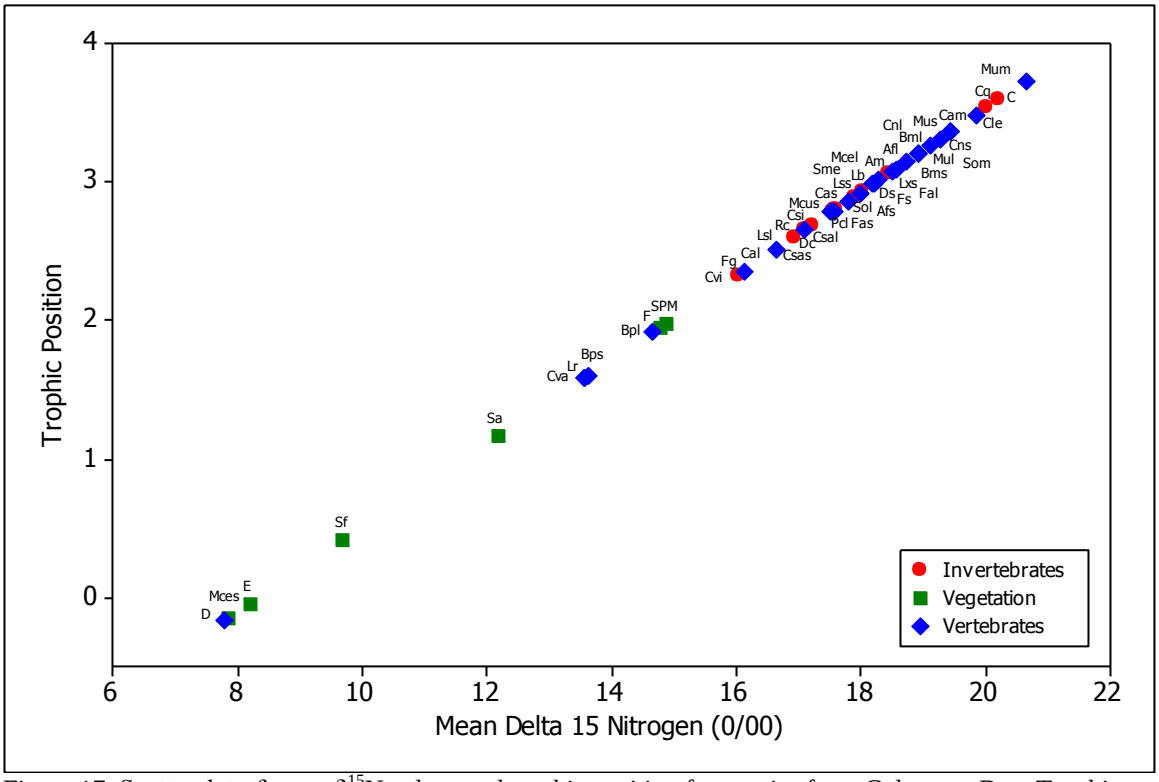

Figure 17. Scatterplot of mean $\delta^{15}N$ values and trophic position for species from Galveston Bay. Trophic positions were determined from the formula $TP = [(\delta^{15}N_{consumer} - \delta^{15}N_{reference})/3.3] + 1$.

and large *B. patronus*) had trophic positions before the last two species of primary production appeared (filamentous algae and phytoplankton) with values of 1.94 and 1.97, respectively. The rest of the crustaceans and nekton closely followed one another in trophic position up to the top position that was held by medium *M. undulatus* (TP = 3.72). The other top consumers that closely followed were the parasitic isopod, *C. exigua.* (TP = 3.59) which held the highest invertebrate trophic position, *C. quinquecirrha* (TP = 3.53), and *C. leucas* (TP = 3.48).

In Trinity Bay, the reference value used to calculate the trophic position of the species was 5.90 (Appendix 8 and Figure 18). When comparing the trophic position based on the $\delta^{15}N$ values taken from Trinity Bay, benthic algae was found to have the lowest trophic position value (-0.88) and was also the only species from Trinity Bay to have a negative value. The next closest value was that of vegetative detritus (TP = 1.25) and was followed closely by SPM (TP = 1.51) and *S. alterniflora* (TP = 1.57). The other values then followed each other closely beginning with epiphytes (TP = 2.65) and continuing on with the smaller species of invertebrates such as *Palaemonetes* spp. (TP = 2.82), *F. aztecus* (TP = 3.33), *C. sapidus* (TP = 3.60), and *L. setiferus* (TP = 3.73) and juvenile species of fish such as *M. cephalus* (TP = 3.01), *M. curema* (TP = 3.18), and *B. patronus* (TP = 3.72). Included at the apex of the trophic positions from Trinity Bay were both medium and large *C. nebulosus* (TP = 5.25 and 4.96, respectively), *D. cepedianum* (TP = 5.03), along with several other Sciaenid (medium and large *M. undulatus*, medium *S. ocellatus*, small *L. xanthurus*, and small *C. arenarius*) and Ariidae (small *B. marinus* and large *A. felis*) species. The invertebrate species with the highest trophic position was *C. exigua* (TP = 4.44).

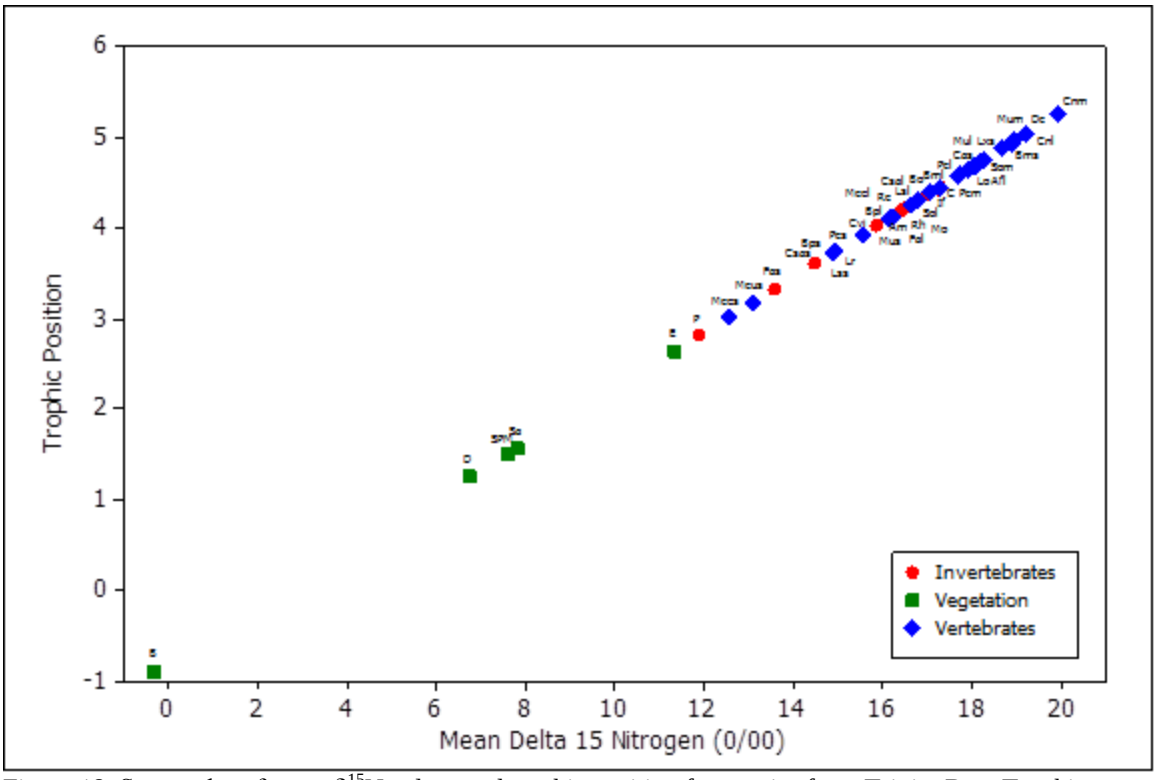

Figure 18. Scatterplot of mean $\delta^{15}N$ values and trophic position for species from Trinity Bay. Trophic positions were determined from the formula $TP = [(\delta^{15}N_{consumer} - \delta^{15}N_{reference})/3.3] + 1$.

For West Bay, a reference value of 6.01 was used to calculate the trophic positions of the species sampled from this bay (Appendix 9 and Figure 19). The lowest trophic position belonged to vegetative detritus (TP = 0.37). The other basal carbon sources had values between vegetative detritus and narrow leaf *Sargassum* (*Sargassum natans*) (TP = 1.67) along with *C. variegatus* (TP = 0.52) and *Palaemonetes* spp. (TP = 1.35). Several species of small fish and crustaceans follow sources of primary productivity including small *L. xanthurus* (TP = 1.74), small *F. aztecus* (TP = 1.81), small *L. setiferus* (TP = 1.87), lesser blue crab (*Callinectes similis*) (TP = 2.05), and *F. similis* (TP = 2.06). The highest trophic position for an invertebrate was held by the Atlantic brief squid (*Lolliguncula brevis*) (TP = 3.86) and the highest trophic positions for all of the species sampled in West Bay were held by large *C. arenarius* (TP = 4.48), *M. terrapin* (TP = 4.33), large *B. marinus* (4.26), *R. terraenovae* (TP = 4.05), and large *C. nebulosus* (TP = 4.01).

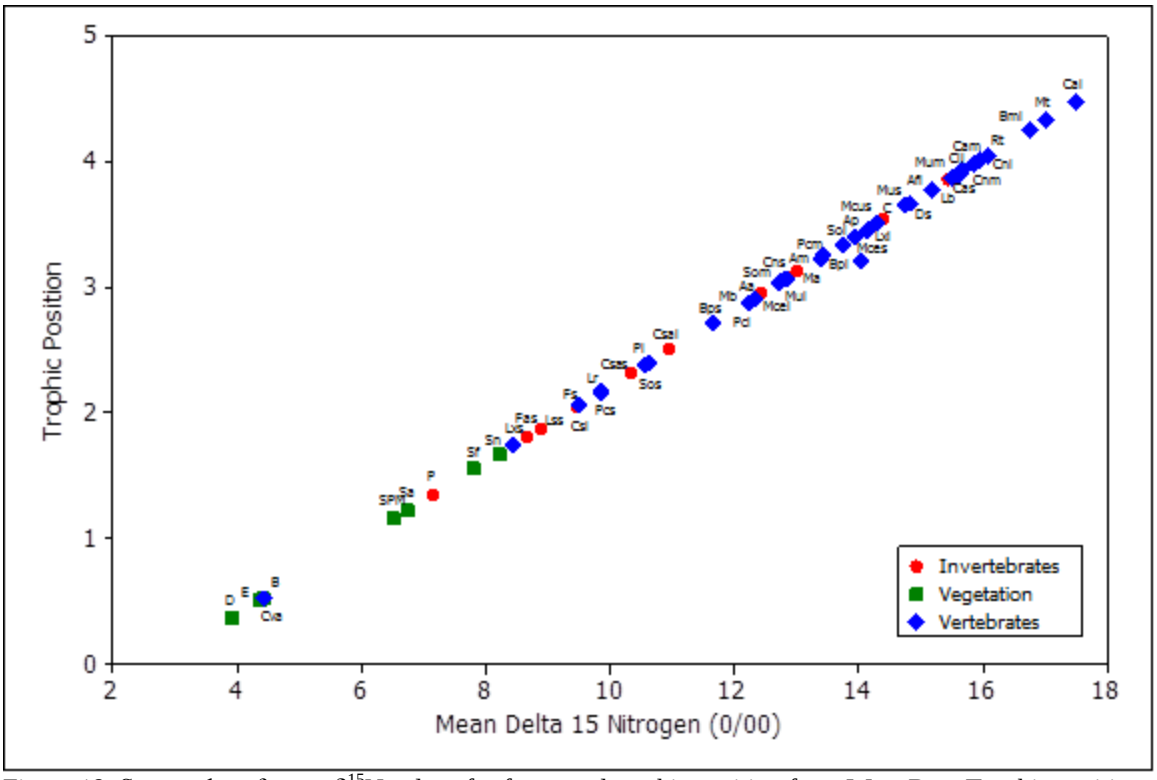

Figure 19. Scatterplot of mean $\delta^{15}N$ values for fauna and trophic position from West Bay. Trophic positions were determined from the formula $TP = [(\delta^{15}N_{consumer} - \delta^{15}N_{reference})/3.3] + 1$.

The mean trophic positions were compared for all 22 species that were collected from the 5 selected sub-bays of the GBEE (Table 10). Three species (vegetative detritus, epiphytes, and small *M. cephalus*) from two different bays (East and Galveston) received negative values for their trophic positions. The greatest difference in TP belonged to small *M. cephalus*, which had a TP of -0.17 in Galveston Bay and a TP in West Bay of 3.43. The smallest difference in TP occurred with small *M. undulatus* which had its highest TP of 4.19 in Christmas Bay and its lowest TP of 3.28 in East Bay. The average TP difference for all of the species from each sub-bay was 1.85.

To determine the trophic positions of all of the species sampled in the GBEE during this study, the mean $\delta^{15}N$ values were used along with a reference value of 6.80 which was found by averaging all of the sources of primary productivity together from

Table 10. Mean trophic position for 22 different species collected from all 5 sub-bays of the GBEE.

Species	Trophic Positions					
	Christmas	East	Galveston	Trinity	West	Mean ± SD
Vegetative detritus	0.61	-0.17	-0.15	1.25	0.37	0.38 ± 0.59
Suspended particulate matter	3.28	2.17	1.97	1.51	1.16	2.02 ± 0.81
Epiphytes	0.59	0.67	-0.05	2.65	0.5	0.87 ± 1.03
S. alterniflora	0.34	0.74	1.16	1.57	1.23	1.01 ± 0.48
F. aztecus (≤ 75)	1.99	2.54	2.8	3.33	1.81	2.49 ± 0.62
L. setiferus (≤ 75)	1.95	2.74	2.8	3.73	1.87	2.62 ± 0.76
C. sapidus (≤ 109)	2.05	2.6	2.65	3.6	2.31	2.64 ± 0.59
C. sapidus (> 109)	3.07	2.32	2.78	4.38	2.5	3.01 ± 0.82
B. patronus (≤ 152)	3.69	2.49	1.60	3.72	2.71	2.84 ± 0.89
B. patronus (> 152)	4.35	3.52	1.91	4.12	3.34	3.45 ± 0.95
A. mitchilli	3.32	4.41	3.07	4.12	3.23	3.63 ± 0.60
A. felis (> 155)	4.12	3.84	3.14	4.69	3.78	3.91 ± 0.56
B. marinus (> 339)	4.65	4.17	3.20	4.45	4.26	4.15 ± 0.56
M. cephalus (≤ 233)	1.21	2.30	-0.17	3.01	3.43	1.96 ± 1.46
M. cephalus (> 233)	3.17	3.11	3.01	4.25	3.03	3.31 ± 0.53
L. rhomboides	3.36	2.57	1.58	3.73	2.17	2.68 ± 0.87
C. nebulosus (≥ 381)	4.65	4.32	3.26	4.96	4.01	4.24 ± 0.65
L. xanthurus (≤ 136)	2.37	3.41	3.09	4.74	1.74	3.07 ± 1.14
M. undulatus (≤ 136)	4.19	3.28	3.36	4.10	3.65	3.72 ± 0.42
M. undulatus (137-226)	4.25	3.77	3.72	4.93	3.87	4.11 ± 0.50
M. undulatus (≥ 227)	4.32	3.68	3.31	4.71	3.04	3.81 ± 0.69
P. cromis (≥ 319)	4.04	3.98	2.78	4.59	2.88	3.65 ± 0.79

the entire GBEE. The data showed benthic algae (-0.10) with the lowest TP (Figure 20). All other sources of primary productivity followed with a range of trophic positions from 0.38 to 1.43, with the exceptions of SPM (TP = 2.11) and filamentous algae (TP = 3.42). *C. variegatus* (TP = 1.22) was the only species that was not a source of primary productivity to fit into this range. The largest number of species (20) fit into the trophic positions 3.63 – 3.96. Of all the species collected from the GBEE, the species that had the highest trophic positions were *L. oculatus* (TP = 4.37), small *A. felis* (TP = 4.39), and the invertebrate *C. quinquecirrha* (TP = 4.41).

