Incorporating Blue Carbon into Ecosystem Service Valuations for the Galveston Bay Region, Texas

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TEXAS A&M UNIVERSITY CORPUS CHRISTI | HARTE RESEARCH INSTITUTE FOR GULF OF MEXICO STUDIES

February 2018

Prepared for:

RESTORE AMERICA'S ESTUARIES

Suggested citation:
Yoskowitz, D.W. and L.M. Hutchison. 2018. *Incorporating Blue Carbon into Ecosystem Service Valuations for the Galveston Bay Region, Texas.* Harte Research Institute for Gulf of Mexico Studies. Report prepared for Restore America's Estuaries. pp.27.

Acknowledgements:
This research was funded by the U.S. Fish and Wildlife Service's Coastal Program. Special thanks to Stefanie Simpson (Restore America's Estuaries) for her written contribution to this report and for her identification of sources of information incorporated into the report. Thanks also to Carlota Plantier-Santos for her research and written contribution to this report.

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EXECUTIVE SUMMARY

The purpose of this report is to operationalize blue carbon ecosystem services within the suite of ecosystem services generally considered for Galveston Bay, Texas. If blue carbon is to be incorporated into policy and decision making, policy hurdles such as the need for regionally specific estimates of carbon sequestration, storage, and emissions from coastal habitats need to be overcome (Sutton-Grier and Moore, 2016). The research herein documents what we know about blue carbon in the Galveston Bay region (and more broadly in Texas) and highlights data gaps that need to be filled if dependable estimates are to be used to operationalize blue carbon and guide future decision making.

We provide blue carbon information and data that is relevant to decision making within the Galveston Bay region within the context of previous research that has been conducted on ecosystem services in the Galveston Bay region and along the Texas coast (Biltonen 2011; Ko 2007; www.gecoview.org). This information highlights the value of environmental resources and ecosystem services in the region.

Previous research shows that residents in the Houston/Galveston region are willing to pay to protect habitats, environmental quality, and freshwater inflow, with more willingness to pay to protect water conservation rather than carbon sequestration or enhanced forest cover (Biltonen 2011). A recent ecosystem services valuation study of Gulf of Mexico coastal habitats found that Texans valued salt marshes and mangroves and their ecosystem services at approximately $268 million and $120 million per year, respectively (www.gecoview.org). Also important to note is the value of flood mitigation as an ecosystem service of great concern for decision makers in the Houston/Galveston area.

Blue carbon refers to carbon stored in vegetated coastal ecosystems such as marshes, mangroves, and seagrass beds and comprises three components: carbon sequestered on an annual basis, carbon stored in plant biomass and soil organic matter, and carbon emitted (Pendleton *et al.* 2012). Most data on carbon stored in Texas salt marshes is available for the carbon stored in aboveground biomass, followed by carbon stored in belowground biomass and soil carbon, respectively. Estimations of carbon stored in Texas mangroves are lacking, especially for mangrove belowground biomass and soil carbon. There is also a lack of understanding of seagrass carbon stock and how it varies spatially and in relation to environmental factors (Thorhaug *et al.* 2017). For Texas wetlands, there are more data on carbon sequestration rates than emission rates. Further, very little data exists on carbon emissions from coastal systems, especially for coastal systems in Texas. Details on blue carbon data availability are included in the blue carbon sections of this report and in the appendix.

We conclude this report with a case study that utilizes the social cost of carbon to value climate change mitigation provided by salt marshes in the Galveston Bay region. Our research documents that salt marshes in the Galveston Bay region are worth approximately $9 million per year (2017$).

BACKGROUND

Ecosystem services are contributions from ecosystems that support, sustain, and enrich human life (Yoskowitz *et al.* 2010). Coastal ecosystems provide disproportionately more ecosystem services than those provided by most other natural systems (MEA 2005). For example, coastal wetlands provide many ecosystem services that humans depend on for their well-being, including water purification, fish supply, detoxification of wastes, wave buffering, shoreline stabilization and mitigation of climate change.

Blue carbon refers to carbon stored in vegetated coastal ecosystems (i.e. marshes, mangroves, and seagrass beds) and comprises three components: carbon sequestered on an annual basis, carbon stored in plant biomass and soil organic matter, and carbon emitted (Pendleton *et al.* 2012). Conversion of coastal ecosystems can lead to the emission of previously sequestered carbon that is stored in plant biomass and in the soil (Pendleton *et al.* 2012). This release of carbon into the atmosphere has climate change implications that are felt worldwide and affects the climate change mitigation ecosystem service provided by these coastal habitats.

Restoration of coastal systems can reverse negative impacts on the climate change mitigation ecosystem service and can enhance coastal resilience by replacing lost ecosystem services. Because of the recognized value of blue carbon, protection and restoration of coastal habitats is becoming increasingly relevant to policy and decision making. Operationalizing blue carbon requires documenting what we know about blue carbon within a specific area, identifying data gaps and research needs, and using available knowledge to inform policy, decision-making, and potentially, the development of markets associated with blue carbon.

The purpose of this report is to provide needed information to help operationalize blue carbon ecosystem services within the suite of ecosystem services generally considered for Galveston Bay, Texas. If blue carbon is to be incorporated into policy and decision making, policy hurdles such as the need for regionally specific estimates of carbon sequestration, storage, and emissions from coastal habitats need to be overcome (Sutton-Grier and Moore, 2016). The research herein documents what we know about blue carbon in the Galveston Bay region and highlights data gaps that need to be filled if dependable estimates are to be used to guide future decision making and operationalize blue carbon. Due to a dearth of data availability, data from nearby marshes in Texas and Louisiana were used to supplement data available for the Galveston Bay region.

The value of climate mitigation benefits associated with blue carbon can be captured many ways, including by conducting a benefit transfer, through the establishment of a carbon tax, an emissions trading system, a voluntary market for carbon credits, or through the application of the social cost of carbon in an effort to inform decision-making.

GALVESTON BAY CHARACTERIZATION

Galveston Bay is the largest bay in Texas, encompassing approximately 600 square miles (384,000 acres), surrounded by 232 miles of shoreline. The bay is located on the northern portion of the Texas coast in a highly urbanized region that includes the Houston metropolitan area (Figure 1). Half the population of Texas (nearly 12 million people) resides in the Galveston Bay watershed, an area of 24,000 square miles, with approximately 5 million people living in the five counties bordering the bay (Brazoria, Chambers, Galveston, Harris, and Liberty counties) (Lester and Gonzalez 2011). Freshwater inflows from the Trinity and San Jacinto Rivers feed into the bay, which opens up into the Gulf of Mexico, allowing for the mixture of salt and freshwater that make estuaries such productive ecosystems. The Galveston Bay region supports diverse habitats including coastal prairie, marsh, intertidal mudflats, seagrass meadows, and oyster reefs.

