Ecosystem characterization and proposed methodologies for measuring the carbon sequestration potential of bottomland hardwood forests on the Texas coast

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Abstract

The bottomland hardwood forests of Texas make up the largest remnant expanse of forest on the Gulf Coast. These forests provide many different ecosystem services including flood control, wildlife habitat, and air and water pollution reduction. While this ecosystem has withstood decades of timber harvest, it is currently facing the threat of fragmentation due to development and urban expansion. To protect these lands, Texas Coastal Exchange (TCX) is working to include bottomland hardwood forests of the Texas coast in our Carbon Storage Program Inventory so that we can provide grant support to local landowners to keep these forests intact for 10 years. A literature review characterizing and defining the boundaries of this unique ecosystem type was completed. As well as a review of the current knowledge on annual carbon sequestration rates of bottomland hardwood forests on the upper Texas coast. Two methodologies are proposed to estimate the annual carbon sequestration capacity of bottomland hardwood forest properties for inclusion in the TCX Carbon Storage Program Inventory. The first uses a conservative average carbon sequestration rate of 3.5 metric tons CO_2/acre/year, which is based on estimated values from the scientific literature. The second utilizes the USDA Forest Service's i-Tree Canopy tool (v. 7.0) to determine the total carbon sequestration capacity for individual properties using an estimated carbon sequestration rate based on tree cover and geographic location of 5 metric tons CO_2/acre/year.

Introduction

Coastal areas are the most developed and densely populated regions of the world, as well as some of the most vulnerable to climate change (Gambolati et al. 1999, Harley et al. 2006, He and Silliman 2019). The state of Texas has 3,359 miles of coastline along the Gulf of Mexico with 24.5% of the state's population living on the coast (NOAA 2020 (a), NOAA 2020 (b)). In 2019, the estimated population size of the Greater Houston region alone was 7.1 million people, making it one of the most populous metro areas in the United States (US Census Bureau 2019). As the population of the Greater Houston metro area has grown, development has spread further out from the center of the city resulting in the fragmentation of ecosystems including the bottomland forests of the Brazos, Colorado, and San Bernard rivers, known locally as the Columbia Bottomlands. These floodplain forests act as carbon sinks, removing carbon dioxide (CO_2) from the atmosphere through the process of photosynthesis and storing it as biomass in trunks, limbs, and roots. In addition to the carbon in the plants themselves, forests also store carbon in the leaf litter on the forest floor and within organic soil components. The biomass and leaf litter are referred to as organic matter. The loss of these forests due to development and land-use change has greatly reduced the continued long-term storage of carbon. It is the goal of TCX to both protect and provide an incentive to expand upon the remaining bottomland forests as well as to educate the public on the importance of the carbon uptake and storage they provide.

Overview of Texas coastal bottomland forests

Flooding and soil chemistry

Two types of Southern floodplain forest grow along the rivers and bayous of the upper Texas coast. Both are commonly referred to as bottomland forests. However, these are unique and distinct ecosystems defined as bottomland hardwood forests and deep-water alluvial swamps and are best represented by the Trinity Bottomlands (deep-water alluvial swamps) and the Columbia Bottomlands (bottomland hardwoods) (Rosen et al. 2008).

The freshwater swamps of the Trinity Bottomlands are characterized by bald cypress (*Taxodium distichum*) and black tupelo (*Nyssa sylvatica*). These bottomlands experience frequent flooding and retain water for long durations throughout the year. Located within the Trinity River floodplain just north of Houston, this ecosystem stretches from southern San Jacinto county to northern Chambers County (Figure 1, Houston Wilderness (a) 2007). The hydroperiod in this system, defined as the frequency and duration of flooding, controls the soil chemistry and reduction-oxidation (redox) potential of the soil. In soils that are saturated with water, the bacterial activity rapidly depletes the dissolved oxygen, which leads to anaerobic conditions and lower redox potentials, resulting in less energetically efficient bacterial decomposition of organic matter. One of the least efficient of these decomposition pathways is methanogenesis, which is the process by which bacteria decompose organic matter and produce methane (CH_4). Methane is a potent greenhouse gas, resulting in 25 times the warming effect of CO_2 by mass (Forster et al. 2007).

While the less efficient organic matter decomposition occurring in anaerobic flooded soils results in high rates of carbon sequestration, or the removal and storage of CO_2 from the atmosphere by trees, the production and release of CH_4 back into the atmosphere has the potential to effectively cancel out the benefit of CO_2 sequestration in terms of the total reduction in greenhouse gases in the atmosphere. While freshwater swamps such as the Trinity Bottomlands provide many essential ecosystem services, they may not provide a net uptake of atmospheric greenhouse gases that occur in other less flooded forests and wetland types. Therefore, further investigation is needed to better understand the ratio of CO_2/CH_4 dynamics related to the hydroperiod in the Trinity Bottomlands before these forests can be included in the TCX inventory.

In contrast, the Columbia Bottomlands are a mosaic ecosystem comprised of varied topographies and hydrological regimes which result in a greater diversity of bottomland habitat types than those that are found in the Trinity River Basin. These dense forests are found in the floodplains of the Brazos, San Bernard, and Colorado Rivers located southwest of Houston in Brazoria, Fort Bend, Matagorda, and Wharton counties (Figure 2, Houston Wilderness (b) 2007, Audubon.org). The most common tree species of these forests are hardwoods such as live oak (*Quercus virginiana var. virginiana*), green ash (*Fraxinus pennsylvanica*), sugar hackberry (*Celtis laevigata var. laevigata*), honey locust (*Gleditsia triacanthos*), water hickory (*Carya aquatica*), cherry laurel (*Prunus caroliniana*), American beech (*Fagus grandifolia*), magnolia (*Magnolia grandifolia*), and pecan (*Carya illinoinensis*) (Houston Wilderness (b) 2007). This high tree species diversity and variation in topography and hydroperiod within the Columbia Bottomland forests results in heterogenous soil chemistry. Specifically, areas of higher elevation (e.g., ridges) are CH_4 sinks, whereas, areas of lower elevation that tend to hold water are CH_4 sources (Yu et al. 2008). Because of the dense vegetation present in these bottomland hardwood forests, in addition to the variation in CH_4 uptake and release from the soils, it is assumed that the release of CH_4 from methanogenesis has a negligible effect on net greenhouse gas emissions from this ecosystem. However, further study is needed to evaluate the validity of this assumption. Due to the lower likelihood of high CH_4 releases in these less often flooded forests, the following review and proposed methodologies for inclusion in the TCX Carbon Storage Program will focus on the mixed-species bottomland hardwood ecosystems of the Gulf Coast of which the Columbia Bottomlands is the prime example in Texas.

Figure 1 Map showing the area occupied by the Trinity Bottomlands. Source for area polygon: http://houstonwilderness.org/trinity-bottomlands. Inset of deep-water alluvial swamp in the Trinity Bottomlands. Source: https://www.fws.gov/refuge/trinity_river/

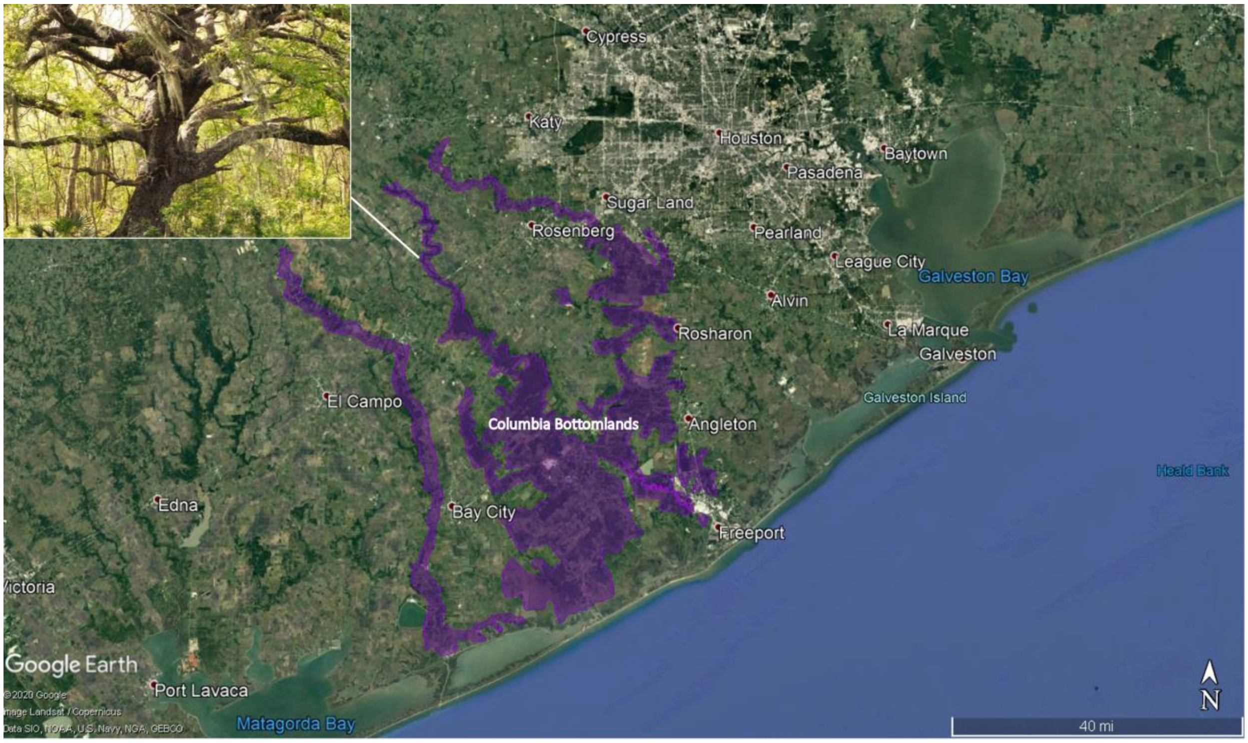

Figure 2 Map showing the area occupied by the Columbia Bottomlands. Source for area polygon: http://houstonwilderness.org/colombia-bottomlands. Inset of the bottomland hardwood forests of the Columbia Bottomlands. Source: https://www.usgs.gov/media/images/moss-draped-oak-columbia-bottomlands