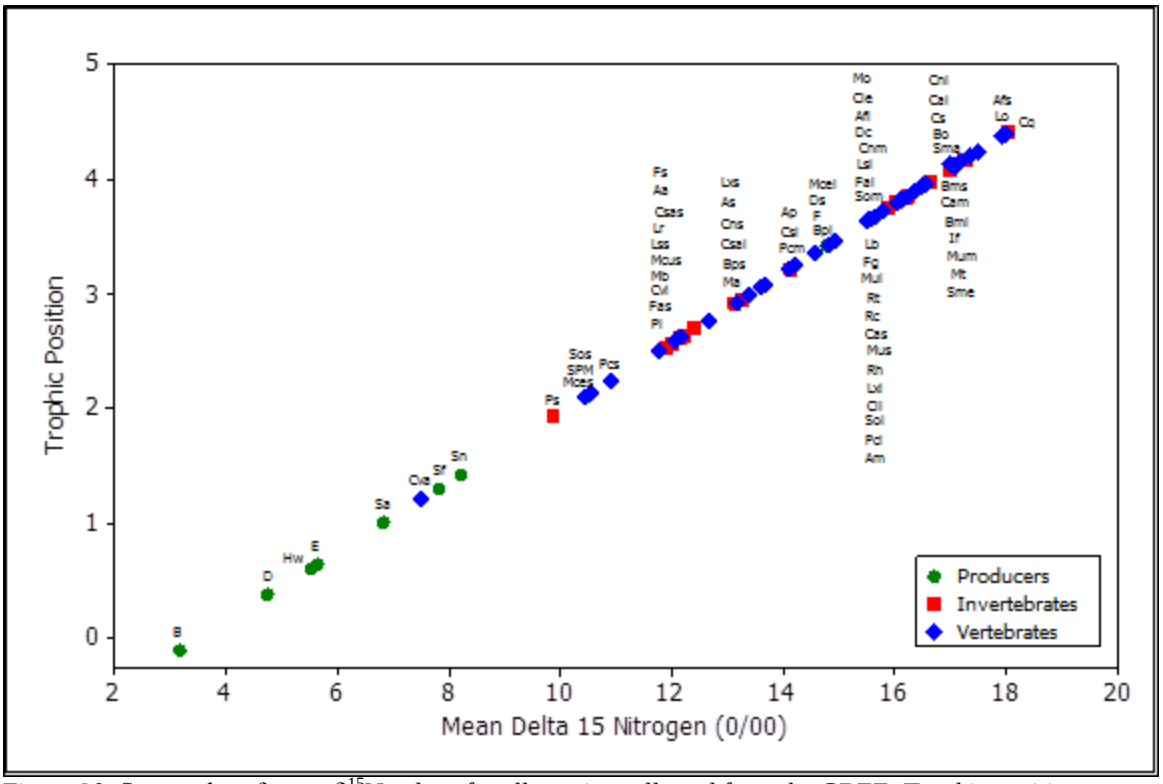

Figure 20. Scatterplot of mean $\delta^{15}N$ values for all species collected from the GBEE. Trophic positions were determined from the formula $TP = [(\delta^{15}N_{consumer} - \delta^{15}N_{reference})/3.3] + 1$.

Comparison to Previous Studies

The lowest $\delta^{15}N$ values of any vertebrate or invertebrate belonged to *C. variegatus*. In Christmas, East, Galveston, and West Bays, the $\delta^{15}N$ values were 4.23 ± 0.37, 5.33 ± 0.00, 13.57 ± 0.95, and 4.43 ± 0.64, respectively. Alexander (1983) sampled 114 sheepshead minnows from West Bay and found that 64.6% of their stomach contents were composed of primary production sources, while Matlock and Garcia (1983) sampled 87 sheepshead minnows from Texas bays and found that 41.85% of their stomachs were composed of primary production sources (Table 11). Stickney and McGeachin (1978) found *C. variegatus* in Galveston Bay, Texas to be entirely feeding on zooplankton (Table 11). The $\delta^{13}C$ results from Christmas Bay and West Bay show that *C. variegatus* relied on benthic algae and a mixture of benthic algae and detritus, respectively (Figures

10 and 14). In East Bay, it appeared that *C. variegatus* consumed a mixture of mainly detritus and epiphytes while in Galveston Bay, a mixture of phytoplankton and detritus and or epiphytes was consumed (Figures 11 and 12). Galveston Bay was also the location in which *C. variegatus* had the highest trophic position (1.58) (Figure 17). Another trophic position found for sheepshead minnow (2.9 ± 0.3) places it higher than these results (Appendix 16) (Froese and Pauly 2009).

Table 11. Diet composition of *C. variegatus* based on previous studies.

Prey items	Study[1]	Study[2]	Study[3]	Average
Benthic invertebrates	1.20	0	3.70	1.63
Zooplankton	1.20	100.00	20.74	40.65
Primary productivity	64.60	0	41.85	35.48
Detritus	33.00	0	33.71	22.24
Total	100.00	100.00	100.00	100.00

1. Alexander 1983 - West Bay, TX – 114 individuals (25 - 46 mm)
2. Stickney and McGeachin 1978 - Galveston Bay, TX - 248 individuals
3. Matlock and Garcia 1983 - Texas bays – 87 individuals (19 - 67 mm SL)

Based on trophic position, small *M. cephalus* was separated from large *M. cephalus* by 1.35 (Table 10). Large *M. cephalus* had a mean trophic position of 3.31 ± 0.53 and *small M. cephalus* had a mean trophic position of 1.96 ± 1.46 (Table 10). In West Bay, small *M. cephalus* had a higher trophic position than large *M. cephalus* (Figure 19). In Christmas Bay and West Bay, it appeared that striped mullet consumed mainly detrital material and benthic algae (Figures 10 and 14) While in East, Galveston and Trinity Bays, striped mullet appeared to consume a mixture of detrital material and SPM (Figures 11, 12, and 13). Darnell (1961) found that *M. cephalus* in Lake Ponchartrain, Louisiana, had stomach contents that consisted predominately of detritus followed by primary productivity (Table 12). Alexander (1983) and Matlock and Garcia (1983) also documented that *M. cephalus* consumed large amounts of primary productivity in Galveston Bay (Table 12).

Table 12. Diet composition of *M. cephalus* based on previous studies.

Prey items	Study[1]	Study[2]	Study[3]	Average
Benthic invertebrates	3.01	0	2.00	1.67
Zooplankton	3.01	0	4.50	2.50
Primary productivity	62.34	90.35	14.50	55.73
Detritus	31.64	9.65	79.00	40.10
Total	100.00	100.00	100.00	100.00

1. Alexander 1983 – West Bay, TX – 37 individuals (69 – 199)
2. Matlock and Garcia 1983 – Texas bays – 16 individuals (29 – 196 mm SL)
3. Darnell 1961 – Lake Ponchartrain, LA – 54 individuals (97 – 327 mm)

All of the shark species fell at the same level based on trophic position (*R. terraenovae, Carcharhinus limbatus* (blacktip shark), and *C. leucas*) (Figure 20). The species collected from Galveston and West Bays relied on a food chain centered on detrital material (Figures 12 and 14). In East Bay, *C. leucas* appeared to have been utilizing a food chain that was based on a mixture of mainly benthic algae and detrital material (Figure 11). Diet information compiled from stomach contents of the bull and

Table 13. Diet composition of 3 species of sharks sampled in the GBEE based on previous studies.

Prey items	Study[1]	Study[2]	Study[3]	Average
Shark	0	0	7.14	2.38
Rays	0	0	8.58	2.86
Black drum	6.66	0	0	2.22
Sheepshead	0	0.40	0	0.13
Southern flounder	0	0	7.63	2.54
Sand seatrout	0	2.85	0	0.95
Gafftopsail catfish	0	1.24	7.63	2.96
Hardhead catfish	0	0	0	0.00
Benthivores	0	19.06	7.63	8.90
Croaker	6.67	20.95	15.24	14.29
Gulf menhaden	66.67	50.18	41.86	52.90
Mullet	6.67	0	0	2.22
Anchovies	0	1.18	0	0.39
Squid	0	0.31	0	0.10
Blue crab	6.66	0	0	2.22
Penaeid shrimp	6.67	1.59	4.29	4.18
Other benthic invertebrates	0	0.62	0	0.21
Primary productivity	0	1.62	0	0.54
Total	100.00	100.00	100.00	100.00

1. Darnell 1961 – Lake Ponchartrain, LA – 3 individuals (780 -805 mm) – bull shark
2. Bethea et al. 2004 – Apalachicola Bay, FL – 146 individuals (445 – 1030 mm FL) – blacktip shark
3. Castro 1996 – Southeastern U.S. – 89 individuals (~600 – 1950 mm TL) – blacktip shark

blacktip shark provides evidence that their primary food source consisted of menhaden followed by different species of croaker (Table 13) (Darnell 1961; Castro 1996; Bethea et al. 2004).

Anthropogenic Nitrogen Differences

After comparing the mean $\delta^{15}N$ values for the 22 species caught from each sub-bay, Galveston Bay had the highest average $\delta^{15}N$ value of $15.98^{0}/_{00}$, followed by Trinity Bay ($14.92^{0}/_{00}$), East Bay ($12.29^{0}/_{00}$), West Bay ($11.24^{0}/_{00}$), and Christmas Bay ($10.82^{0}/_{00}$) (Figure 4). From the most enriched bay (Galveston) to the least (Christmas Bay), there was a $5.16^{0}/_{00}$ difference. Even when the upper GBEE's (Galveston and Trinity Bays) mean $\delta^{15}N$ values were compared with the lower GBEE (Christmas, East, and West Bays) there was a $4^{0}/_{00}$ difference. Furthermore, isotopic values were compared from both lower and upper Galveston Bay sites. Two species, *D. cepedianum* and *C. arenarius* ($\leq$ 99 TL) were collected from both portions of the bay. The average $\delta^{15}N$ value for *D. cepedianum* caught in upper Galveston Bay was $17.61^{0}/_{00}$, while the other sample collected from lower Galveston Bay was $16.11^{0}/_{00}$. Likewise, the average $\delta^{15}N$ value for *C. arenarius* ($\leq$ 99 TL) was $18.13^{0}/_{00}$ from upper Galveston Bay and $17.01^{0}/_{00}$ from lower Galveston Bay. When only comparing the primary producers from all 5 sub-bays, Galveston Bay never had a $\delta^{15}N$ value that fell below $7.31^{0}/_{00}$ (Figure 5 and 21). Higher $\delta^{15}N$ values from Galveston Bay are also evident when separating invertebrates, primary consumer fish, omnivorous fish, and predatory fish caught from each of the five sub-bays (Figures 6 – 9).

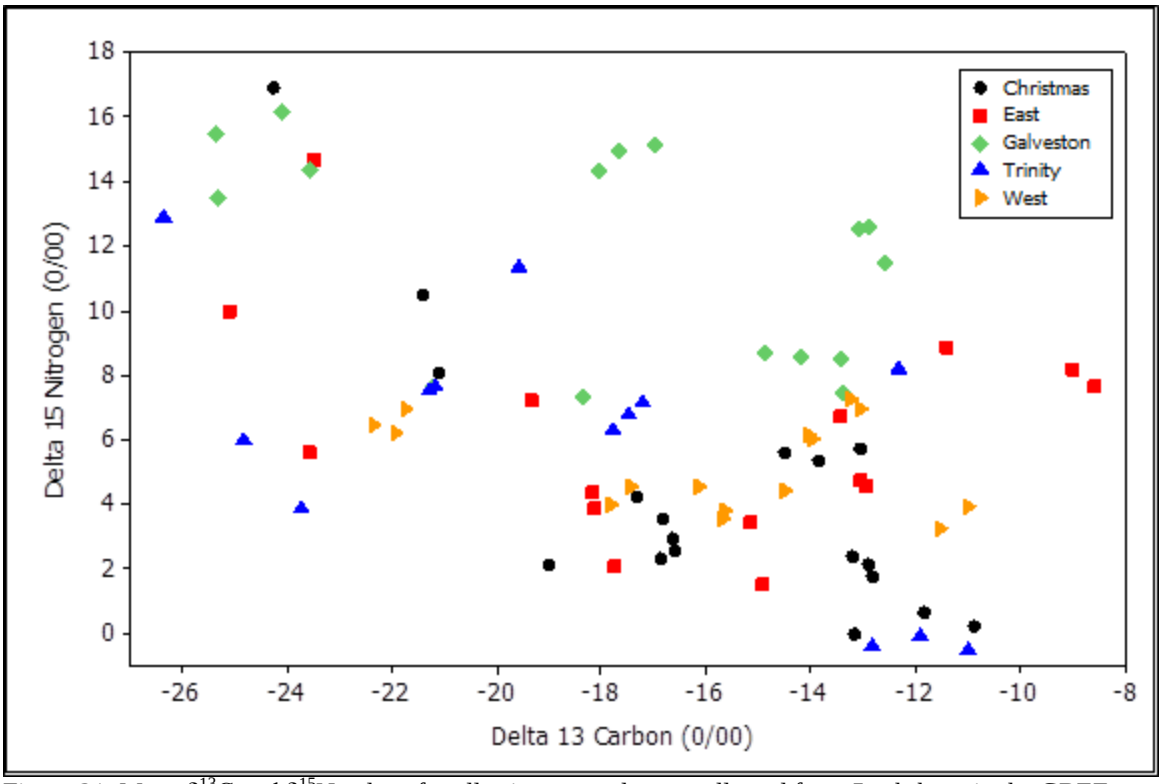

Figure 21. Mean $\delta^{13}C$ and $\delta^{15}N$ values for all primary producers collected from 5 sub-bays in the GBEE.

Storage Methods and Thawing Treatments

There were no statistically significant differences between $\delta^{13}C$ ($p = 1.000$) and $\delta^{15}N$ ($p = 0.900$) values when using ice or flash freezing in liquid nitrogen or when measuring the thawing period from zero to ten days. The samples not left out to thaw that were stored in ice and liquid nitrogen show very similar values (Figure 22). The average difference between these two preservation methods from the five samples is only $0.11^{0}/_{00}$ and $-0.09^{0}/_{00}$ for $\delta^{13}C$ and $\delta^{15}N$, respectively. Likewise, there was not much change in either isotopic value after the samples had been left out to thaw for one day ($\delta^{13}C = -0.18^{0}/_{00}$ and $\delta^{15}N = -0.02^{0}/_{00}$). When thawed for three days, the difference in $\delta^{13}C$ values from the sample not thawed and stored in liquid nitrogen was only $-0.19^{0}/_{00}$, but for $\delta^{15}N$

the difference was -0.24$^{0}/_{00}$. This represented an increase of -0.22$^{0}/_{00}$ from the sample left out to thaw for one day. After a five day thawing period, the δ^{13}C value difference remained low (-0.14$^{0}/_{00}$) and again the δ^{15}N difference deviated further (0.66$^{0}/_{00}$ enrichment). An even greater enrichment occurred in δ^{15}N with the samples that were thawed for ten days (1.71$^{0}/_{00}$), while the δ^{13}C difference was only -0.05$^{0}/_{00}$. Of the 5 species of *A. felis* sampled, sample one has the most variability, with a δ^{15}N range of 3.16$^{0}/_{00}$. Sample 2 has the lowest variability, with a range of only 1.21$^{0}/_{00}$. However, none of these values were statistically significant.

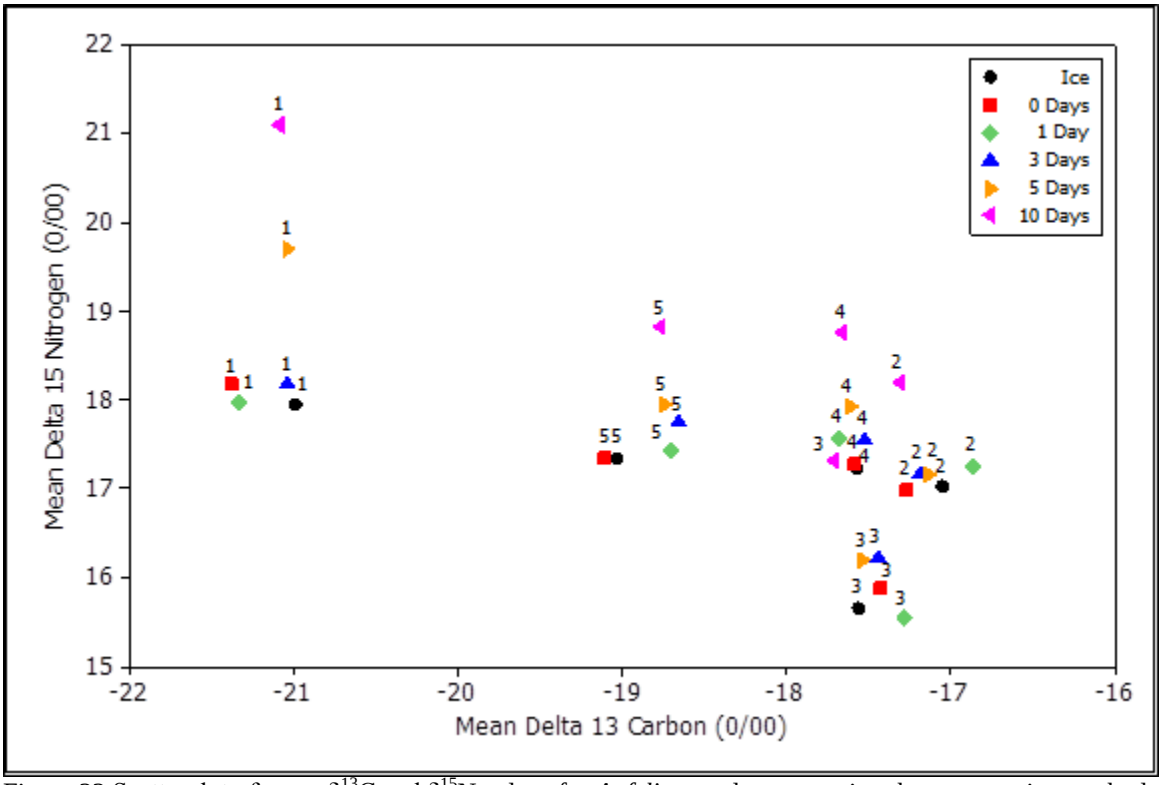

Figure 22.Scatterplot of mean δ^{13}C and δ^{15}N values for *A. felis* samples comparing the preservation method (ice or flash freezing in liquid nitrogen) and measuring the thawing period from 0 – 10 days. The numbers 1-5 indicate which samples came from each of the five fish.