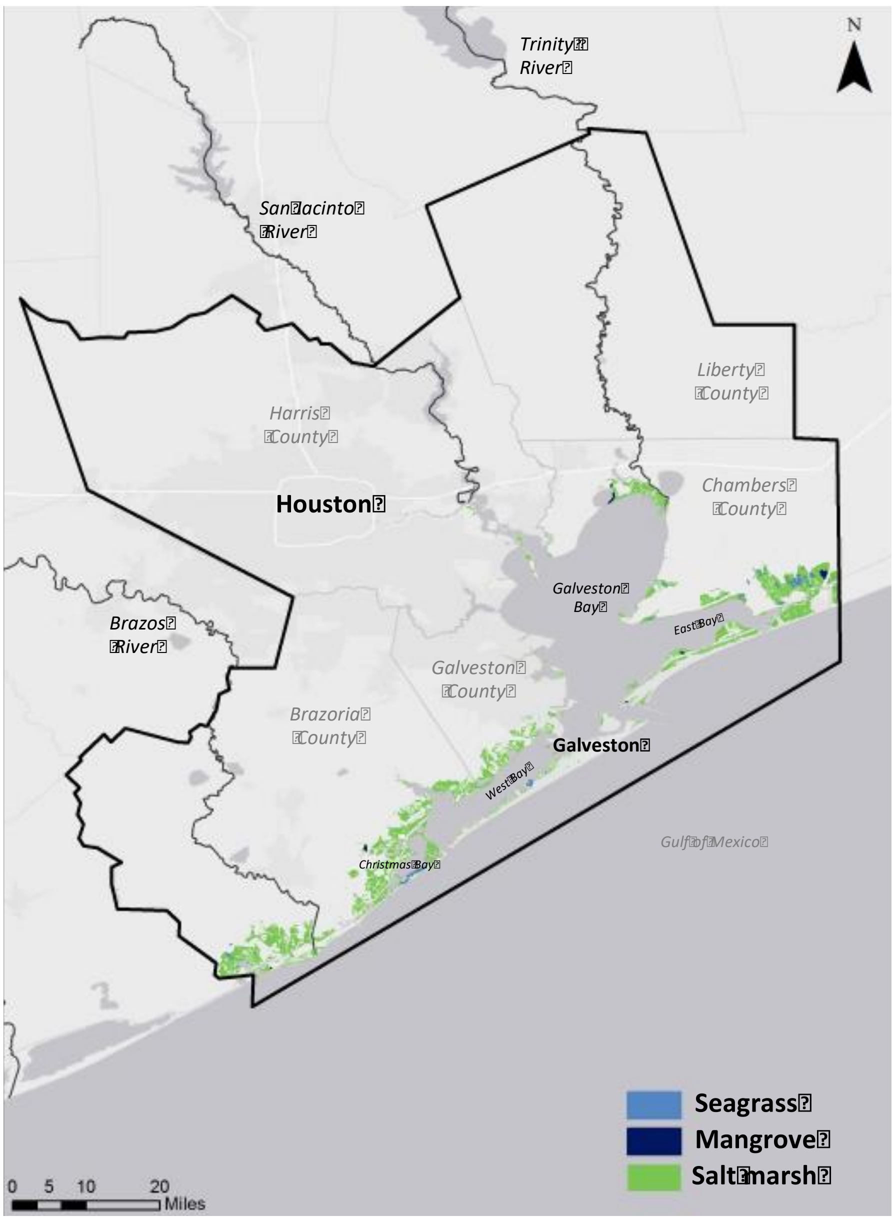

Figure 1. Map of the Galveston Bay region and blue carbon habitats therein.

Galveston Bay is an “estuary of national significance” as named by the U.S. Congress and a critical resource for the Houston-Galveston region. Galveston Bay has historically been a region important for fisheries, transportation, and oil extraction. Commercial and recreational fishing, tourism and other water-based industries supported by the bay contribute billions of dollars and thousands of jobs to the region’s economy (Lester and Gonzalez 2011). However it is because of these uses that the area’s population has seen continued growth, and a subsequent loss of wetland habitat. An estimated 35,000 acres of wetlands have been loss since the 1950s due to development, subsidence due to groundwater and oil and gas extraction, and shoreline erosion (Galveston Bay Foundation 2017).

Over the past few decades, there have been increasing efforts to balance the use and development of the region with maintaining a healthy bay and ecosystem. The Galveston Bay Estuary Program (GBEP) was established in 1989 with the mission of preserving the bay for future generations. The GBEP works with partner organizations and agencies in the region to accomplish this mission and to implement the Galveston Bay Plan, a comprehensive conservation management plan for Galveston Bay. An understanding of the ecosystem services provided by the bay can aid the region’s decision-makers in making informed decisions that reduce harmful impacts to the bay and surrounding community.

ECOSYSTEM SERVICE LITERATURE REVIEW

Galveston Bay Ecosystem Service Values

Several studies have been conducted that value ecosystem services provided by Galveston Bay and relevant habitats on the Texas coast (Biltonen 2011; Ko 2007; www.gecoview.org). Major findings show that residents in the Houston/Galveston region are willing to pay to protect habitats, environmental quality, and freshwater inflow, with more willingness to pay to protect water conservation rather than carbon sequestration or enhanced forest cover (Biltonen 2011). A recent ecosystem services valuation study of Gulf of Mexico coastal habitats found that Texans valued salt marshes and mangroves and their ecosystem services at approximately $268 million and $120 million per year, respectively (www.gecoview.org).

Biltonen (2011) offers an overview of ecosystem services relevant to the Lower Galveston Bay watershed. The habitats and their services within the watershed are discussed, as are commonly used methods to value these ecosystem services. Flood mitigation was highlighted as an ecosystem service of great concern for decision makers in the Houston/Galveston area. The author notes a need for the adaptation of tools and valuation methods using data and modeling assumptions that are relevant to the Texas gulf coast.

The Biltonen (2011) study also highlights several previous studies conducted in the Houston/Galveston area that assessed benefits to residents associated with green spaces, residents’ willingness to pay for ecosystem services and freshwater inflow, and landowner perceptions related to participation in willingness to pay programs. In summary, residents in the Houston/Galveston region are willing to pay to protect environmental quality and freshwater inflow, with more willingness to pay to protect water conservation rather than carbon sequestration or enhanced forest cover.

