Economic Viability of Blue Carbon Offsets in Coastal North Carolina & Louisiana

by

Natalie Kraft
Leland Moss
Xiaoyun Dong
Yifei Wang

Dr. Curtis Richardson, Advisor

Duke Carbon Offset Initiative, Client

May 2013

Master’s project submitted in partial fulfillment of the requirements for the Master of Environmental Management degree in the Nicholas School of the Environment of Duke University

2013
Abstract

Carbon offsets are becoming a necessary tool in carbon emission reduction. The offsets obtained through sequestration in coastal wetland vegetation and sediment is referred to as blue carbon. Our client, the Duke Carbon Offset Initiative (DCOI), is currently researching blue carbon to help meet Duke University’s goal of carbon neutrality by 2024. Through cost-benefit analyses and stakeholder collaboration a matrix was constructed to a) characterize the current state of blue carbon opportunities in North Carolina and Louisiana and b) guide DCOI’s development of a blue carbon decision. The unit cost of a blue carbon project in North Carolina is 170 times greater than the cost in Louisiana, mainly due to the lack of wetland restoration infrastructure in North Carolina. Environmental factors, such as land conversion and sea level rise, have a significant effect on the feasibility of the blue carbon projects. Although net wetland loss rate is low in North Carolina, the total converted wetland area is large. These areas are undesirable for blue carbon projects as they lack permanence. A risk analysis shows that in the Albemarle-Pamlico Peninsula, there are low elevation counties with a lower wetland replacement rate; these areas are more prudent choices for blue carbon project sites. In addition, an analysis of sea level rise impacts indicates that due to smaller critical tidal range, Louisiana has a higher carbon sequestration rate than North Carolina when sea level rises from 0.1-1 cm/year, not taking into account natural disturbances. Recommendations from this broad assessment of blue carbon include identifying potential sites for economical pilot studies and monitoring policy developments.
# Table of Contents

**ABSTRACT** .................................................................................................................. 2

**INTRODUCTION** ........................................................................................................... 7

- Greenhouse Gas Reduction ............................................................................................. 7
- Importance of Wetlands .................................................................................................. 8
- Current Policies ................................................................................................................ 9
  - Lack of Regulatory Structure ....................................................................................... 10
  - California Carbon Market ........................................................................................... 11

**BLUE CARBON PROJECT** .......................................................................................... 13

- Project Goals .................................................................................................................... 13
- Work Accomplished in Louisiana .................................................................................... 15

**MATRIX DESIGN** ........................................................................................................ 19

- Potential Partners .......................................................................................................... 20
- Methodology/Law/Policy .................................................................................................. 20
- Wetland Restoration Options .......................................................................................... 22
- Costs & Benefits .............................................................................................................. 23

**ANALYSIS OF COASTAL WETLANDS IN NORTH CAROLINA** .................................. 28

- Research Goals .............................................................................................................. 28
- Characterization of Coastal Wetlands in North Carolina .................................................. 28

**Mapping Analysis** ....................................................................................................... 30

- Data Input ...................................................................................................................... 30
- Annual Carbon Loss ....................................................................................................... 30

**THE ALBEMARLE-PAMLICO PENINSULA** .................................................................. 33

- Modeling Wetland Change ............................................................................................ 37
- Detailed Wetland Change Analysis ................................................................................... 40
  - Vulnerability Assessment .............................................................................................. 41
  - Risk Analysis ................................................................................................................ 43

**SEA LEVEL RISE EFFECTS** ........................................................................................ 45

- Target Species and Study Areas ..................................................................................... 47
- A Simple Model of Sea Level Rise .................................................................................. 50
- The Marsh Equilibrium Model ....................................................................................... 52
  - Morris Model Description .......................................................................................... 52
  - Conclusions on Sea Level Rise .................................................................................... 55

**NEXT STEPS** .............................................................................................................. 61

**ACKNOWLEDGEMENTS** ............................................................................................. 62

**REFERENCES** .............................................................................................................. 63
List of Tables

Table 1. Coastal wetland acreage in Louisiana by parish..................................................17

Table 2. Carbon sequestration, storage, and density results sorted by peer-reviewed paper and location. ......................................................................................................................................................18

Table 3. A general matrix of factors to consider when planning a blue carbon project.
Site Specific (SS) cannot be determined in a broad sense and would be filled in on a project-by-project basis............................................................................................................................................19

Table 4. A list of potential partners for Duke to collaborate with on blue carbon projects based on geographic location..................................................................................................................................................20

Table 5. Costs and permanence for various wetland restoration methods..........................27

Table 6. Net wetland increases from other land types in the Albemarle-Pamlico Peninsula, NC from 1992 to 2006. .................................................................................................................................37

Table 7. Population change in the five counties of Albemarle-Pamlico Peninsula, NC from 1992 to 2006. .........................................................................................................................................................40

Table 8. Land use change between 1992 and 2006 in Albemarle-Pamlico Peninsula, NC by county............................................................................................................................................................40

Table 9. Net land type increase rate and net land type conversion rate to wetland. ............41

Table 10. Potential factors that cause wetland loss in Albemarle-Pamlico Peninsula, NC by county...........................................................................................................................................................43

Table 11. The effect of net sea level rise on salt marshes in North Carolina. .......................51
List of Figures

Figure 1. Wetland carbon storage potential compared to other ecosystems (Tierra Resources 2012) ........................................................................................................ 7

Figure 2. The coastal watersheds of the continental United States. Blue carbon projects are being researched along the Gulf of Mexico (light green) and the South Atlantic (purple), where salt marshes, mangrove forests, and seagrass beds are the dominant coastal habitats. The rocky shorelines found in the North Atlantic, the Pacific Northwest, and California are not suitable for blue carbon initiatives as carbon sequestration is limited (EPA 2012a) .................................................................................. 14

Figure 3. Wetland loss and gain over the next 50 years along the Louisiana coast (Louisiana’s Comprehensive Master Plan for a Sustainable Coast 2012) ............. 16

Figure 4. Coastal wetland loss in Chauvin, Terrebonne Parish, Louisiana between 1990 and 2011. The red outline here is showing the total property being assessed and the green is representative of the land present during each year, clearly eroding over the 21-year period ........................................................................................................ 17

Figure 5. The 20 coastal counties of North Carolina that are covered by CAMA (DCM 2007) .................................................................................................................. 29

Figure 6. Coastal wetland areas in North Carolina in 1992. Total wetland area is 865,268 hectares ........................................................................................................ 31

Figure 7. Coastal wetland areas of North Carolina in 2006. Total wetland area is 862,581 hectares ........................................................................................................ 32

Figure 8. Distribution of wetland types in the Albemarle-Pamlico Peninsula (DCM 2008) .................................................................................................................. 34

Figure 9. Coastal wetland areas in the Albemarle-Pamlico Peninsula, NC in 1992. The total wetland area is 299,630 hectares ..................................................................... 35

Figure 10. Coastal wetland areas in the Albemarle-Pamlico Peninsula, NC in 2006. The total wetland area is 298,786 hectares ..................................................................... 36

Figure 11. Increased wetland area in Albemarle-Pamlico Peninsula, NC from 1992 to 2006. The total area that is converted from other land types to wetland is 42,050 hectares .................................................................................................................. 38

Figure 12. Decreased wetland area in Albemarle-Pamlico Peninsula, NC from 1992 to 2006. The total area that is converted from wetland to other land types is 42,895 hectares .................................................................................................................. 39

Figure 13. Linear relationship between wetland replacement rate and elevation ........ 44

Figure 14. Salt marshes in Albemarle-Pamlico Peninsula, NC in 2006. The total salt marsh area is 29,302 hectares ......................................................................... 48
Figure 15. Salt marshes in Dare and Hyde counties, NC in 2006. The total salt marsh area in the two counties is 26,622 hectares.................................................................49

Figure 16. The effect of net sea level rise on salt marsh area..........................................................51

Figure 17. The relationship between mean high tide, marsh surface depth, and mean sea level (Morris and Sundareshwar 2002).................................................................53

Figure 18. Rate of carbon sequestration in Hyde and Dare counties, North Carolina........56

Figure 19. Rate of carbon sequestration in central Louisiana (soil age = 750 years).............56

Figure 20. Rate of carbon sequestration in eastern coast of Louisiana (soil age = 2000 years)................................................................................................................57

Figure 21. Rate of carbon sequestration in western part of Louisiana (soil age = 4500 years)................................................................................................................57

Figure 22. Comparison of carbon sequestration rate between North Carolina and Louisiana under the sea level rise of 0.3 cm/year: ..............................................................59

Figure 23. Comparison 2 of carbon sequestration rates and sea level rise between North Carolina and Louisiana..................................................................................60
Introduction

Greenhouse Gas Reduction

There are a variety of ways to reduce a carbon footprint – the primary method being to directly limit the amount of greenhouse gases (GHGs) emitted. After technologically or economically exhausting that option, the next path is offsetting the remaining emissions. Offsets come in many forms, but the core concept is to capture or sequester, in another location, the same amount of carbon (or GHG equivalent) being emitted. One common offset type is preserving or reforesting a heavily deforested area. “Blue carbon” is a specific type of offset derived from mangrove, seagrass, and salt marsh restoration and/or preservation where carbon is sequestered both in the soil and in the plants themselves (Figure 1) (Siikamäki et al. 2012). The anoxic state of wetland soils allows for the sequestration of carbon by inhibiting decomposition (Kristensen and Bouillon 2008). While blue carbon projects show promise for carbon offsets, little is known about how carbon sequestration and capacity in coastal wetlands will change due to anthropogenic disturbance and sea level rise.

Figure 1. Wetland carbon storage potential compared to other ecosystems (Tierra Resources 2012).
Importance of Wetlands

The biophysical ecology of blue carbon includes all coastal wetland areas, ranging from shallow seagrass beds, to salt marshes, to mangrove forests. Southeast Asia has approximately half of the world’s mangroves and a quarter of the global seagrass area, making it a primary center of study for blue carbon (Siikamäki et al. 2012). All three blue carbon ecosystems have been studied from numerous perspectives, but the literature on carbon sequestration capacity is limited, partially due to structural variability. In other words, a salt marsh in one area may sequester a vastly different amount of carbon than another salt marsh one state away because of species composition, nutrient availability, and/or other limiting biotic and abiotic factors. This is also true for mangrove forests and seagrass beds, resulting in wide ranges of carbon sequestration potential estimates. A recent report by Siikamäki et al. (2012) estimates that mangrove forests, salt marshes, and seagrass beds currently hold approximately 42 billion t CO₂ e (tons of carbon dioxide equivalent).