Land-use change and the importance of carbon sequestration

Many old-growth forests of the Columbia Bottomlands remain because the timber is not of high commercial value. Despite the lack of logging pressure, much of it was still cleared for grazing and other agricultural uses. And, it continues to be cleared for housing development, roads, and pipeline right-of-ways (ROWs). This has led to increased habitat fragmentation as Houston and the surrounding cities expand due to population growth. Thousands of acres of forested habitat in this ecosystem are lost every year. Key threats include urbanization, logging, drainage and clearing for agriculture, pipeline construction, road building, and powerline construction. Very few landowners can afford to keep their land as undisturbed forest, as agricultural lands provide greater economic value (Texas Mid-coast NWR Complex Draft CCP and EA 2012).

Bottomland hardwood forests are the most diverse ecosystem in Texas and are also one of the most endangered ecosystems in the United States. It is estimated that about 12% of bottomland hardwood forests are lost in the state every decade (USFWS 2013). The first and most recent statewide inventory of forests in Texas was completed in 2013 by the U.S. Department of Agriculture (USDA) Forest Service in partnership with the Texas A&M Forest Service. This survey showed that 63.1 million acres (37%) of the total area of Texas was forested at the time. About 58.8 million acres (93%) of these Texas forests were privately owned (Dooley and McCollum 2013). Texas forests were also estimated to provide ecosystem services valued at $92.9 billion annually in 2013. These services include sequestering and storing carbon long-term in biomass, watershed regulation, wildlife habitat, and recreational and spiritual value to people. Specifically, climate regulating services, such as storing ($3.1 billion) and accumulating ($1.2 billion) carbon, were estimated to be worth a total of $4.3 billion annually. The authors used $22 per metric ton of carbon (tC) to place the previously stated values on carbon stocks and accumulation. Carbon stocks were amortized over 20 years to obtain an annualized carbon stock value (Simpson et al. 2013).

Carbon storage and sequestration are regulating ecosystem services which are essential to the survival of all life on the planet and cannot be replaced by current technologies due to their global scale. However, landowners are not being compensated for the services that these forests on their lands provide to us all. Large tracts of privately owned lands are becoming less common as inheritance taxes and development pressures increase (USFWS 2013). To protect the existing forests from development and support landowners so that they can keep their forest properties intact, TCX is working to incorporate the bottomland hardwood forests of the Texas coast into our Carbon Storage Program Inventory.

Forests of the Gulf Coast

Coastal forests are woody plant communities that grow within 100 km of the coast. These forests typically occur on barrier islands, ridges, delta splays, and along river and bayou drainages. There are 19 different community types of coastal forest along the Gulf coast stretching from the Florida Keys to the Yucatan Peninsula. Development resulting from population growth, urbanization, oil and gas exploration, and pollution are issues that impact coastal forests throughout the Gulf region (Barrow et al. 2005).

As was mentioned in the introduction, there are two main types of coastal forest on the upper Texas coast. Both occur within the floodplains of major river and bayou systems and are sometimes referred to as riparian forests. Riparian areas according to Hardey and Davis (2013) “are complex transitional areas between aquatic environments of rivers and streams and terrestrial environments of upland areas.” When these systems experience drought, upland species tend to move in and replace the more water-tolerant riparian vegetation. Also, the riparian vegetation may start to invade stream channels during times of drought which causes channel narrowing. This decreases riparian species diversity and habitat availability. Therefore, flooding is essential for healthy riparian ecosystems such as floodplain forests. Some riparian zone indicator species include Green ash (*Fraxinus pennsylvanica*), cottonwood (*Populus deltoides*), and black willow (*Salix nigra*) (Hardey and Davis 2013).

Within these floodplain ecosystems, different habitat types are distinguished by dominant plant species and range of environmental variability caused by spatiotemporally variable flows and geomorphic disturbance during large floods (Figure 3). This is because the tolerances among plant species to elevation-specific inundation and soil saturation regimes vary, resulting in a system with a habitat mosaic of different plant species and forest structure. Floodplain forests are comprised of both forested wetlands (lower and upper swamps) at lower elevations and bottomland hardwood forests (seasonally and temporarily flooded forests) at higher elevations (Figure 3). In Texas, most floods occur in the winter or spring. This increases the availability of carbon and nutrients when warmer temperatures arrive and enhances downstream productivity in the river, as well as in the estuaries at the river's mouth (Hayes 2016). Productivity is so great in these forests that their potential role in mitigating climate change is significant (Hayes 2016, Gosselink et al. 1981). This is because of their high productivity rates due to overbank flooding, which allows these forests to obtain the highest biomass per area of any temperate ecosystem (Gosselink et al. 1981). Research in the riparian forests of northeast Louisiana found that the range of carbon storage there was 90-124 Mg C/ha (approximately 36-50 metric tons C/acre) (Hunter et al. 2008).

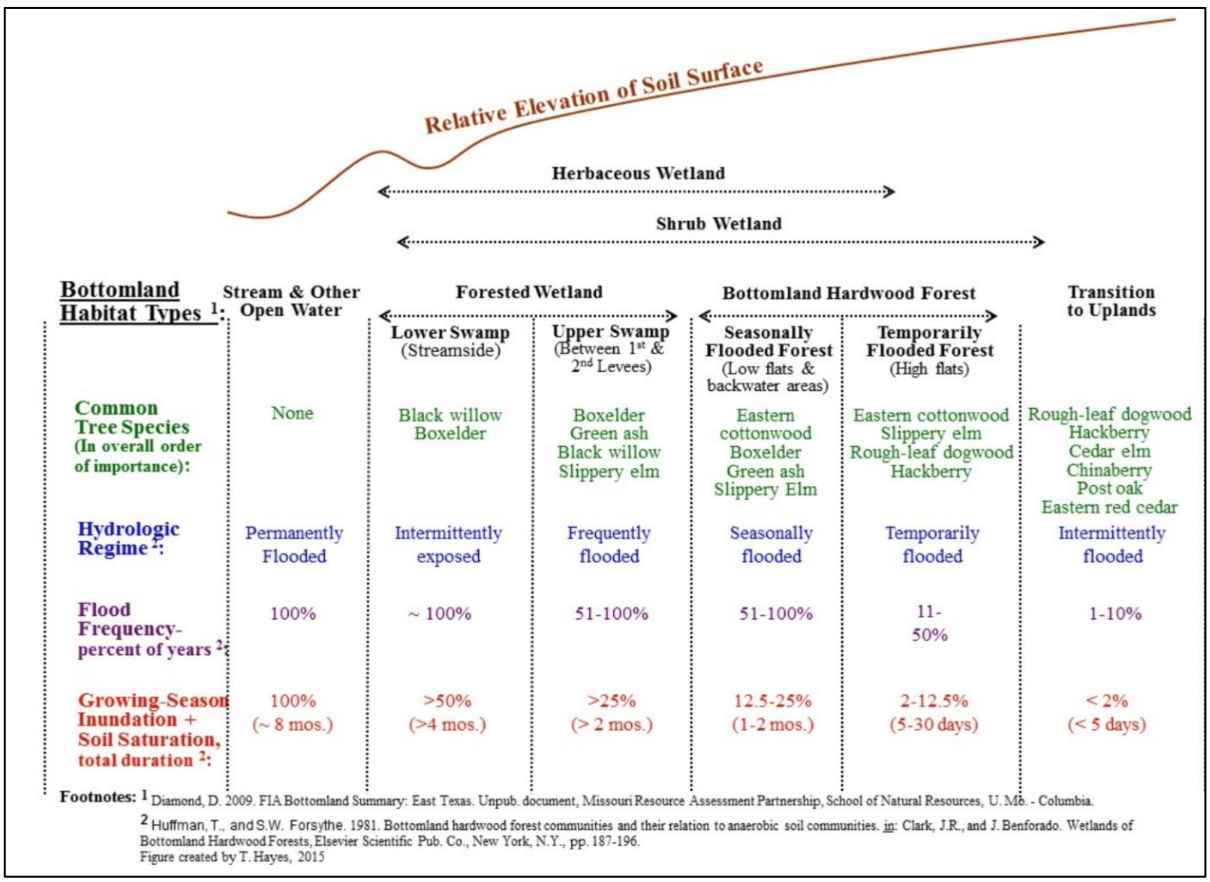

Figure 3 Landscape context, tree species present, and hydrology of riparian areas at a survey site near Herne, Texas along the middle Brazos River. From Hayes 2016.