DISCUSSION

The first objective for this study was to collect $\delta^{13}C$ and $\delta^{15}N$ values from the predominate species in the Galveston Bay estuarine ecosystem and to compare the differences in these values from each of the major sub-bays (Christmas, East, Galveston, Trinity, and West). While conducting this study, additional data was taken on the physical nature of the study sites, as well as supplementary data that was essential to evaluate the results of our study due to an unforeseen event relating to the storage of the samples that could have possibly affected the data. The information generated by this study provides new data and knowledge that can be added to a growing database on stable isotopes from the GBEE, the Texas coast, and throughout the world. This will provide a critical resource for future researchers interested in modeling and evaluating the response of estuarine communities to various stressors including directed fisheries, bycatch, pollution, habitat loss, and altered freshwater inflow regime.

Water Quality

Water temperature changes are an essential factor that contributes to the estuary's continuously changing biological, chemical, and physical processes. Thronson and Quigg (2008) found the average annual water temperature for Galveston Bay to be 29.5˚C, compared to the average annual water temperature found by this study, 27.1˚C. The temperature differences found among the sub-bays were primarily due to the season in

which the sampling was conducted (April – October). For example, Trinity Bay had the lowest mean temperature of all of the sub-bays sampled, but this bay was sampled more heavily than any other sub-bay during April and May when the water temperatures were cooler. Galveston Bay, which had the highest mean temperature, was sampled more in July and at the beginning of September. Temperature data taken from Lester et al. (2002) regularly throughout the year supports that temperature variation in the bay is due to seasonal change.

Salinity in the eastern GBEE is determined predominately by freshwater inflow from the Trinity and San Jacinto Rivers in the north and by saline water inflow from the Gulf of Mexico through Bolivar Roads in the south. The Trinity River is the largest source of freshwater flowing into Galveston Bay and contributes about 83% of gauged inflow while the San Jacinto contributes an estimated 8% (Clark et al. 1999). When freshwater inflows are high, the water in Trinity Bay can have very low salinity values and support large populations of freshwater species. The average salinity value for Trinity Bay was 4.7 ppt, while East Bay and Galveston Bay averaged 15.0 ppt and 16.9 ppt, respectively (Table 3 and Figure 2). These averages are consistent with data collected by Clark et al. (1999) that found Trinity Bay naturally exhibiting a range from 0-5 ppt, the central portion of Galveston Bay ranged, on average, between 15-25 ppt, while Upper Galveston and East Bays ranged from 5-15 ppt.

The western section of the GBEE does not have a major source of freshwater inflow. The freshwater inflow from the Trinity and San Jacinto Rivers is cut off by the Texas City Dike and is influenced more by the saline waters of the Gulf of Mexico that enter through Bolivar Roads and the San Luis Pass. This geographical separation and the

resulting low amount of freshwater inflow to the western section of the bay accounts for the higher average salinities of West Bay (26.3 ppt) and Christmas Bay (30.2 ppt), which had the highest average salinity values of all the sub-bays (Table 3 and Figure 2). Both of these values corresponded to Pulich and White's (1991) assessment that this portion of the bay typically has polyhaline waters with a salinity range between 15-32 ppt.

Dissolved oxygen is primarily affected by several factors such as water temperature, salinity, wind and water turbulence, the presence of oxygen-demanding compounds and organisms, and photosynthesis. Usually, higher DO values are attributed to increased survival and fitness of most aerobic aquatic organisms. Overall, the mean DO value for the GBEE was 6.3 ppm and all DO values were above critical hypoxic (< 2.0 ppm) levels. During this study, West Bay was found to have the lowest mean DO value (5.7 ppm) compared to the other four sub-bays (Table 3 and Figure 2). Historically, Upper Galveston Bay's Houston Ship Channel has displayed low DO levels and demonstrated biological and abiotic water quality concerns due most likely to pollution (Holland et al. 1973; McElyea 2003). In this study, Galveston Bay had a higher mean DO value than West, Christmas, and East Bay (Table 3 and Figure 2). The highest mean DO levels (7.7 ppm) were taken from the most expansive bay system, Trinity Bay where wind turbulence likely contributed to high reaeration rates (Table 3 and Figure 2).

Turbidity measures the clarity of the water. Lower turbidity values denote higher clarity water and increased levels of turbidity are usually associated with greater amounts of suspended solids. However, other factors including dissolved organic compounds and high phytoplankton concentration can lead to high turbidity. Sediment and other particles that are suspended in the water limit the primary production, especially of SAV, due to

reduced light penetration. Pulich and White (1991) found the only SAV habitat in the GBEE that supports populations of *H. wrightii* was Christmas Bay, which was found to have the third lowest mean turbidity level (35.7 NTU) after West Bay (30.1 NTU) and Galveston Bay (35.3 NTU), respectively (Table 3 and Figure 2). Biber et al. (2005) noted that seagrasses had high light requirements (15 to 25% surface irradiance) compared to those of other aquatic primary producers, such as algae, with much lower light requirements. Therefore, seagrasses are sensitive indicators of declining water quality and light levels and increased suspended solids. These pollutant sources have become important factors in the determination of the distribution of seagrasses in coastal areas (Livingston et al. 1998). The highest average turbidity was found in East Bay (66.9 NTU) (Table 3 and Figure 2). Reid (1955a) noted that throughout East Bay the water was highly turbid (Secchi disk measurements averaged 50 cm) and the clearest water was found near the mouth in the vicinity of Hanna Reef (60-70 cm). Sheridan et al. (1989) found East Bay to be devoid of SAV. Additionally, Pulich and White (1991) showed that mean turbidity levels from Christmas Bay and West Bay were not appreciably different, 44.59 ± 35.05 and 37.95 ± 20.25 JTU (Jackson Turbidity Units) and that Trinity Bay's turbidity was higher due to freshwater inflow which carries suspended solids from the Trinity River. For this study, the turbidity of Trinity Bay was found to be the second highest (53.6 NTU) (Table 3 and Figure 2).

Chlorophyll-α reflects the concentration of the main photosynthetic pigment in green plants and can be used as an indicator of the amount of algae that is present in the water. Pulich and White (1991) found that Christmas Bay had significantly lower seasonal chlorophyll levels than West Bay. This study's results are consistent with this

statement showing Christmas Bay with levels of chlorophyll-α at 3.3 mg/m^3 and West Bay at 12.3 mg/m^3 (Table 3 and Figure 2). Santschi (1995) found that like most temperate estuaries and coastal embayments, maximum levels for chlorophyll-α occur in March and April. Therefore, the time of year that chlorophyll-α samples were taken is important to establishing any relationships between the five sub-bays. For instance, West Bay was sampled for chlorophyll-α in May and Christmas Bay was sampled in July and October and could explain the large differences in their chlorophyll-α values (Appendix 3).

Sub-bay Primary $\delta^{13}C$ Sources

When several possible sources of primary productivity are available in an estuary, determining which source(s) of carbon were ultimately assimilated by an organism can be complicated, especially if two or more of those primary sources have similar $\delta^{13}C$ values (Fry et al. 1982a; Peterson et al. 1985; Peterson and Howarth 1987; Post 2002; Litvin and Weinstein 2003; Rooker et al. 2006). For instance, in this study, *S. alterniflora* and *H. wrightii* had $\delta^{13}C$ values that were very close to one another. From Christmas Bay, where both of these producers were sampled, *S. alterniflora* had a mean $\delta^{13}C$ value of -12.98 ± 0.11 while *H. wrightii* had a mean $\delta^{13}C$ value of -13.82 ± 0.41 (Appendix 5). Peterson and Howarth (1987) reported a $\delta^{13}C$ value for *S. alterniflora* of -12.90 ± 0.5 and Moncreiff and Sullivan (2001) reported a $\delta^{13}C$ value for *H. wrightii* of -12.2 ± 1.2, both of which were very similar to the values found in this study (Appendix 10). Moreover, *S. alterniflora* $\delta^{13}C$ values corresponded to the average range of C_4 macrophytes (approximately -12 to $-14^0/_{00}$) (Peterson and Howarth 1987; Deegan and Garritt 1997).

Additionally, the mean $\delta^{13}C$ value of detritus, epiphytes, and filamentous algae from Galveston Bay had isotopic values that did not have enough separation to be able to distinguish between the three sources of primary productivity, -16.02 ± 2.60, -15.81 ± 1.29, and -17.58 ± 0.32, respectively. When comparing course vegetative detritus and filamentous algae, Winemiller et al. (2007) found the mean $\delta^{13}C$ values to be separated by ~$3^{0}/_{00}$ (Appendix 10). Receiving similar values for detritus, epiphytes, and filamentous algae from Galveston Bay could indicate that there were high levels of epiphytes in the detritus and/or filamentous algae, causing isotopic values from these three sources to overlap. The mean $\delta^{13}C$ value of epiphytic algae from all sub-bays (-17.26 ± 0.44) was similar to Moncreiff and Sullivan (2001) from off the coast of Horn Island, Mississippi (-17.5 ± 1.7) (Appendix 10). Isotopic overlapping did not occur when looking at benthic algae or SPM because the mean stable isotope ratios of carbon from both sources were different (mean $\delta^{13}C$ values differed by more than $12^{0}/_{00}$). Benthic algae samples were more enriched in $\delta^{13}C$, while SPM has more depleted values around $-21^{0}/_{00}$ (Figure 3).

In the western GBEE, Christmas Bay and West Bay had very similar $\delta^{13}C$ values, which could be in great part due to their proximity to each other, their similar habitats, and the comparable water quality they exhibited (Figure 1 and Figure 2). In Christmas Bay, the data suggested that the food web supporting the majority of the species sampled was based largely on epiphytes (epiphytic algae) and/or detritus and less on *H. wrightii*, benthic macroalgae, and SPM. The $\delta^{13}C$ values taken from Christmas Bay species appeared to predominately fall over epiphytes and vegetative detritus as the main sources of primary production for the sub-bay (Figures 4 and 10). *H. wrightii* appeared as the main secondary source of primary productivity, possibly supporting juvenile and smaller

species that are finding food and shelter from predators amongst the blades of SAV (Fry and Parker 1979). Species that appeared to utilize *H. wrightii* included small *P. cromis*, small *L. xanthurus*, and *F. similis*, while species such as small *C. sapidus*, small *F. aztecus*, large *C. sapidus*, and large *M. cephalus* seemed to be mostly utilizing a mixture of detritus and epiphytes as well as *H. wrightii*. Moncreiff and Sullivan (2001) found that epiphytic algae dominate the base of the foodweb in *H. wrightii* beds of Mississippi Sound and even when stomach contents reveal large amounts of seagrass detritus, $\delta^{13}C$ values indicated that this detritus was not assimilated. Hyndes and Lavery (2005) also found that seagrass may be ingested, but that it was not assimilated and may reflect the preference of herbivores for algal material because of the poor nutritional value and high lignocellulose content of seagrasses. Therefore, instead of assimilating *H. wrightii*, the $\delta^{13}C$ values could represent a mixture of benthic macroalgae and epiphytic algae being consumed. *C. variegatus* (-12.21 ± 0.23) and small *M. curema* (-12.68 ± 0.53) had isotopic values in Christmas Bay that were the most enriched in $\delta^{13}C$ compared to all other species sampled in the sub-bay (Figure 10). Therefore, these species appeared to be predominately utilizing benthic macroalgae (-11.97 ± 0.67) as their primary source of carbon. This data corresponds to the feeding life style compiled by Patillo et al. (1997) for *C. variegatus* which was considered a primary consumer of algae and appeared to feed benthically due to the presence of sand and mud in its stomach. Likewise, Collins (1985) compiled literature on *M. curema* which found several types of algae in their stomachs. On the other side of the spectrum, large *B. patronus* had very depleted $\delta^{13}C$ values and appeared to be feeding predominately from the phytoplankton food chain, while medium *P. cromis* and *C. virginica*, appeared to be using intermediate portions of

the phytoplankton food chain in addition to the food chain surrounding epiphytes and/or detrital material. This data is reasonable because oysters are suspension filter feeders that filter phytoplankton and detritus particles, adult Gulf menhaden have been found to have a diet that consists largely of phytoplankton, and black drum prey on oysters (Patillo et al. 1997; Livingston 2003).

Similar to Christmas Bay, West Bay consisted of an array of species that seemed to mainly rely on epiphytes and/or detritus (Figures 4 and 14). The species that appeared to be utilizing this food chain from both Christmas Bay and West Bay were large *B. marinus*, large *C. nebulosus*, medium *C. nebulosus*, large *P. cromis*, large *A. felis*, and small *M. undulatus* (Figures 10 and 14). All of these species have been found to consume a variety of benthic invertebrates and white shrimp which in turn were found to depend heavily on plant matter such as detritus and algae (Darnell 1958; Diener et al. 1974; Overstreet and Heard 1982; McTigue and Zimmerman 1991; Manickchand-Heileman et al. 1998). Fry and Parker (1979) found similar $\delta^{13}C$ values for white shrimp (-16.8$^{0}/_{00}$) as this study did in Christmas and West Bay (Appendix 12) Therefore, it is possible that white shrimp in southern Texas estuaries depend largely on epiphytes and/or detritus there, too. Another type of algae, *Sargassum* (-15.06 to -16.8$^{0}/_{00}$), was found to have similar $\delta^{13}C$ values as epiphytes and detritus (-14.90 to -17.65$^{0}/_{00}$) (Figure 14 and Appendix 9). This macroalgae accumulates in large mats on the beaches in the GBEE. Like other species of brown algae, *Sargassum* has high levels of polyphenols, which serve as a chemical defense against grazers, and was why these algae were not considered to be incorporated in higher trophic levels of the GBEE (Rooker et al. 2006). For SPM in West Bay, none of the species sampled had $\delta^{13}C$ values that aligned with SPM. Although,

there were several species that had $\delta^{13}C$ values midway between SPM and epiphytes and/or detritus, suggesting that these species fed from a mixture of both food chains. Peterson and Howarth (1987) observed from the salt marsh estuaries of Sapelo Island, Georgia that $\delta^{13}C$ values frequently fell in the range of -15 to $-18^{0}/_{00}$, as they do for Christmas and West Bays (Figures 10 and 14). They concluded that a mixture of plankton and *Spartina* detritus and/or benthic diatoms were major components of the food chain. Unlike Christmas Bay, the $\delta^{13}C$ values of the species from West Bay were not as enriched, but several species lie intermediately between the carbon sources of epiphytes and/or detritus and macrobenthic algae (Figures 10 and 14). Those species included small *M. cephalus*, small *M. curema*, *C. variegatus*, small *S. ocellatus*, small *F. aztecus*, and small *L. xanthurus*. Because there is very limited SAV in West Bay, it is less likely that these species are receiving their carbon from *H. wrightii*, and more plausibly, that these species were ingesting intermediate levels of carbon from benthic macroalgae, epiphytes, and detritus.

Past research has indicated that the epiphytic algal assemblage may be the primary food source, as opposed to *H. wrightii*, *S. alterniflora*, and the detrital material they generate (Gleason 1986; Moncreiff and Sullivan 2001). *Spartina* epiphytes represent a mixture of many species of diatoms, blue-green algae, and green algae of which benthic diatoms were found to be the principal source of organic material assimilated by macro-consumers in littoral marshland (Gleason 1986; Créach et al. 1997). Deegan and Garritt (1997) suggested that algae contribute more production to higher trophic levels because of the higher digestibility of most algae compared to that of vascular plants. Similarly, Créach et al. (1997) noted that only 5 to 10% of the primary production from salt marshes

is grazed and that the rest is transferred to invertebrates only after being subjected to the action of micro-organisms. Epiphytic algae is a main characteristic of other lentic coastal systems with low tidal amplitude and irregularly flooded marshes in the Northern GOM that favor the development and retention of in situ algal production and a food web more dependent on algal production (Gleason 1986; Créach et al. 1997; Deegan and Garritt 1997). Similar results for the importance of epiphytic algae as opposed to other carbon sources have been found by Winemiller et al. (2007) in Matagorda Bay, Texas and Moncreiff and Sullivan (2001) in the seagrass meadows of Horn Island, Mississippi. In the Florida Keys, Behringer and Butler (2006) found the autochthonous production of algal detritus to be an important source of secondary production in the hard-bottom communities. Therefore, based on the isotopic data, epiphytic algae represent a reliable and highly nutritious food source controlling food web dynamics in the western GBEE.