All coastal wetland areas are extremely dynamic ecosystems with constantly changing boundaries. Increasing rates of coastal erosion and subsidence are causing even larger changes to occur. Effects of global climate change, such as sea level rise and more frequent and stronger storms, are exacerbating erosion and subsidence issues in already vulnerable areas like Louisiana (Scavia et al. 2002). Coastal development is also changing the biophysical setting as houses, hotels, and stores are built on top of sand-filled wetlands (Siikamäki et al. 2012). Clear-cutting mangrove forests for development and coastal aquaculture is also common in Southeast Asia and South America (Giesen et al. 1991; FAO 2007). The global loss of mangroves causes approximately 120 million tons of CO₂ emissions every year. Including the loss of salt marshes and seagrass beds worldwide, roughly 215 million tons of CO₂ are returned to the atmosphere due to blue
carbon habitat losses (Siikamäki et al. 2012). Anthropogenic effects can also be seen in manmade boat channels through salt marshes and propeller scars through seagrass beds. These changes to the wetland boundaries often lead to even larger shifts in ecosystem function.

As mangroves have been more thoroughly studied for carbon potential than salt marshes, and are easier to manage than seagrass beds, mangrove ecosystems have received the most attention for economically viable blue carbon projects (Spalding et al. 2010). Globally, salt marshes are estimated to store approximately 393 t C ha\(^{-1}\) (tons of carbon per hectare), slightly less than mangrove forests at 470 t C ha\(^{-1}\). The United States is one of the top five countries with the greatest area of seagrass beds, but seagrasses sequester the least amount of carbon, approximately 72 t C ha\(^{-1}\) (Siikamäki et al. 2012). Unlike mangrove forests and seagrass beds, the global area of salt marshes is poorly documented but roughly estimated at 5,100,000 ha compared to 13,917,000 ha of mangrove forests and 31,900,000 ha of seagrass beds (Siikamäki et al. 2012). The large surface area of seagrass beds makes the ecosystem's contribution to carbon sequestration rather significant despite its low storage capacity. In the United States, mangroves are very geographically limited and seagrass beds have significant logistical challenges, so salt marshes are now being researched for domestic blue carbon projects.

Current Policies

Carbon offsets can only be claimed if the carbon sink would have otherwise been lost. Commonly, this loss refers to development of some kind, such as real estate, aquaculture, or any number of other land uses. However, with blue carbon, the loss of wetland ecosystems to sea level rise and erosion must be taken into account as well. North Carolina and, especially, Louisiana are areas that are losing large stretches of
wetlands to sea level rise every year. This kind of loss complicates how blue carbon offsets can be measured and claimed, so specific sites for projects must be chosen carefully to ensure maximum cost effectiveness. Inland lakes and freshwater wetland systems in North Carolina may also be considered for offset purposes.

**Lack of Regulatory Structure**

Legal mandates for a carbon cap-and-trade system are what create the demand not only for tradable permits but for offsets as well. Without legal backing, demand only comes from a small group of institutions, such as Duke University, that are voluntarily looking to offset their emissions to be environmentally responsible. Currently, there are three primary carbon registries, or voluntary offset programs, in the United States: American Carbon Registry, Verified Carbon Standard, and Climate Action Reserve. At this time, the American Carbon Registry and Verified Carbon Standard have developed a methodology for calculating carbon offsets from wetland restoration (Market Watch 2012). Verified Carbon Standard is considered by many as the world leader in carbon trading, holding over half of the world carbon market shares (Emmett-Mattox 2012).

Blue carbon policy involves an interesting agreement between private and public policymakers. Currently, the U.S. Environmental Protection Agency regulates GHG emissions and offsets through the Clean Air Act, specifically Title V, which is a permitting process for major polluters nationwide (EPA 2011). The Clean Water Act will likely affect blue carbon policy as well because it addresses wetland mitigation. Permanence and ownership will be a delicate issue in the formation of blue carbon policy. For example, in Louisiana, there is contention of property rights between the state and private landowners. As land becomes watery marsh, the ownership changes from private to state (Wilkins and Wascon 1992). Restoration of these marshes for
carbon offset purposes may lead back to private ownership of the land and ownership by a third party, such as Duke, of the carbon rights.

*California Carbon Market*

Rather than belabor the fact that there are no national legal mandates for blue carbon or similar offset types in the United States, a better explanation of these mandates can be provided via the emissions program and carbon offset policies currently being implemented in California. The legal mandate for carbon regulation in California stemmed from the passing of AB 32, also known as the Global Warming Solutions Act of 2006. This act gave administrative authority to the California Environmental Protection Agency’s Air Resources Board (ARB) to implement “market-based compliance mechanisms” (CEPA 2012). The act outlines a series of specific requirements, which include determining the level of statewide emissions in 1990 (427 million metric tons of CO₂) and establishing a regulatory system that will reduce statewide emissions to the 1990 level by 2020. These rules will apply to 360 businesses, which will be freely allotted allowances totaling approximately 90% of current emissions (CEPA 2012).

The ARB is also mandated to develop offset protocols, ensuring that “a registry offset credit must: represent a GHG emission reduction or GHG removal enhancement that is real, additional, quantifiable, permanent, verifiable and enforceable” (CARB 2012a). Currently, the ARB has four compliance offset methodologies: two regarding forestry projects, one for livestock projects, and one addressing reduction of ozone depleting substances (CARB 2012b).

Although not an official mandate, AB 32 authorizes the ARB to approve an offset registry, which would provide more readily available credits to participating companies rather than requiring them to develop their own offset projects. Registry offsets would
then have to be converted to ARB offset credits before being traded in the market. SB 1771, passed in 2000, did not create such a registry but established a nonprofit corporation called the California Climate Action Registry (CAR), which has independently created its own registry through the Secretary of the Resources Agency (CCAR 2000).

The judicial system largely impacts how the aforementioned legal mandates are interpreted and their effectiveness. In regards to the California law, there have already been court cases, such as Association of Irritated Residents (AIR) et al. v. California Air Resources Board (C2ES 2012), which debated whether or not the ARB violated requirements of AB 32 in setting up a market system. AIR believes that the ARB should have set up a carbon tax as a more effective and efficient solution than a carbon market. Future court cases are highly probable in the near future over other mandates within the new legislation.
Blue Carbon Project

Project Goals

The overarching goal of this team based Master’s Project is to determine and evaluate the economic, policy, and logistical issues involved with potential blue carbon offset projects, specifically in Louisiana and North Carolina. The Duke Carbon Offset Initiative (DCOI) is currently researching blue carbon as a potential offset option to help meet Duke University's goal of carbon neutrality by 2024 (Duke Campus Sustainability Committee 2009). DCOI is particularly interested in North Carolina and Louisiana for potential blue carbon projects because of connections to the Duke community. The university is obtaining offsets as part of a private, voluntary offset goal rather than under legal mandate, thus avoiding most policy issues revolving around carbon markets. However, in order to capitalize on potential blue carbon offsets, Duke still must abide by some standard set of guidelines for claiming said offsets.

In the United States, the Atlantic and Gulf of Mexico coastlines offer the greatest potential for blue carbon projects (Figure 2). The Gulf of Mexico coast is the premier area for domestic blue carbon offset projects because it is lined with marshland from Texas to Florida, where seagrass beds and mangrove forests become abundant. The southern half of the Atlantic coast is predominantly wetland as the wide continental shelf minimizes wave action, promoting soft sediment habitats rather than rocky shorelines. Georgia and South Carolina have the highest acreage of marshland on the eastern seaboard, composing approximately 400,000 hectares combined (Bertness 2007). Marshland is present all the way to Maine but is much less prevalent north of New York, where colder temperatures and a narrower continental shelf limit wetland habitat potential. Blue carbon has great potential for carbon offsets and can provide additional benefits in the form of ecosystem services by preserving existing wetlands that would
otherwise erode away or become developed without action (Laffoley and Grimsditch 2009).

Figure 2. The coastal watersheds of the continental United States. Blue carbon projects are being researched along the Gulf of Mexico (light green) and the South Atlantic (purple), where salt marshes, mangrove forests, and seagrass beds are the dominant coastal habitats. The rocky shorelines found in the North Atlantic, the Pacific Northwest, and California are not suitable for blue carbon initiatives as carbon sequestration is limited (EPA 2012a).

This project will be expanding upon the progress made by previous Duke environmental students, looking at the economic feasibility of blue carbon as a broader offset initiative while also factoring in the benefits gained from the ecosystem services that blue carbon efforts could provide. When considering the economic feasibility, it is necessary to take into consideration the opportunity costs of what the land could possibly be used for instead of blue carbon projects (Murray et al. 2011). As Murray et
al. (2010) discuss, blue carbon is currently unable to economically outcompete the construction of hotels or other real-estate endeavors that will net large amounts of revenue. However, if the offset market is priced high enough, blue carbon initiatives will likely be financially competitive with coastal agriculture and aquaculture.

Work Accomplished in Louisiana

During the summer of 2012, two members of this team, Natalie Kraft and Leland Moss, spent eight weeks in coastal Louisiana to further develop this project. Louisiana and the Mississippi River Delta are especially important to consider for blue carbon potential because high erosion rates are resulting in the loss of approximately 75 km² of coastal wetland each year (Figure 3 and Table 1) (USGS 2013). Research into blue carbon offset protocols was greatly enhanced through communication and work with Restore America’s Estuaries as they continued to develop their national protocol through the Verified Carbon Standard. A grant proposal to the Society of Environmental Toxicology and Chemistry (SETAC) was submitted over the summer in collaboration with Matrix New World Engineering, Inc. and the University of Louisiana at Lafayette to execute a pilot study in Chauvin, Terrebonne Parish, Louisiana (Figure 4). Field measurements of carbon sequestration capacity, erosion rates, etc. would have been taken at the project site to gain more specific data than was found during literature reviews (Table 2). Even though this pilot study did not go forward due to lack of funding, the collaboration and data brought together are very valuable in planning potential future projects.