Studies highlighted by Biltonen (2011) are elaborated on below. Biltonen (2011) focused on two types of studies: 1) studies that conducted economic valuations and 2) studies that assessed stakeholder perceptions of value. Economic valuations were conducted to assess the value of ecosystem services such as water quality, climate change mitigation, and freshwater inflow. Stakeholder perceptions of water conservation and carbon sequestration were also assessed.

In a study conducted by Whittington *et al.* (1994), researchers determined that the average household in the Houston/Galveston region was willing to pay approximately \$80 per year to implement a management plan to improve environmental quality in Galveston Bay. If this value were extrapolated to all households in the five county region surrounding the Houston/Galveston area (according to the 1990 census data), the results suggest that residents were willing to pay approximately \$110 million per year (in 1994 dollars) to implement a plan to improve the quality of Galveston Bay. Another study, by Anthony *et al.* (2009), assessed the value of tree canopy loss in the Houston area between 1972 and 1999. Anthony *et al.* (2009) estimated the lost CO_2, SO_2, and O_3 potential to be worth approximately \$38 million per year; lost stormwater value was estimated to be approximately \$237 million; and, lost benefits to residents in reduced cooling costs was valued at approximately \$26 million per year. Yoskowitz and Montagna (2008) determined that willingness to pay to protect freshwater inflow into San Antonio Bay and Lower Rio Grande Valley, TX, the impacts that it would have on ecosystem function, and the associated services, was approximately \$4.1 million and \$9.8 million, respectively. Although this study did not focus on stakeholders in the Houston/Galveston region, results could be extrapolated to residents in that region.

Biltonen (2011) also included an assessment of highly valuable ecosystem services to Texans. Olenick, Kreuter and Conner (2005) documented Texas landowners' perceptions of ecosystem services and willingness to participate in payment for ecosystem service schemes and determined that landowners were more willing to participate in programs targeting water conservation over programs aimed at carbon sequestration or increasing forest cover. These results suggest that a payment for ecosystem services scheme in the Houston/Galveston area might be more successful if it focused on protecting water quality and quantity, with blue carbon marketed as a co-benefit.

Ko (2007) conducted a study on the value of ecosystem services provided by Galveston Bay. The study was intended to be the first phase of a systematic valuation effort. Two stakeholder workshops were conducted in association with the study, output from which included a list of Galveston Bay ecosystem services and the appropriate valuation method that could be used to value each ecosystem service (Table 1). Descriptions of these valuation methods are included in the "Methods Used to Value Ecosystem Services" section of this report. Ko (2007) also established lists of ecosystem services that were highly valued, most at risk, and priorities for future research according to local stakeholders (Table 2).

In addition to this baseline assessment of stakeholder values and methods used to assess those values, Ko (2007) also conducted case studies on ecosystem service value. Ko (2007) estimated the water quality improvement value associated with the wetlands in the five county region surrounding the Houston/Galveston area was worth $124.3 million. Ko (2007) also estimated the water quality improvement value of the wetlands in the Brazoria National Wildlife Refuge to be worth approximately $5.6 million.

Ko (2007) also considered the market value of commercial fisheries and recreation on the Galveston Bay region. The total ex vessel value of commercial fisheries (finfish and shellfish) from the Galveston Bay system was worth approximately $6 to $27 million from 1981 to 2005 (Ko 2007). This value increases when the direct and indirect impacts of commercial fisheries are considered. For example, the total economic output of commercial fishing for Galveston Bay area ports was estimated to be approximately $77 million in 2001 (Mouton 2003).

Sport fishing is the dominant economic driver related to recreational activity in the Houston/Galveston area. In the Trinity-San Jacinto estuary, sport fishing had an economic impact of $171.5 million as of 1987 (Fescenmaier *et al.* 1987 as per Ko 2007). Other recreational activities (such as boating, swimming, bird watching, hunting, camping and picnicking) had an economic impact of approximately $122 million.

Ko (2007) also highlighted resources that could be used to conduct nonmarket value analysis for flood mitigation, water quality, and habitat provision ecosystem services. For example:

- *Flood mitigation* for the Houston/Galveston region can be valued using information from Schuyt and Brander (2004), Scodari (1990), Coenco (1985), Dannenbaum (2001), and Leschine *et al.* (1997). For example, Leschine *et al.* (1997) estimated the flood mitigation value of wetlands in Washington based on factors including the wetland's ability to reduce flow and estimated a value between $7,830 and $51,095 per acre. And, using values from Coenco (1985) and Dannenbaum (2001), Ko (2007) estimated a flood mitigation value of wetlands in Friendswood, Texas (in the Houston/Galveston area) to be worth approximately $5,800 per acre.

- *Water quality improvement* for the Houston/Galveston region can be valued using information from Tchobanoglous and Burton (1991), Ko *et al.* (2004), Cardoch *et al.* (2000). For example, Ko *et al.* (2004) estimated the value of natural wetlands in improving municipal wastewaters was equal to $129 per acre. In a decision making context, water quality benefits can be highlighted by emphasizing the energy savings and financial benefits associated with using wetlands to filter water as opposed to building infrastructure which has to be maintained. Using wetlands to clean water can be beneficial for small communities and non-toxic industrial processors and would serve as good examples for future case studies.

- *Habitat provision* can be valued using project cost data from successful wetland restoration projects, some of which are documented in Oden *et al.* (2003). The Ko (2007) study used values from Oden *et al.* (2003) to calculate a crude cost estimation of restoration projects of approximately $6,000 per acre of wetland.

Table 1. Ecosystem services and valuation methods for Galveston Bay. *Reprinted from Ko (2007)*

Ecosystem Service	Appropriate Valuation Method(s)
Storm water abatement	A/RC, H
Water quality	A/RC, CV, H
Erosion control	A/RC, H
Flood and storm protection	A/RC
Subsidence abatement	A/RC
Cultural and historical activities	CV, M, TC
Gas regulation	CV
Nutrient regulation	A/RC, CV
Open space	CV, H
Fish and wildlife habitat	CV, P, E
Spawning and nursery habitat	CV, P, E, R
Commercial transportation	M
Commercial fishing	M. P, E
Recreational fishing	M, TC, E, R
Recreational activities	TC, CV, R
Ecotourism	TC, CV, R
Scientific and educational activities	CV, P, M
Aesthetics	H, CV, TC, R

AC= avoidance cost, CV= contingent valuation, E= embodied energy, H= hedonic pricing, M= market pricing, P= productivity approach, R= ranking, RC= replacement cost, TC= travel cost

Table 2. Top three ecosystem services for the Galveston Bay region. *Reprinted from Ko (2007)*

Question	First rank	Second rank	Third rank
Most overall value	Fish and wildlife habitats	Recreation, ecotourism, aesthetics, open space	Protection from flooding, storm, erosion
Most economic value	Recreation, ecotourism, aesthetics, open space	Commercial fishing	Marine transportation
Most at risk	Fish and wildlife habitats	Water quality	Protection from flooding, storm, erosion
Priorities for future work	Fish and wildlife habitats	Protection from flooding, storm, erosion	Water quality

Ko (2007) explicitly stated that gas and climate regulation ecosystem services provided by coastal wetlands (i.e. blue carbon) were not included in analysis due to lack of research, but were important ecosystem services. Our report is an attempt to build on previous ecosystem service valuation work conducted for the Galveston Bay region by Ko, Biltonen and others.