However, the bottomland hardwood forests of the upper Texas coast, specifically the Columbia Bottomlands, are likely to have much lower productivity levels and, therefore, less total carbon storage and lower carbon sequestration rates, than the forests of Louisiana. Specifically, the lack of sufficient overbank flooding of the Brazos River may no longer be able to maintain the geomorphic disturbance needed to maintain high riparian productivity levels (Hayes 2016). This is likely true for the San Bernard and Colorado Rivers, as well, and will likely worsen as the climate crisis progresses.

Bottomland hardwood ecosystems are comprised of seasonally flooded basins and flats, as well as forested wetlands. The earliest Forest Inventory and Analysis (FIA) surveys, which were completed between 1934 and 1948, showed that the bottomland hardwood forests of the south-central coastal plain once covered 8.3 million ha (20.5 million acres). Over half of these trees were located on the Mississippi Alluvial Plain. Most of these forests have since been lost due to clearing and draining. However, the bottomland forests of the western Gulf region, which includes those on the Texas coast, have remained stable (Figure 4). The western Gulf region is 60% forested and upland pine and hardwood forests are the dominant type. Less than 1/5 of these forests are bottomland hardwood forests. Sweetgum and water oak are the dominant species of the western Gulf bottomland forests, with Oak spp., ash, and black tupelo also present in abundance. Specifically, the sweetgum/nuttal oak/willow oak type occupies 1/3 of the bottomland forests area in the Coastal Plain (Figure 5). Sugarberry/American elm/green ash are often temporarily in abundance after a disturbance and take up 1/5 of the bottomland forest area. These two types comprise over 50% of the bottomland hardwood forests of the Coastal Plain. The vulnerability of these forests is correlated with the moisture continuum with moist sites more vulnerable to clearing for other land uses, and wet sites being more vulnerable to disturbance from canal-building and channelization (McWilliams and Rosen 1990).

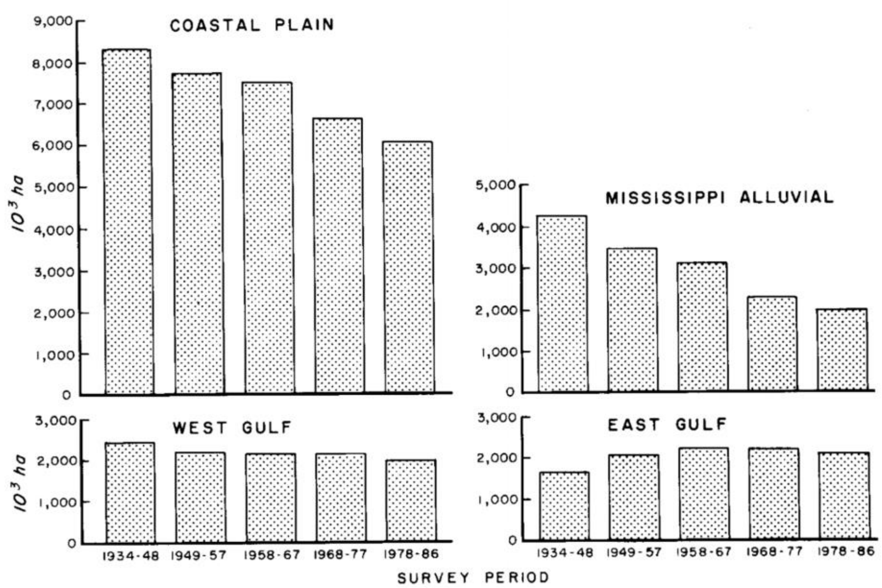

Figure 4 Historical trends in bottomland hardwood forest area in for different regions on the Gulf coast. From McWilliams and Rosen (1990).

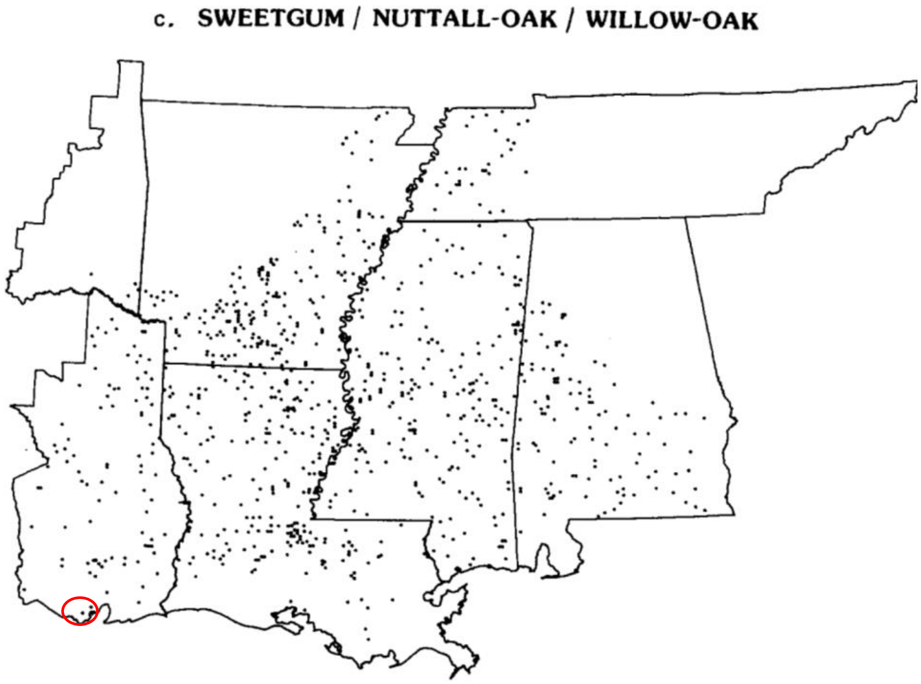

Figure 5 FIA survey locations for sweetgum/nuttal-oak/willow-oak forest type. The red circle indicates part of the Columbia Bottomlands. From McWilliams and Rosen (1990).

Ecosystem characteristics of Texas coastal bottomland hardwood forests

The Columbia Bottomlands is the largest expanse of bottomland hardwood forest on the upper Texas coast (Rosen et al. 2008). This ecosystem is unique and is the southernmost expanse of bottomland hardwood forest along the Gulf coast (Texas Mid-coast NWR Complex Draft CCP and EA 2012). These forests are more similar to the coastal forests of the eastern Gulf Coast, rather those of the remainder of the Texas coast, which grow in a much drier climate (Rosen et al. 2008, Rosen and Miller 2005, Barrow et al. 2005). At one time, this ecosystem was expansive and covered approximately 699,726 acres (Barrow et al. 2005). Today, these forests have been reduced to less than 177,840 acres, which is about 25% of their original range (Barrow et al. 2005, Rosen et al. 2008). Despite this, the area remains the most important stopover habitat for migrating neotropical birds in the entire state of Texas (Houston Wilderness (b) 2007, Barrow et al. 2005). It is known to host about 29 million birds annually during migration based on radar studies conducted by Dr. Sidney Gauthreaux of the Clemson University Radar Ornithology lab. Because of this, it has been designated an Audubon Important Bird Area and is utilized by over 240 different bird species that migrate through, overwinter, or breed in Texas (Audubon.org, Barrow et al. 2005).

These floodplain forests extend from the coast to 150 km inland (Figure 2) and are located in the Coastal Plain Province within the subtropical vegetation zone (tpwd.texas.gov). The regional climate is moist sub-humid mesothermal with long, hot, and dry summers, wet springs and falls, and dry, mild winters (Rosen and Miller 2005, USFWS 2015). Found within the Coastal Prairies and Marshes ecoregion of Texas, these forests are unique in that much of the region is comprised of grassland and marsh habitat types. It is still unknown whether the Columbia Bottomland forests are the result of a disruption in the natural fire cycle and disturbance in this prairie dominated landscape, or if the unique hydrology or other environmental factors has led to the development of this ecosystem (tpwd.texas.gov, Texas Mid-coast NWT Complex Draft CCP and EA 2012).

One of the defining characteristics of these forests is variable topography and soil types (Rosen and Miller 2005). The landscape where these forests are found is mostly level with a series of swales, depressions, and natural levees. Most flooding is caused by seasonal precipitation and tropical storms, not overbank flooding, which is less frequent, occurring about every 15-25 years. Soils are most often clayey (Pledger or Brazoria clays) or loamy (Asa or Norwood series) bottomland soil types (tpwd.texas.gov). In areas of higher elevation (e.g., natural levees and ridges), Asa soils are found which are slightly acidic to basic silty clay loams. Pledger soils are basic calcareous clays and are found in broad mostly level flats or concave abandoned stream channels. The soils (pledger) have the typical vertisol gilgai microtopography of the Coastal Prairie and Marshes ecoregion (Rosen and Miller 2005). Soils within this region are primarily Vertisols with some Alfisols. Vertisol soils are heavy clay soils that develop deep cracks during dry seasons and swell during wetter times. This soil type is typically found under expansive grassland communities. Alfisols develop from weathering processes that leach clay minerals and other components off the surface layer and into the subsoil. These are typically found below forests and mixed vegetation cover (USFWS 2013).