Leland and Natalie also contributed to the additionality section of the new methodology Restore America’s Estuaries was developing through the Verified Carbon Standard, by assessing regional viability of projects based on the National Estuary Programs. Although the official methodology has not been published yet, this gives
confidence in discussing it as an option for Duke and comparing it to the American Carbon Registry methodology. In addition to getting this policy related experience Leland and Natalie also did actual plantings both with a private firm (Matrix New World Engineering), a non-profit (Restore the Earth), and government entities (BTNEP and a local parish). This experience allowed for better understanding of how actual restorations will be implemented and what adjustments may need to be made in order to make them viable as carbon projects.

**Figure 3.** Wetland loss and gain over the next 50 years along the Louisiana coast (Louisiana's Comprehensive Master Plan for a Sustainable Coast 2012).
Table 1. Coastal wetland acreage in Louisiana by parish.

<table>
<thead>
<tr>
<th>Parish</th>
<th>Wetlands 2012 (acres)</th>
<th>Total Area 2012 (acres)</th>
<th>Percentage Wetland</th>
<th>Wetlands 2004 (acres)</th>
<th>Total Area 2004 (acres)</th>
<th>Percentage Wetland</th>
<th>Wetland Lost (acres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cameron</td>
<td>682734</td>
<td>1050269</td>
<td>0.4629936</td>
<td>87048</td>
<td>778356</td>
<td>0.1118357</td>
<td>-298434</td>
</tr>
<tr>
<td>Vermilion</td>
<td>385482</td>
<td>832586</td>
<td>0.5684414</td>
<td>55376</td>
<td>352571</td>
<td>0.1570634</td>
<td>-172490</td>
</tr>
<tr>
<td>Iberia</td>
<td>227866</td>
<td>400861</td>
<td>0.6645810</td>
<td>51677</td>
<td>439805</td>
<td>0.1174998</td>
<td>-241483</td>
</tr>
<tr>
<td>St. Mary</td>
<td>293160</td>
<td>441120</td>
<td>0.6767418</td>
<td>173164</td>
<td>945527</td>
<td>0.1831402</td>
<td>-467678</td>
</tr>
<tr>
<td>Terrebonne</td>
<td>640842</td>
<td>946952</td>
<td>0.6726065</td>
<td>108499</td>
<td>752161</td>
<td>0.1442497</td>
<td>-398002</td>
</tr>
<tr>
<td>Lafourche</td>
<td>506501</td>
<td>753042</td>
<td>0.3760469</td>
<td>23798</td>
<td>302805</td>
<td>0.0785918</td>
<td>-90198</td>
</tr>
<tr>
<td>Jefferson</td>
<td>113996</td>
<td>303143</td>
<td>0.5353558</td>
<td>107599</td>
<td>522914</td>
<td>0.2057680</td>
<td>-248660</td>
</tr>
<tr>
<td>Plaquemines</td>
<td>356259</td>
<td>665462</td>
<td>0.6500563</td>
<td>160448</td>
<td>1050039</td>
<td>0.1528019</td>
<td>-522286</td>
</tr>
<tr>
<td>St. Bernard</td>
<td>219411</td>
<td>308390</td>
<td>0.7114724</td>
<td>86373</td>
<td>301514</td>
<td>0.2864643</td>
<td>-133038</td>
</tr>
</tbody>
</table>

Figure 4. Coastal wetland loss in Chauvin, Terrebonne Parish, Louisiana between 1990 and 2011. The red outline here is showing the total property being assessed and the green is representative of the land present during each year, clearly eroding over the 21-year period.
Table 2. Carbon sequestration, storage, and density results sorted by peer-reviewed paper and location.

<table>
<thead>
<tr>
<th>Location</th>
<th>Author</th>
<th>Sequestration Rate (ton/ha*yr)</th>
<th>Carbon Storage (ton/ha)</th>
<th>Carbon Density (ton/ha*m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Past</td>
<td>Current</td>
<td>Future</td>
</tr>
<tr>
<td>MD</td>
<td>Hussein et al.</td>
<td>0.032 +/- 0.006</td>
<td>0.092 +/- 0.025</td>
<td>0.441 +/- 0.179</td>
</tr>
<tr>
<td>Gulf of Mexico</td>
<td>Engle et al.</td>
<td></td>
<td>0.304</td>
<td></td>
</tr>
<tr>
<td>LA</td>
<td>Chmura et al.</td>
<td>0.367</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC</td>
<td>Chmura et al.</td>
<td>0.089</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TX, FL, MS</td>
<td>Chmura et al.</td>
<td>0.148</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MD</td>
<td>Chmura et al.</td>
<td>0.316</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northwest FL</td>
<td>Choi et al.</td>
<td></td>
<td></td>
<td>143.3 +/- 66.1</td>
</tr>
</tbody>
</table>


Matrix Design

As no environmental decision can be made in complete isolation, the research and recommendations of this report have been formed into a matrix of interconnected pieces (Table 3). These pieces are described below and do not need to be considered sequentially while evaluating blue carbon projects. Every specific project will have its own unique circumstances that may limit other decisions. For example, some of the potential partners listed limit their work to certain geographic areas, like the Mississippi Delta and therefore are not applicable to projects in North Carolina.

| Table 3. A general matrix of factors to consider when planning a blue carbon project. Site Specific (SS) cannot be determined in a broad sense and would be filled in on a project-by-project basis. |
|---------------------------------|------|-----|-----|----------------|------|
| **Matrix New World**            |      |      |      |                |      |
| Gulf Saver Bags                 | ACR  | $500,000 | SS  | LA  | SS  | Medium |
| Spartina plugs                  | ACR/VCS | $450,000 | SS  | LA  | SS  | Short  |
| **RAE**                         |      |      |      |                |      |
| Spartina plugs                  | VCS  | $450,000 | SS  | NC/LA | SS  | Short  |
| Seagrass meadow restoration     | VCS  | SS  | NC  | SS  |      |
| **TNC**                         |      |      |      |                |      |
| Oyster reefs                    | VCS/ACR | $6,000,000 | SS  | NC/LA | $85,000 (SS) | Long  |
| Spartina plugs                  | VCS/ACR | $450,000 | SS  | NC/LA | SS  | Short  |
| **Tierra Resources**            |      |      |      |                |      |
| Spartina plugs                  | ACR  | $450,000 | SS  | LA  | $60,000 | Short |
| **NC Coastal Fed**              |      |      |      |                |      |
| Spartina plugs                  | VCS  | $450,000 | SS  | NC  | SS  | Short  |
| Oyster reefs                    | VCS  | $450,000 | SS  | NC  | SS  | Long   |
Potential Partners

National potential partners that would be less limited by the location chosen include larger non-profits such as The Nature Conservancy, World Wildlife Fund, and Restore America’s Estuaries (RAE) (Table 4). Partners in the North Carolina area could be Albermarle-Pamlico National Estuary Partnership (APNEP), The North Carolina Coastal Federation, and/or North Carolina Land Trust. In Louisiana, government partners include Barataria-Terrebonne National Estuary Program (BTNEP). There are also private companies in Louisiana with expertise in wetland restoration and blue carbon projects, such as Matrix New World Engineering, Inc. and Tierra Resources, LLC. However, depending on the arrangement, partnering with private companies may incur higher costs. Potential partners may be financial partners, able to provide funding for blue carbon projects, or on-the-ground partners, actually participating in the restoration and monitoring.

Table 4. A list of potential partners for Duke to collaborate with on blue carbon projects based on geographic location.

<table>
<thead>
<tr>
<th>LA Partners</th>
<th>NC Partners</th>
<th>Partners for both</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tierra Resources, LLC</td>
<td>APNEP</td>
<td>The Nature Conservancy</td>
</tr>
<tr>
<td>Matrix New World Engineering, Inc.</td>
<td>The NC Coastal Federation</td>
<td>World Wildlife Fund</td>
</tr>
<tr>
<td>BTNEP</td>
<td>NC Land Trust</td>
<td>RAE</td>
</tr>
</tbody>
</table>

Methodology/Law/Policy

All carbon offsets must abide by rules and regulations set forth by recognized carbon standards, such as the American Carbon Registry or the Verified Carbon Standard. These agencies develop and certify methodologies for offset projects to follow in order to be accredited and transferable in a market. As blue carbon is still in the development stages, there are fundamental challenges and questions that will arise if a
project is pursued. One challenge is determining which methodology to use; this will require anticipating future carbon laws and policies in the United States. Duke may also experience some logistical issues with using certain methodologies as Duke plans to create and keep their own offset credits without ever needing to participate in a market. Because Duke is not trying to sell their created offset credits, they could develop a methodology of their own, circumventing the carbon standards altogether; however, doing so would require significant time, money, and research and the final methodology would be intensely scrutinized and possibly not recognized by national carbon registries. Using an already established methodology is recommended for blue carbon projects that Duke may pursue in the future.

As Duke is assessing potential blue carbon sites across the country, they must decide which carbon standard and methodology suits their criteria best. The methodology developed by the American Carbon Registry only applies to the Mississippi Delta whereas the Verified Carbon Standard’s methodology is nationwide. The ACR methodology can be found at: [http://americancarbonregistry.org/carbon-accounting/restoration-of-degraded-deltaic-wetlands-of-the-mississippi-delta](http://americancarbonregistry.org/carbon-accounting/restoration-of-degraded-deltaic-wetlands-of-the-mississippi-delta). The VCS methodology will not be officially released until June, but since some of the group members have worked with it already as mentioned previously it is discussed as a viable option. Using the VCS methodology is recommended because of the freedom it would allow Duke in their search for suitable blue carbon project locations. The national standard may also be more applicable in future carbon policies, safeguarding Duke’s investments over time.