In the eastern section of the GBEE, East Bay had isotopic values that were intermediate of those from the other four sub-bays (Figure 4). The $\delta^{13}C$ values fell mostly from -18 to $-21^{0}/_{00}$, grouping the majority of the species in between the basal carbon sources of SPM and epiphytes (Figure 11). Similar to Christmas Bay and West Bay, epiphytes are an important source of primary productivity in East Bay because it is a narrower bay and is surrounded by *S. alterniflora*, which the algal epiphytes colonize (Gleason 1986). Additionally, large *B. marinus*, small *M. undulatus*, and small *L. setiferus* again have comparable $\delta^{13}C$ values to epiphytes. Similarly, in both West Bay and East Bay *P. lethostigma* and small *C. sapidus* have $\delta^{13}C$ values that align with epiphytes as the primary source of their food chain. In Clear Lake, a secondary bay system located on the west side of upper Galveston Bay, Diener et al. (1974) found *P.*

lethostigma to have stomach contents that contained grass shrimp, blue crab, and croaker. Likewise, in Barataria Bay, Louisiana, Fox and White (1969) found that southern flounder consumed striped mullet, *Penaeus* spp., *Callinectes* spp., *Palaemonetes* spp., and croaker. All of these species have $\delta^{13}C$ values that are similar to epiphytes in East Bay (Figure 11). Only two species in East Bay, the filter feeding *R. cuneata* and large *L. xanthurus*, were found to be strictly utilizing the phytoplankton food chain. Both Darnell (1961) and Matlock and Garcia (1983) found the spot croaker to consume common *Rangia*. The most enriched species, *C. leucas* and small *P. cromis* had $\delta^{13}C$ values that linked them to prey that were consuming variable quantities of benthic macroalgae and vegetative detritus or epiphytes in their diets.

Isotopic evidence indicated that the primary basal food source of consumers did not vary greatly among Galveston and East Bays. Again, a large majority of the species had $\delta^{13}C$ values that clustered in-between SPM and the values for detritus and/or epiphytes. Only one species from Galveston Bay exhibited $\delta^{13}C$ values in close alignment with SPM and that was the oyster, *C. virginica*. Peterson and Howarth (1987) also found that the American oyster was isotopically more similar to phytoplankton than any other primary producer. Two species, Gulf killifish (*Fundulus grandis*) and small *M. curema*, appeared to exclusively receive their carbon from epiphytes and/or detritus. Winemiller et al. (2007) found Gulf killifish to have a $\delta^{13}C$ value of-15.60 ± 0.9 (Appendix 14). Compared to Galveston Bay's $\delta^{13}C$ value of $-16.70^{0}/_{00}$, it appears that in Matagorda Bay this species relies on epiphytes and/or detritus, too. Patillo et al. (1997) found Gulf killifish to be opportunistic predators that can also feed omnivorously on such items

including, but not limited to insects, benthic invertebrates, detritus substrate, vascular plant tissue, and algae.

Trinity Bay had the most depleted $\delta^{13}C$ values when compared to the other four sub-bays (Figure 4). Organisms collected in this bay appeared to rely on a food chain that predominately originated from SPM, but also included intermediate values between epiphytes and/or detritus, suggesting dietary generalists. Once more, the filter feeder *C. virginica* exhibited $\delta^{13}C$ values in close alignment with SPM. Unlike any other sub-bay, two species in Trinity Bay displayed $\delta^{13}C$ values that were more depleted than SPM. *M. ohione* and *L. oculatus* had $\delta^{13}C$ values of -28.19 and -25.84$^{0}/_{00}$, respectively. Sheridan et al. (1989) noted that *M. ohione* is found in low salinity areas of the GBEE during April and May. Deegan and Garritt (1997) found that consumers in the oligohaline upper estuary of Plum Island Sound, Massachusetts had $\delta^{13}C$ values of -29 to -21$^{0}/_{00}$, which indicated dependence on a mixture of fresh marsh emergent vegetation and phytoplankton. Previous studies have all found values for C_3 plants, terrestrial runoff, and riverine particulate inputs that all ranged from -22 to -34$^{0}/_{00}$ (Teeri and Schoeller 1979; Peterson et al. 1985; Peterson and Howarth 1987; Gannes et al. 1997; Kelley et al. 1998; Kang et al. 2003) (Appendix 10). Therefore, the more depleted $\delta^{13}C$ values for the Ohio River shrimp and the spotted gar suggested that their long-term primary source of nutrition was associated with sources from the Trinity River. These two species were collected during the middle of April in the northern section of Trinity Bay. During this time, the salinity level was found to be between 0.2 and 0.7 ppt. Species from Trinity Bay that had $\delta^{13}C$ values that aligned more with carbon from epiphytes included *Palaemonetes* spp., small *M. cephalus*, small *F. aztecus*, *L. rhomboids*, small *M.*

undulates, small *P. cromis*, and small *B. marinus*. Species that aligned more with the detrital food chain were small *M. curema* and large *B. marinus*. None of the species' isotopic values in Trinity Bay appeared to be associated with benthic macroalgae.

In the eastern section of the GBEE (East, Galveston, and Trinity Bays), the data suggests that the food web supporting the majority of the species sampled is based largely on epiphytes (epiphytic algae) and/or detritus like the western section of the bay, but there seems to be more dependence on phytoplankton. Several possible explanations for the differences in $\delta^{13}C$ values from the eastern and western GBEE exist. One of the main factors is the difference in the habitats in these two areas. The western GBEE is shallower and narrower than the eastern section. The decreased depth would allow more algae to grow on the bottom of these bays. This would explain why this carbon source is utilized more often by species that do not appear to utilize it as much in the eastern section of the bay, with the exception of East Bay. Also, the species in the western GBEE would have more marsh habitat compared to the eastern GBEE which would have more open bay habitat that would depend on a more pelagic oriented food chain focusing on phytoplankton. Another component possibly aiding in the depleted isotopic values of the upper section of the eastern GBEE could be riverine particulate organic matter (POM) introduced along with the freshwater inflow. POM appears to be a small component of most estuarine food webs, though, because even in the relatively small regions of the upper GBEE where its availability is the highest, estuarine consumer dependence on it has been found to be minimal (Deegan and Garritt 1997). Furthermore, the nutrients in the freshwater inflow would fuel larger levels of phytoplankton production, allowing this

carbon source to be utilized more by consumers and therefore appear more in the isotopic samples.

Sub-bay Trophic Positions

Unlike carbon isotopes, nitrogen isotopes are enriched as the trophic levels increase due to isotopic fractionation. In most instances, the first trophic level was composed of primary producers, such as detritus, benthic algae, epiphytes, *S. alterniflora*, and *H. wrightii*. In some instances, consumers had lower values than the primary producers. The lowest mean $\delta^{15}N$ values of any vertebrate or invertebrate belonged to *C. variegatus* and implied that this species was feeding predominately, if not entirely, on primary producers. Martin (1970) found sheepshead minnows to feed mainly on organic detritus, sand, green algae, blue-green algae, diatoms, polychaetes, and vascular plants. Patillo et al. (1997) describes the sheepshead minnow as a primary consumer with a diet consisting primarily of plant material, diatoms and other algae, detritus, amphipods, copepods, and mosquito larvae and pupae.

Sargassum species (TP = 1.31 to 1.43), SPM (TP = 2.11), and filamentous algae (TP = 3.42) were all basal carbon sources that had trophic positions above *C. variegatus*. A possible explanation for these cases is the periphyton might have not been fully cleaned off and the attached contaminating organisms could be causing false values, resulting in elevated trophic positions above other primary producers and some consumers. For instance, Winemiller et al. (2007) collected filamentous algae samples that had mean $\delta^{15}N$ values of 6.3 ± 0.1 and SPM samples with mean $\delta^{15}N$ values of 3.5 ± 0.7, whereas the mean $\delta^{15}N$ values from this study were 14.77 ± 0.25 and 10.47 ± 1.09,

respectively (Appendix 11). Besides the species aforementioned, there were very few species that appeared in the second trophic level (~ 1.22 to 2.24), which would consist of consumers of primary productivity. During this study, we were unable to collect sufficient amounts of zooplankton to determine isotopic ratios for this potential food source. Like Reid (1955a), difficulties collecting zooplankton occurred because numerous tows were made of which all contained excessive amounts of the ctenophore comb jelly (*Beroe ovata*). Understanding zooplankton trophic relationships are fundamental since zooplankton plays a role linking basal resources to organisms at higher trophic levels (Feuchtmayr and Grey 2003). Further isotope samples from polychaete worms, the bivalve *Mulinia lateralis*, gastropods, amphipods, nemerteans, and oligochaete worms would be useful to better describe the detrital food chain in the GBEE, as well. These species were all found to occur in Galveston Bay, especially polychaete worms which made up 69.5% of the total abundance of benthic invertebrates sampled by McElyea (2003).

Other second level consumers that were sampled included *Palaemonetes* spp. and the small *M. cephalus, S. ocellatus*, and *P. cromis*. Grass shrimp were found by Morgan (1980) to aid in the breakdown of epiphytic microalgae in addition to consuming some benthic microinvertebrates. Quinones-Rivera and Fleeger (2005) documented that grass shrimp consumed cyanobacteria, diatoms, brown algae, green algae, and red algae from the surface of *S. alterniflora*. Furthermore, Peterson and Howarth (1987) found $\delta^{15}N$ values for grass shrimp (8.55 ± 0.35) to be very similar to the values received from Christmas Bay (8.93 ± 0.29) (Appendix 13). Moncreiff and Sullivan (2001) also found striped mullet to have a lower $\delta^{15}N$ value of $10.2^{0}/_{00}$ which would indicate that it was

feeding very low in the food chain (Appendix 15). Minello et al. (1989a) documented that 13.62% of the stomach contents of *S. ocellatus* (8 – 131 mm TL) consisted of primary productivity sources in Galveston Bay and Matlock and Garcia (1983) documented that 37.99% of the stomach contents of *P. cromis* (26 – 225 mm SL) consisted of detritus. These species, besides *C. variegatus*, could represent a trophic position that fluctuates in between the second and third levels because of their consumption of primary productivity and detritus in addition to feeding on zooplankton and microinvertebrates.

The third trophic level in this study, ~2.50 to 3.46, included 23 species; fourteen vertebrates, eight invertebrates, and the basal carbon source filamentous algae. Filamentous algae had an exceptionally high trophic position, which could have been the result of contamination by microbenthic invertebrates. Both small and large *B. patronus* fit into this trophic level. Previous studies completed by Matlock and Garcia (1983) and Darnell (1961) found their stomach contents to contain large percentages of detritus and primary productivity. If this species assimilated this material, then it would seem that their trophic position would fall closer to the second trophic level. When examining the stomach contents, Winemiller et al. (2007) came to a similar conclusion when they noted that detritus was by far the dominant food resource consumed by Gulf menhaden. After determining the trophic levels calculated from stable isotope analysis, Gulf menhaden and gizzard shad (which was determined to reside in the fourth trophic level of this study) were found to have much higher trophic levels than a species should that was primarily consuming detritus. Therefore, isotopic analysis inferred that invertebrates were the primary nutritional resource for menhaden (Winemiller et al. 2007).

In general, it would seem that the $\delta^{15}N$ values of adults would be higher than those of juveniles. When averaging the trophic position from all five sub-bays, this trend was observed for most species, the sea catfish was one of the exceptions (Figure 19). Small *A. felis* had a trophic position of 4.49 compared to a trophic position of 3.94 for large *A. felis* and small *B. marinus* had a trophic position of 4.14, while large *B. marinus* was found to have a trophic position of 4.12. All of these species appeared in the fourth trophic level of this study (~3.63 to 4.41). All of the shark species that were sampled appeared at this level in addition to all large species of Sciaenids and Ariids. Even though these large estuarine predators had some of the highest trophic positions, the highest belonged to *C. quinquecirrha*, which had a trophic position of 4.41. This trophic position is quite large for a species that is considered to be a zooplanktivore, but *A. mitchilli*, another zooplanktivore, had a trophic position of 3.63 and was also considered to feed in the fourth trophic level (Johnson et al. 1990; Diener et al. 1974).

In this study, an enrichment factor of $3.3^{0}/_{00}$ was used to help identify consumers and their sources (Yoshii et al. 1999; Winemiller et al. 2007). Therefore, the species that were previously identified to exist in similar food chains should be separated by this factor if they were exclusively eating from one item. For instance, in Christmas Bay *C. variegatus* ($\delta^{15}N = 4.23^{0}/_{00}$) is vertically separated from benthic algae ($\delta^{15}N = 0.31^{0}/_{00}$) by a factor of $3.92^{0}/_{00}$. In East Bay, SPM ($\delta^{15}N = 10.08^{0}/_{00}$), *R. cuneata* ($\delta^{15}N = 12.57^{0}/_{00}$), and large *L. xanthurus* ($\delta^{15}N = 18.21^{0}/_{00}$) appeared to represent a food chain. The $5.64^{0}/_{00}$ difference could infer that large spot croaker not only fed on primary consumers like the common *Rangia*, but also fed on other secondary consumers which would cause it to have a greater nitrogen value.

Anthropogenic Nitrogen Loading

Eutrophication of coastal waters prompted by the increasing nitrogen loading from watersheds, is arguably the principal and most pervasive anthropogenic alternation to coastal ecosystems everywhere (Valiela et al. 1997a). The stable isotope, ^{15}N, can be used to track the increase in nitrogen loading (Aravena et al. 1993; McClelland and Valiela 1998). After the samples from this study were analyzed, the greatly enriched $\delta^{15}N$ values from the upper GBEE (Figure 4 and 21) suggested that anthropogenic nitrogen inputs, such as wastewater effluent, were being introduced into this system via freshwater inflow. Galveston Bay species had the highest difference in mean $\delta^{15}N$ values (a mean enrichment of $5.16^{0}/_{00}$) from the more remote Christmas Bay ($15.98^{0}/_{00}$). Trinity Bay species had a mean $\delta^{15}N$ enrichment of $4.1^{0}/00$, followed by East Bay ($1.47^{0}/_{00}$), and then West Bay ($0.42^{0}/_{00}$). The consumers from the five study bays had enrichment in their $\delta^{15}N$ values that did not solely reflect an elevated trophic position (Vander Zanden and Rasmussen 1999). The species that had the largest differences in TP were small *M. cephalus* and small *L. xanthurus* and most likely were experiencing an ontogenetic shift in diet (Table 10).

Anthropogenic nitrogen loading is occurring because the Trinity and San Jacinto rivers are most likely receiving high wastewater inputs from the Dallas-Ft. Worth and Houston metropolitan areas. McElyea (2003) found that the GBEE received 60% of the state's wastewater effluent and upper and mid Galveston Bay and Trinity Bay were found to be experiencing nutrient concerns that have led to macrobenthic degradation. Sources of ambient nitrate levels in water include direct leaching of fertilizers, increased oxidation of soil organic nitrogen from cultivation, and animal wastes (Kreitler 1979).

Santschi (1995) states that the major sources of nitrogen inputs are wastewater treatment plants (50%), industrial facilities (30%), and agriculture (10% for N) and his study found that nutrient concentrations were highest in the upper GBEE (specifically in upper Trinity Bay and at Morgan's Point) and gradually get lower the farther away from the mouths of the rivers one gets.

Several studies have found that nitrogen inputs to river estuaries can affect food sources by primary producers integrating available nitrate and then transferring it up the food chain through higher trophic level consumers (Bucci et al. 2007). Hannson et al. (1997) showed that discharges from a sewage treatment plant significantly increased $\delta^{15}N$ values in the whole food web in the coastal Baltic Sea. In the Waquoit Bay region of Massachusetts, McClelland and Valiela (1998) showed that $\delta^{15}N$ values increased in producers as the wastewater contributions increased. Vander Zanden and Rasmussen (1999) noticed that the two Canadian lakes that had the most substantial human population in their watershed contained primary consumers with the most elevated $\delta^{15}N$ values. The trophic position of native fishes in these disturbed lakes differed from that of natives in undisturbed lakes by approximately 0.6 trophic levels. Holt and Ingall (2000) showed that $\delta^{15}N$ values from *C. nebulosus* collected from Galveston Bay reflected a greater contribution of sewage-derived nitrogen than *C. nebulosus* collected from Upper Laguna Madre, Texas. In two North Carolina estuaries, Bucci et al. (2007) found that $\delta^{15}N$ values increased at sites with high nitrate concentrations and that the sites that had these elevated values were located down river from a municipal wastewater treatment plant. In Mobile Bay, Alabama, biological changes in $\delta^{15}N$ values of oysters and SPM

caused by wastewater treatment plant effluent were analyzed by Daskin et al. (2008) to assess short-term ecological and human health effects.

Thawing Treatments and Storage Methods

An additional study was performed to ascertain that all of the samples that were taken were not significantly affected by a thawing incident that occurred when one of the freezers stopped working. The samples thawed for three days until they were discovered. The results from this study showed that there were no significant differences between the samples that were not left out to thaw and the samples that were left out to thaw for up to ten days. The largest change occurred with $\delta^{15}N$ values from the flash freeze control that was not left out to thaw and the samples that were left out for 10 days ($1.71^{0}/_{00}$ enrichment). It appears that when samples were left out to thaw for longer periods, greater amounts of lighter isotopes were lost. For this study, ^{15}N-enrichment occurred for all preservation treatments relative to control values, which was consistent with other studies (Bosley and Wainright 1999; Feuchtmayr and Grey 2003).

Kaehler and Pakhomov (2001) and Dannheim et al. (2007) stated that freezing or exposing organic matter to below zero temperatures had no effect on initial stable isotope ratios for both carbon and nitrogen. This was held true by this study in which no significant differences existed between the storage methods of flash freezing and storing the samples on ice. Bosley and Wainright (1999) did not find any effects on stable isotope ratios of carbon or nitrogen when comparing freezing and freeze-drying, but Feuchtmayr and Grey (2003) found that freezing treatments resulted in the greatest deviation from control carbon values while shock freezing treatments were not significantly different. The immediacy of shock freezing or flash freezing under liquid

nitrogen reduces the time that ice crystals form within the tissues and may explain why the $\delta^{13}C$ values resulted in minimal change (Feuchtmayr and Grey 2003). Slower freezing allows for the formation of more ice crystals inside tissues which can destroy cells mechanically and lead to cell content leakage (Dannheim et al. 2007).