Plant species composition also varies within this ecosystem and is based on a moisture gradient that ranges from wet sites along stream margins and depressions to dry sites on ridges and natural levees (Rosen et al. 2008). Therefore, a range of different habitat types is found within the Columbia Bottomlands ecosystem (Table 1, Figure 6). The hardwood forest and woodland habitat type make up 47% of this ecosystem (tpwd.texas.gov). Bottomland hardwood ecosystems are at least 10% forested, located in bottomlands (i.e., floodplains), and are comprised predominantly of hardwood tree species which must make up at least half of the stock of dominant and codominant trees with pines being less than 25% of the tree species (McWilliams and Rosen 1990). The dominant canopy tree species of the Columbia Bottomlands are green ash (*Fraxinus pennsylvanica*), live oak (*Quercus virginiana var. virginiana*), sugar hackberry (*Celtis laevigata var. laevigata*), cedar elm (*Ulmus crassifolia*), Drummond's western soapberry (*Sapindus saponaria var. drummondii*), water oak (*Quercus nigra*), and American elm (*Ulmus americana*) (Rosen and Miller 2005).

Table 1 Habitat types of the Columbia Bottomlands from tpwd.texas.gov (Ecological Mapping Systems).

Habitat Classification	**Location in Ecosystem**	**Plant Species Composition**
Live oak forest and woodland	Dry sites on levees and ridges	Coastal live oak (*Quercus virginiana*) dominant canopy species
Mixed evergreen/hardwood	Unspecified*	Coastal live oak (*Quercus virginiana*) and other hardwood species in canopy
Hardwood forest and woodland	Unspecified*	Deciduous tree species in canopy
Evergreen shrubland	Often found in disturbed areas	Yaupon (*Ilex vomitoria*), Dwarf palmetto (*Sabal minor*), coastal live oak (*Quercus virginiana*), Macartney rose (*Rosa bracteata*), or baccharis (*Baccharis spp.*); may also be dominated by Chinese tallow (*Triadica sebifera*); other species such as sugar hackberry (*Celtis laevigata*) and black willow (*Salix nigra*) may be present
Deciduous shrubland	Often found in disturbed areas	Common buttonbush (*Cephalanthus occidentalis*), black willow (*Salix nigra*), Swamp privet (*Forestiera acuminata*), and/or roughleaf dogwood (*Cornus drummondii*); may also be dominated by Chinese tallow (*Triadica sebifera*)
Grassland	Bottomland soils; majority managed lands	Dominated by grasses including bermudagrass (*Cynodon dactylon*), bahiagrass (*Paspalum notatum*), and Italian ryegrass (*Lolium perenne*)
Herbaceous wetland	Wet areas	Dominated by herbaceous species such as crowfoot sedge (*Carex crus-corvi*), other sedges (*Carex spp.*), squarestem spikesedge (*Eleocharis quadrangulata*), beaksedges (*Rhynchospora spp.*), rushes (*Juncus spp.*), arrowheads (*Sagittaria spp.*), lizard's tail (*Saururus cernuus*), heartleaf burhead (*Echinodorus cordifolius*), cattails (*Typha spp.*), and/or smartweeds (*Polygonum spp.*)
Riparian live oak forest and woodland	Along drainages outside range of bottomland soils	Coastal live oak (*Quercus virginiana*) dominant canopy species
Riparian mixed evergreen/hardwood forest & woodland	Along drainages outside range of bottomland soils	Coastal live oak (*Quercus virginiana*) and other hardwood species in canopy
Riparian hardwood forest & woodland	Along drainages outside range of bottomland soils	Deciduous tree species in canopy
Riparian evergreen shrubland	Often found in disturbed areas along drainages outside range of bottomland soils	Baccharis (*Baccharis spp.*), Macartney rose (*Rosa bracteata*), yaupon (*Ilex vomitoria*), or small coastal live oak (*Quercus virginiana*) can be dominant species; Some areas dominated by Chinese tallow (*Triadica sebifera*)
Riparian deciduous shrubland	Often found in disturbed areas along drainages outside range of bottomland soils	Western soapberry (*Sapindus saponaria var. drummondii*), Common buttonbush (*Cephalanthus occidentalis*), roughleaf dogwood (*Cornus drummondii*), or rattlebox sesbania (*Sesbania drummondii*) can be dominant species; May be dominated by honey mesquite (*Prosopis glandulosa*), huisache (*Acacia farnesiana*), or Chinese tallow (*Triadica sebifera*)
Riparian grassland	Mostly managed areas on upland drainages	Dominated by non-native species such as King Ranch bluestem (*Bothriochloa ischaemum var. songarica*), bermudagrass (*Cynodon dactylon*), bahiagrass (*Paspalum notatum*), and Eqyptian ryegrass (*Lolium perenne*)
Riparian herbaceous wetland	Wet areas along drainages outside of bottomland soils	Dominated by sedges, rushes, and forbs such as smartweeds (*Polygonum spp.*)

*The topography not stated in the TPWD habitat description.

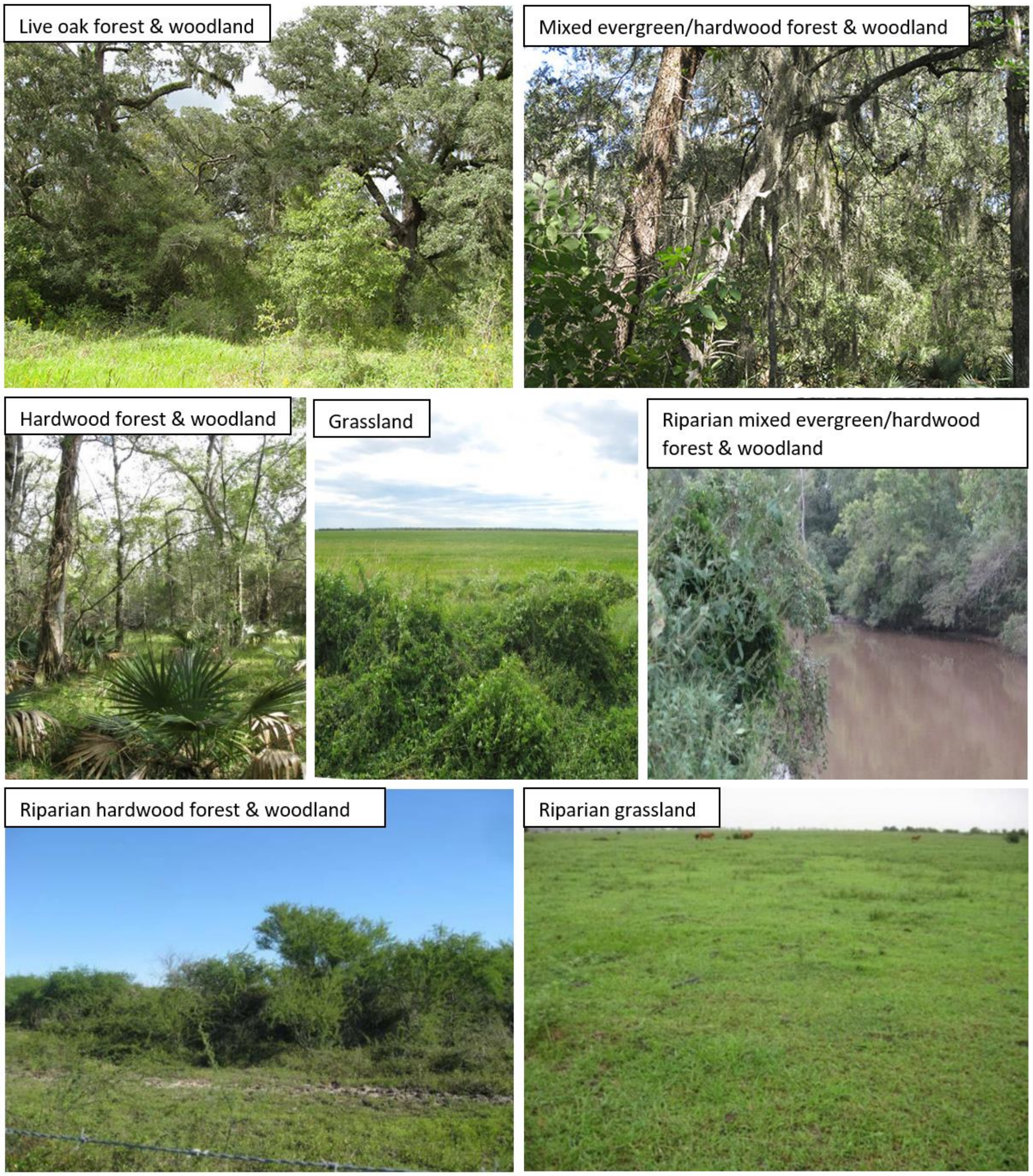

Figure 6 Examples of habitat types found in the Columbia Bottomlands from tpwd.texas.gov (Ecological Mapping Systems).

The varied topography and slight variations in soil type found throughout the Columbia Bottomlands lead to the high plant species diversity and structural complexity of the ecosystem that millions of birds depend on annually during migration. In addition to providing essential habitat for migrating songbirds and other wildlife, this ecosystem provides many other benefits including improving water quality and retaining stormwater during floods (Rosen et al. 2008).

Key threats to these bottomland hardwood forests include residential and commercial development, agricultural conversion, timber removal, and infestation by invasive plants (Barrow et al. 2005). Because this ecosystem is critical to the survival of hundreds of bird species and is threatened by fragmentation, large tracts have been protected through the Columbia Bottomlands Conservation Plan. This is a land acquisition and conservation program that is administered by the U.S. Fish and Wildlife Service (USFWS) along with its governmental and non-governmental partners, which has resulted in the protection of 14,000 acres worth approximately $12 million since 1997 (Rosen et al. 2008, Houston Wilderness (b) 2007). The primary goal of this program is to establish a network of protected areas to conserve ecosystem functions by preserving 10% of the original extent of the Columbia Bottomlands. Having a network of interconnected protected areas is essential for the health of this floodplain ecosystem with the threat of commercial and housing development spreading further out from the urban center of Houston. Fee title interests and conservation easements are being used as tools by the USFWS to conserve these areas in perpetuity. These protected forests are used for scientific research, hunting, fishing, and environmental education programs and can never be developed (Rosen et al. 2008).