How the California market potentially incorporates blue carbon will be a key indicator of how blue carbon may be addressed at the national level; however, variations in state laws must be taken into consideration. Under the North Carolina
Coastal Zone Management Plan (1974), the state has certain rights to limit development and construction on coastal land. In Louisiana, the state owns waters adjacent to coastal marshlands, so creating new marsh areas may require extensive cooperation between Duke and state agencies to avoid any property right issues (Louisiana’s Comprehensive Master Plan for a Sustainable Coast 2012). This relates back to Duke determining how they want the ownership of the property to be arranged. Options include paying the current property owner for the offset credits, purchasing an easement, and purchasing the land with or without partners. An easement would help to enable legal recourse if the credits were no longer supported in the future but would not provide as much control as complete ownership. The safest, as far as ensuring credits, would be to have a third party purchase the land and guarantee the credits, but this would likely also be the most costly choice.

The final piece in assessing the methodology is understanding that, regardless of the potential partners and methodology, monitoring costs will vary based on the type of project. A main difference in monitoring costs is the location of the project in relation to equipment, materials, and personnel. For example, a project that requires any type of marine transportation (i.e. boats and barges) has a heavily increased cost both for constructing the restoration and for subsequent returns to assess the carbon storage.

**Wetland Restoration Options**

Assuming the likely choice of a salt marsh restoration, for logistical reasons described earlier in this report, there are several restoration options that vary in cost and speed of restoration. The main choices are *Spartina* plugs, *Spartina* bags, boxes/baskets of *Spartina*, and oyster reef restoration/creation. There are many other restoration choices, but these are the most popular choices and can be implemented
individually or in combination with each other. The least expensive option is the *Spartina* plugs, but these also tend to take the longest to establish and are the most likely to be wiped out by a storm. *Spartina* plugs also require more frequent maintenance in the beginning. The *Spartina* bags provide better stability to the shoreline and are filled with organic fertilizers that promote faster plant growth. For restoration sites that are rapidly eroding or experience higher tidal energy, wire baskets weighted down with sand bags and topped with *Spartina* plugs or bags are the best option for artificial marsh construction. Oyster reefs also are a good option for high-energy coastlines as they provide an excellent physical buffer. Oyster reefs will create better conditions for marsh areas to naturally rebuild. The marsh restoration could be completed relatively quickly if oyster reefs were used in conjunction with *Spartina* plugs/bags.

**Costs & Benefits**

To determine the economic viability of a blue carbon project site, in terms of being a cost effective carbon offset, the first step is looking at previous research and the ecology of viable regions. Many areas around the world have started to include mangrove stands as possible carbon offsets, but only based on what is above ground in the trees themselves, not including carbon sequestration capacity of the soil. Blue carbon initiatives seek to incorporate this important underground aspect in order to make wetland preservation more economically appealing. Blue carbon is especially necessary in areas like Louisiana where mangroves are not widely present but marshland abounds, as marshes have very little above-ground sequestration but great opportunity for carbon sequestration below the water (Sifleet *et al*. 2011). Blue carbon projects in Louisiana would also serve a second purpose through erosion control and
wetland restoration along a coastline that is losing 75 square kilometers of land each year (USGS 2013).

A basic benefit equation was developed while working with Matrix New World Engineering, Inc. to choose potential blue carbon project sites. This equation was designed to determine the amount of carbon that would be sequestered through true sequestration as well as prevention of emission from wetland soil.

\[(S_O + S_a)(n \times r) + (R \times S_O)\]

The variable \(S_O\) is the currently existing wetland area that is potentially lost if the restoration project does not occur. \(S_a\) is the newly created marsh due to the restoration. These two areas are multiplied by the number of years \(n\) and the sequestration rate \(r\) in order to determine the amount of carbon sequestration that occurs after project completion. The area potentially lost \(S_O\) multiplied by the carbon storage \(R\) is then added to this in order to incorporate the carbon prevented from being lost, or stop-loss. If the marsh under consideration had reached its carbon storage capacity, the first \(S_O\) would be removed, but as this is rarely the case, it usually will be included.

\[\frac{C_V + C_F}{(S_O + S_a)(n \times r) + (R \times S_O)}\]

To make it a cost-benefit equation, the numerator above is a combination of the variable cost, based on the per acre restoration cost \((C_V)\), and the fixed cost \((C_F)\), which would be, for the most part, the monitoring costs. This equation can easily be used for project-by-project assessments by entering the proposed project into \(S_a\), determining \(S_O\) from the erosion rate at the site, and determining sequestration rate and storage – optimally, on a site-by-site basis, but if that is not possible, by using the model described later.
\[ S_o = (RLC \times S_a) \]

The flaw with this equation is that it really only works for specific projects. However, the idea was to create an equation that applied to a general regional assessment of North Carolina and Louisiana. In order to make this, the equation was adjusted, making the \( S_o \) variable proportional to the \( S_a \) variable rather than confining \( S_o \) to a specific amount; in actuality, \( S_o \) is site specific, but it can be shown as proportional to state-wide loss. This was done by replacing \( S_o \) with \( S_a \) multiplied by the Relative Loss Coefficient (RLC).

\[ RLC = (Area \ Lost \ Yearly/Coastal \ Zone) \]

The Relative Loss Coefficient is the area lost yearly, determined by the state, divided by coastal zone. For North Carolina, yearly loss is 1.9 km\(^2\)/year (Pendleton and Donato 2012) and for Louisiana it is 75 km\(^2\)/year (USGS 2013). The coastal zone is slightly more difficult to determine. Although NOAA (1975) has the coastline length of each state – 5,430 km for North Carolina and 12,423km for Louisiana – that is only a distance rather than an area, so the shoreline depth has to be determined. NOAA (2012) also has a state-by-state breakdown of this, with some states defining it and some not. Unfortunately, there is no reliable consistency between the states that do have a shoreline depth value. North Carolina has a variable zone and Louisiana does not use one, so for the purposes of this analysis, a common distance among other states – 100 ft or 0.0003 km – was chosen. This means the RLC for North Carolina is 0.117 and for Louisiana, it is 2.01. If the coastal depth is increased, this RLC will decrease causing the stop-loss portion of the equation to have a reduced impact.

\[ \frac{C_V + C_F}{((RLC \times S_a) + S_a)(n \times r) + (R \times (RLC \times S_a))} \]

\[ NC \ (1\ ha): \ \frac{500,000+60,000}{((0.117+1)(1+0.089)+(24.24+(0.117+1)))} = \$755,774 \ per \ ton \]
Above shows the equation filled in for both North Carolina and Louisiana with the difference between 1 hectare and 50 hectares for each. Scaling up beyond 50 hectares does not reduce the cost per ton anymore because of the inability to have a decreasing variable cost. Although the equation is fully functional, the main flaw with the results is the cost. Projects like this have not, to our knowledge, been done on a large scale, so there is no way to determine what the cost reduction would be as the project is scaled up. This equation assumes that the planting is done through the entire area, but in actuality, in large-scale projects, planted area could be reduced and allowed to fill in naturally to greatly reduce costs. However, there is no way to determine what that ratio would be without a pilot study. What this equation does show is the proportional cost difference between North Carolina and Louisiana and how much lower Louisiana is per ton assuming comparable costs. An additional piece missing from this equation is the possible loss of carbon released by the wetland as it fluctuates between carbon sequestration and carbon emission.

Erosion rates can be calculated through geographic information systems (GIS) mapping for specific sites (Figure 4), but average erosion and sequestration rates can be determined through an extensive literature review. Project costs can also be assessed but are highly variable depending on site location and size as well as the restoration method used (Table 5).
Table 5. Costs and permanence for various wetland restoration methods.

<table>
<thead>
<tr>
<th>Restoration Method</th>
<th>Creation Costs</th>
<th>Permanence</th>
<th>Longevity (maintenance)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Labor Intensity</td>
<td>Cost/Meter (materials)</td>
<td></td>
</tr>
<tr>
<td>Spartina plug</td>
<td>Very Low</td>
<td>45</td>
<td>Low (50%)</td>
</tr>
<tr>
<td>Gulf Saver Bag</td>
<td>Low</td>
<td>50</td>
<td>Moderate</td>
</tr>
<tr>
<td>HESCO box</td>
<td>Moderate</td>
<td>65</td>
<td>Moderate</td>
</tr>
<tr>
<td>Oyster reef (rebar)</td>
<td>High</td>
<td>600</td>
<td>High</td>
</tr>
<tr>
<td>Oyster reef (cement)</td>
<td>Very High</td>
<td></td>
<td>High</td>
</tr>
</tbody>
</table>

Based on what is known thus far, Louisiana projects, on a larger scale, could be created at a reasonable price. Monitoring costs are considerably variable depending on what matrix selection choices are made. The biggest expense would be becoming accredited through a methodology, which is in the range of $60,000-$100,000 (according to verbal communication with Tierra Resources). Conversely, if Duke did its own monitoring through graduate students and researchers, the price could be much lower, but would require greater commitment and involvement from Duke. North Carolina’s potential is still being assessed but due to the lack of wetland restoration infrastructure, costs are expected to be higher in North Carolina than in Louisiana.
Analysis of Coastal Wetlands in North Carolina

Research Goals

The analysis of blue carbon feasibility in North Carolina included three main objectives: 1) mapping the coastal wetland areas suitable for potential restoration/preservation projects, 2) modeling sea level rise and the effects on coastal wetlands, and 3) performing localized risk and economic analyses. Mapping efforts quantified historical wetland conversion and estimated the potential carbon release due to wetland conversion and/or degradation. Modeling aided in predicting future conditions and changing trends in wetland preservation/restoration. The risk and economic analyses identified potentially suitable regions within the state for blue carbon projects.

Characterization of Coastal Wetlands in North Carolina

North Carolinian coastal wetlands sit upon geologic remnants of the Appalachian Mountains and comprise one of the most significant wetland areas in the United States (Sawyer 2010). North of Cape Lookout is considered the Northern Coastal Province, consisting of younger, unconsolidated sediment deposits, and south of the Cape is the Southern Coastal Province, where older sediments form steeper slopes (Riggs 2001). The primary threats to this wetland network are land conversion due to urban and agricultural development as well as inundation due to rapid sea level rise.