CONCLUSIONS

To my knowledge, this study was the first to examine stable isotope ratios from multiple species in the GBEE at one time. The results document that the dominant GBEE primary production varies between sub-bay systems and suggests that there are possibly four major basal carbon sources for the fauna of the GBEE: *Spartina* detritus and/or epiphytic algae, while phytoplankton and benthic algae are both important in varying degrees depending on the sub-bay. Based on the species collected, few derive their carbon from one basal carbon source exclusively and therefore are not feeding exclusively within one food web. Depending on the sub-bay, consumers appeared to use a mixture of carbon sources derived from phytoplankton, *Spartina* detritus, epiphytic algae, and benthic algae. These producers are the most important in sustaining the secondary production in the GBEE's food webs and development of future ecosystem models will have to address the relative contribution of the various sources of primary production and how these are affected by freshwater inflow

Anthropogenic sources from the San Jacinto and Trinity Rivers dominated nitrogen pathways in the upper bay system, which affects the relative position of trophic levels. This agrees with past research conducted in a variety of diverse aquatic ecosystems. The $\delta^{15}N$ values taken from each sub-bay indicated that Galveston Bay was the most affected by anthropogenic nitrogen loading, followed by Trinity, East, West, and Christmas Bays.

When conducting a study on stable isotopes, it is best to use flash-freezing in liquid nitrogen, but storing samples on ice did not cause any significant difference in the isotopic ratios of C and N of the test species, *A. felis*. Also, after being initially frozen, samples that were left out to thaw for up to ten days did not show any significant difference from the control that was stored in liquid nitrogen in the field and immediately put into the freezer without any thawing period. Samples that were left out to thaw from five to ten days did appear to show some enrichment in their $\delta^{15}N$ values, however this was not significantly different. Therefore, we conclude that the isotopic signatures of samples from this study were not affected within the range of conditions tested.

FUTURE RESEARCH NEEDS

Another way of reducing the uncertainties when trying to identify consumer's sources of carbon is by adding another isotope tracer. Future studies using sulfur isotopes are recommended because the sulfur isotope has a high probability of distinguishing the contribution of different producers to aquatic food webs. Where isotopic values of two producers are not able to be separated using carbon and nitrogen, sulfur as an additional tracer frequently discriminates between those signatures (Connolly et al. 2004). To continue monitoring nitrogen loading to the GBEE, routine tissue samples could be taken from resident species in each sub-bay along with freshwater inflow data. Measuring these effects and creating models of estuarine food webs can be important tools for managing and sustaining productive fisheries. Another possible application of stable isotope analysis is combining these efforts with studies of organochlorine contaminants and mercury in organisms to examine trophic level biomagnifications (Jarman et al. 1997). Chumchal et al. (2008) identified how mercury is bioaccumulated in the food chain of Lake Caddo by using stable isotopes to gain information of trophic interactions. This information is of high importance to the public and health officials dealing with mercury and other contaminants in aquatic environments where there is a risk involved in the consumption of fish. The human population is predicted to double in Texas by 2050 and the majority of this increase to occur around the coastal areas (Thronson and Quigg 2008). Therefore additional research that provides critical information on trophic

interactions of key components of Galveston Bay is needed by scientists and natural resource managers. This critical data can be used to develop predictive environmental models to evaluate the response of natural resources to various stressors and environmental changes including freshwater inflow, persistent contaminants and even climate change. Continued work in this area is therefore needed to ensure the protection of the species and habitat of the GBEE.

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APPENDICES

Appendix 1. Sites sampled in the GBEE from each of the 5 sub-bays.

Bay	TPWD	Latitude (N)			Longitude (W)		
	Bay Code	Degrees	Minutes	Seconds	Degrees	Minutes	Seconds
Christmas	2-110-704	29	4	18	-95	9	25
	2-110-702	29	4	15	-95	11	29
	2-110-708	29	3	22	-95	12	35
	2-110-710	29	3	30	-95	10	30
	2-110-711	29	2	55	-95	9	56
	2-110-723	29	1	45	-95	12	36
	2-110-710	29	2	43	-95	12	13
	2-110-711	29	2	56	-95	9	54
	2-110-711	29	2	55	-95	9	53
East	2-150-385	29	29	30	-94	36	30
	2-150-292	29	32	30	-94	35	30
	2-150-288	29	32	18	-94	39	48
	2-150-360	29	30	7	-94	34	46
	2-150-316	29	31	33	-94	46	9
	2-150-285	29	32	17	-94	42	1
	2-150-286	29	32	18	-94	41	28
	2-150-284	29	32	1	-94	43	20
	2-150-320	29	31	22	-94	42	57
	2-150-382	29	29	32	-94	39	32
	2-150-379	29	29	30	-94	42	30
	2-150-327	29	31	12	-94	35	2
	2-150-329	29	31	39	-94	33	13
	2-150-284	29	32	2	-94	43	8
	2-150-238	29	31	22	-94	34	50
	2-150-228	29	34	23	-94	32	57
	2-150-288	29	32	40	-94	39	55
	2-150-411	29	28	56	-94	36	14
Galveston	2-180-125	29	38	30	-95	0	30
	2-180-150	29	37	26	-94	56	26
	2-180-129	29	38	17	-94	56	49
	2-180-150	29	37	30	-95	56	30
	2-180-110	29	39	20	-94	56	26
	2-180-90	29	40	12	-94	56	17
	2-180-311	29	31	30	-94	51	30
	2-180-194	29	35	30	-94	53	30
	2-180-167	29	36	16	-94	59	2
	2-180-188	29	35	38	-94	59	23
	2-180-211	29	34	30	-94	57	30
	2-180-235	29	33	30	-95	0	30
	2-180-459	29	25	30	-94	48	30
	2-180-424	29	27	30	-94	46	30
	2-180-461	29	25	30	-94	46	32
	2-180-470	29	24	30	-94	51	30
	2-180-505	29	21	44	-94	46	54
	2-180-338	29	30	16	-94	56	51

Appendix 1 cont.

Bay	TPWD	Latitude (N)			Longitude (W)		
	Bay Code	Degrees	Minutes	Seconds	Degrees	Minutes	Seconds
Galveston	2-180-146	29	37	7	-95	0	6
	2-180-270	29	32	30	-94	58	30
	2-180-303	29	31	30	-94	59	30
	2-180-149	29	37	46	-94	57	2
	2-180-210	29	34	30	-94	58	30
	2-180-468	29	24	28	-94	53	16
	2-241-433	29	26	33	-94	56	10
	2-312-68	29	41	52	-94	59	25
	2-180-495	29	22	19	-94	46	39
Trinity	2-330-8	29	46	36	-94	46	9
	2-330-139	29	38	33	-94	46	30
	2-330-93	29	40	30	-94	51	30
	2-330-111	29	39	30	-94	53	30
	2-330-249	29	33	3	-94	46	30
	2-330-117	29	39	45	-94	47	29
	2-330-183	29	36	37	-94	43	0
	2-330-103	29	40	29	-94	41	45
	2-330-81	29	41	30	-94	45	30
	2-330-42	29	43	30	-94	46	30
	2-330-55	29	42	50	-94	51	14
	2-330-75	29	41	12	-94	51	42
	2-330-103	29	40	32	-94	41	46
	2-330-47	29	43	14	-94	41	31
	2-330-37	29	43	4	-94	51	0
	2-330-75	29	41	46	-94	51	49
	2-330-38	29	43	56	-94	50	24
	2-330-164	29	37	32	-94	42	23
West	2-350-641	29	10	30	-95	5	31
	2-350-564	29	16	58	-94	55	15
	2-350-602	29	13	3	-94	57	11
	2-350-673	29	7	33	-95	5	8
	2-350-662	29	8	29	-95	5	28
	2-350-694	29	5	35	-95	8	44
	2-350-663	29	8	11	-95	4	3
	2-350-655	29	9	13	-95	2	13
	2-350-696	29	5	58	-95	6	31
	2-350-646	29	10	39	-95	0	58
	2-350-633	29	11	6	-95	0	23
	2-180-530	29	19	38	-94	49	18
	2-180-526	29	19	47	-94	53	51
	2-350-674	29	7	41	-95	4	52
	2-350-696	29	5	59	-95	6	29
	2-350-665	29	8	57	-95	2	37
	2-350-620	29	12	55	-94	57	19
	2-350-578	29	15	19	-94	55	5

Appendix 2. Depth and water quality parameters measured at each site in the GBEE. Turbidity measurements labeled in centimeters signifies the use of a Secchi tube. Asterisks denote abnormal data not included in mean values for each sub-bay.

Date	Latitude	Longitude	Depth (m)	Temp (˚C)	Salinity (ppt)	DO (ppm)	Turbidity (NTU)
4/8/2008	29-36-37	-94-43-00	0.9	21.7	4.3	7.8	27
4/8/2008	29-40-29	-94-41-45	0.8	22.2	2.8	7.7	9
4/8/2008	29-41-30	-94-45-30	3.3	21.6	0.5	8.4	3
4/8/2008	29-43-30	-94-46-30	3.0	22.8	0.7	9.5	2
4/8/2008	29-42-50	-94-51-14	0.1 - 0.6	23.9	1.5	9.3	65
4/8/2008	29-41-12	-94-51-42	2.0	23.7	3.5	8.8	7
4/16/2008	29-40-32	-94-41-46	0.7 - 1.1	17.8	0.4	7.8	33
4/16/2008	29-43-14	-94-41-31	0.3 - 1.2	17.9	0.2	7.9	35
4/30/2008	29-08-11	-95-04-03	0.2 - 0.6	20.2	23.3	7.3	10
4/30/2008	29-09-13	-95-02-13	0.2 - 0.5	19.9	24.0	7.1	11
5/6/2008	29-30-16	-94-56-51	0.2 - 0.6	21.8	10.4	8.7	95
5/8/2008	29-37-07	-95-00-06	0.1 - 1.0	25.3	8.1	8.9	100
5/8/2008	29-32-30	-94-58-30	2.1	23.4	8.1	6.9	32
5/8/2008	29-31-30	-94-59-30	2.6	23.5	7.0	7.4	25
5/8/2008	29-37-46	-94-57-02	0.1 - 0.4	24.5	6.8	6.8	55
5/8/2008	29-34-30	-94-58-30	2.1	23.6	8.7	7.2	22
5/13/2008	29-43-04	-94-51-00	0.6 - 1.0	23.8	0.9	7.5	200
5/13/2008	29-41-46	-94-51-49	0.7 - 1.3	24.0	1.7	7.3	130
5/13/2008	29-43-56	-94-50-24	0.6 - 0.8	23.5	1.9	7.7	170
5/15/2008	29-31-22	-94-34-50	0.5 - 1.7	25.5	11.8	6.8	55
5/15/2008	29-34-23	-94-32-57	0.5 - 1.1	25.4	13.7	5.9	20
5/19/2008	29-07-41	-95-04-52	0.6 - 0.7	23.3	23.6	5.8	25
5/19/2008	29-05-59	-95-06-29	0.4 - 0.7	23.5	21.7	6.3	10
6/3/2008	29-41-52	-94-59-25	0.1 - 1.2	27.5	5.6	5.2	60
6/5/2008	29-10-39	-95-00-58	0.2 - 1.1	27.1	26.5	6.2	45
6/5/2008	29-11-06	-95-00-23	0.8 - 1.1	27.1	26.5	6.1	45
6/10/2008	29-19-38	-94-49-18	0.1 - 1.6	28.2	20.0	6.3	34
6/10/2008	29-19-47	-94-53-51	0.2 - 0.8	27.5	26.6	4.8	18
6/12/2008	29-32-40	-94-39-55	0.5 - 0.9	27.6	13.6	5.8	164
6/16/2008	29-24-28	-94-53-16	0.3 - 1.1	29.2	18.6	5.7	9
6/16/2008	29-26-33	-94-56-10	0.2 - 1.7	29.6	18.9	5.6	10
6/17/2008	29-05-58	-95-06-31	0.3 - 0.9	28.4	27.8	2.9	33
6/17/2008	29-01-45	-95-12-36	2.7	31.1	27.6	5.3	-
6/20/2008	29-01-45	-95-12-36	3.0	-	-	-	-
6/24/2008	29-29-32	-94-39-32	2.1	29.5	14.3	5.8	111
6/24/2008	29-29-30	-94-42-30	2.7	29.3	13.1	5.8	33
6/24/2008	29-31-12	-94-35-02	0.2 - 0.6	29.4	15.0	5.3	22
6/24/2008	29-31-39	-94-33-13	0.3 - 0.7	28.9	15.5	5.8	63
6/24/2008	29-32-02	-94-43-08	0.1 - 0.6	26.7	11.9	6.5	134
6/30/2008	29-08-57	-95-02-37	0.3 - 0.5	30.3	27.3	6.1	18
6/30/2008	29-12-55	-94-57-19	0.3 - 0.6	30.5	26.3	6.0	16
7/2/2008	29-32-01	-94-43-20	0.2 - 0.3	28.6	13.1	6.6	34
7/2/2008	29-31-22	-94-42-57	3.0	29.2	14.2	5.8	21
7/2/2008	29-25-30	-94-48-30	3.1	29.9	28.8	5.6	7
7/2/2008	29-27-30	-94-46-30	2.5	30.3	25.6	5.6	58

Appendix 2 cont.

Date	Latitude	Longitude	Depth (m)	Temp (˚C)	Salinity (ppt)	DO (ppm)	Turbidity (NTU)
7/2/2008	29-25-30	94-46-32	2.4	30.0	28.6	5.7	10
7/2/2008	29-32-18	94-41-28	0.1- 0.3	28.2	13.5	6.0	19
7/8/2008	29-46-36	94-46-09	0.2-0.4	33.3	4.2	8.2	23
7/8/2008	29-38-33	94-46-30	3.0	30.2	10.0	6.9	13
7/8/2008	29-40-30	94-51-30	1.9	30.0	11.6	6.8	21
7/8/2008	29-39-30	94-53-30	2.1	29.8	11.5	6.6	26
7/10/2008	29-02-43	95-12-13	0.6	31.2	30.2	5.5	32
7/12/2008	29-02-56	95-09-54	0.3	23.3	34.0	3.6	20.0 cm
7/16/2008	29-33-03	94-46-30	0.2-0.6	31.3	14.1	5.8	31
7/16/2008	29-39-45	94-47-29	2.7	30.3	13.0	6.3	105
7/16/2008	29-31-30	94-51-30	3.0	30.5	17.8	5.4	14
7/16/2008	29-35-30	94-53-30	3.1	33.4	14.7	6.1	115
7/16/2008	29-36-16	94-59-02	0.3	-	-	-	-
7/18/2008	29-35-38	94-59-23	0.1-0.4	31.5	17.0	5.2	29
7/18/2008	29-34-30	94-57-30	3.2	30.0	18.6	3.8	31
7/18/2008	29-33-30	95-00-30	3.0	31.3	17.1	3.8	24
7/19/2008	29-02-55	95-09-56	0.4	27.0	34.0	5.0	21.2 cm
7/30/2008	29-10-30	95-05-31	1.5	29.9	28.0	5.7	43
7/30/2008	29-16-58	94-55-15	0.1-0.5	29.8	30.7	5.7	15
7/30/2008	29-13-03	94-57-11	0.3-0.8	29.7	31.5	5.3	19
7/30/2008	29-07-33	95-05-08	0.1-0.3	33.6	34.9	5.1	47
7/30/2008	29-08-29	95-05-28	2.5	29.6	32.3	4.9	109
8/12/2008	29-04-18	95-09-25	0-0.5	29.8	35.2	5.6	134
8/14/2008	29-29-30	94-36-30	1.3	28.9	17.1	5.4	60
8/14/2008	29-32-30	94-35-30	1.5	32.1	18.8	7.5	15
8/14/2008	29-32-18	94-39-48	1.7	30.7	19.8	7.0	11
8/14/2008	29-30-07	94-34-46	0.2-0.7	29.9	17.1	4.3	17
9/5/2008	29-38-30	95-00-30	2.8	28.8	23.0	6.7	16
9/5/2008	29-37-26	94-56-26	0.1-0.2	29.2	19.9	6.6	22
9/5/2008	29-38-17	94-56-49	0.2-0.5	29.1	20.8	5.4	18
9/5/2008	29-37-30	95-56-30	0.9	29.0	19.8	7.7	40
9/5/2008	29-39-20	94-56-26	0.2-0.4	30.7	19.6	6.9	16
9/5/2008	29-40-12	94-56-17	1.3	29.5	22.1	7.9	25
9/25/2008	29-04-15	95-11-29	1.8-0.7	27.3	26.3	7.4	14
9/25/2008	29-03-22	95-12-35	1.5-0.1	27.7	26.7	7.3	14
10/4/2008	29-02-55	95-09-56	0.4	26.0	36.0	-	13.5 cm
10/15/2008	29-03-30	95-10-30	1.4	26.7	26.0	6.7	8
10/15/2008	29-05-35	95-08-44	0.1	-	-	-	-
10/21/2008	29-31-33	94-46-09	0.3-1.0	22.0	14.9	7.4	167
10/21/2008	29-32-17	94-42-01	0.2-1.3	22.0	19.2	7.1	252
5/19/2009	29-02-55	95-09-53	0.4	22.1	26.2	*15.5	12
5/19/2009	29-28-56	94-36-14	0.3	24.1	13.1	*20.5	6
5/19/2009	29-22-19	94-46-39	0.4	27.5	19.6	*15.0	15
5/19/2009	29-37-32	94-42-23	0.3	24.3	1.4	*23.5	64
5/19/2009	29-15-19	94-55-05	0.4	24.0	16.5	*23.4	14

Appendix 3. Chlorophyll-α and pheophytin-α values taken at select sites associated with phytoplankton/SPM samples in the GBEE.