Findings from previous research suggest:

- Flood mitigation is an ecosystem service of great concern for decision makers in the Galveston Bay region
- Each household in the Galveston Bay region is willing to pay approximately $80 per year to (in 1994 dollars) implement a management plan to improve environmental quality in Galveston Bay
- Landowners are more willing to participate in programs targeting water conservation over programs aimed at carbon sequestration or increasing forest cover

BLUE CARBON LITERATURE REVIEW

Blue Carbon

Blue carbon refers to carbon stored in vegetated coastal ecosystems such as marshes, mangroves, and seagrass beds and comprises three components: carbon sequestered on an annual basis, carbon stored in plant biomass and soil organic matter, and carbon emitted (Pendleton *et al.* 2012). Data available for each of these three components of blue carbon are elaborated on in the following sections.

Blue Carbon: Carbon Storage

The most comprehensive literature review on carbon storage in Texas coastal wetlands (salt marshes and mangroves) was conducted by Hutchison (2016). Hutchison documented six publications that measured and quantified carbon storage in Texas salt marshes and two publications that estimated carbon storage in Texas mangroves. (Appendix A; Table A1). Most data on carbon stored in Texas salt marshes is available for the carbon stored in aboveground biomass, followed by carbon stored in belowground biomass and soil carbon, respectively. Estimations of carbon stored in Texas mangroves are lacking, especially for mangrove belowground biomass and soil carbon. There is also a lack of understanding of seagrass carbon stock and how it varies spatially and in relation to environmental factors (Thorhaug *et al.* 2017).

Aboveground Carbon Storage: Estimates of carbon stored in Texas salt marsh aboveground biomass range from 182 gC m^{-2} to 920 gC m^{-2} and estimates of carbon stored in Texas mangrove aboveground biomass range from 336 gC m^{-2} to 1,900 gC m^{-2} (Hutchison 2016).

Belowground Carbon Storage: Estimates of carbon stored in Texas salt marsh belowground biomass range from 276 gC m^{-2} to 2,817 gC m^{-2} and, to the best of our knowledge, estimates of carbon stored in Texas mangrove belowground biomass do not exist.

Soil Carbon Storage: Soils comprise the largest carbon pool in salt marsh and mangrove habitat, storing organic matter from dead aboveground and belowground matter (Alongi 2014). Unfortunately, these soil carbon storage pools, known to contain the largest amounts of carbon, are not well understood. From the limited data that we were able to find, we know that estimates of carbon stored in Texas salt marsh soils range from 7,371 gC m^{-2} to 9,072 gC m^{-2}. Estimates of Texas mangrove soil carbon were not available. However, estimates of soil carbon in salt marshes and mangroves in other parts of the northern Gulf of Mexico are available in Hutchison (2016) and Guannel *et al.* (2014).

Seagrass Carbon Storage: There is a lack of understanding of seagrass carbon stock and how it varies spatially and in relation to environmental factors. Factors known to affect carbon accumulation in seagrass beds include direct sediment trapping, pumping of photosynthates into the sediments by seagrass plants, diagenesis, seagrass species type, and sediment microbial activity (Thorhaug *et al.* 2017).

A recent study by Thorhaug *et al.* (2017) quantified the carbon stock in natural and restored seagrass beds in the northern Gulf of Mexico. Authors estimated the mean organic carbon stock in the natural seagrass beds to be 25.7 ± 6.7 Mg ha^{-1} in the top 20cm of sediments (Thorhaug *et al.* 2017).

Texas has lost many hectares of seagrass beds, especially in the northern industrialized estuaries, such as Galveston Bay. Most seagrasses in the Galveston Bay system have been lost, except for in Christmas Bay (TPWD 1998). Organic carbon stock in the natural seagrass beds at San Luis Pass, near Galveston Bay, is 6.89 Mg ha^{-1} and is 11.42 Mg ha^{-1} in the restored seagrass beds (Thorhaug *et al.* 2017). In Texas, the highest seagrass carbon stocks are in the Laguna Madre, where salinity and turbidity conditions are more conducive for seagrass growth and where there are fewer impacts from human activities (Thorhaug *et al.* 2017; TPWD 1998).

Blue Carbon: Carbon Sequestration

For Texas wetlands, there are more data on carbon sequestration rates than emission rates. Sequestration rates of salt marshes and mangroves in Texas are available from two publications (Appendix A; Table A2). Sequestration rates documented for estuarine emergent salt marshes in Texas were collected at five locations and range from 0.95 to 2.03 tC $ha^{-1}yr^{-1}$. Sequestration rates documented for mangroves in Texas were collected at one location and range from 2.53 to 2.7 tC $ha^{-1}yr^{-1}$.

Blue Carbon: Carbon Emissions

Quantification of greenhouse gas emissions enables us to better understand climate change-related topics, including blue carbon. Climate-relevant trace gases are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Oertel *et al.* 2016). Methane is created under anaerobic conditions where carbon dioxide is reduced to methane by methanogens (Smith *et al.* 1983a). Factors that affect greenhouse gas production in soils include microbial activity, root respiration, chemical decay processes, and heterotrophic respiration of soil fauna and fungi (Oertel *et al.* 2016). Emissions flux rates are affected by soil water content, soil temperature, nutrient availability, pH, and landcover and/or habitat type (Oertel *et al.* 2016; Livesley and Andrusiak 2012; DeLaune *et al.* 1986; Smith *et al.* 1983a).

Very little data exists on carbon emissions from coastal systems, especially for coastal systems in Texas. Therefore, we discuss emissions data from a nearby location, Barataria Basin in Louisiana, which is a well-studied coastal system.

Methane fluxes from marshes in Barataria Basin have been documented to range from 43 to 160 g CH_4-C m^{-2}, with lower rates associated with salt marshes and higher rates associated with fresh marshes (DeLaune *et al.* 1982 as per Smith *et al.* 1983a). Given estimates from DeLaune *et al.* (1982) and Smith *et al.* (1983a), the total annual methane and carbon dioxide evolution from salt, brackish and fresh marshes ranges from 253 to 776 g C m^{-2} (Smith *et al.* 1983a). Annual emission of nitrous oxide from coastal marshes in Barataria Basin, Louisiana is estimated to be between 31 and 55 mg N m^{-2} (Smith *et al.* 1983b).