Spurred by the passing of the federal Coastal Zone Management Act (CZMA) in 1972, North Carolina enacted the state Coastal Area Management Act (CAMA) in 1974 with the goal of protecting the state’s coastal and public trust resources (DCM 2007). CAMA established the Coastal Resources Commission (CRC), charged with designating “Areas of Environmental Concern,” or AECs, within North Carolina’s 20 coastal counties.
(Figure 5). An AEC is defined as “an area of natural importance: it may be easily destroyed by erosion or flooding; or it may have environmental, social, economic or aesthetic values that make it valuable to [North Carolina]” (DCM 2007). The epicenter of the wetland network in North Carolina is the Albemarle-Pamlico Peninsula, which is comprised of five coastal counties: Dare, Hyde, Beaufort, Tyrell, and Washington. The wetlands on this peninsula provide wildlife habitat, serve as a flood buffer, prevent shoreline erosion, improve water quality, and sequester carbon. However, due to subsidence and climate change, coastal wetlands are extremely vulnerable to storm flooding and anthropogenic disturbance (Gedan and Silliman 2009).

Figure 5. The 20 coastal counties of North Carolina that are covered by CAMA (DCM 2007).
**Mapping Analysis**

To estimate potential carbon emissions from the conversion of coastal wetlands in North Carolina, the rate of area conversion (km² lost per year) was calculated via GIS mapping.

**Data Input**

Land cover and land type data were obtained through The National Land Cover Datasets from 1992 and 2006, containing Landsat Thematic Mapper satellite data (USGS 2012). Coastal wetland maps showed that only 27 km² of coastal wetland area was lost in this 14-year period (Figure 6 and Figure 7).

**Annual Carbon Loss**

Globally, the rate of annual wetland loss is 0.7-3% for mangroves, 1-2% for salt marshes, and 0.4-2.6% for seagrasses (Pendleton and Donato 2012). The average rate of annual coastal wetland loss in North Carolina is 1.9 km²/year, approximately 0.02% of land loss for the state, much lower than the global average. Despite the relatively low rate of wetland area loss, the highly variable amount of carbon that may be released due to wetland conversion (25-100%) calls for consideration in the analysis of blue carbon feasibility. However, because coastal wetlands greatly vary in structural complexity, and thus carbon storage capacity, an estimate of all wetland carbon emissions is not estimated here.
Figure 6. Coastal wetland areas in North Carolina in 1992. Total wetland area is 865,268 hectares.
Figure 7. Coastal wetland areas of North Carolina in 2006. Total wetland area is 862,581 hectares.
The Albemarle-Pamlico Peninsula

The Albemarle-Pamlico Peninsula comprises 6637 km² of land and water located in the Northern Coastal Province. Approximately 45% of the peninsula is coastal wetland, predominantly salt marsh (North Carolina County Map 2005). The area hosts a variety of wetland ecosystems (Figure 8) including pocosins, loblolly pine forests, and brackish marsh vegetation (Schafale and Weakley 1990).

Between 1992 and 2006, wetland loss rate within the Albemarle-Pamlico Peninsula was 0.3% (Figure 9 and Figure 10), approximately 50% higher than the state average percent loss and nearing the average rate of global wetland reduction. This higher rate of wetland loss is likely the result of increased tidal inundation due to sea level rise. The Northern Coastal Province is characterized by stronger tidal energy than its southern counterpart (Riggs 2001). Also, the average elevation of the Peninsula is less than 5 meters and approximately 30% of the Peninsula is below 1 meter in elevation (Poulter 2005). The combination of low elevation and higher tide energy makes wetland restoration and/or preservation an urgent need in the Albemarle-Pamlico Peninsula.
Figure 8. Distribution of wetland types in the Albemarle-Pamlico Peninsula (DCM 2008).
Figure 9. Coastal wetland areas in the Albemarle-Pamlico Peninsula, NC in 1992. The total wetland area is 299,630 hectares.
Figure 10. Coastal wetland areas in the Albemarle-Pamlico Peninsula, NC in 2006. The total wetland area is 298,786 hectares.
Modeling Wetland Change

A discrete change analysis was performed to assess the encroachment of other land uses into wetland areas in the Albemarle-Pamlico Peninsula. The results were used to examine the effectiveness of protection/preservation of coastal wetlands between 1992 and 2006. The assessment is based on classified land cover maps retrieved from the National Land Cover Dataset (NLCD). It should be noted that there are inherent mapping discrepancies as the two NLCD data products have slightly different classification categories. This may have greater impact on the measurement of sparse areas but provides preliminary estimates that are adequate for the purposes of this study.

A comparison of the Albemarle-Pamlico Peninsula land cover maps for 1992 and 2006 show that land use conversion predominantly occurs between forest, agricultural land, and wetlands. A total of 14% of coastal wetland area in the Peninsula has been changed, including restoration and loss. In other words, approximately 420 km$^2$ of other land use types became wetlands, while 429 km$^2$ of wetlands were converted to other land uses (Figure 11 and Figure 12). About 93% of the emerging wetland was previously forest or agricultural lands. Conversely, approximately 74% of coastal wetlands were converted to forest and agricultural lands during the 14-year period. Table 6 shows the net wetland increases from other land types in the Albemarle-Pamlico Peninsula.

Table 6. Net wetland increases from other land types in the Albemarle-Pamlico Peninsula, NC from 1992 to 2006.

<table>
<thead>
<tr>
<th>From</th>
<th>Forest</th>
<th>Agriculture</th>
<th>Water</th>
<th>Non-natural woody</th>
<th>Shrub land</th>
<th>Barren</th>
<th>Developed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetland</td>
<td>72.5</td>
<td>35.8</td>
<td>15.9</td>
<td>-24.7</td>
<td>-71</td>
<td>-1.1</td>
<td>-35.7</td>
</tr>
</tbody>
</table>
Figure 11. Increased wetland area in Albemarle-Pamlico Peninsula, NC from 1992 to 2006. The total area that is converted from other land types to wetland is 42,050 hectares.
Figure 12. Decreased wetland area in Albemarle-Pamlico Peninsula, NC from 1992 to 2006. The total area that is converted from wetland to other land types is 42,895 hectares.
**Detailed Wetland Change Analysis**

From 1992 to 2006, the population of Albemarle-Pamlico Peninsula increased about 15% (Table 7). The fastest population increase was 46% in Dare County (OSBM 1998 and 2006). Population change has a real effect on land use change in the five counties as development increases. For example, development in Tyrell County increased 1843% from 1992 to 2006 (Table 8). Wetlands in Dare and Hyde counties are doubly impacted as they are directly adjacent to open ocean, where the effects of sea level rise and sediment shifting are most prominent. A vulnerability assessment and a risk analysis were developed to analyze land use change in North Carolina. Due to differences in categories from the source data, both analyses are based on the following land types: agriculture, water, developed land, and forest.

**Table 7.** Population change in the five counties of Albemarle-Pamlico Peninsula, NC from 1992 to 2006.

<table>
<thead>
<tr>
<th></th>
<th>Washington</th>
<th>Beaufort</th>
<th>Hyde</th>
<th>Dare</th>
<th>Tyrell</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992 Pop.</td>
<td>14,226</td>
<td>42,905</td>
<td>5,458</td>
<td>23,570</td>
<td>3,879</td>
<td>90,038</td>
</tr>
<tr>
<td>2006 Pop.</td>
<td>13,369</td>
<td>45,964</td>
<td>5,766</td>
<td>34,421</td>
<td>4,287</td>
<td>103,807</td>
</tr>
<tr>
<td>Growth rate</td>
<td>-6.02%</td>
<td>7.13%</td>
<td>5.64%</td>
<td>46.04%</td>
<td>10.52%</td>
<td>15.29%</td>
</tr>
</tbody>
</table>

**Table 8.** Land use change between 1992 and 2006 in Albemarle-Pamlico Peninsula, NC by county.

<table>
<thead>
<tr>
<th></th>
<th>Washington</th>
<th>Beaufort</th>
<th>Hyde</th>
<th>Dare</th>
<th>Tyrell</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture (km²) in 1992</td>
<td>450.2</td>
<td>695.4</td>
<td>483</td>
<td>20.1</td>
<td>290.2</td>
<td>1938.9</td>
</tr>
<tr>
<td>Agriculture (km²) in 2006</td>
<td>407.3</td>
<td>622.6</td>
<td>447.5</td>
<td>21.7</td>
<td>293.2</td>
<td>1792.3</td>
</tr>
<tr>
<td>Agriculture increase (km²)</td>
<td>-42.9</td>
<td>-72.8</td>
<td>-35.5</td>
<td>1.6</td>
<td>3</td>
<td>-146.6</td>
</tr>
<tr>
<td>Agricultural increase rate</td>
<td>-9.5%</td>
<td>-10.5%</td>
<td>-7.3%</td>
<td>8.0%</td>
<td>1.0%</td>
<td>-7.6%</td>
</tr>
<tr>
<td>Water (km²) in 1992</td>
<td>179.4</td>
<td>340.7</td>
<td>2042.5</td>
<td>2206.6</td>
<td>550.8</td>
<td>5320</td>
</tr>
<tr>
<td>Water (km²) in 2006</td>
<td>181.8</td>
<td>341.6</td>
<td>2000.1</td>
<td>2137.6</td>
<td>550.7</td>
<td>5211.8</td>
</tr>
<tr>
<td>Water increase (km²)</td>
<td>2.4</td>
<td>0.9</td>
<td>-42.4</td>
<td>-69</td>
<td>-0.1</td>
<td>-108.2</td>
</tr>
<tr>
<td>Water increase rate</td>
<td>1.3%</td>
<td>0.3%</td>
<td>-2.1%</td>
<td>-3.1%</td>
<td>0.0%</td>
<td>-2.0%</td>
</tr>
<tr>
<td>Developed (km²) in 1992</td>
<td>5</td>
<td>37.2</td>
<td>4.1</td>
<td>42.2</td>
<td>1.4</td>
<td>89.9</td>
</tr>
<tr>
<td>Developed (km²) in 2006</td>
<td>44.2</td>
<td>119.2</td>
<td>46.6</td>
<td>75.7</td>
<td>27.2</td>
<td>312.9</td>
</tr>
<tr>
<td>Developed increase (km²)</td>
<td>39.2</td>
<td>82</td>
<td>42.5</td>
<td>33.5</td>
<td>25.8</td>
<td>223</td>
</tr>
<tr>
<td>Developed increase rate</td>
<td>784.0%</td>
<td>220.4%</td>
<td>1036.6%</td>
<td>79.4%</td>
<td>1842.9%</td>
<td>248.1%</td>
</tr>
<tr>
<td>Forest 1992 (km²)</td>
<td>226.6</td>
<td>883</td>
<td>186.1</td>
<td>79.4</td>
<td>131.3</td>
<td>1506.4</td>
</tr>
<tr>
<td>Forest 2006 (km²)</td>
<td>114.1</td>
<td>620.7</td>
<td>123.3</td>
<td>27.8</td>
<td>65.6</td>
<td>951.5</td>
</tr>
<tr>
<td>Forest increase (km²)</td>
<td>-112.5</td>
<td>-262.3</td>
<td>-62.8</td>
<td>-51.6</td>
<td>-65.7</td>
<td>-554.9</td>
</tr>
<tr>
<td>Forest increase rate</td>
<td>-49.6%</td>
<td>-29.7%</td>
<td>-33.7%</td>
<td>-65.0%</td>
<td>-50.0%</td>
<td>-36.8%</td>
</tr>
</tbody>
</table>
Vulnerability Assessment