Surveys of an old-growth Columbia Bottomland forest

Rosen et al. (2008) conducted a survey of the vegetation and soil composition of the Dance Bayou Unit in Brazoria County, which was the first parcel of land donated to the Columbia Bottomlands Conservation Plan in 1997. This is a 266 ha (~657 ac) tract within the San Bernard National Wildlife Refuge (Rosen et al. 2008, Rosen and Miller 2005). It contains one of the largest tracts of old-growth forest in the Southern U.S. and is considered to be a good representation of the character of the original Columbia Bottomland forests (Houston Wilderness (b) 2007). This forested area represents mature vegetation because it does not have any large-scale human disturbances such as timbering, thinning, selective cutting, burning, or overgrazing. Areas that have been disturbed (e.g., minor clearing for hunting, limited grazing, an abandoned county road, and a pipeline ROW) are relatively small in respect to the rest of the forest (Rosen and Miller 2005). The Dance Bayou Unit is surrounded by private farms and pastures. In 2008, Rosen et al. sampled 25 different plots and identified 46 woody species and 79 herbaceous species. Their survey results were used to develop a conceptual model of topography, soil type, and plant species composition of old-growth Columbia Bottomland forests (Figure 7).

The researchers found that this bottomland forest appeared to be healthy at the time of the survey. Canopy taxa such as green ash, sugarberry, and elms were well represented in the understory size classes (<7.5 cm diameter at breast height (dbh)). The density of these canopy species also decreased with increasing size class, which indicated that they were successfully regenerating within this forest tract. The only canopy genus that was not well represented in the understory size class was oak (Rosen et al. 2008).

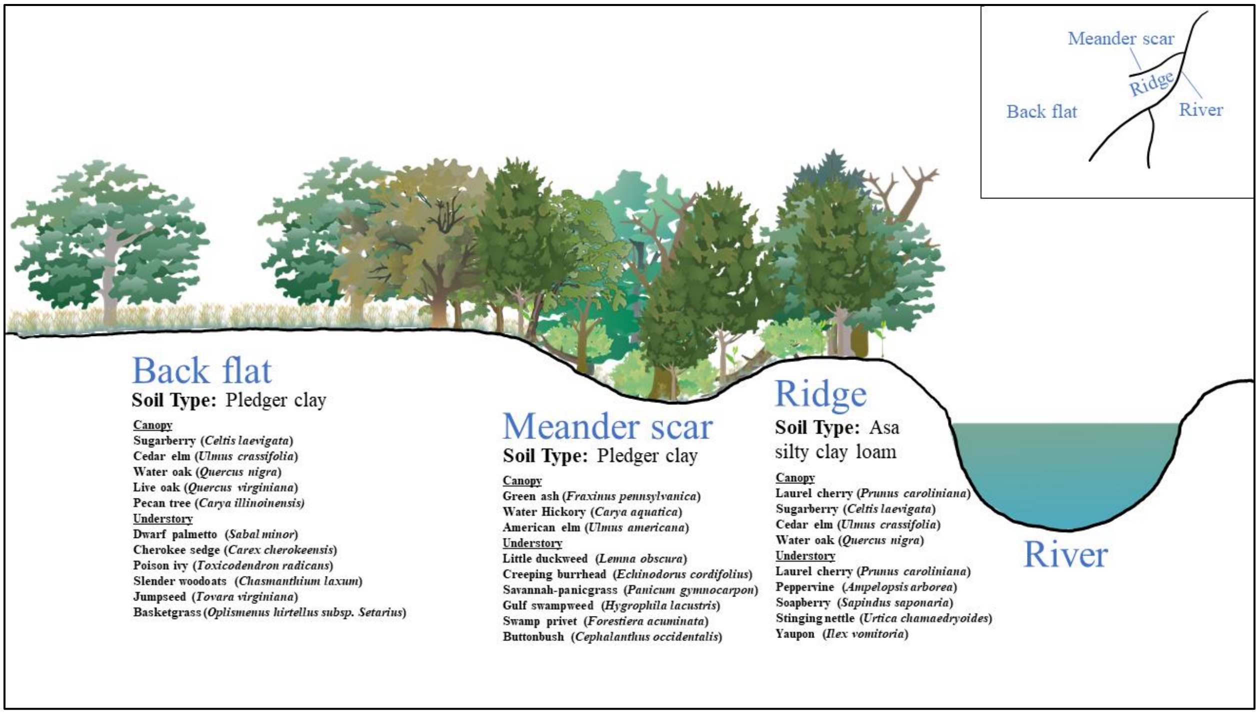

Figure 7 Shows the topography, soil type, and plant community of the Columbia Bottomlands. The information came from a survey conducted by Rosen et al. (2008) of the Dance Bayou Unit, a remnant, old-growth bottomland hardwood forest in Brazoria County, Texas. Symbols for this diagram courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/). Created by Kirsten Vernin and Lorelei Dearing.

Of the total overstory basal area that was surveyed (32 m^2/ha) on the Dance Bayou Unit survey plots, 87% was composed of canopy trees (Rosen et al. 2008). Therefore, we can assume that only measuring the canopy species accounts for a large amount of the above-ground carbon storage and sequestration in the system and is a scientifically valid way to estimate these metrics. Plant species composition was found to vary within the ecosystem due to variations in microtopography, soil type, and flooding patterns which results in the high plant species diversity of the Columbia Bottomlands (Rosen et al. 2008, Houston Wilderness (b) 2007). Meander scars, which are small stream channels, are flooded seasonally and the areas with higher elevations including back flats and ridges experience inundations less frequently (Figure 7). Through an ordination analysis, the researchers found that ridges and flats had 65% of plant species in common, whiles the meander scars only had 35-39% of species in common with either the ridges or flats (Rosen et al. 2008). Therefore, plant species found within these different topographic regions of the bottomland forests have different tolerances for flooding.

The most common canopy species were green ash (*Fraxinus pennsylvanica*), sugarberry (*Celtis laevigata*), cedar elm (*Ulmus crassifolia*), and American elm (*Ulmus americana*).

Sugarberry and cedar elm were found most often in areas that are flooded less often. In the understory, the most common species is Carolina laurel cherry (*Prunus caroliniana*), which is often found on ridges that have open disturbed areas (e.g., a fallen tree that opens up the canopy or logging). The canopy stem density was found to be lower on flats (347 stems/ha) than on either ridges or meander scars (600 stems/ha). The species composition of the understory also varied across the different topographies and soil types found in this forest. The wetter meander scars had lower understory species richness and had a distinct species composition with wetland and aquatic plants such as heartleaf burhead and little duckweed. These areas are also often colonized by the invasive Chinese tallow tree (*Triadica sebifera*), which has a high tolerance for flooding and can crowd out these other characteristic bottomland species (Rosen et al. 2008). By altering the species composition and structure of the forests, this invasive species affects resource availability for migrating birds (Barrow et al. 2005). Dwarf palmetto and Cherokee caric-sedge were found to be more abundant on drier back flats. On the ridges, because of their different predominant soil type, the understory was sparse and had a greater representation of woody species compared to either the flats or meander scars (Rosen et al. 2008).

A prior survey of the Dance Bayou unit by Rosen and Miller in 2005, found that the elevation of the Dance Bayou Unit ranges from 12-13 ft above sea level and slopes upward gradually from SW to NE with the highest elevation at the natural levee banks of Dance Bayou. While there are some variations in the topography of the area in the form of swales and depressions, it remains mostly flat. The authors also found that the major soil series are Asa silty clay loam on levee ridges and Pledger clay in the back flats and meander scars.

While the researchers identified soil types and topography variations within the Dance Bayou Unit, the survey was focused on classifying the vascular flora of the area. They found 356 species of vascular plants from 83 families and 237 genera. The four most abundant families were Poaceae (54 species, grasses), Asteraceae (35 species, flowering plants), Cyperaceae (32 species, sedges), and Fabaceae (20 species, legumes). Non-native species comprised 15% (55 species) of the total flora observed. Non-native plants were mostly restricted to disturbed areas (ROWs, roadsides, forest edges, clearings). However, they were also found in tree-fall gaps and seasonally flooded forested wetlands, which are susceptible to colonization by the Chinese tallow tree (*Triadica sebifera*). Of the 53 native woody species identified in the survey area, only 16 were identified as canopy species. The rest were understory, shrubs, or vines, which are mostly found in tree-fall gaps and contribute to the structural complexity of the forest, typical of old-growth Columbia Bottomlands forests. When under brushing, thinning and grazing occur in these areas, the plant species richness and structural complexity are reduced. (Rosen and Miller 2005).

Carbon storage and sequestration in Texas forests

There are six different forest ecosystem carbon pools: live trees, standing dead trees, understory vegetation, down dead wood, forest floor, and soil organic carbon (Figure 8). The amount of carbon stored in forest ecosystems is controlled by the region where the forest is located, forest type, previous land use, management, and productivity (Smith et al. 2006).