Date	Latitude	Longitude	Filtered water (mL)	Chlorophyll a (mg/m^3)	Pheophytin a (mg/m^3)
7/16/2008	29-39-45	94-47-29	450	6.9301	-1.169
7/16/2008	29-35-30	94-53-30	300	8.9089	0.1620
7/19/2008	29-02-55	95-09-56	250	3.5030	3.8533
8/14/2008	29-29-30	94-36-30	300	10.7601	1.4071
8/14/2008	29-32-30	94-35-30	300	9.5319	0.6355
9/5/2008	29-38-30	95-00-30	250	8.1168	21.0022
9/5/2008	29-37-30	95-56-30	250	17.0453	6.8181
10/4/2008	29-02-55	95-09-56	220	3.0038	5.4068
5/19/2009	29-28-56	94-36-14	600	1.1348	0.1891
5/19/2009	29-37-32	94-42-23	150	3.1150	2.3363
5/19/2009	29-15-19	94-55-05	300	12.3488	23.3803

Appendix 4. Phylogenetic classification of all species collected in the GBEE. http://www.itis.gov.

Phylum/Division	Class	Order	Family	Species	Common name
					Vegetative detritus
					Suspended particulate matter
					Epiphytes
					Benthic algae
					Filamentous algae
Phaeophyta	Phaeophyceae	Fucales	Sargassaceae	*Sargassum fluitans*	Fatleaf sargassum
				Sargassum natans	Narrowleaf sargassum
Magnoliophyta	Liliopsida	Cyperales	Poaceae	*Spartina alterniflora*	Smooth cordgrass
		Najadales	Cymodoceaceae	*Halodule wrightii*	Shoalweed
Ctenophora	Nuda	Beroida	Beroidae	*Beroe ovata*	Comb jelly
Cnidaria	Scyphozoa	Semaeostomeae	Pelagiidae	*Chrysaora quinquecirrha*	Sea nettle
			Ulmaridae	*Aurelia aurita*	Moon jelly
		Rhizostomeae	Rhizostomatidae	*Stomolophus meleagris*	Cannonball jelly
Arthropoda	Malacostraca	Isopoda	Cymothoidae	*Cymothoa exigua*	Tongue-eating isopod
		Decapoda	Menippidae	*Menippe adina*	Gulf stone crab
			Palaemonidae	*Palaemonetes* spp.	Grass shrimp
				Macrobrachium ohione	Ohio River shrimp
			Panopeidae	*Rhithropanopeus harrisii*	Mud crab
			Penaeidae	*Farfantepenaeus aztecus*	Brown shrimp
				Litopenaeus setiferus	White shrimp
			Portunidae	*Callinectes sapidus*	Blue crab
				Callinectes similis	Lesser blue crab
Mollusca	Bivalvia	Veneroida	Mactridae	*Rangia cuneata*	Common rangia
		Ostreoida	Ostreidae	*Crassostrea virginica*	Eastern oyster
	Cephalopoda	Teuthida	Loliginidae	*Lolliguncula brevis*	Atlantic brief squid
Chordata	Eslamobranchii	Carcharhiniformes	Carcharhinidae	*Carcharhinus leucas*	Bull shark
				Carcharhinus limbatus	Blacktip shark
				Rhizoprionodon terraenovae	Atlantic sharpnose shark
		Rajiformes	Dasyatidae	*Dasyatis sabina*	Atlantic stingray
	Actinopterygii	Lepisosteiformes	Lepisosteidae	*Atractosteus spatula*	Alligator gar
				Lepisosteus oculatus	Spotted gar
		Clupeiformes	Clupeidae	*Brevoortia patronus*	Gulf menhaden
				Dorosoma cepedianum	Gizzard shad
			Engraulidae	*Anchoa mitchilli*	Bay anchovy
		Siluriformes	Ictaluridae	*Ictalurus furcatus*	Blue catfish
			Ariidae	*Ariopsis felis*	Hardhead catfish
				Bagre marinus	Gafftopsail catfish
		Mugiliformes	Mugilidae	*Mugil cephalus*	Striped mullet
				Mugil curema	White mullet
		Atheriniformes	Fundulidae	*Fundulus grandis*	Gulf killifish
				Fundulus similis	Longnose killifish
			Cyprinpodontidae	*Cyprinodon variegatus*	Sheepshead minnow
			Atherinidae	*Menidia beryllina*	Inland silverside
		Perciformes	Sparidae	*Archosargus probatocephalus*	Sheepshead
				Lagodon rhomboides	Pinfish
			Sciaenidae	*Cynoscion arenarius*	Sand seatrout
				Cynoscion nebulosus	Spotted seatrout
				Leiostomus xanthurus	Spot
				Micropogonias undulatus	Atlantic croaker
				Pogonias cromis	Black drum
				Sciaenops ocellatus	Red drum
			Scombridae	*Scomberomorus maculatus*	Spanish mackerel
		Pleuronectiformes	Bothidae	*Paralichthys lethostigma*	Southern flounder
	Reptilia	Testudines	Emydidae	*Malaclemys terrapin*	Diamondback terrapin

Appendix 5. Sample type, common name, species code, total length (TL) in mm, sample number (n), mean $\delta^{13}C$ and $\delta^{15}N$ values ± standard error (SE), and trophic position (TP) based on the mean $\delta^{15}N$ value of fauna collected from Christmas Bay.

Sample Type	Common name	Code	TL	n	$\delta^{13}C$	$\delta^{15}N$	TP
Vegetation	Vegetative detritus	D		3	-17.65 ± 0.71	2.99 ± 0.64	0.61
	Suspended particulate matter	SPM		3	-22.26 ± 1.00	11.81 ± 2.63	3.28
	Epiphytes	E		3	-16.78 ± 0.07	2.94 ± 0.36	0.59
	Benthic algae	B		3	-11.97 ± 0.67	0.31 ± 0.20	-0.20
	Smooth cordgrass	Sa		3	-12.98 ± 0.11	2.12 ± 0.18	0.34
	Shoalweed	Hw		3	-13.82 ± 0.41	5.54 ± 0.11	1.38
Invertebrates	Gulf stone crab	Ma	91	1	-15.71 ± 0.00	13.58 ± 0.00	3.82
	Grass shrimp	Ps	10 - 28	2	-16.49 ± 0.07	8.93 ± 0.29	2.41
	Brown shrimp (≤ 75)	Fas	50 - 66	3	-15.00 ± 0.30	7.54 ± 0.19	1.99
	White shrimp (≤ 75)	Lss	24 - 57	3	-16.42 ± 0.64	7.43 ± 0.58	1.95
	Blue crab (≤ 109)	Csas	34 - 78	3	-14.53 ± 0.25	7.75 ± 0.25	2.05
	Blue crab (> 109)	Csal	149 - 163	3	-15.02 ± 0.22	11.10 ± 0.80	3.07
	Eastern oyster	Cvi	52 - 60	3	-19.90 ± 0.44	7.85 ± 0.09	2.08
	Atlantic brief squid	Lb	64	1	-17.93 ± 0.00	14.57 ± 0.00	4.12
Vertebrates	Atlantic stingray	Ds	131 - 425	2	-15.86 ± 1.05	12.90 ± 2.31	3.61
	Gulf menhaden (≤ 152)	Bps	83 - 87	3	-18.16 ± 0.14	13.15 ± 0.13	3.69
	Gulf menhaden (> 152)	Bpl	243	1	-21.14 ± 0.00	15.33 ± 0.00	4.35
	Bay anchovy	Am	17 - 32	3	-17.01 ± 1.40	11.95 ± 1.60	3.32
	Hardhead catfish (> 155)	Afl	222 - 314	3	-17.60 ± 0.13	14.59 ± 0.25	4.12
	Gafftopsail catfish (≤ 339)	Bms	207 - 227	3	-17.95 ± 0.55	14.99 ± 0.17	4.25
	Gafftopsail catfish (> 339)	Bml	510 - 562	3	-16.60 ± 0.14	16.34 ± 0.07	4.65
	Striped mullet (≤ 233)	Mces	68	1	-13.58 ± 0.00	4.97 ± 0.00	1.21
	Striped mullet (> 233)	Mcel	323	1	-14.63 ± 0.00	11.43 ± 0.00	3.17
	White mullet (≤ 233)	Mcus	85 - 98	3	-12.68 ± 0.53	6.07 ± 0.40	1.54
	Longnose killifish	Fs	84 - 94	2	-13.36 ± 0.45	8.68 ± 0.17	2.33
	Sheepshead minnow	Cva	24 - 44	3	-12.21 ± 0.23	4.23 ± 0.37	0.98
	Inland silverside	Mb	48 - 54	2	-16.83 ± 0.26	11.69 ± 0.24	3.24
	Pinfish	Lr	73 - 133	3	-15.90 ± 0.30	12.06 ± 1.24	3.36
	Sand seatrout (≥ 199)	Cal	335	1	-17.03 ± 0.00	17.35 ± 0.00	4.96
	Spotted seatrout (≤ 216)	Cns	60 - 214	3	-15.72 ± 0.77	11.90 ± 1.69	3.31
	Spotted seatrout (217-380)	Cnm	240 - 351	3	-16.96 ± 0.08	15.83 ± 0.33	4.50
	Spotted seatrout (≥ 381)	Cnl	498 - 535	3	-17.12 ± 0.46	16.32 ± 0.25	4.65
	Spot croaker (≤ 136)	Lxs	51 - 58	3	-13.42 ± 0.46	8.81 ± 0.68	2.37
	Spot croaker (> 136)	Lxl	185 - 201	2	-17.28 ± 0.40	14.56 ± 0.40	4.11
	Atlantic croaker (≤ 136)	Mus	120 - 133	3	-18.01 ± 0.16	14.82 ± 0.22	4.19
	Atlantic croaker (137-226)	Mum	212 - 222	3	-17.88 ± 0.33	15.02 ± 0.34	4.25
	Atlantic croaker (≥ 227)	Mul	231 - 244	3	-17.93 ± 0.57	15.23 ± 0.19	4.32
	Black drum (≤ 198)	Pcs	62 - 66	2	-13.55 ± 0.06	8.39 ± 0.33	2.24
	Black drum (199-318)	Pcm	215 - 312	3	-19.26 ± 1.07	13.90 ± 1.09	3.91
	Black drum (≥ 319)	Pcl	319 - 382	3	-16.77 ± 0.44	14.33 ± 0.44	4.04
	Total			102			

Appendix 6. Sample type, common name, species code, total length (TL) in mm, sample number (n), mean $\delta^{13}C$ and $\delta^{15}N$ values ± standard error (SE), and trophic position (TP) based on the mean $\delta^{15}N$ value of fauna collected from East Bay.

Sample Type	Common name	Code	TL	n	$\delta^{13}C$	$\delta^{15}N$	TP
Vegetation	Vegetative detritus	D		3	-15.94 ± 0.90	2.35 ± 0.57	-0.17
	Suspended particulate matter	SPM		3	-24.06 ± 0.51	10.08 ± 2.62	2.17
	Epiphytes	E		3	-18.55 ± 0.40	5.41 ± 1.04	0.67
	Benthic algae	B		3	-9.69 ± 0.88	8.23 ± 0.37	1.61
	Fatleaf sargassum	Sf		1	-17.89 ± 0.00	6.02 ± 0.00	0.94
	Smooth cordgrass	Sa		3	-13.15 ± 0.15	5.34 ± 0.70	0.74
Invertebrates	Sea nettle	Cq		3	-19.36 ± 0.30	17.39 ± 0.57	4.39
	Cannonball jelly	Sme	90	1	-19.36 ± 0.00	15.93 ± 0.00	3.94
	Grass shrimp	Ps	30 - 39	3	-17.73 ± 0.24	10.55 ± 0.39	2.31
	Mud crab	Rh	23	1	-21.03 ± 0.00	14.34 ± 0.00	3.46
	Brown shrimp (≤ 75)	Fas	58 - 74	2	-21.28 ± 1.10	11.32 ± 1.58	2.54
	Brown shrimp (> 75)	Fal	78 - 80	2	-20.10 ± 0.54	11.36 ± 1.02	2.56
	White shrimp (≤ 75)	Lss	44 - 70	4	-18.67 ± 0.93	11.97 ± 1.55	2.74
	White shrimp (> 75)	Lsl	115 - 172	2	-20.33 ± 1.07	14.60 ± 1.86	3.54
	Blue crab (≤ 109)	Csas	20 - 85	3	-18.67 ± 1.70	11.51 ± 2.41	2.60
	Blue crab (> 109)	Csal	115 - 139	3	-17.47 ± 0.65	10.56 ± 1.32	2.32
	Common rangia	Rc	51	1	-23.56 ± 0.00	12.57 ± 0.00	2.92
	Eastern oyster	Cvi	53 - 72	3	-21.65 ± 0.09	10.84 ± 0.18	2.40
	Atlantic brief squid	Lb	43	1	-19.98 ± 0.00	16.66 ± 0.00	4.16
Vertebrates	Bull shark	Cle	740	1	-11.99 ± 0.00	13.31 ± 0.00	3.15
	Atlantic stingray	Ds	160	1	-18.91 ± 0.00	15.12 ± 0.00	3.70
	Alligator gar	As	716 - 1008	4	-19.71 ± 0.41	13.60 ± 1.90	3.24
	Gulf menhaden (≤ 152)	Bps	45	1	-20.64 ± 0.00	11.12 ± 0.00	2.49
	Gulf menhaden (> 152)	Bpl	226 - 255	3	-21.10 ± 0.51	14.53 ± 0.40	3.52
	Gizzard shad	Dc	281 - 375	4	-20.04 ± 0.30	14.67 ± 0.49	3.56
	Bay anchovy	Am	41 - 69	3	-21.17 ± 0.27	17.47 ± 1.69	4.41
	Hardhead catfish (> 155)	Afl	230 - 285	3	-19.67 ± 0.36	15.58 ± 0.61	3.84
	Gafftopsail catfish (≤ 339)	Bms	226 - 319	3	-19.59 ± 0.80	16.01 ± 0.54	3.97
	Gafftopsail catfish (> 339)	Bml	360 - 567	3	-19.05 ± 0.57	16.67 ± 0.69	4.17
	Striped mullet (≤ 233)	Mces	149 - 199	3	-16.87 ± 0.50	10.51 ± 0.42	2.30
	Striped mullet (> 233)	Mcel	234 - 448	3	-18.95 ± 0.76	13.18 ± 2.50	3.11
	Sheepshead minnow	Cva	53	1	-17.42 ± 0.00	5.33 ± 0.00	0.73
	Pinfish	Lr	105 - 109	3	-19.20 ± 0.80	11.40 ± 0.81	2.57
	Sand seatrout (≤ 99)	Cas	52 - 61	3	-19.71 ± 0.08	13.72 ± 0.23	3.27
	Sand seatrout (100-198)	Cam	162 - 175	3	-20.14 ± 0.35	16.10 ± 0.14	4.00
	Sand seatrout (≥ 199)	Cal	274	1	-20.57 ± 0.00	18.47 ± 0.00	4.71
	Spotted seatrout (≥ 381)	Cnl	420 - 598	4	-19.86 ± 0.37	17.18 ± 1.04	4.32
	Spot croaker (≤ 136)	Lxs	86 - 100	3	-18.82 ± 0.53	14.18 ± 0.32	3.41
	Spot croaker (> 136)	Lxl	220 - 236	3	-23.78 ± 0.68	18.21 ± 0.51	4.63
	Atlantic croaker (≤ 136)	Mus	78 - 128	3	-18.06 ± 0.71	13.75 ± 0.25	3.28
	Atlantic croaker (137-226)	Mum	142 - 200	3	-21.11 ± 1.28	15.34 ± 2.73	3.77
	Atlantic croaker (≥ 227)	Mul	246 - 294	3	-20.44 ± 1.11	15.08 ± 0.54	3.68
	Black drum (≤ 198)	Pcs	64 - 110	3	-14.65 ± 1.98	10.54 ± 0.41	2.31
	Black drum (199-318)	Pcm	241	1	-20.48 ± 0.00	13.21 ± 0.00	3.12
	Black drum (≥ 319)	Pcl	372 - 410	2	-20.96 ± 0.06	16.05 ± 0.38	3.98
	Red drum (277-518)	Som	401 - 515	4	-20.54 ± 0.23	14.87 ± 0.36	3.62
	Red drum (≥ 519)	Sol	522 - 573	2	-19.58 ± 0.14	15.84 ± 0.38	3.91
	Spanish mackerel	Sma	555	1	-17.99 ± 0.00	17.17 ± 0.00	4.32
	Southern flounder	Pl	359	1	-18.84 ± 0.00	15.19 ± 0.00	3.72
	Total			121			

Appendix 7. Sample type, common name, species code, total length (TL) in mm, sample number (n), mean $\delta^{13}C$ and $\delta^{15}N$ values ± standard error (SE), and trophic position (TP) based on the mean $\delta^{15}N$ value of fauna collected from Galveston Bay.