The vulnerability assessment compares the net land type increase rate and the net wetland conversion increase rate in each county (Table 9). The two rates can be calculated via the following formulas (for clarity purposes, agriculture in Washington County is used as an example):

Net agriculture increase rate= (Washington agriculture in 2006 - Washington agriculture in 1992)/the total area of Washington

Net agriculture increase rate to wetland= (the area of agriculture converted from wetland in Washington - the area of wetland replaced by agriculture in Washington)/the total area of wetland in Washington in 1992

<table>
<thead>
<tr>
<th>County</th>
<th>Washington</th>
<th>Beaufort</th>
<th>Hyde</th>
<th>Dare</th>
<th>Tyrell</th>
</tr>
</thead>
<tbody>
<tr>
<td>County area (km²)</td>
<td>902.51</td>
<td>2144.43</td>
<td>1587.15</td>
<td>993.47</td>
<td>1009.86</td>
</tr>
<tr>
<td>Wetland area (km²) in 1992</td>
<td>208.20</td>
<td>490.20</td>
<td>899.10</td>
<td>814.30</td>
<td>584.40</td>
</tr>
<tr>
<td>Agriculture increase (km²)</td>
<td>-42.9</td>
<td>-72.8</td>
<td>-35.5</td>
<td>1.6</td>
<td>3</td>
</tr>
<tr>
<td>Net agriculture increase rate</td>
<td>-4.75%</td>
<td>-3.39%</td>
<td>-2.24%</td>
<td>0.16%</td>
<td>0.30%</td>
</tr>
<tr>
<td>Net agriculture increase from wetland (km²)</td>
<td>-15.6</td>
<td>-12.9</td>
<td>-12.4</td>
<td>4.1</td>
<td>1.9</td>
</tr>
<tr>
<td>Net agriculture increase rate from wetland</td>
<td>-7.5%</td>
<td>-2.6%</td>
<td>-1.4%</td>
<td>0.5%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Developed land increase (km²)</td>
<td>39.2</td>
<td>82</td>
<td>42.5</td>
<td>33.5</td>
<td>25.8</td>
</tr>
<tr>
<td>Net developed land increase rate</td>
<td>4.34%</td>
<td>3.82%</td>
<td>2.68%</td>
<td>3.37%</td>
<td>2.55%</td>
</tr>
<tr>
<td>Net developed land increase from wetland (km²)</td>
<td>3.9</td>
<td>8.9</td>
<td>10.5</td>
<td>7.5</td>
<td>5</td>
</tr>
<tr>
<td>Net developed land increase rate from wetland</td>
<td>1.87%</td>
<td>1.82%</td>
<td>1.17%</td>
<td>0.92%</td>
<td>0.86%</td>
</tr>
<tr>
<td>Forest increase (km²)</td>
<td>-112.5</td>
<td>-262.3</td>
<td>-62.8</td>
<td>-51.6</td>
<td>-65.7</td>
</tr>
<tr>
<td>Net forest increase rate</td>
<td>-12.47%</td>
<td>-12.23%</td>
<td>-3.96%</td>
<td>-5.19%</td>
<td>-6.51%</td>
</tr>
<tr>
<td>Net forest increase from wetland (km²)</td>
<td>-44.5</td>
<td>1.2</td>
<td>-8</td>
<td>-7.6</td>
<td>-13.7</td>
</tr>
<tr>
<td>Net forest increase rate from wetland</td>
<td>-21.37%</td>
<td>0.24%</td>
<td>-0.89%</td>
<td>-0.93%</td>
<td>-2.34%</td>
</tr>
</tbody>
</table>
Wetlands are near equally as vulnerable to forest conversion as forests are to wetland conversion (Table 9). The conversion rate from forest to wetland was higher on average than the conversion rate from wetland to forest, possibly because the regeneration of forests is more sensitive to wind damage, fire, storm surge, and other environmental factors (Poulter 2005). Also, sea level rise causes an increase in soil salinity and makes the environment more suitable for the growth of salt or brackish marshes rather than forests. The deforestation rates in the five counties are close to or above 30% (Table 9). Due to the high rates of deforestation and increasing rates of saltwater intrusion in the Peninsula counties, wetland restoration may be more prudent than forest protection efforts.

Agriculture accounts for 27% of the area of the Peninsula based on 2006 NLCD data. Mapping and research also shows that agriculture is common in higher elevation areas and sparse in lower elevations where saltwater intrusion is a threat (Table 9) (Poulter 2005). In Tyrell County, the net agriculture increase rate is equal to the conversion rate to wetlands from agriculture; however in Dare County, the conversion rate is 200% higher than the net agriculture increase rate.

Among the three land types, only urban areas have a consistent positive erosion rate in wetlands. However, the increased rate of developed areas in entire counties is far greater than its growth into wetlands. It can thus be inferred that wetland areas are more likely to withstand urban expansion when compared to agriculture and forests. This provides further evidence that wetlands may be a better option for carbon offsets than forests in North Carolina.
Risk Analysis

The risk analysis addressed several potential threats to wetland preservation sites and demonstrated the determinants. Potential threats include: 1) population growth, 2) urban expansion, 3) agricultural expansion, and 4) elevation declines. By testing the correlations between these factors and wetland loss, we can determine which factor threatens wetlands the most (Table 10). We used replacement rate to measure the wetland deterioration, which equals wetland loss divided by total wetland areas in a county. The equation is: replacement rate = wetland lost area in a county/wetland area in 1992 in the same county. Among the four potential threats, only elevation correlated with replacement rate (p=0.0009). According to a linear equation run via STATA, the wetland loss risk will increase by 4.32% when elevation decreases by 1 m (Figure 13). In the Albemarle-Pamlico Peninsula, coastal wetlands in Hyde, Dare, and Tyrell counties are prudent to be selected as the potential wetland preservation sites. The analysis suggests that when choosing potential blue carbon sites, areas where the wetland conversion rate is high should be avoided. Also, in the Albemarle-Pamlico Peninsula, low elevation land shows a lower replacement rate by other land uses, and thus should be considered for potential blue carbon sites.

Table 10. Potential factors that cause wetland loss in Albemarle-Pamlico Peninsula, NC by county.

<table>
<thead>
<tr>
<th></th>
<th>Washington</th>
<th>Beaufort</th>
<th>Hyde</th>
<th>Dare</th>
<th>Tyrell</th>
</tr>
</thead>
<tbody>
<tr>
<td>County agriculture</td>
<td>-4.75%</td>
<td>-3.39%</td>
<td>-2.24%</td>
<td>0.16%</td>
<td>0.3%</td>
</tr>
<tr>
<td>increase rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>County development</td>
<td>4.34%</td>
<td>3.82%</td>
<td>2.86%</td>
<td>3.37%</td>
<td>2.55%</td>
</tr>
<tr>
<td>increase rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elevation (m)</td>
<td>3.61</td>
<td>5.9</td>
<td>0.5</td>
<td>0.26</td>
<td>0.49</td>
</tr>
<tr>
<td>Population increase</td>
<td>-6.02%</td>
<td>7.13%</td>
<td>5.64%</td>
<td>46.04%</td>
<td>10.52%</td>
</tr>
<tr>
<td>rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 13. Linear relationship between wetland replacement rate and elevation.

**Equation:**

\[ y = 4.3219x + 1.4994 \]

**Statistical values:**

- \( R^2 = 0.92311 \)
- \( P = 0.009 \)
Sea Level Rise Effects

Sea level rise is a key factor that may greatly impact coastal wetland areas. On a global scale, fifty percent of annual marine carbon is released in shallow water ecosystems such as mangrove forests, seagrass meadows, and salt marshes (Durarte et al. 2005). In the United States, North Carolina and Louisiana are expected to have higher rates of sea level rise and therefore are critical areas of study for wetland restoration/preservation and blue carbon. Currently, global sea level rise is approximately 1-2 mm/year (Poulter and Feldman 2009). However, the rate of sea level rise varies greatly with regions. Recent U.S. Geological Survey studies show that the rate of sea level rise in North Carolina is four times higher than the average global rate (Phillips 2012). Also, coastal wetlands in the Gulf of Mexico and South Atlantic are low elevation areas with high vulnerability to flooding and sea level rise. Lastly, due to the acceleration of anthropogenic greenhouse gas emissions and global climate change, the rate of sea level rise is expected to increase over the next century; this is largely caused by water expansion and polar ice/glacier melting due to increasing atmospheric temperatures (NECIA 2007).