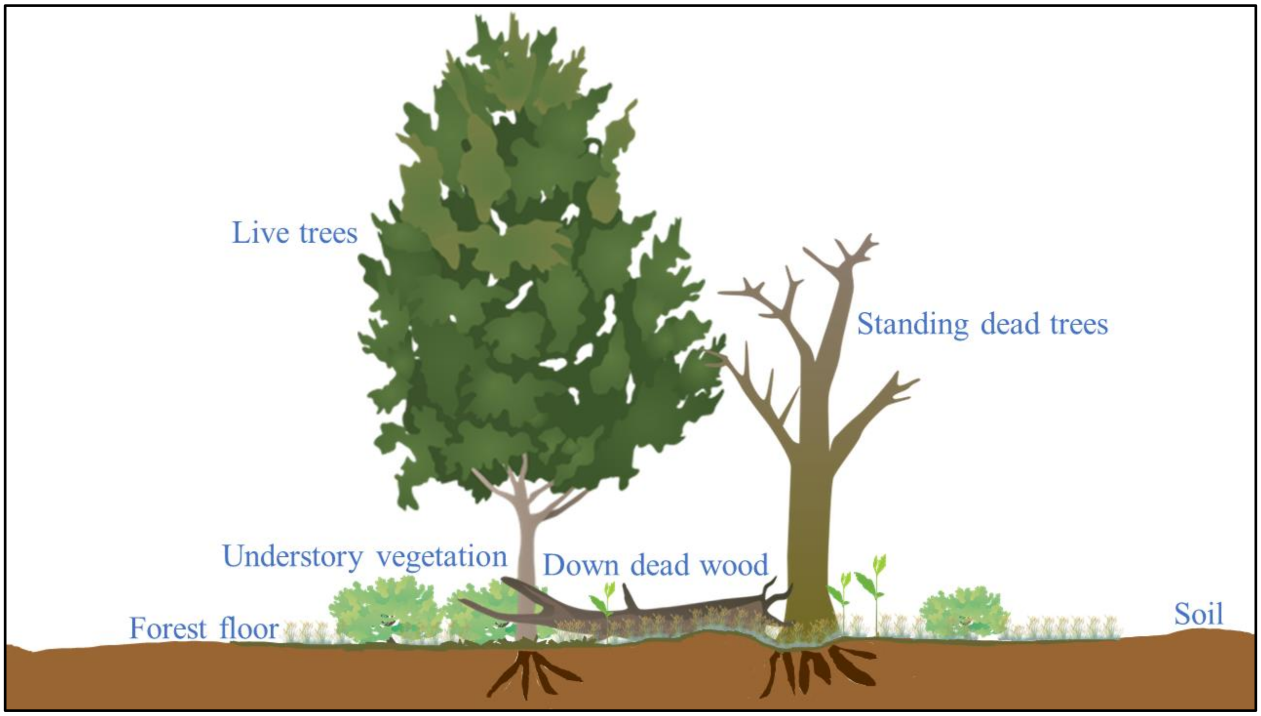

Figure 8 Shows the forest carbon pools as defined by Smith et al. (2006). Live trees: all living trees with a dbh ≥ 2.5 cm (1 in) including coarse roots, stems, branches, and foliage. Standing dead trees: all dead trees with a dbh ≥ 2.5 cm (1 in) including coarse roots, stems, and branches. Understory vegetation: live vegetation including seedlings < 2.5 cm (1 in) and shrubs. Down dead wood: Woody material larger than 7.5 cm in diameter, stumps, and coarse roots of stumps. Forest floor: all organic matter on the forest floor excluding down dead wood and above the soil. Soil: all belowground carbon to a depth of 1 meter, excluding coarse roots. Symbols for this diagram courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/). Created by Kirsten Vernin.

The scientific literature contains limited information on annual carbon sequestration rates for the bottomland hardwood forests of Texas. However, several methods have been developed and utilized to identify and quantify terrestrial carbon sinks that include atmospheric transport models, land-use models, and forest inventories (Almaguer-Reisdorf 2003). A substantial amount of data on forest health and biomass accumulation has been collected by the USDA Forest Service, Southern Research Station's (SRS) FIA program through forest inventories (Dooley and McCollum 2013). Historically, these forest inventories have been used to inform forest managers about forest health.

Measurements of tree size are generally collected as tree height using a clinometer or a range finder and as diameter at breast height (dbh) which in the United States is the diameter around the trunk of the tree at 4.5 ft (1.37 m) from the ground. These measurements are then used to estimate the biomass and volume for the above-ground portion of the trees using an allometric regression equation derived from many measurements of biomass, height, and diameter for individual species of trees. These techniques are based on the allometric relationship between plant dimensions such as dbh and above-ground biomass for a species, group of species, or growth form. Estimates of carbon stocks and fluxes (storage and sequestration rates) can then be calculated from the above-ground biomass estimates and an estimate of the annual rate of growth of the tree (Jenkins et al. 2003, Almaguer-Reisdorf 2003).

Each year, the SRS FIA Research Unit conducts forest inventories in partnership with state forest agencies in 13 Southern States, including Texas (Dooley and McCollum 2013). Through the FIA program, the USDA Forest Service continuously monitors and surveys permanently established forest units to obtain information on growth, composition, mortality, ownership, disturbance, and other variables for forests throughout the United States (Simpson et al. 2013). These annual surveys, which are mandated by law through the Agricultural Research Extension and Education Reform Act of 1998 (Farm Bill) are completed with a common sample design that is used throughout the U.S. and its territories by other FIA research units (Dooley and McCollum 2013).

To develop a set of consistent national-scale above-ground biomass regression equations for tree species found in the U.S., Jenkins et al. (2003) compiled all of the available diameter-based allometric regression equations for estimating total above-ground biomass (dry weight) and then completed a meta-analysis based on published equations. These equations are more generalizable and can be used in large-scale inventory-based forest carbon budgets. Chojnacky et al. (2014) updated the published biomass regression equation database created by Jenkins et al. (2003) and refined the model through the development of equations based on allometric scaling theory using taxonomic groupings and wood specific gravity as substitutes for scaling parameters that could not be estimated. The results were 35 theoretically based generalized equations (13 conifer, 18 hardwood, 4 woodland) compared to the 10 previously empirically derived ones (Chojnacky et al. 2014). These equations are used by the USDA Forest Service to estimate biomass from FIA survey data.

Large-scale carbon estimates typically use FIA data to estimate biomass per unit area. This is then multiplied by the area to obtain a total forest biomass metric. Forest area is usually determined with dot grid counts overlaid on aerial photography. The results from this area determination are then compared to actual field conditions at permanent survey plots and used to adjust forest or non-forest area estimates. FIA data are typically used to estimate merchantable timber volumes at the county, state, and national levels. However, these biomass estimates may also be alternatively used to estimate forest carbon storage. These forest inventories are typically conducted every 7-11 years by trained field crews. Each sample site is classified based on forest type and quality, as well as land use. Tree measurements are also taken and include species, dbh, and total height (Almaguer-Reisdorf 2003).

In Texas, 62.4 million acres of forests are represented in the FIA datasets (Simpson et al. 2013). The USDA Forest Service divides Texas into seven different forest survey units with the Columbia Bottomlands located in the FIA Unit 4 – South (Figure 8, Dooley and McCollum 2013). These data are updated on a routine basis and 10-20% of the units in Texas are surveyed on an annual basis by the Texas A&M Forest Service and the USDA Forest Service's SRS FIA Research Unit (Simpson et al. 2013). Stand level (or forest type-specific) data are presented by area usually in acres, but sometimes in hectares. To obtain carbon storage metrics the SRS FIA research simply divides the measured biomass of each forest by 2 (biomass/2=carbon) (Dooley and McCollum 2013). This is the standard method as proposed by Birdsey (1992).

Figure 9 Texas forest survey units used by the USDA Forest Service. The Columbia Bottomlands are located in the South region (Dooley and McCollum 2013).

Carbon storage and sequestration estimates by ecoregion and forest type in Texas

Simpson et al. (2013) completed an assessment of all the forests in Texas to estimate the economic value of the services provided by these diverse ecosystems. The dollar values in the report are in 2011 U.S. dollars (USD). This study included both publicly and privately owned forests in Texas. One of the services estimated was carbon stock (the total amount of carbon held in forest biomass) and accumulation rates (the annual rate that carbon is removed from the atmosphere and sequestered in plant biomass) for the different ecoregions (Pine Woodlands, Coastal Woodlands, Post Oak, Hackberry-Oak, Mesquite-Juniper, High Plains, and Mountain) of Texas using FIA data from 2010. Specifically, the FIA data was used to estimate the number of forested acres in Texas and to determine the landownership type (private or public). The ecoregions were defined by the authors based on similarities in growth and site characteristics, as well as the ecological sections mapped by the USDA Forest Service's National Hierarchical Framework of Ecological Units.

The Columbia Bottomlands are located within the Coastal Woodlands region, which is an aggregate of the USDA Forest Service Ecological Sections Louisiana Coastal Prairies and Marshes and Central Gulf Prairies and Marshes (Simpson et al. 2013). However, this region also includes forests farther south which tend to have lower plant species diversity and are much drier than the bottomland forests of the upper Texas coast. The ecosystem services provided by forests in Texas are dependent upon geographic location and plant species composition. Because of this, the researchers defined nine different forest types within the 8 ecoregions. The Columbia Bottomlands were classified as Hardwood-Bottomland (FIA forest type oak/gum/cypress) (Simpson et al. 2013). However, based on the Dance Bayou survey, riparian vegetation is also present. Therefore, I also included the Hardwood-Riparian metrics from Simpson et al. (2013) in my annual carbon sequestration estimates, which included FIA forest type elm/ash/cottonwood.