BLUE CARBON DATA GAPS AND RESEARCH NEEDS

There are a lack of data on carbon storage in belowground compartments (compared to aboveground compartments) of Texas salt marshes and mangroves. According to the best available data, carbon storage in Texas salt marsh soil is greater than carbon storage in both aboveground and belowground biomass compartments. Compared to data availability for Texas salt marshes, studies on Texas mangrove biomass and soil organic matter are relatively scarce (Hutchison 2016).

Research on Texas mangrove biomass, distribution, and change in coverage over time are currently active areas of research due to the implications associated with mangrove expansion in the northern Gulf of Mexico. Currently, mangroves do not exist in the Houston/Galveston region. However, research suggests that with an anticipated 2°C to 4°C increase in mean annual minimum temperature, 95-100% of salt marshes in Texas could be vulnerable to displacement by mangroves by the year 2100 (Osland *et al.* 2013).

In addition to the need for enhanced understanding of carbon storage in salt marshes and mangroves, there is also need to focus future research efforts on regional carbon sequestration and emission rates. Prioritizing research on emissions should be considered, as emission fluxes can be much greater than sequestration fluxes (Ullman, Bilbao-Bastida, and Grimsditch 2013) and have to potential to release large amounts of greenhouse gases into the atmosphere due to land use changes such as wetland draining and dewatering (Donato *et al.* 2011). Thus, research on emissions that occur upon destruction of wetlands should be prioritized (Ullman, Bilbao-Bastida, and Grimsditch 2013). Because coastal wetland systems maintain a long-term carbon stock, efforts should be made to protect and minimize disturbance to these systems (Livesley and Andrusiak 2012).

Further, because there is very little if any seagrass habitat in Galveston Bay, the dearth of data on carbon storage, sequestration and emission in seagrass habitats is not a relevant data need for this case study. However, better understanding of the role seagrasses play in Texas blue carbon is a research need.

ECOSYSTEM SERVICE VALUATION METHODS

There exist many different approaches to measure the "value" of benefits that we humans receive from natural systems. Some of these methods involve measuring attitudes, preferences, or intentions of the individual or community. Other methods assess the "economic value" generated because of a change in the provision of an ecosystem service (EPA 2009). Values, and therefore valuation methods, mean different things to different people. It may not always be appropriate to try to put "a dollar value" on ecosystem services. In general, methods for valuation can fall into two broad categories: 1) Monetary, and 2) Nonmonetary. These methods are elaborated on below and summarized in a list of methods potentially useful for estimating economic value of ecosystem services in the Galveston Bay region created by Biltonen (2011) (see Table 3).

Nonmonetary Valuation Methods

In general, nonmonetary valuation methods involve eliciting information about preferences, attitudes, and intentions through surveys, focus groups, or passive observation (EPA 2009). The output from these approaches can be very robust and are typically quantitative.

More recently, there has been a movement to include ecosystem benefit indicators and biophysical ranking methods to express value (Olander *et al.* 2018; Liu *et al.* 2010). Examples of the output provided by these approaches include spatially differentiated metrics or maps showing the demand and supply of ecosystem services; the energy required to produce a particular ecosystem service; and the area of an ecosystem required to support a consumption pattern or population (EPA 2009).

Monetary Valuation Methods

Monetary methods used to value ecosystem services include market and nonmarket methods. When the value of ecosystem services are not captured in the market (such as the market value of commercial fish), there are two methods that can be applied to assess the nonmarket value of ecosystem services: stated preference and revealed preference methods.

Stated preference methods are useful for determining values for ecosystem services that are far removed from market transactions. These approaches infer values or economic benefits from responses to survey questions about hypothetical tradeoffs that the individual is confronted with. Some of the techniques directly ask what individuals or households are willing to pay, while others elicit information about tradeoffs and then quantitative analysis is conducted to generate a monetary value (EPA 2009).

Revealed preference methods are based on the actual behavior of an individual, such as preference revealed by actions or choices (Freeman III, 2003). Examples of revealed preference methods include the travel cost, market, hedonic pricing, and production function methods.

When limited resources prevent the option for conducting original nonmarket valuation studies, the benefit transfer method can be used. Benefit transfer uses information from previous research in a different context to inform decision making (Rosenberger and Loomis, 2003).

A useful resource that can be used as a starting place for conducting coastal ecosystem service valuations is the Gulf of Mexico Ecosystem Service Valuation Database (GecoServ) available at http://www.gecoserv.org. GecoServ catalogues ecosystem services for coastal habitat types found in the Gulf of Mexico region. For inclusion in this report, the GecoServ database was queried for ecosystem services provided by blue carbon-relevant habitat types—wetlands, mangroves, and seagrasses. Most ecosystem service valuation data is available for freshwater wetlands, followed by mangroves. The least amount of data is available for seagrass habitat (Table 4).

Table 3. List of methods commonly used to value ecosystem services. *Adapted from Biltonen (2011).*

Method	Description	Preference Statement	Direct or Indirect
Travel cost	Values of site amenities are estimated based on costs actually incurred for travelling to the site	Revealed	Indirect
Market method	Valuations of natural services derived from actual market transactions using either competitive market prices or simulated prices	Revealed	Direct
Hedonic pricing method	Value of service is estimated based on actual purchase of related goods	Revealed	Indirect
Production function	Values are derived from a production function for which the natural amenity is an input	Revealed	Indirect
Contingent valuation	People are asked directly to state value for an amenity via a survey	Stated	Direct or Indirect
Conjoint analysis	People are asked to pick or rank various states of ecosystem services	Stated	Indirect
Replacement cost	The value is estimated based on what it would cost to provide the equivalent service via the next best means	Cost-based	Indirect
Avoidance cost	The value is based on costs avoided if the natural service is maintained	Cost-based	Indirect
Individual index based method	Preferences are expressed as either ranks or ratings	Non-monetized	Not applicable
Group-based method	Preferences are expressed by voting	Non-monetized	Not applicable

Table 4. Total number of ecosystem service valuation studies available in the GecoServ database.