Wetland soil is a large carbon reservoir (Donato et al. 2011) as the wet and low oxygen conditions keep organic materials from decomposing and thus prevent the release of sequestered carbon into the atmosphere (Freeman et al. 2011). The carbon sequestration ability of coastal wetlands could increase with greater sediment deposits and/or lower oxygen content. However, understanding how stress-tolerant salt marshes adapt to sea level rise is a difficult undertaking. A moderate rate of sea level rise would carry more solid sediments over a marsh surface and promote soil accretion, which also reduces inundation risks. Low oxygen can be better maintained through extended inundation duration and increased flood frequency affected by sea level rise. However,
when the rate of sea level rise reaches a critical point, marsh plant seedlings cannot survive the degree of saltwater inundation. Also, soil salinity could rise to an intolerable level and irreversibly turn wetlands into barren areas. In addition to the impacts of sea level rise, the increase in CO₂ concentration as well as global temperature can accelerate marsh elevation and increase plant productivity, consequently contributing to the increase in carbon sequestration. (Langley and McKee 2009; Charles and Dukes 2009). The adaption of the salt marshes relies on the extent of sea level rise as well as the combined effects of salt marsh soil parameters and plant productivity. These condition parameters, including: soil accretion rate, soil organic materials content, soil mineral content, tidal amplitude, flood duration, and total suspended solids (TSS), interact with each other and are subject to the rate of sea level rise.

Although carbon sequestration rate changes primarily with the rate of sea level rise, fluctuations in tidal range also have a noticeable effect because the vertical range over which vegetation can grow is determined by tidal range (Morris et al. 2012). In other words, brackish vegetation can grow at higher elevations where there is a large tidal range because the saltwater prevents salt intolerant plants from colonizing. However, frequent and severe tidal flooding can damage even salt marshes (Pennings and Mark 2001). The tidal range in Pamlico Sound is approximately 0-40 cm (NOAA 2013) and flooding patterns depend on atmospheric pressure and wind direction (Stout 1984). As North Carolina faces a higher risk of inundation, the protection of coastal wetlands is extremely important for both ecological and economical reasons.
**Target Species and Study Areas**

The low-lying coastal wetland communities in Louisiana and North Carolina are dominated by salt marshes (Figure 14) (Fish & Wildlife Service 1990). Salt marshes grow across a wide range of latitudes, making them strong study species for evaluating the relationship between sea level rise and wetland structure (Pennings and Mark 2001). Due to their relatively simple community structure and tolerance of tough physical conditions, salt marshes can aid in studying how physical and biological characters interact with natural disturbances (Pennings and Mark 2001). Salt marshes are a key target species in the study of the potential impacts of sea level rise on coastal communities. In North Carolina, Hyde and Dare counties account for approximately 91% of the total salt marsh area in the Albemarle-Pamlico Peninsula (Figure 14 and Figure 15). Salt marshes in these two counties are adjacent to the Sound and therefore are frequently inundated with full-strength seawater that allows for the growth of only the most salt-tolerant plants, such as *Spartina* spp (Figure 15). These particular coastal marshes are critical to coastal protection and if they are lost to sea level rise, larger areas of wetlands further inland may also be diminished. To analyze the effects of sea level rise on the productivity and stability of North Carolina salt marshes, two models were implemented: 1) a simple model addressing sea level rise and sediment accretion/erosion and 2) the Morris Marsh Equilibrium Model.
Figure 14. Salt marshes in Albemarle-Pamlico Peninsula, NC in 2006. The total salt marsh area is 29,302 hectares.
Figure 15. Salt marshes in Dare and Hyde counties, NC in 2006. The total salt marsh area in the two counties is 26,622 hectares.
A Simple Model of Sea Level Rise

The basic assumption of this model is that sedimentation maintains the current accretion rate under the influence of increasing sea level rise. If the sediment accretion keeps pace with sea level rise, marshes can be maintained in their original locations, and coastlines will be less vulnerable to erosion. However, if the sediment accretion rate is slower than sea level rise, marshes will either migrate inland or be lost entirely.

Like sea level rise, sediment accretion rates differ globally. To get an accurate accretion rate at a specific location, Cesium-137, Lead-210, and Carbon-14 profiles from a marsh sediment core are used for analysis (Smith 2009). Plant type, plant age, tidal range, and the rate of sea level rise can impact sediment accretion rates (Callaway and DeLaune 1997). At Grove Creek Basin, North Carolina, the estimated sediment accretion rate is 9.14–18.29 mm/year (Stamey 2012). Vertical accretion rates along the Gulf of Mexico coast average 1.8–8.9 mm/year (Callaway and DeLaune 1997). However, at Breton Sound, Louisiana, the average sediment accretion rate is 4.3–7.7 mm/year (Smith 2009). This higher sediment accretion rate is due to the large quantity of sediment discharge from the Mississippi River. Low marsh has been found to have maximum sediment deposition (Letzsch and Frey 1980). In this model, we used the sedimentation accretion rate by the Duke Wetland Center in 1993. The sedimentation rate in irregularly inundated marshes (“inundated only during spring and storm tides”) is approximately 3.6 mm/year, while regularly inundated marshes (“flooded twice daily by the astronomical tides”) is closer to 2.7 mm/year (Craft and Seneca 1993).

Because rates of sea level rise and sediment accretion vary, this model employs relative sea level rise above marsh platform to estimate how salt marsh areas would change. Expecting that future sea level rise rate will range from 0-1 cm/year, relative sea level rise rate can be calculated to 0-0.73 cm/year. GIS mapping identified the remaining
salt marsh areas that could withstand the assigned relative sea level rise rates (Table 11). A linear relationship between relative sea level rise and remaining salt marsh area was found, estimating the remaining salt marsh area if sea level increases more rapidly than sediment accretion. That is, when relative sea level rise increases by 0.1 m, 28 km$^2$ of coastal wetland will migrate inland or be inundated (Figure 16). Overall, as sea level rises from 0-1 cm/year, at most, approximately 250 km$^2$ of salt marshes would disappear or migrate inland in Hyde and Dare County without preservation efforts.

Table 11. The effect of net sea level rise on salt marshes in North Carolina.

<table>
<thead>
<tr>
<th>Relative sea level rise (m)</th>
<th>Salt marsh area (km$^2$)</th>
<th>%</th>
<th>CO$_2$ lost (ton/km$^2$/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>266.2</td>
<td>100</td>
<td>3538</td>
</tr>
<tr>
<td>0.05</td>
<td>222.3</td>
<td>83.5</td>
<td>540</td>
</tr>
<tr>
<td>0.1</td>
<td>215.6</td>
<td>81.0</td>
<td>701</td>
</tr>
<tr>
<td>0.15</td>
<td>206.9</td>
<td>77.7</td>
<td>943</td>
</tr>
<tr>
<td>0.2</td>
<td>195.2</td>
<td>73.3</td>
<td>1233</td>
</tr>
<tr>
<td>0.25</td>
<td>179.9</td>
<td>67.6</td>
<td>1515</td>
</tr>
<tr>
<td>0.3</td>
<td>161.1</td>
<td>60.5</td>
<td>3506</td>
</tr>
<tr>
<td>0.4</td>
<td>117.6</td>
<td>44.2</td>
<td>3466</td>
</tr>
<tr>
<td>0.5</td>
<td>74.6</td>
<td>28.0</td>
<td>1652</td>
</tr>
<tr>
<td>0.7</td>
<td>21.1</td>
<td>7.9</td>
<td>169.3</td>
</tr>
<tr>
<td>1</td>
<td>3.5</td>
<td>1.3</td>
<td></td>
</tr>
</tbody>
</table>

Figure 16. The effect of net sea level rise on salt marsh area.
Coastal wetlands serve as carbon sinks, sequestering large amounts of carbon in the soil. However, the degradation of wetlands will result in the release of CO₂ and other greenhouse gases into the atmosphere, exacerbating global climate change. If 1 km² of coastal wetland in North Carolina were lost in one year, an estimated 80.6 tons of carbon would be emitted. With only a 0.05 m net sea level rise, more than 3500 tons of sequestered carbon will be released from salt marshes, not taking into account the loss from other wetland types (Table 11).

The main limitation of this model is that it does not take into consideration the influences that sea level rise could have on growth patterns and conditions of salt marsh communities. However, the theory is complex and the next model measures these factors in an equilibrium state.

The Marsh Equilibrium Model

This blue carbon model was developed from the Marsh Equilibrium Model created by Morris et al. (2012), which describes how sediments, tides, and wetland carbon stocks react to rising sea levels. Morris’ model, combined with field data from South Carolina, best predicts the interaction between salt marsh communities and sea level rise in the southeast coastal areas of the United States. Local tidal range and suspended solids data of Albemarle-Pamlico Peninsula and Louisiana were applied to the Marsh Equilibrium Model in order to compare the changes in carbon storage capacity.

Morris Model Description

A previous field study conducted by Morris and Sundareshwar (2002) in South Carolina found the relationship between biomass density and marsh surface depth to be:

\[ B = aD + bD^2 + c \]  \hspace{1cm} (1)
In this equation, $B$ is the biomass density and $D$ is the depth of mean high tide relative to the marsh platform (Figure 17). $A$, $b$, and $c$ are coefficients equal to 155, -1.855, and -1364, respectively (Morris and Sundareshwar 2002).

Figure 17. The relationship between mean high tide, marsh surface depth, and mean sea level (Morris and Sundareshwar 2002).

The net rate of elevation change of the salt marsh surface ($dY_2/dt$) is proportional to the depth of marsh surface below the mean high tide ($D$), and $dY_2/dt$ is also a function of biomass density ($B$) (Morris and Sundareshwar 2002). The linear function between these variables is:

$$dY_2/dt=(q+kB)*D$$

(2)

In this equation, $q$ and $k$ are coefficients that are equal to 0.0018 and 0.000015, respectively. However, the two parameters may change slightly by location (Morris and Sundareshwar 2002).