Simpson et al. (2013) estimated that the total carbon stock of all Texas forests was 2.1 billion metric tons for 62.4 million acres of forests with a total annual value of $3.1 billion. The total carbon accumulation rate for the above-ground, live biomass in the entire state was estimated to be 52.8 million tC/year with an annual value of approximately $1.2 billion. For the Coastal Woodlands ecoregion where the Columbia Bottomlands are located, the annual economic value of carbon stock and accumulation was estimated to be $162.9 million. This ecoregion had the smallest number of forested acres (2.1 million acres) in this study but contained a large carbon stock (approximately 37.5 tC/acre). The total value of annual carbon stock and accumulation in the Coastal Woodlands region was valued at $162.9 million. Using conservative literature values, the authors determined that within the Coastal Hardwood ecoregion, Hardwood-Bottomland forests had an above-ground accumulation rate for above-ground live carbon of 1.01 metric tons/acre/year and that Harwood-Riparian forests were at 1.09 metric tons/acre/year. One important caveat is that if the forest is lost to wildfire, insect infestations, disease, extreme weather events, or is converted to other land uses, the value of carbon storage in the ecosystem is lost. However, the value of carbon accumulation is the value of the net annual fixation of carbon in a growing forest, which avoids this issue.

In an older report by Birdsey (1992), carbon storage for each forest carbon pool (tree, soil, forest floor, understory vegetation) was estimated for the major forest types in 8 geographic regions in the United States using statewide forest inventories (i.e., FIA data). These inventories are based on a statistical sample design that represents a broad range of forest conditions present in each state making these carbon storage estimates representative average values. The error rates associated with these estimates are small because the forest inventories have small sampling errors and were completed in large areas. Carbon storage estimates for soil, forest floor, and understory vegetation were derived through models based on data from forest ecosystem studies and are only valid for these specific ecosystems. Only the estimates for carbon changes in live trees were used for the estimates of change in carbon storage over time.

The Columbia Bottomlands, which are a mosaic ecosystem, fit best into two forest categories specified by Birdsey (1992). The first is oak-gum-cypress, which are bottomland forests consisting primarily of tupelo, black gum, sweetgum, oaks, or southern cypress where pines make up less than 25% of the tree species present. Other common species in this forest type include cottonwood, willow, ash, elm, hackberry, and maple. The second forest type is elm-ash-cottonwood which is comprised of these tree species, as well as willow, sycamore, beech, and maple trees. The average carbon accumulation rate in live trees for oak-gum-cypress was determined to be 1685 lbs/ac/yr and 1999 lbs/ac/yr for elm-ash-cottonwood forests in the South Central region which includes the Columbia Bottomlands of Texas.

Annual carbon sequestration rate for the Columbia Bottomlands

In Table 2, I converted the annual carbon sequestration rates from the literature into annual CO_2 sequestration rates (metric tons CO_2/acre/year). I then averaged the values for both USDA forest type classifications within the bottomland hardwood forests for both papers (Simpson et al. 2013 and Birdsey 1992) to determine that bottomland hardwood forests in Texas sequester an estimated 3.5 metric tons of CO_2 each year. It should be noted that these literature values are estimates as previously explained. I was unable to locate any papers that specifically measured carbon stocks and fluxes within the Columbia Bottomlands ecosystem.

Table 2 Estimated annual carbon sequestration rates for the two main USDA forest types found within the Columbia Bottomlands.

Estimated annual carbon sequestration rate (from literature)	**Annual CO_2 sequestration rate (metric tons/acre/year)**	**Source**
Oak-gum-cypress: 1.01 Elm-ash-cottonwood: 1.09 (metric tons/acre/year)	Oak-gum-cypress: 3.7 Elm-ash-cottonwood: 4.0	Simpson et al. (2013)
Oak-gum-cypress: 1685 Elm-ash-cottonwood: 1999 (lbs/acre/year)	Oak-gum-cypress: 2.8 Elm-ash-cottonwood: 3.3	Birdsey (1992)

Proposed methodologies for estimating carbon sequestration capacity in bottomland hardwood forests on the Texas coast

The objective of TCX is to provide a means to support, through grant funding, forested properties that undergo carbon sequestration in the Columbia Bottomlands of coastal Texas. To estimate the amount of CO_2 sequestered on an annual basis on properties with stands of bottomland hardwood forest, a standardized methodology needs to be developed. Here, I briefly discuss two strategies that may be used for this process and the inclusion of this coastal ecosystem in the TCX inventory. These methods will need to be refined in greater detail and the selected method will be described in a separate technical report.

Method 1: Using GIS and literature values

After obtaining the initial bottomland hardwood forest property outline from the landowner, a refined boundary will be generated by the GIS analysts for a precise estimate of the forest area to be included in the TCX inventory. This will be done using National Wetlands Inventory (NWI), National Landcover Dataset (NLCD) and Forest Inventory and Analysis (FIA) data, and potentially, Texas Ecoregion and floodplain data. Specifically, it is important to use the FIA data along with the NLCD data as this is a more comprehensive strategy (Almaguer-Reisdorf 2003). The inclusion of the other data sets will be done if they are determined to be informative as well.

Once we know the estimated bottomland hardwood forest area in acres, this will then be used to estimate the annual amount of CO_2 sequestered on the property using the average estimated annual carbon sequestration rate of 3.5 metric tons of CO_2/acre/year. If used, this process will be further developed and refined with the GIS team. This strategy is similar to the already developed methodology followed for coastal wetlands and uses a conservative estimate from the scientific literature.

Dataset links:

FIA National Forest Type dataset:
https://data.fs.usda.gov/geodata/rastergateway/forest_type/

TPWD Ecological Mapping Systems dataset:
https://tpwd.texas.gov/gis/programs/landscape-ecology/by-ecoregion-vector
(download the information for the Western Gulf Coastal Plain)

Method 2: Using the USDA Forest Service i-Tree Canopy tool

This tool (https://canopy.itreetools.org/) can be used to estimate the annual carbon sequestration rate for an individual property, as well as other ecosystem service values. All estimated values generated using the tool are based on FIA data and peer-reviewed, USDA Forest Service research. Property boundaries can be drawn within the tool interface which uses Google Maps, or an ESRI shapefile can be uploaded. Random sample points are then selected by the tool and the land cover type is assessed by the user for each sample point. Then, a general summary is generated based on the sample points and geographic area. To evaluate the appropriateness of this method for TCX, I completed a pilot study of the Pierce Ranch property in Wharton County, Texas.

Pierce Ranch bottomland forest pilot study using i-Tree Canopy

The i-Tree Canopy tool (v 7.0) was used to estimate the carbon sequestration rate of bottomland hardwood forests present on the Pierce Ranch property in Wharton County, Texas. I uploaded a shapefile of the original outline provided by the property owner to obtain 1000 randomly selected survey points using this tool. The land cover types were defined as the following: agricultural field, buildings, grass/herbaceous, road, soil/bare ground, tree/shrub, and water (Figure 10). Tree/Shrub was the dominant cover type representing 55.81% of the total area surveyed (Table 3). The amount of carbon sequestered in trees annually on the property was estimated to be 8.82 kT (8,820 metric tons) based on an annual carbon sequestration rate of 0.874 kT/mi^2/year (1.4 metric tons/acre/year), which is equivalent to 5 metric tons CO_2/acre/year.

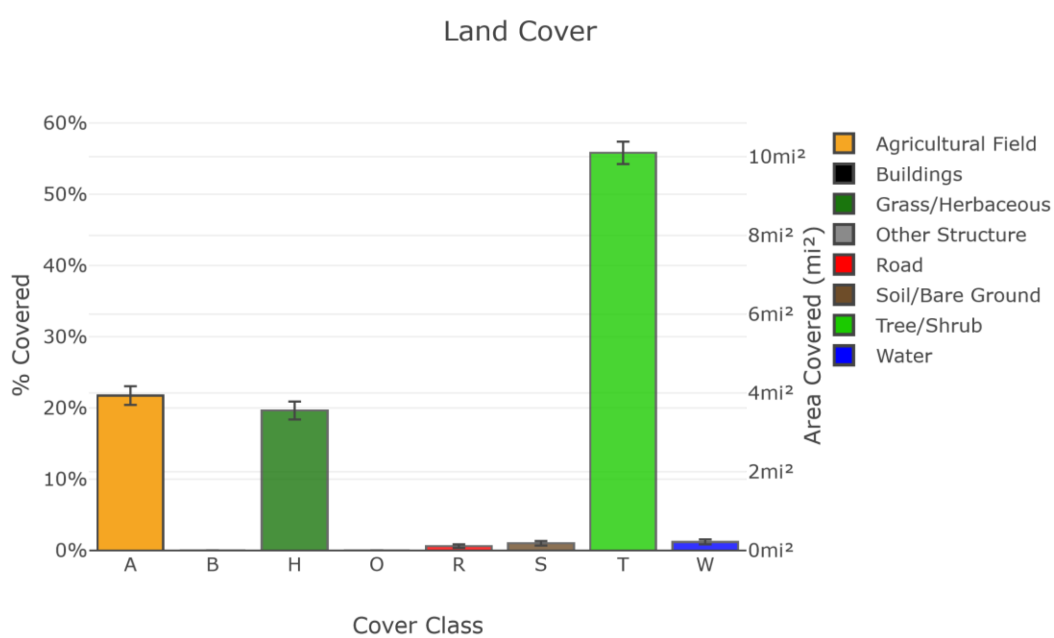

Figure 10 Land cover percentages for the Pierce Ranch property obtained using the i-Tree Canopy tool.