Ecosystem service/ Value	Fresh and saltwater wetlands	Freshwater wetlands	Saltwater wetlands	Mangroves	Seagrass	**TOTAL**
Aesthetics	2	13	6			**21**
Bequest				2		**2**
Biodiversity		1				**1**
Biological control	1	2	1	3	1	**8**
Climate regulation*	1	4	1	1		**7**
Cultural, spiritual, and historic	1	4	7			**12**
Disturbance regulation	7	24	40	28		**99**
Erosion control and soil retention	1	8	1	13		**23**
Existence		2	1	8		**11**
Food	2	24	17	44	6	**93**
Gas regulation*	2	16	6	15	2	**41**
Genetic resources and gene pool	2	3	2		7	**14**
Habitat	8	23	23	43		**97**
Medicinal resources		4		3		**7**
Net primary production*		2	5			**7**
Nutrient cycling	1	3	3	2	2	**11**
Nutrient regulation		3	1	1		**5**
Option				3		**3**
Ornamental resources		1				**1**
Pollination	1	2	1			**4**
Raw materials	5	22	8	40	3	**78**
Recreation	7	43	49	23		**122**
Science and education		2	1	4	2	**9**
Soil formation	1	2	1	2		**6**
Total economic value (TEV)			3	1	3	**7**
Waste regulation/treatment	4	25	19	8	1	**57**
Water regulation	2	11	1			**14**
Water supply	4	29	7	1		**41**
TOTAL	**52**	**273**	**204**	**245**	**27**	**801**

* Ecosystem services denoted with an asterisk refer to potentially useful sources of information for a blue carbon assessment.

BLUE CARBON VALUATION METHODS

In an effort to inform decision-making, the value of climate mitigation benefits associated with blue carbon can be captured many ways including by conducting a benefit transfer, through the establishment of a carbon tax, an emissions trading system, a voluntary market for carbon credits, or through the application of the social cost of carbon. For entities interested in participating in carbon markets, it is critical to be able to verify emission reductions generated by projects via an independent, third party verifier, such as the Verified Carbon Standard. These third party verifiers could be a potential source of information needed to fill research gaps.

The cost of a carbon credit varies greatly depending on the market mechanism used. Credits on the voluntary market generally cost much less than credits sold under a regulated market (Ullman, Bilbao-Bastida, and Grimsditch 2013). In 2015, carbon credits on the voluntary market cost $3.3/tonne ($3.41 in 2017 dollars), down from an average value of approximately $4.6/tonne ($4.76 in 2017 dollars) (Hamrick and Goldstein 2016). The price of carbon on the California compliance market averaged approximately $11.3/metric ton in 2015 ($11.69 in 2017 dollars), whereas the RGGI allowance prices were approximately $4/short ton ($4.14 in 2017 dollars) (Ranson and Stavins 2016).

Values outside of market transactions also exist. The social cost of carbon (SCC) is an estimate of social benefits associated with reducing carbon dioxide emissions that is used to conduct cost-benefit analyses and inform decision-making and regulatory actions (IWGSCGG 2016). The SCC includes estimates of monetized damages associated with (among other factors) net agricultural productivity, human health, property damage from increased flood risk, and the value of ecosystem services due to climate change (IWGSCGG 2016). Various estimations of the SSC exist including $31 per ton in 2010 (Nordhaus 2017) to as high as $220 per ton (Moore and Diaz 2015). The U.S. Government Interagency Working Group on the Social Cost of Carbon bases its' SCC estimations on a present value calculation which varies according to the year of the emissions and the discount rate chosen (e.g. 2.5%, 3%, or 5%). For 2016, the SCC estimates were $11, $38, $57 (in 2007 dollars/metric ton CO_2) (IWGSCGG 2016). The SCC values are, in general, much higher than the costs of carbon credits in both compliance and voluntary markets in the United States.

CASE STUDY

Methodology

In order to value the climate change mitigation ecosystem service in the Galveston Bay region, the social cost of carbon was applied to blue carbon habitats within the study area. Analysis was conducted according to the following steps: 1) identification of carbon sequestration rates for salt marshes, mangroves and seagrass beds in/near the Galveston Bay region (if data were unavailable, data from other parts of Texas and Louisiana were supplemented), 2) conversion of sequestration data units from tons of carbon sequestered to tons of carbon dioxide (CO_2) sequestered, 3) monetization of the climate benefits of blue carbon habitats in reducing CO_2 emissions, and 4) conversion of annual "per hectare" values to total annual values for the study area. A detailed methodology is included below.

A literature review was conducted to identify studies that provided carbon sequestration rates for salt marshes and mangroves in Texas (Appendix A; Table A2). The average of salt marsh and mangrove sequestration rates documented for Texas (1.4 tC $ha^{-1}year^{-1}$ and

2.6 tC ha^{-1}year^{-1}, respectively) were used. Because of lack of time and resources and a dearth of data, we were unable to determine a seagrass carbon sequestration rate for Texas.

The carbon sequestration rates were converted to a carbon dioxide sequestration rates because the social cost of carbon is represented in units of carbon dioxide (Interagency Working Group on Social Cost of Carbon, 2016). A multiplier of 3.67, the molecular weight ratio of carbon to carbon dioxide was used (i.e. 1tC equals 3.67 tCO_2) (Table 7).

The social cost of carbon (SCC) was then used to monetize the tons of carbon dioxide sequestered by blue carbon habitats. SCC is an estimate of the monetized damages associated with a marginal increase (one metric ton) in carbon emissions in a given year. In this case, it represents the value of the avoided damages from a reduction in emissions derived from the presence of blue carbon habitats. SCC is intended to include (but is not limited to) changes in human health, net agricultural productivity, property damages from increased flood risk, and the value of ecosystem services due to climate change; it is therefore a useful measure to assess the benefits of CO_2 reductions (Interagency Working Group on Social Cost of Carbon, 2016).

Table 7. Carbon and carbon dioxide sequestration rates used for analysis.

	Salt marsh	Mangrove	Seagrass
Carbon sequestration rate (tC ha^{-1}year^{-1})	1.4	2.6	n/a
Carbon dioxide sequestration rate (tCO_2 ha^{-1}year^{-1})	5.1	9.5	n/a

To value the SCC, a rate of \$36/t CO_2 (2007 US\$) was used to represent the present value of the damages that would occur from the release of one ton of carbon dioxide (Interagency Working Group on Social Cost of Carbon, 2016). The 2007-dollar value associated with the CO_2 sequestration rate was converted to a 2017-dollar value (\$42.83/t CO_2) to adjust for the rate of inflation. The carbon dioxide sequestration rates were then multiplied by \$42.83/t CO_2 to obtain annual values per hectare for the services blue carbon habitats provide by sequestering carbon. A discount rate of 3% can be used to extrapolate the annual value into the future. A 3% discount rate was chosen as it is the central value across models used to estimate the SCC and considered a conservative estimate (Interagency Working Group on Social Cost of Carbon, 2016).