When the growth of marsh is in equilibrium with the sea level rise ($r$):

$$dY_2/dt=r$$

(3)

Combining the above three equations results in an integrated equation that calculates the depth of the marsh below the mean high tide ($D$) for a specific rate of sea level rise (Morris and Sundareshwar 2002):

$$kbD^3+kaD^2+(q+kc)*D-r=0$$

(4)
The basic assumption in this model is that “sedimentation of suspended solids carried by tides over the marsh surface increases with the concentration of suspended solids \(m\), duration of flooding, and standing biomass density \(B_s\)”, as well as “the production of organic matter and primarily of roots and rhizomes” (Morris et al. 2012). Flood duration is proportional to depth \(D\) divided by tidal range \(T\) (Morris et al. 2012). The general equation is shown here:

\[
\frac{dS}{dt} = m(q+k_sB_s)D^2/T+k_rB_r \tag{5}
\]

\(B_s\) is the standing biomass density, and \(k_s\) is the trapping coefficient. \(K_r\) is the organic matter fraction resistance decay, and \(B_r\) is the production of roots and rhizomes (Morris et al. 2012). The permanent carbon that is buried in the soil equals \(K_r \times B_r\) (Morris et al. 2012). In the southeastern United States, the average carbon sequestration rate is 7% of the total permanent carbon in the soil (Morris et al. 2012), therefore:

\[
k_rB_r = \text{Carbon sequestration (C)} / 0.07 \quad \tag{6}
\]

According to Morris, \(dS/dt\) is equal to the sea level rise rate \(r\) multiplied by the age of the wetland. In Hyde County, the mean elevation is approximately 0.5 meters, and in Dare County, the mean elevation is 0.3 meters. Age was estimated to be 500 years in Hyde County as a 1-meter wetland is known to be 1000 years old on average (Morris et al. 2012).

\[
dS/dt = 500*r \quad \tag{7}
\]

Combining equations (2) and (7) results in the following integrated equation:

\[
500*r = m*r*D/T+C/0.07 \quad \tag{8}
\]

Similarly, in Louisiana, sediment age is separated into three regions. The western coastal region of the state, west of the Atchafalaya River, contains sediment that is 4500 years old, the central region between the Atchafalaya River and the Mississippi River is
500-1000 years old, and the eastern region beyond the Mississippi River is 2500-1500 years old (Kolb and Lopik 1996). Using the average age of each region mentioned above, the integrated equations for the three regions are:

- **Western part:** \[ 4500r = m * r * D / T + C / 0.07 \] (9)
- **Central part:** \[ 750r = m * r * D / T + C / 0.07 \] (10)
- **Eastern part:** \[ 2000r = m * r * D / T + C / 0.07 \] (11)

Equation (4) shows the relationship between \( r \) and \( D \). If the rate of sea level rise is known, depth \( (D) \) can be calculated and it is then possible to plot a 3-dimensional graph that contains only the tidal range \( (T) \), the suspended solid \( (m) \) and the carbon sequestration \( (C) \).

**Conclusions on Sea Level Rise**

The results showed the combined effects of tidal range, TSS, and sea level rise on carbon sequestration rate. Computed rates of carbon sequestration for Louisiana and Dare and Hyde counties in North Carolina were predicted based on the forecasted sea level rise rates of 0.3 cm/year, 0.6 cm/year, and 1 cm/year (Figure 18, Figure 19, Figure 20, and Figure 21). TSS and tidal range describe how salt marshes will likely respond to different rates of sea level rise, which are functions of sediment accretion rate, plant productivity, flood duration, and vertical range over which salt marsh can grow (Morris et al. 2012). For both states, the response surfaces show that compared to tidal range, TSS has a negligible impact that can only minimally alter the response surfaces (Figure 18, Figure 19, Figure 20, and Figure 21). Conversely, tidal range serves an important role, determining whether carbon sequestration rate of the soil would increase or decrease with the rising sea level.
Figure 18. Rate of carbon sequestration in Hyde and Dare counties, North Carolina.

Figure 19. Rate of carbon sequestration in central Louisiana (soil age = 750 years).
Figure 20. Rate of carbon sequestration in eastern coast of Louisiana (soil age = 2000 years).

Figure 21. Rate of carbon sequestration in western part of Louisiana (soil age = 4500 years).

In Hyde and Dare counties in North Carolina (Figure 18), under a certain sea level rise rate, when the tidal range is less than 10 cm, the carbon sequestration rate tends to be weakened. As the rate of sea level rise increases, stored carbon will be released back to the atmosphere more quickly. The carbon stock is proportional to the product of the production of roots and rhizomes and the fraction resistance of organic materials to
decay (Morris et al. 2012). Thus, the decreasing carbon sequestration rate also suggests that when the tidal range is relatively small, salt marshes are unlikely to increase productivity. It is possible for the carbon sequestration rate to fall precipitously into negative values, meaning the salt marsh can no longer survive inundation without a larger vertical range. However, if the tidal range is greater than 10 cm, sea level rise would have a promotion effect. Meaning to say that more carbon can be sequestered and stored with an increase in the rate of sea level rise. When tidal range reaches 20 cm, under a certain sea level rise rate, the response surface would begin to flatten and the carbon sequestration rate would go unchanged. According to NOAA (2006 and 2009) calculations, the tidal range in Pamlico Sound is 0-40 cm with an average of approximately 21.9 cm. Thus, the sea level rise rate ranging from 0-1 cm/year can either have negative or positive effects on carbon sequestration rates in the coastal wetlands of Albemarle-Pamlico Peninsula. Under the current average tidal range, salt marshes have the potential to store more carbon in their soil with increased sea level rise rates.

Results for Louisiana (Figure 19, Figure 20, and Figure 21) are similar to those of Dare and Hyde counties in North Carolina. However, the critical tidal range is smaller – approximately 5 cm (Figure 19, Figure 20, and Figure 21). Only when the tidal range is smaller than 5 cm will sea level rise rate reduce the carbon stock of the salt marshes more quickly. However, if the tidal range is large enough, higher rates of sea level rise are conducive to higher carbon sequestration rates. If the tidal range is greater than 15 cm, the carbon capacity of the plants would remain unchanged at a certain sea level rise rate. With the average tidal range in Louisiana being approximately 35.01 cm, sea level rise can help to store more carbon in Louisiana, not taking into account natural disturbances, namely hurricanes (NOAA 2006; NOAA 2009).
To compare the carbon sequestration capacities in the coastal wetlands of Louisiana and North Carolina, Hyde and Dare counties were used to predict the overall impact in North Carolina, and eastern Louisiana was used to forecast all of Louisiana. As mentioned earlier, Louisiana has a lower critical point for the tidal range and a larger average tidal range, indicating that it is more likely that sea level rise would actually improve the carbon stock in Louisiana than in North Carolina. Also, under the sea level rise rate of 0.3 cm/year, the carbon sequestration rate in Louisiana is considerably higher than that of North Carolina (Figure 22).

![Figure 22. Comparison of carbon sequestration rate between North Carolina and Louisiana under the sea level rise of 0.3 cm/year.](image)

This trend applies to all values of sea level rise rate in the two states because Louisiana has older soils than North Carolina. When the age of the soil increases, the carbon sequestration ability will increase accordingly. How much carbon sequestration rate would increase with the increasing sea level rise was also estimated. To find a direct relation, the average tidal range (Dare and Hyde = 21.09 cm, eastern Louisiana = 35.01 cm) was substituted back into the model. TSS was assigned to be 50 kg/l since the variable itself can only minimally change the results. A linear relationship between
carbon sequestration rate and sea level rise rate was found (Figure 23). In North Carolina, if sea level rises by 1 cm/year, the carbon stock would increase by 0.3 tons per hectare per year. And in Louisiana, the increase rate is four times higher than the one in North Carolina. In short, these results indicate that without considering natural disturbances, Louisiana is the better choice for wetland restoration and preservation projects from the perspective of sea level rise.

Figure 23. Comparison of carbon sequestration rates and sea level rise between North Carolina and Louisiana.
Next Steps

Continued research is necessary before Duke can decide whether or not to go forward with blue carbon projects as part of their carbon neutrality commitment. Under the guidance of this report’s broader assessment, specific blue carbon sites should be identified for pilot studies that would provide accurate carbon sequestration data. An important addition would be to search for locations larger than that evaluated by the 2012 blue carbon group, as small-scale projects are not likely to be economical. In North Carolina, these sites would likely be found on the Albemarle-Pamlico Peninsula. The Peninsula is North Carolina’s largest and North America’s third largest estuary or lagoon with an area of 6,630 km² (Gross 1972) and is exposed to some of the highest rates of sea level rise in the nation (Poulter 2005). In regards to Louisiana, so long as a site was large enough to be economical, there are few restrictions to the actual region chosen as the state’s entire coastline is severely threatened by erosion and subsidence. Perhaps the best region to investigate in Louisiana is around the Atchafalaya basin as the river supplies new sediment, aiding in permanence.

Monitoring the evolution of blue carbon policy is also an essential next step in evaluating the feasibility of blue carbon projects. There is currently very little policy in place for claiming blue carbon offsets, but it is becoming a popular subject with increased interest from scientists and regulators. Similarly, further research into the available monitoring and assessment methods will be important in determining the cost of blue carbon projects. Monitoring assessments are important to the quality of the carbon offset; in other words, strong monitoring protocols can determine if there is carbon being released from the wetland project and if increased site maintenance is required.
Also, just outside of the scope of blue carbon, Duke may want to consider offset options in freshwater wetlands, such as peatlands. Coastal property on average is more expensive than inland, which may drive up the cost of restorations. There are concerns regarding the emission of other greenhouse gases, such as methane, from freshwater wetlands. Coastal wetlands do not undergo the same biochemical processes that produce these greenhouse gases in freshwater wetlands, which is certainly a benefit of blue carbon. These costs and benefits would need to be taken into account if this avenue is pursued.

Acknowledgements

Our team would like to thank our client, the Duke Carbon Offset Initiative, especially David Cooley, who was supportive and enthusiastic throughout the entire project. We would also like to thank Margo Moss and her team at Matrix New World Engineering, Inc. as well as Steve Emmett-Mattox with Restore America's Estuaries for providing valuable knowledge and experience with wetland restorations and blue carbon policy in Louisiana. And finally, we would like to thank our advisor, Dr. Curt Richardson, and our unofficial advisor, Charlotte Clark, for their help and support.
References


Gedan, K., & Silliman, B. (2009). Centuries of Human-Driven Change in Salt Marsh Ecosystems.


Smith, R. (2009). Historic Sediment Accretion Rates in A Louisiana Coastal Marsh and Implications for Sustainability. (Master), Louisiana State University.