Table 3 Percent cover by land cover type for the Pierce Ranch property.

Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (mi^2) ± SE
A	Agricultural Field		217	21.74 ± 1.31	3.93 ± 0.24
B	Buildings		0	0.00 ± 0.00	0.00 ± 0.00
H	Grass/Herbaceous		196	19.64 ± 1.26	3.55 ± 0.23
O	Other Structure		0	0.00 ± 0.00	0.00 ± 0.00
R	Road		6	0.60 ± 0.25	0.11 ± 0.04
S	Soil/Bare Ground		10	1.00 ± 0.32	0.18 ± 0.06
T	Tree/Shrub		557	55.81 ± 1.57	10.10 ± 0.28
W	Water		12	1.20 ± 0.35	0.22 ± 0.06
Total			**998**	**100.00**	**18.09**

This method could potentially be used for each property. However, this would likely complicate donation and landowner grant tracking procedures, as multiple annual carbon sequestration rates would be generated. Also, using an annual CO_2 sequestration rate estimated from one property is problematic because the amount of carbon taken up by a forest varies based on soil and tree quality, topography, disturbance frequency, and geographic location, which is not uniform across the bottomland hardwood forests of the Texas coast.

Discussion

Here I proposed different methods by which Texas Coastal Exchange (TCX) can quantify annual carbon sequestration rates for properties with bottomland hardwood forests within the Columbia Bottomlands region of Texas. This will allow for the eventual inclusion of this ecosystem into the TCX inventory and for the protection of these lands from development. However, it should be noted that the carbon sequestration values presented in this paper from the scientific literature are estimates based on biomass regressions that rely on the allometric relationship between physical properties of the tree (dbh, height) and biomass. While this is a common practice, it must be understood that these are not actual measurements of carbon in trees. There are also several sources of error in estimating forest biomass at large-scales using these biomass equations, including non-representative samples of trees and wood density measurements for the target population, as well as inconsistent standards, definitions, and methodologies (Jenkins et al. 2003).

There are also other limitations to using FIA data such as that there is considerable stand-to-stand variation in biomass, and, therefore, carbon storage and sequestration. Also, differences in land and/or forest management practices, soil moisture levels, and nutrient availability impact tree growth rates and size at any age class. This in turn impacts biomass accumulation and carbon dynamics in a growing forest. Also, only above-ground live biomass was considered in these estimates. The carbon in live biomass is most impacted by human activities and natural disturbance (Jenkins et al. 2003). However, one study in the Neches river floodplain found that harvesting had minimal and short-term impacts on forest ecosystem dynamics that usually only last for the first year following harvest (Shoenholtz and Londo 1997).

Even with consideration of these potential sources of error in these estimates, the proposed methodologies are a practical way for TCX to move forward on the inclusion of bottomland hardwood forest properties in its Carbon Storage Inventory. Other strategies involve precise measurements and expert forestry experience to obtain actual carbon sequestration values. TCX does not have the resources to accomplish this task, nor is it necessary to have such precise measurements to meet the purpose of this project. The estimates obtained, while not entirely precise, are scientifically valid and based on methods and data collected by expert foresters. Therefore, using either the literature estimates or the i-Tree Canopy tool (both of which are based on FIA data) to determine annual carbon sequestration rates for bottomland hardwood forests on the Texas coast are scientifically valid methods.

References

Almaguer-Reisdorf, J. (2003) “Thesis submission: Carbon Sequestration in the Forests of East Texas.” *Rice University*.

Audubon.org “Important bird areas, Columbia Bottomlands, Texas.” *Audubon*, https://www.audubon.org/important-bird-areas/columbia-bottomlands (Accessed 10 June 2020).

Barrow, Jr., W.C. et al. (2005) “Coastal forests of the Gulf of Mexico: A description and some thoughts on their conservation.” *USDA Forest Service Technical Report*.

Birdsey, R. (1992) “Carbon Storage and Accumulation in the United States.” USDA Forest Service.

Chojnacky, D.C. et al. (2014) “Updated generalized biomass equations for North American tree species.” *Forestry*, Vol. 87, pp. 129-151.

Dooley, K. and J. McCollum (2013) “Texas’s Forests 2013.” *USDA Forest Service, Southern Research Station*.

Forster, P. et al. in Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds Solomon, S. et al.) (Cambridge Univ. Press, 2007)

Gambolati, G. et al. (1999) “Coastline regression of the Romagna region, Italy, due to natural and anthropogenic land subsidence and sea level rise.” *Water Resources Research*, Vol. 35(1), pp. 163-184.

Gosselink, J.G. (1981) “Ecological factors in the determination of riparian wetland boundaries.” In: Clark, J.R., and J. Benforado (eds.). Wetlands of bottomland Hardwood Forests. *ElsevierScientific Publishing Co.*, New York, N.Y.

Harley, C.D.G. et al. (2006) “The impacts of climate change in coastal marine systems.” *Ecology Letters*, Vol. 9(2), pp. 228-241.

Hayes, T. (2016) “Riparian assessments on the Guadalupe and Brazos Rivers.” *Environmental Conservation Alliance, Inc. (report produced for Texas Parks and Wildlife Department*).

He, Q. and B.R. Silliman (2019) “Climate change, human impacts, and coastal ecosystems in the Anthropocene.” *Current Biology*, Vol. 29, R1021-R1035.

Houston Wilderness (a) (2007) “Trinity Bottomlands.” *Texas A&M University Press*, pp. 33-40.

Houston Wilderness (b) (2007) “Columbia Bottomlands.” *Texas A&M University Press*, pp. 41-48.

Hunter et al. (2008) “The importance of hydrology in restoration of bottomland hardwood wetland functions.” *Wetlands*, Vol. 28 (3), pp. 605-615.

Jenkins, J. et al. (2003) “National-scale biomass estimators for United States Tree Species.” *Forest Science*, Vol. 49 (1), pp. 12-35.

McWilliams, W.H. and J.F. Rosen, Jr. (1990) “Composition and vulnerability of bottomland hardwood forests of the Coastal Plain Province in the south central United States.” *Forest Ecology and Management*, Vol. 33/34, pp. 485-501.

NOAA 2020 (a) “Shoreline Mileage of the United States.” *NOAA Office for Coastal Management*, https://coast.noaa.gov/data/docs/states/shorelines.pdf.

NOAA 2020 (b) “Fast Facts: Texas.” *NOAA Office for Coastal Management*, https://coast.noaa.gov/states/texas.html#:~:text=Coastal%20Demographics,coastal%20portions%20of%20the%20state (Accessed 22 June 2020).

Rosen, D. J and W.L. Miller (2005) “The vascular flora of an old-growth Columbia Bottomland forest remnant, Brazoria County, Texas.” *Texas Journal of Science*, Vol. 57 (3), pp. 223-250.

Rosen, D.J. et al. (2008) "Conservation Strategies and Vegetation Characterization in the Columbia Bottomlands, an Under-recognized Southern Floodplain Forest Formation." *Natural Areas Journal,* Vol 28 (1), pp. 74-82.

Schoenholtz, S.H. and A. Londo (1997) "Initial response of woody vegetation, water quality, and soils to harvesting intensity in a Texas bottomland hardwood ecosystem." *Forest Ecology and Management*, Vol. 90, pp. 201-215.

Simpson, H., E. Taylor, Y. Li, B. Barber (2013) "Texas Statewide Assessment of Forest Ecosystem Services." *Texas A&M Forest Service*.

Smith, J.E. et al. (2006) "Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States." *USDA Forest Service*.

Texas Mid-coast NWR Complex Draft Comprehensive Conservation Plan and Environmental Assessment (2012).

Texas Parks and Wildlife Department "Columbia Bottomlands Forest and Woodland." *tpwd.texas.gov*. https://tpwd.texas.gov/landwater/land/programs/landscape-ecology/ems/emst/woody-wetlands-and-riparian/columbia-bottomlands-forest-and-woodland (Accessed 3 June 2020).

U.S. Census Bureau (2019) "Metropolitan and Micropolitan Statistical Areas Population Totals and Components of Change: 2010-2019." *census.gov*. https://www.census.gov/data/tables/time-series/demo/popest/2010s-total-metro-and-micro-statistical-areas.html#par_textimage_1139876276 (Accessed 25 June 2020).

USFWS (2015) "DRAFT Environmental Assessment, Issuance of Right-of-Way Permit Praxair Duel Pipeline System Project, 4.3-mile segment."

USFWS (2013) "Texas Mid-coast National Wildlife Refuge Complex, Comprehensive Conservation Plan and Environmental Assessment."

Yu, K. et al. (2008) “Effect of hydrological conditions on nitrous oxide, methane, and carbon dioxide dynamics in a bottomland hardwood forest and its implication for soil carbon sequestration.” *Global Change Biology*, Vol. 14, pp. 798-812.