Lastly, the annual per hectare values (US\$ 2017 ha^{-1}year^{-1}) were multiplied by the total number of hectares of blue carbon habitats in the Galveston Bay region, to estimate the total annual value for carbon dioxide sequestration (US\$ 2017 year^{-1}), or the annual value of the climate benefits of blue carbon habitats in reducing CO_2 emissions.

Current habitat extent of salt marsh, mangrove, and seagrass habitat in the Houston/Galveston region was calculated in ArcMap© 10.4.1 using U.S. Fish and Wildlife Service (USFWS) National Wetlands Inventory (NWI) and the National Oceanic and Atmospheric Administration (NOAA) Benthic Habitat Atlas (BHA) data. NWI data were obtained from the USFWS's Wetlands Inventory website and BHA data were obtained from NOAA's Gulf of Mexico Data Atlas website in December 2017.

Using NWI data, salt marsh extent was calculated using the Estuarine Intertidal Emergent (E2EM) classification, mangrove extent was calculated using the Estuarine Intertidal Scrub Shrub Broad-leaved Evergreen (E2SS3) classification, and seagrass extent was calculated using the Estuarine Subtidal and Intertidal Aquatic Bed Rooted Vascular (E1AB3 and E2AB3) classifications. NWI mangrove data were supplemented with Texas mangrove data from the NOAA BHA data. A new mangrove dataset was created using the update tool, where NWI data were used as the input layer and BHA data were used as the update layer.

Final salt marsh, mangrove, and seagrass datasets were then clipped to the Galveston Bay region, which is comprised of the five counties surrounding Galveston Bay (i.e. Brazoria, Chambers, Galveston, Harris, and Liberty counties).

Findings

Blue carbon in the Galveston Bay region is characterized mostly by salt marsh habitat, the most abundant blue carbon habitat type in the region (Figure 2; Table 8). In addition to salt marsh habitat, our spatial analysis suggests that there is also a small amount of seagrass and mangrove habitat in the region. However, the presence of mangrove habitat could be an artifact of how the National Wetlands Inventory data is classified and the classification we chose to use to represent mangrove habitat (since there is not a mangrove category). According to the literature, mangroves are not documented to occur that far north in Texas. Further, seagrass data provided by the National Wetlands Inventory dataset is outdated and likely does not reflect the actual presence of seagrass habitat in the region. Most of the seagrass habitat mapped (approximately 117 hectares) occurs within the five National Wildlife Refuges that are within the Galveston Bay region (i.e. Trinity River, Moody, McFaddin, San Bernard, and Anahuac National Wildlife Refuges). Further, approximately 126 hectares of seagrass documented in the NWI dataset occurs in the Christmas, West and Drum Bays, which are south of Galveston Bay proper.

Table 8. Data on carbon sequestration rates, carbon dioxide sequestration rates, hectares of habitat, and blue carbon value used for analysis.

	Salt marsh	Mangrove	Seagrass
Carbon sequestration rate (tC $ha^{-1}year^{-1}$)	1.4	2.6	n/a
Carbon dioxide sequestration rate (tCO_2 $ha^{-1}year^{-1}$)	5.138	9.542	n/a
Amount of habitat in study area (hectares)	40,846	40	209
Blue carbon value using SCC (2017$ ha^{-1} $year^{-1}$)	$220	$409	n/a
TOTAL blue carbon value (2017$ $year^{-1}$)*	**$8,988,593**	**$16,347**	n/a

*Discount rate should be applied when estimating blue carbon value into the future.

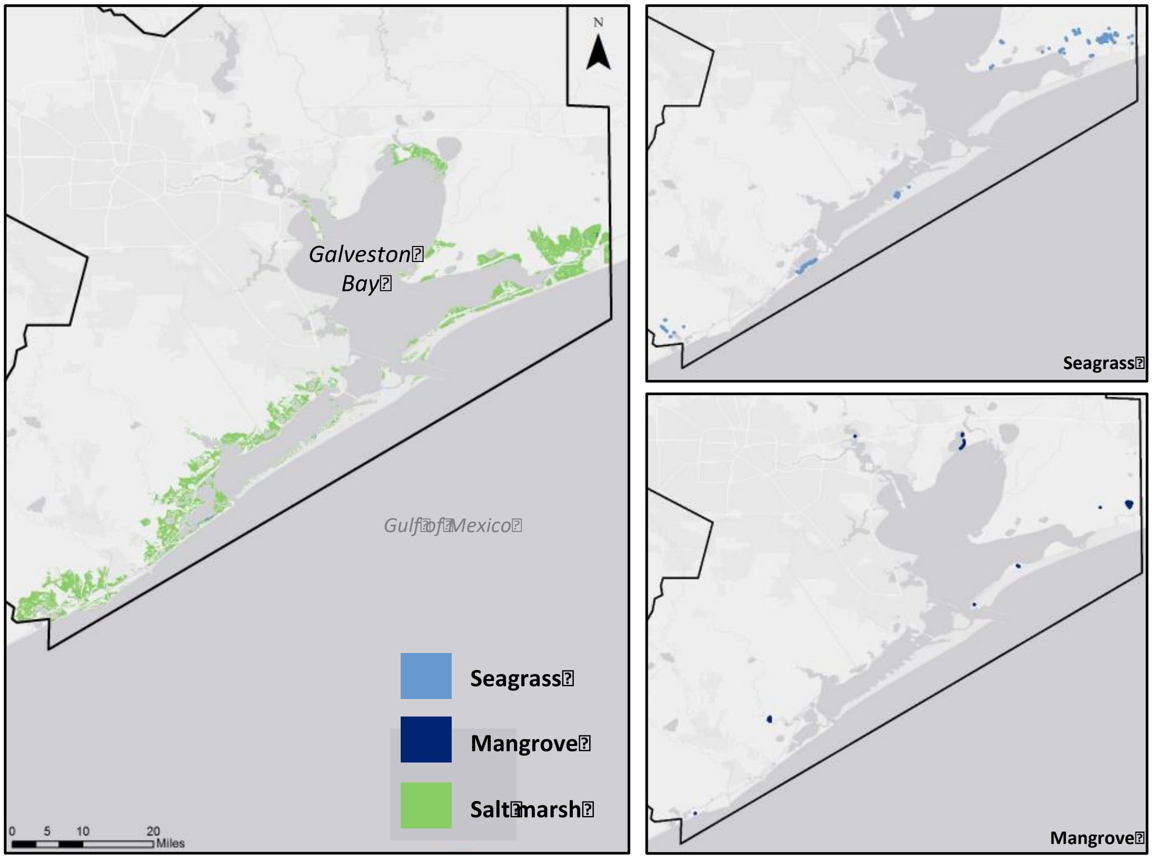

Figure 2. Map of blue carbon habitats in the Galveston Bay region. The size of seagrass and mangrove habitats are exaggerated in the enlarged maps (on the right) so that habitat locations can be easily identified.