Sample type	Common name	Code	TL	n	$\delta^{13}C$	$\delta^{15}N$	TP
Vegetation	Vegetative detritus	D		3	-16.02 ± 2.60	7.85 ± 0.33	-0.15
	Suspended particulate matter	SPM		4	-24.60 ± 0.45	14.87 ± 0.59	1.97
	Epiphytes	E		3	-15.81 ± 1.29	8.20 ± 0.45	-0.05
	Filamentous algae	F		3	-17.58 ± 0.32	14.77 ± 0.25	1.94
	Fatleaf sargassum	Sf		1	-15.63 ± 0.00	9.70 ± 0.00	0.41
	Smooth cordgrass	Sa		3	-12.87 ± 0.14	12.18 ± 0.34	1.16
Invertebrates	Sea nettle	Cq		1	-17.92 ± 0.00	20.00 ± 0.00	3.53
	Cannonball jelly	Sme		1	-21.10 ± 0.00	18.04 ± 0.00	2.93
	Tongue-eating isopod	Ce	10 - 15	1	-20.25 ± 0.00	20.20 ± 0.00	3.59
	Brown shrimp (≤ 75)	Fas	42 - 64	3	-20.46 ± 0.42	17.61 ± 0.65	2.80
	Brown shrimp (> 75)	Fal	83 - 108	4	-19.89 ± 0.97	18.44 ± 0.70	3.06
	White shrimp (≤ 75)	Lss	28 - 62	3	-18.99 ± 0.27	17.59 ± 0.19	2.80
	White shrimp (> 75)	Lsl	118 - 150	3	-20.13 ± 0.17	16.93 ± 0.40	2.60
	Blue crab (≤ 109)	Csas	27 - 90	3	-19.68 ± 0.35	17.11 ± 0.40	2.65
	Blue crab (> 109)	Csal	157 - 180	3	-21.58 ± 0.52	17.53 ± 0.74	2.78
	Lesser blue crab	Csi	27 - 29	3	-19.36 ± 0.02	17.22 ± 0.25	2.69
	Common rangia	Rc	51 - 55	2	-22.70 ± 0.10	17.12 ± 0.01	2.65
	Eastern oyster	Cvi	75 - 140	3	-24.28 ± 0.28	16.03 ± 0.09	2.32
	Atlantic brief squid	Lb	55 - 78	2	-18.55 ± 0.73	17.91 ± 0.70	2.89
Vertebrates	Bull shark	Cle	755	1	-18.55 ± 0.00	19.85 ± 0.00	3.48
	Atlantic stingray	Ds	400	1	-19.91 ± 0.00	18.21 ± 0.00	2.99
	Gulf menhaden (≤ 152)	Bps	30 - 37	3	-20.66 ± 0.06	13.63 ± 0.31	1.60
	Gulf menhaden (> 152)	Bpl	153 -255	3	-20.27 ± 0.45	14.65 ± 0.16	1.91
	Gizzard shad	Dc	360 - 401	3	-20.30 ± 0.49	17.11 ± 0.57	2.65
	Bay anchovy	Am	55 - 58	3	-20.77 ± 0.06	18.49 ± 0.09	3.07
	Hardhead catfish (≤ 155)	Afs	48 - 58	3	-17.56 ± 0.55	18.00 ± 0.48	2.92
	Hardhead catfish (> 155)	Afl	186 - 412	4	-19.39 ± 0.57	18.73 ± 0.69	3.14
	Gafftopsail catfish (≤ 339)	Bms	109 - 125	3	-18.67 ± 0.21	18.91 ± 0.25	3.20
	Gafftopsail catfish (> 339)	Bml	403 - 521	2	-19.08 ± 0.29	18.92 ± 0.72	3.20
	Striped mullet (≤ 233)	Mces	106 - 204	3	-20.13 ± 1.65	7.80 ± 0.52	-0.17
	Striped mullet (> 233)	Mcel	324 - 334	3	-20.05 ± 0.55	18.29 ± 0.78	3.01
	White mullet (≤ 233)	Mcus	72 - 92	2	-16.27 ± 1.21	17.53 ± 0.41	2.78
	Gulf killifish	Fg	89	1	-16.70 ± 0.00	16.13 ± 0.00	2.35
	Longnose killifish	Fs	59 - 60	2	-18.15 ± 0.29	18.20 ± 1.12	2.98
	Sheepshead minnow	Cva	35 - 41	3	-20.07 ± 0.83	13.57 ± 0.95	1.58
	Pinfish	Lr	120	1	-18.34 ± 0.00	13.56 ± 0.00	1.58
	Sand seatrout (≤ 99)	Cas	71 - 87	4	-19.04 ± 0.58	17.57 ± 0.58	2.79
	Sand seatrout (100-198)	Cam	118 - 181	3	-19.63 ± 1.25	19.45 ± 2.00	3.36
	Sand seatrout (≥ 199)	Cal	240 - 251	2	-18.55 ± 0.13	16.63 ± 0.53	2.51
	Spotted seatrout (≤ 216)	Cns	66	1	-18.41 ± 0.00	19.45 ± 0.00	3.36
	Spotted seatrout (≥ 381)	Cnl	425 - 562	3	-23.19 ± 0.44	19.12 ± 0.23	3.26
	Spot croaker (≤ 136)	Lxs	114 - 124	3	-20.51 ± 0.83	18.57 ± 1.18	3.09
	Atlantic croaker (≤ 136)	Mus	92 - 125	4	-20.73 ± 0.56	19.45 ± 0.43	3.36
	Atlantic croaker (137-226)	Mum	137 - 178	3	-20.70 ± 0.60	20.64 ± 0.49	3.72
	Atlantic croaker (≥ 227)	Mul	250 - 286	3	-21.98 ± 0.33	19.27 ± 0.53	3.31
	Black drum (≥ 319)	Pcl	359 - 490	3	-20.38 ± 0.20	17.52 ± 0.43	2.78
	Red drum (277-518)	Som	416 - 499	3	-19.92 ± 0.75	18.91 ± 0.88	3.20
	Red drum (≥ 519)	Sol	609	1	-19.38 ± 0.00	17.80 ± 0.00	2.86
Total				123			

Appendix 8. Sample type, common name, species code, total length (TL) in mm, sample number (n), mean $\delta^{13}C$ and $\delta^{15}N$ values ± standard error (SE), and trophic position (TP) based on the mean $\delta^{15}N$ value of fauna collected from Trinity Bay.

Sample Type	Common name	Code	TL	n	$\delta^{13}C$	$\delta^{15}N$	TP
Vegetation	Vegetative detritus	D		3	-17.49 ± 0.16	6.72 ± 0.24	1.25
	Suspended particulate matter	SPM		3	-24.97 ± 0.76	7.59 ± 2.72	1.51
	Epiphytes	E		1	-19.56 ± 0.00	11.35 ± 0.00	2.65
	Benthic algae	B		3	-11.92 ± 0.52	-0.31 ± 0.14	-0.88
	Smooth cordgrass	Sa		3	-18.27 ± 2.96	7.79 ± 0.21	1.57
Invertebrates	Comb jelly	Bo		3	-21.68 ± 0.26	17.23 ± 0.20	4.43
	Tongue-eating isopod	Ce	15	1	-21.50 ± 0.00	17.27 ± 0.00	4.44
	Grass shrimp	Ps	31 - 38	4	-19.29 ± 0.72	11.89 ± 0.78	2.82
	Ohio river shrimp	Mo	90	1	-28.19 ± 0.00	16.65 ± 0.00	4.26
	Mud crab	Rh	16 - 25	3	-22.97 ± 0.11	16.40 ± 0.13	4.18
	Brown shrimp (≤ 75)	Fas	36 - 55	4	-19.32 ± 0.36	13.59 ± 0.85	3.33
	Brown shrimp (> 75)	Fal	78 - 92	3	-20.53 ± 0.23	16.53 ± 0.91	4.22
	White shrimp (≤ 75)	Lss	42 - 59	3	-20.99 ± 0.23	14.92 ± 0.20	3.73
	White shrimp (> 75)	Lsl	99 -107	3	-21.04 ± 0.70	16.65 ± 0.41	4.26
	Blue crab (≤ 109)	Csas	20 - 40	3	-21.51 ± 0.90	14.48 ± 0.32	3.60
	Blue crab (> 109)	Csal	138 - 175	3	-22.09 ± 2.31	17.04 ± 1.17	4.38
	Common rangia	Rc	45 - 56	3	-23.26 ± 0.12	16.46 ± 0.13	4.20
	Eastern oyster	Cvi	40 - 46	1	-24.73 ± 0.00	15.87 ± 0.00	4.02
Vertebrates	Spotted gar	Lo	581	1	-25.84 ± 0.00	17.92 ± 0.00	4.64
	Gulf menhaden (≤ 152)	Bps	33 - 47	3	-23.38 ± 0.57	14.89 ± 0.27	3.72
	Gulf menhaden (> 152)	Bpl	270	1	-21.31 ± 0.00	16.21 ± 0.00	4.12
	Gizzard shad	Dc	305 - 381	2	-21.98 ± 0.05	19.20 ± 1.61	5.03
	Bay anchovy	Am	60 - 69	3	-23.50 ± 1.63	16.19 ± 0.36	4.12
	Blue catfish	If	367 - 484	3	-23.62 ± 0.36	17.08 ± 0.47	4.39
	Hardhead catfish (> 155)	Afl	175 - 359	3	-21.42 ± 0.42	18.08 ± 0.20	4.69
	Gafftopsail catfish (≤ 339)	Bms	95 - 98	3	-19.09 ± 0.75	18.69 ± 0.86	4.88
	Gafftopsail catfish (> 339)	Bml	468 - 570	2	-17.48 ± 1.38	17.29 ± 2.05	4.45
	Striped mullet (≤ 233)	Mces	67 - 111	3	-19.50 ± 0.98	12.54 ± 1.24	3.01
	Striped mullet (> 233)	Mcel	302 - 417	3	-20.62 ± 0.26	16.63 ± 0.67	4.25
	White mullet (≤ 233)	Mcus	91 - 111	3	-17.21 ± 0.43	13.08 ± 0.26	3.18
	Pinfish	Lr	77 - 120	3	-19.86 ± 1.42	14.92 ± 0.31	3.73
	Sand seatrout (≤ 99)	Cas	92	1	-20.34 ± 0.00	18.04 ± 0.00	4.68
	Spotted seatrout (217-380)	Cnm	327	1	-22.60 ± 0.00	19.93 ± 0.00	5.25
	Spotted seatrout (≥ 381)	Cnl	419 - 501	3	-21.84 ± 0.69	18.96 ± 0.63	4.96
	Spot croaker (≤ 136)	Lxs	98 - 113	3	-21.69 ± 0.14	18.25 ± 1.42	4.74
	Atlantic croaker (≤ 136)	Mus	69 - 90	4	-19.80 ± 0.20	16.13 ± 0.56	4.10
	Atlantic croaker (137-226)	Mum	171 - 197	3	-22.75 ± 0.11	18.88 ± 0.35	4.93
	Atlantic croaker (≥ 227)	Mul	276 - 344	3	-23.30 ± 0.94	18.15 ± 1.00	4.71
	Black drum (≤ 198)	Pcs	81 - 105	2	-18.99 ± 0.07	15.53 ± 1.10	3.92
	Black drum (199-318)	Pcm	285	1	-21.97 ± 0.00	17.69 ± 0.00	4.57
	Black drum (≥ 319)	Pcl	396 - 452	3	-22.40 ± 0.50	17.75 ± 0.25	4.59
	Red drum (277-518)	Som	387 - 500	2	-23.37 ± 1.29	18.19 ± 0.51	4.72
	Red drum (≥ 519)	Sol	536 - 614	3	-23.04 ± 0.62	16.80 ± 0.59	4.30
Total				110			

Appendix 9. Sample type, common name, species code, total length (TL) in mm, sample number (n), mean $\delta^{13}C$ and $\delta^{15}N$ values ± standard error (SE), and trophic position (TP) based on the mean $\delta^{15}N$ value of fauna collected from West Bay.

Sample Type	Common name	Code	TL	n	$\delta^{13}C$	$\delta^{15}N$	TP
Vegetation	Vegetative detritus	D		3	-15.29 ± 0.39	3.93 ± 0.26	0.37
	Suspended particulate matter	SPM		3	-22.01 ± 0.18	6.53 ± 0.21	1.16
	Epiphytes	E		3	-17.14 ± 0.51	4.36 ± 0.17	0.50
	Benthic algae	B		3	-12.19 ± 0.95	4.44 ± 0.87	0.52
	Fatleaf sargassum	Sf		3	-15.37 ± 0.31	7.81 ± 0.55	1.55
	Narrowleaf sargassum	Sn		3	-16.10 ± 0.70	8.21 ± 0.32	1.67
	Smooth cordgrass	Sa		3	-13.42 ± 0.28	6.76 ± 0.36	1.23
Invertebrates	Moon jelly	Aa		1	-17.03 ± 0.00	12.43 ± 0.00	2.95
	Tongue eating isopod	Ce	10 -18	1	-19.93 ± 0.00	14.38 ± 0.00	3.54
	Gulf stone crab	Ma	24 - 96	3	-18.46 ± 0.57	12.99 ± 1.14	3.12
	Grass shrimp	Ps	28 - 39	3	-16.21 ± 0.08	7.15 ± 0.26	1.35
	Brown shrimp (≤ 75)	Fas	50 - 57	3	-14.31 ± 0.07	8.68 ± 0.17	1.81
	White shrimp (≤ 75)	Lss	35 - 58	3	-16.92 ± 1.80	8.89 ± 2.49	1.87
	Blue crab (≤ 109)	Csas	30 - 38	3	-17.18 ± 0.56	10.34 ± 2.12	2.31
	Blue crab (> 109)	Csal	141 - 162	4	-18.55 ± 1.07	10.94 ± 0.36	2.50
	Lesser blue crab	Csi	25 - 30	2	-16.00 ± 0.38	9.48 ± 0.78	2.05
	Atlantic brief squid	Lb	32 - 41	3	-17.96 ± 0.10	15.44 ± 0.17	3.86
Vertebrates	Blacktip shark	Cli	580 - 590	2	-15.30 ± 0.41	15.62 ± 0.67	3.91
	Atlantic sharpnose shark	Rt	593	1	-16.21 ± 0.00	16.07 ± 0.00	4.05
	Atlantic stingray	Ds	115 - 124	2	-18.57 ± 0.35	14.83 ± 0.17	3.67
	Gulf menhaden (≤ 152)	Bps	57 - 73	3	-19.42 ± 0.07	11.64 ± 0.35	2.71
	Gulf menhaden (> 152)	Bpl	230 - 275	3	-19.80 ± 0.23	13.73 ± 0.05	3.34
	Bay anchovy	Am	44 - 50	3	-19.09 ± 0.06	13.38 ± 0.10	3.23
	Hardhead catfish (> 155)	Afl	209 - 417	4	-17.78 ± 0.32	15.19 ± 0.50	3.78
	Gafftopsail catfish (> 339)	Bml	530 - 572	1	-16.94 ± 0.00	16.76 ± 0.00	4.26
	Striped mullet (≤ 233)	Mces	101 - 138	2	-14.41 ± 1.04	14.02 ± 1.01	3.43
	Striped mullet (> 233)	Mcel	362 - 437	3	-15.24 ± 0.56	12.72 ± 1.98	3.03
	White mullet (≤ 233)	Mcus	84 - 106	2	-13.13 ± 0.43	14.27 ± 0.03	3.50
	Longnose killifish	Fs	35	1	-15.05 ± 0.00	9.51 ± 0.00	2.06
	Sheepshead minnow	Cva	34 - 43	2	-13.39 ± 0.69	4.43 ± 0.64	0.52
	Inland silverside	Mb	53 - 56	3	-18.22 ± 0.253	12.31 ± 0.20	2.91
	Sheepshead	Ap	362 - 385	3	-19.47 ± 0.88	14.11 ± 0.53	3.45
	Pinfish	Lr	53 - 65	3	-15.99 ± 0.22	9.86 ± 0.19	2.17
	Sand seatrout (≤ 99)	Cas	88 - 98	3	-17.83 ± 0.07	15.59 ± 0.09	3.90
	Sand seatrout (100-198)	Cam	156 - 182	3	-18.79 ± 0.64	15.85 ± 0.30	3.98
	Sand seatrout (≥ 199)	Cal	249 - 273	3	-18.96 ± 0.64	17.49 ± 0.51	4.48
	Spotted seatrout (≤ 216)	Cns	55 - 112	3	-16.36 ± 0.82	12.83 ± 1.50	3.07
	Spotted seatrout (217-380)	Cnm	344 - 379	3	-17.63 ± 0.28	15.66 ± 0.31	3.93
	Spotted seatrout (≥ 381)	Cnl	556 - 588	3	-17.77 ± 0.36	15.95 ± 0.37	4.01
	Spot croaker (≤ 136)	Lxs	54 - 61	3	-13.63 ± 1.30	8.46 ± 0.84	1.74
	Spot croaker (> 136)	Lxl	216 - 237	3	-18.96 ± 0.26	14.14 ± 0.03	3.46
	Atlantic croaker (≤ 136)	Mus	110 - 120	3	-17.40 ± 0.07	14.74 ± 0.08	3.65
	Atlantic croaker (137-226)	Mum	158 - 191	3	-18.14 ± 0.13	15.49 ± 0.37	3.87
	Atlantic croaker (≥ 227)	Mul	249 - 268	3	-18.58 ± 0.60	12.75 ± 0.33	3.04
	Black drum (≤ 198)	Pcs	92 - 105	3	-15.86 ± 0.29	9.84 ± 0.07	2.16
	Black drum (199-318)	Pcm	226 - 305	2	-17.31 ± 0.63	13.42 ± 1.03	3.25
	Black drum (≥ 319)	Pcl	321 - 371	3	-16.54 ± 0.31	12.22 ± 1.13	2.88
	Red drum (≤ 276)	Sos	57	1	-14.01 ± 0.00	10.56 ± 0.00	2.38
	Red drum (277-518)	Som	422 - 511	2	-16.59 ± 0.13	12.80 ± 1.35	3.06
	Red drum (≥ 519)	Sol	525 - 614	4	-16.30 ± 0.34	13.93 ± 0.51	3.40
	Southern flounder	Pl	354 - 428	3	-16.45 ± 0.28	10.61 ± 0.33	2.40
	Diamondback terrapin	Mt		1	-18.90 ± 0.00	16.99 ± 0.00	4.33
Total				137			

Appendix 10. Reference ratios from $\delta^{13}C$ stable isotope analysis for autotrophs.