Utilizing the social cost of carbon, our analysis shows that the value of climate change mitigation gained from blue carbon habitats in the Galveston Bay region is worth approximately $9 million per year (2017$). If these blue carbon habitats were to be destroyed, these habitats would cease to provide this climate change mitigation service in addition to releasing large amounts of greenhouse gases into the atmosphere that are currently stored in their aboveground biomass, belowground biomass, and soils.

CONCLUSION

Incorporating blue carbon into the suite of ecosystem services assessed for decision making is a useful tool to be able to highlight the value of coastal wetlands. If we want to be able to make informed decisions about coastal resources in the Galveston Bay region, we need more data on how coastal blue carbon habitats function and how the distribution of blue carbon habitats is expected to change in the future.

Further, there are opportunities for landowners in the region to participate in markets for carbon. The value of blue carbon on currently existing markets ($3.49-$11.69/t CO_2) is much less than the value captured by using the social cost of carbon ($42.83/t CO_2). Until recently, the only carbon market open to sellers in Texas was the voluntary market, through wetland methodologies approved by the Verified Carbon Standard (VM0033). However, in late 2017, the American Carbon Registry (ACR) approved a carbon-offset methodology for wetland restoration that could also be applied to wetlands outside of the state of California-- thus opening up the potential for sellers in other locations to participate in the California Cap-and-Trade Program (ACR 2017).

The ACR methodology can be used to quantify greenhouse gas removal and emissions reduction for different types of restoration projects including restoration of managed, permanently flooded, non-tidal wetlands. The methodology for managed, non-tidal wetlands therein does not apply solely to wetlands in California, and can therefore be applied to wetland restoration projects outside of the state of California. In order to participate in the California Cap-and-Trade Program, wetland restoration projects would need to meet the ACR applicability criteria, including a demonstration of additionality (i.e. the yield of surplus greenhouse gas reductions that would not otherwise occur in a business-as-usual scenario).

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APPENDIX: Salt Marsh and Mangrove Carbon Storage and Sequestration Rates in Texas.

Table A1. Texas salt marsh and mangrove carbon storage values. *Adapted from Hutchison (2016) to include data from a recent report by Armitage (2017).*

Publication	**Carbon storage compartment**	**g C m^{-2}**
Salt Marsh		
Webb *et al.* (1985)	Aboveground Biomass	182
Webb *et al.* (1985)	Aboveground Biomass	186
Webb *et al.* (1985)	Aboveground Biomass	190
Webb *et al.* (1985)	Aboveground Biomass	213
Webb *et al.* (1985)	Aboveground Biomass	216
Webb *et al.* (1985)	Aboveground Biomass	219
Webb *et al.* (1985)	Aboveground Biomass	221
Webb *et al.* (1985)	Aboveground Biomass	227
Webb *et al.* (1985)	Aboveground Biomass	231
Turner and Gosselink (1975)	Aboveground Biomass	233
Webb *et al.* (1985)	Aboveground Biomass	250
Webb *et al.* (1985)	Aboveground Biomass	255
Webb *et al.* (1985)	Aboveground Biomass	280
Webb *et al.* (1985)	Aboveground Biomass	292
Webb *et al.* (1985)	Aboveground Biomass	298
Webb *et al.* (1985)	Aboveground Biomass	302
Webb *et al.* (1985)	Aboveground Biomass	309
Webb *et al.* (1985)	Aboveground Biomass	316
Webb *et al.* (1985)	Aboveground Biomass	339
Webb *et al.* (1985)	Aboveground Biomass	348
Webb *et al.* (1985)	Aboveground Biomass	355
Webb *et al.* (1985)	Aboveground Biomass	407
Webb *et al.* (1985)	Aboveground Biomass	431
Webb *et al.* (1985)	Aboveground Biomass	452
Turner and Gosselink (1975)	Aboveground Biomass	457
Webb *et al.* (1985)	Aboveground Biomass	464
Turner and Gosselink (1975)	Aboveground Biomass	688
Armitage *et al.* (2017)	Aboveground Biomass	695
Turner and Gosselink (1975)	Aboveground Biomass	738
Armitage *et al.* (2014)	Aboveground Biomass	840
Armitage *et al.* (2017)	Aboveground Biomass	908
Armitage *et al.* (2014)	Aboveground Biomass	920

Armitage *et al.* (2017)	Aboveground Biomass	1080
Shafer and Streever (2000)	Belowground Biomass	276
Shafer and Streever (2000)	Belowground Biomass	525
Shafer and Streever (2000)	Belowground Biomass	587
Shafer and Streever (2000)	Belowground Biomass	843
Shafer and Streever (2000)	Belowground Biomass	864
Shafer and Streever (2000)	Belowground Biomass	1,055
Shafer and Streever (2000)	Belowground Biomass	1,305
Shafer and Streever (2000)	Belowground Biomass	1,421
Shafer and Streever (2000)	Belowground Biomass	1,553
Shafer and Streever (2000)	Belowground Biomass	1,854
Madrid *et al.* (2012)	Belowground Biomass	1,946
Madrid *et al.* (2012)	Belowground Biomass	2,024
Armitage et al. (2014)	Belowground Biomass	2,240
Shafer and Streever (2000)	Belowground Biomass	2,288
Armitage *et al.* (2014)	Belowground Biomass	2,320
Shafer and Streever (2000)	Belowground Biomass	2,331
Shafer and Streever (2000)	Belowground Biomass	2,582
Shafer and Streever (2000)	Belowground Biomass	2,817
Callaway *et al.* (1997)	Soil Carbon	7,371
Callaway *et al.* (1997)	Soil Carbon	9,072
Mangrove		
Hutchison (2016)	Aboveground Biomass	336
Smee (unpublished data)	Aboveground Biomass	700-1,900
Yando *et al.* (2016)	Aboveground Biomass	1,305

Table A2. Texas salt marsh and mangrove carbon sequestration rates.

Wetland type	Sequestration rate (t C ha^{-1} year^{-1})	Location	Source	Citation
Estuarine emergent marsh	1.78	Aransas National Wildlife Refuge, TX	Callaway *et al.* 1997	Chmura *et al.* 2003
Estuarine emergent marsh	2.03	San Bernard, TX	Callaway *et al.* 1997	
Salt marsh	0.95	McFaddin National Wildlife Refuge, TX	Cahoon and Lynch, 1993	
Salt marsh	1.01	Mud Island, TX	Bianchi *et al.* 2013	Bianchi *et al.* 2013
Salt marsh	1.25			
Mangrove	2.53			
Mangrove	2.7			