Species	Source: Cifuentes et al. 1996 (Ecuador estuaries)	Deegan & Garritt 1997 (Plum Is. Sound, MA)	Hyndes & Lavery 2005 (SW Australia)	Kang et al. 2003 (S. Korean bays)	Moncreiff & Sullivan 2001 (Horn Is. MS)
	$\delta^{13}C$	$\delta^{13}C$	$\delta^{13}C$	$\delta^{13}C$	$\delta^{13}C$
Phytoplankton/SPM	-21.5 - -25.7		-12.8 ± 3.2*	-20.8 ± 1.1	-21.8 ± 0.7
Epiphytic algae					-17.5 ± 1.7
Benthic algae			-14.0 ± 0.0	-14.1 ± 0.4	
S. natans			-15.8 - -16.0		-16.8
S. fluitans			-15.8 - -16.0		-16.6
S. alterniflora		-12.9 - -14.8			
H. wrightii					-12.2 ± 1.2

Appendix 10. cont.

Species	Source: Peterson & Howarth 1987 (Sapelo Is. GA)	Peterson et. al 1985 (Sippewissett marsh, MA)	Riera & Richard 1997 (Mar.-Olér. Bay, France)	Rooker et al. 2006 (NW GOM)	Winemiller et al. 2007 (Matagorda Bay, TX)
	$\delta^{13}C$	$\delta^{13}C$	$\delta^{13}C$	$\delta^{13}C$	$\delta^{13}C$
Vegetative detritus					-14.40 ± 0.9
Phytoplankton/SPM	-21.3 ± 1.1	-21.3 ± 1.1			-20.00 ± 2.8
Filamentous algae					-18.70 ± 0.3
Benthic algae	-16.7		-16.1 ± 0.7		
S. natans				-16 to -17	
S. fluitans				-16 to -17	
S. alterniflora	-12.90 ± 0.5	-13.10 ± 0.8			-12.80 ± 0.1
Upland C^3 plants	-29.3 ± 1.4				

Appendix 11. Reference ratios from $\delta^{15}N$ stable isotope analysis for autotrophs, * = S.E.

	Source			
Species	Cifuentes et al. 1996 (Ecuador estuaries)	Deegan & Garritt 1997 (Plum Is. Sound, MA)	Hyndes & Lavery 2005 (SW Australia)	Kang et al. 2003 (S. Korean bays)
	$\delta^{15}N$	$\delta^{15}N$	$\delta^{15}N$	$\delta^{15}N$
Phytoplankton/SPM	5.5 - 6.2		4.9 ± 1.1*	11.4 ± 0.9
Benthic diatoms/algae			6.0 ± 0.00	11.0 ± 0.9
S. natans			5.7	
S. fluitans			5.7	
S. alterniflora		4.0 - 6.4		

Appendix 11. cont.

	Source			
Species	Moncreiff & Sullivan 2001 (Horn Is. MS)	Peterson & Howarth 1987 (Sapelo Is. Marshes, GA)	Peterson et. al 1985 (Sippewissett marsh, MA)	Winemiller et. al 2007 (Matagorda Bay, TX)
	$\delta^{15}N$	$\delta^{15}N$	$\delta^{15}N$	$\delta^{15}N$
Vegetative detritus				5.30 ± 0.4
Phytoplankton/SPM	9.9 ± 0.9		8.6 ± 1.0	3.50 ± 0.7
Epiphytic algae	5.9 ± 0.9			
Filamentous algae				6.30 ± 0.1
S. natans	4.7			
S. fluitans	4.5			
S. alterniflora		6.00 ± 2.1	3.8 ± 2.6	6.50 ± 4.1
H. wrightii	6.0 ± 1.1			
Upland C^3 plants		0.4 ± 0.9	-0.6 ± 1.2	

Appendix 12. Reference ratios from $\delta^{13}C$ stable isotope analysis for invertebrate consumers.

Species	Source: Bucci et al. 2007 (N. Carolina estuaries)	Deegan & Garritt 1997 (Plum Is. Sound, MA)	Fry 2008 (Galveston Bay)	Macko et al. 1984 (NW Gulf of Mexico)
	$\delta^{13}C$	$\delta^{13}C$	$\delta^{13}C$	$\delta^{13}C$
Isopods		-16.2		
Brown shrimp			-20.6 ± 1.6	-15.6 ± 1.1
White shrimp				-15.6 ± 1.1
Blue crab	-20.6 to -26.9			
Common rangia	-27.2 to -24.7			
Eastern oyster		-23.4		

Appendix 12. cont.

Species	Source: Moncreiff & Sullivan 2001 (Horn Is. MS)	Peterson & Howarth 1987 (Sapelo Is. Marshes, GA)	Winemiller et. al 2007 (Matagorda Bay, TX)
	$\delta^{13}C$	$\delta^{13}C$	$\delta^{13}C$
Moon jelly	-19.5		
Grass shrimp		-16.70 ± 0.64	-15.20 ± 0.3
Brown shrimp	-17.7		-18.40 ± 0.6
White shrimp	-19.6	-17.1	-20.60 ± 0.2
Blue crab	-18.0	-16.20 ± 0.71	-19.30 ± 1.4
Common rangia			
Eastern oyster		-19.80 ± 1.42	-22.76 ± 0.3
Atlantic brief squid	-17.8		

Appendix 13. Reference ratios from $\delta^{15}N$ stable isotope analysis for invertebrate consumers.

	Source						
Species	Bucci et al. 2007 (N. Carolina estuaries)	Deegan & Garritt 1997 (Plum Is. Sound, MA)	Fry 2008 (Galveston Bay)	Macko et al. 1984 (NW Gulf of Mexico)	Moncreiff & Sullivan 2001 (Horn Is. MS)	Peterson & Howarth 1987 (Sapelo Is. Marshes, GA)	Winemiller et al. 2007 (Matagorda Bay, TX)
	$\delta^{15}N$	$\delta^{15}N$	$\delta^{15}N$	$\delta^{15}N$	$\delta^{15}N$	$\delta^{15}N$	$\delta^{15}N$
Moon jelly					15.0		
Isopods		6.8					
Grass shrimp						8.55 ± 0.35	11.90 ± 0.3
Brown shrimp			14.4 ± 1.1	12.9 ± 1.1	11.0		8.00 ± 0.5
White shrimp				12.9 ± 1.1	11.4	9.6	10.10 ± 3.3
Blue crab	8.8 - 12.7				13.1	10.00 ± 0.71	11.10 ± 2.3
Common rangia	7.4 - 10.8						
Eastern oyster		6.5				7.70 ± 1.32	10.20 ± 1.3
Atlantic brief squid					15.7		

Appendix 14. Reference ratios from $\delta^{13}C$ stable isotope analysis for vertebrate consumers.

Species	Source: Holt and Ingall 2000 (Galveston Bay)	Hyndes and Lavery 2005 (SW Australia bays)	Litvin and Weinstein 2003 (Delaware Bay, DE)
	$\delta^{13}C$	$\delta^{13}C$	$\delta^{13}C$
Bay anchovy			-17.1 - -24.6
Striped mullet		-13.8 ± 0.4*	
Spotted seatrout	-17 to -22		

Appendix 14. cont.

Species	Source: Moncreiff & Sullivan 2001 (Horn Is. MS)	Peterson & Howarth 1987 (Sapelo Is. Marshes, GA)	Winemiller et al 2007 (Matagorda Bay, TX)
	$\delta^{13}C$	$\delta^{13}C$	$\delta^{13}C$
Atlantic sharpnose shark	-16.9		
Atlantic stingray	-16.2		
Alligator gar			-18.10 ± 1.2
Spotted gar			-17.10 ± 0.0
Gulf menhaden	-19.6		-20.50 ± 1.6
Gizzard shad			-19.90 ± 0.8
Bay anchovy	-19.1		-20.30 ± 0.4
Hardhead catfish	-17.0		-19.00 ± 1.3
Striped mullet	-14.6	-15.05 to -17.91	-17.4 0 ± 0.9
White mullet	-15.7		
Gulf killifish			-15.60 ± 0.9
Longnose killifish	-14.8		
Sheepshead minnow			-14.40 ± 0.0
Inland silverside	-17.1		-19.20 ± 0.5
Pinfish	-16.1		-16.90 ± 1.4
Spotted seatrout	-17.5		-19.40 ± 0.6
Spot	-17.4		-13.50 ± 0.1
Atlantic croaker	-20.1		
Black drum			18.80 ± 1.1
Red drum	-16.2		-17.90 ± 0.6
Spanish mackerel	-17.7		
Southern flounder			-18.50 ± 0.1

Appendix 15. Reference ratios from $\delta^{15}N$ stable isotope analysis for vertebrate consumers.

Species	Source: Holt and Ingall 2000 (Galveston Bay)	Hyndes and Lavery 2005 (SW Australia bays)	Litvin and Weinstein 2003 (Delaware Bay, DE)
	$\delta^{15}N$	$\delta^{15}N$	$\delta^{15}N$
Bay anchovy			11.5 - 20.7
Striped mullet - large		12.6 ± 0.5*	
Spotted seatrout	~14 - 18		

Appendix 15. cont.

Species	Source: Moncreiff & Sullivan 2001 (Horn Is. MS)	Peterson & Howarth 1987 (Sapelo Is. Marshes, GA)	Winemiller et. al 2007 (Matagorda Bay, TX)
	$\delta^{15}N$	$\delta^{15}N$	$\delta^{15}N$
Atlantic sharpnose shark	14.8		
Atlantic stingray	12.2		
Alligator gar			13.20 ± 0.3
Spotted gar			12.40 ± 0.0
Gulf menhaden	11.9		14.50 ± 0.4
Gizzard shad			12.50 ± 0.8
Bay anchovy	14.8		12.80 ± 0.8
Hardhead catfish	13.6		13.70 ± 1.0
Striped mullet - small		6.05 ± 1.77	
Striped mullet - large	10.2	9.10 ± 2.40	10.40 ± 1.8
White mullet	9.8		
Gulf killifish			
Longnose killifish	11.8		
Sheepshead minnow			9.60 ± 0.0
Inland silverside	13.0		11.10 ± 0.4
Pinfish	12.2		9.00 ± 1.7
Spotted seatrout	14.6		13.50 ± 2.2
Spot	13.5		13.30 ± 2.0
Atlantic croaker	12.7		
Black drum			12.90 ± 1.1
Red drum	11.4		13.30 ± 0.9
Spanish mackerel	15.1		
Southern flounder			13.20 ± 1.7

Appendix 16. Trophic level (TL) averaged from all five sub-bays of the GBEE and researched sources. Species with multiple trophic levels for different ontogenetic length were averaged.

Species	Source		
	GBEE	Rooker et al. 2006 (NW GOM)	www.fishbase.org
	TL	TL	TL
Vegetative detritus	0.38		
Suspended particulate matter	2.02		
Epiphytes	0.87		
Benthic algae	0.26		
Filamentous algae	1.94		
Fatleaf sargassum	0.97		
Narrowleaf sargassum	1.67		
Smooth cordgrass	1.01		
Shoalgrass	1.38		
Comb jelly	4.43		
Sea nettle	3.96		
Moon jelly	2.95		
Cannonball jelly	3.44		
Tongue-eating isopod	3.86		
Gulf stone crab	3.47		
Grass shrimp	2.22		
Ohio River shrimp	4.26		
Mud crab	3.82		
Brown shrimp	2.89		
White shrimp	3.05		
Blue crab	2.83	3.4	
Lesser blue crab	2.37	3.2	
Common rangia	3.26		
Eastern oyster	2.71		
Atlantic brief squid	3.76		
Bull shark	3.32		4.3 ± 0.7
Blacktip shark	3.91		4.2 ± 0.7
Atlantic sharpnose shark	4.05		4.3 ± 0.8
Atlantic stingray	3.49		3.5 ± 0.42
Alligator gar	3.24		4.0 ± 0.67
Spotted gar	4.64		4.0 ± 0.66
Gulf menhaden	3.15		2.2 ± 0.07
Gizzard shad	3.75		2.4 ± 0.21
Bay anchovy	3.63		3.5 ± 0.50
Blue catfish	4.39		3.4 ± 0.44
Hardhead catfish	3.42		3.3 ± 0.6
Gafftopsail catfish	4.12		3.3 ± 0.5
Striped mullet	2.64		2.1 ± 0.2
White mullet	2.75		2.0 ± 0.0
Gulf killifish	2.35		3.0 ± 0.5
Longnose killifish	2.46		3.1 ± 0.4
Sheepshead minnow	0.95		2.9 ± 0.3
Inland silverside	3.08		3.1 ± 0.3
Sheepshead	3.45		3.5 ± 0.53
Pinfish	2.68		3.6 ± 0.5
Sand seatrout	3.87		4.3 ± 0.8
Spotted seatrout	4.02		4.0 ± 0.66
Spot	3.57		3.9 ± 0.4
Atlantic croaker	3.88		3.3 ± 0.4
Black drum	3.34		3.9 ± 0.62
Red drum	3.22		4.1 ± 0.7
Spanish mackerel	4.32		4.5 ± 0.7
Southern flounder	3.06		3.6 ± 0.6
Diamondback terrapin	4.33		

Appendix 17. Vial number, total length (TL) in mm, field preservation method after tissue removal, thawing period in days, and stable isotope data from five *A. felis* samples caught by hook and line in lower Galveston Bay on February 27, 2009.

Vial #	TL	Preservation	Thawing period	$\delta^{13}C$	Atom%C^{13}	$\delta^{15}N$	Atom%N^{15}
1	272	Ice	0	-20.99	1.082700	17.94	0.373023
2	272	Liquid N_2	0	-21.38	1.082275	18.17	0.373104
3	272	Liquid N_2	1	-21.33	1.082328	17.97	0.373033
4	272	Liquid N_2	3	-21.04	1.082651	18.18	0.373109
5	272	Liquid N_2	5	-21.04	1.082652	19.71	0.373666
6	272	Liquid N_2	10	-21.09	1.082596	21.10	0.374174
7	300	Ice	0	-17.05	1.087011	17.02	0.372685
8	300	Liquid N_2	0	-17.27	1.086769	16.98	0.372673
9	300	Liquid N_2	1	-16.88	1.087201	17.25	0.372770
10	300	Liquid N_2	3	-17.19	1.086854	17.16	0.372738
11	300	Liquid N_2	5	-17.15	1.086907	17.16	0.372737
12	300	Liquid N_2	10	-17.32	1.086720	18.19	0.373114
13	262	Ice	0	-17.57	1.086446	15.66	0.372189
14	262	Liquid N_2	0	-17.43	1.086596	15.88	0.372270
15	262	Liquid N_2	1	-17.29	1.086747	15.53	0.372142
16	262	Liquid N_2	3	-17.45	1.086573	16.22	0.372393
17	262	Liquid N_2	5	-17.54	1.086477	16.19	0.372384
18	262	Liquid N_2	10	-17.71	1.086287	17.32	0.372796
19	236	Ice	0	-17.58	1.086431	17.23	0.372763
20	236	Liquid N_2	0	-17.59	1.086421	17.28	0.372781
21	236	Liquid N_2	1	-17.69	1.086313	17.57	0.372886
22	236	Liquid N_2	3	-17.53	1.086491	17.55	0.372880
23	236	Liquid N_2	5	-17.62	1.086391	17.93	0.373018
24	236	Liquid N_2	10	-17.66	1.086344	18.77	0.373324
25	220	Ice	0	-19.04	1.084841	17.35	0.372806
26	220	Liquid N_2	0	-19.11	1.084764	17.34	0.372802
27	220	Liquid N_2	1	-18.71	1.085199	17.43	0.372837
28	220	Liquid N_2	3	-18.66	1.085256	17.74	0.372948
29	220	Liquid N_2	5	-18.75	1.085151	17.95	0.373026
30	220	Liquid N_2	10	-18.77	1.085129	18.82	0.373342