Effects of Land Use Changes on the Vegetation of Southeast Texas, United States of America[1]

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Abstract: Land use is a form of human activity which can result in substantial effects to the natural environment. This study examines the effects that land use and the changes thereof have had on the vegetation of southeast Texas by comparing descriptions of the region from the early 19th century to observations of the region in the modern day. This comparison is corroborated by assessing published scientific research on the effects that various changes in land use have had on the plant communities. The overall effect of land use, and changes thereof, is the conversion of a coastal grassland ecosystem to a fragmented forest dominated by species of *Pinus* and *Quercus* with a thick shrub understory. Potential methods of reversing this change are assessed to determine the feasibility of restoring the coastal grassland ecosystem.

Key Words: Land use changes, vegetation, plant communities, southeast Texas

Introduction

Southeast Texas (Figure 1), like much of North America, underwent several substantial changes following the arrival of European settlers. The introduction of new people and cultures brought with them new lifestyles and methods of using and managing natural resources. The Spanish Empire made few efforts to colonize Texas, and Mexico's settlements were concentrated in areas south of San Antonio (Texas Almanac 2019), and so their land use practices would have had little effect on the study area. Colonization of southeast Texas began in earnest in 1823 when Stephen F. Austin, with permission from the Spanish government, organized the settlement of 300 Anglo-American families—later dubbed "The Old Three Hundred" (Texas Almanac 2018), and it is with them that land use analysis will begin. Descriptions of southeast Texas written down by settlers in the early 19th century describe a vast grassland ecosystem (Grace et al. 2005). Stephen F. Austin wrote the earliest such description that was found in the course of this study. Beginning on June 18th, 1821, he led a survey expedition to inspect the land that had just been granted to his father by the Spanish government; Austin compared the landscape to the barrens of Kentucky (Campbell 2015). Austin describes the landscape: "The Country from Corpus to this place is very handsome, rolling Prairies, intersected by [drains] in most of

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which water was standing in holes. Timber rather scarce, but sufficient..." (Austin 1904).

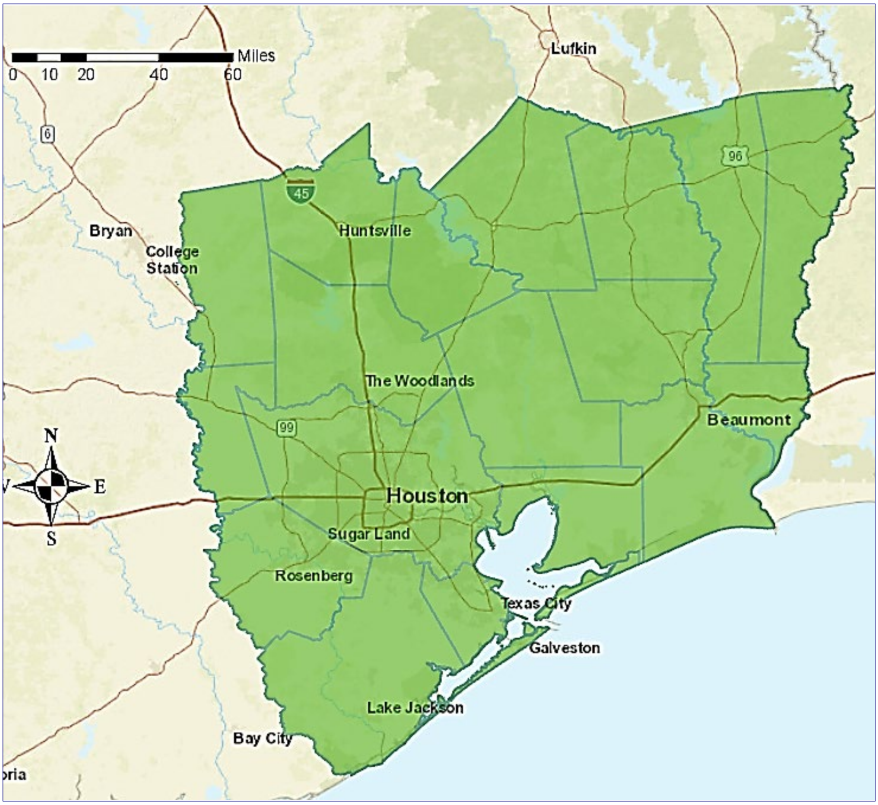

Figure 1. A map of southeast Texas, with the study area shown in green. Source: ArcGIS Living Atlas of the World. The Methods section has additional details.

The timber that Austin saw, as he relates in an earlier entry, was located in heavy quantities along creek bottoms and by the banks of rivers including the Navasota and Brazos, both of which flow generally southeast through the study area. The most abundant species he observed were oak (*Quercus* sp., Fagaceae), hickory and pecan (*Carya* sp., Juglandaceae). Austin (1904) makes little mention of pines. He does, however, mention another plant species which he found in abundance by creeks. He thought of it as a kind of grass and compared it to sugar cane. We now know this species to be giant cane, *Arundinaria gigantea* (Walter) Muhlenberg (Poaceae). Once plentiful, its distribution today is scarce (Grace et al. 2005).

In modern times the northern portion of the region—the counties of Hardin, Jasper, Jefferson, Liberty, Montgomery, Newton, Orange, Polk, San Jacinto, Tyler, and Walker—is a part of what Texas Parks and Wildlife Department (TPWD) calls the Pineywoods region (TPWD 2019), a temperate-to-humid subtropical forest dominated by pines and oaks. The southernmost extent of the Pineywoods is referred to as the Big Thicket, distinguished from the rest of the Pineywoods region by having taller forests that contain more tree species and which receive more precipitation (Marks and Harcombe 1981). The species composition of the Big Thicket varies among the multiple vegetation types that make up the region, but species of *Pinus* and *Quercus* tend to exhibit the greatest basal coverage in most types, with tupelo swamps being dominated by *Nyssa aquatica* Linnaeus (Nyssaceae) (Marks and Harcombe 1981). All of the other counties of southeast Texas are contained in what TPWD (2019) identifies as the Gulf Coast, which the department describes as consisting of partially "remnant prairie". This remnant prairie is dominated by the tall grass species *Schizachyrium scoparium* (Michaux) Nash (Poaceae), *Paspalum plicatulum* Michaux (Poaceae) and *Sorghastrum nutans* (Lehmann) Nash (Poaceae) and may be considered an isolated fragment of the Blackland Prairie to the northwest (Diamond and Smeins 1984).

Specific land cover types within southeast Texas (Figure 2) vary within the ecoregions. Most of the land in and around Houston, Galveston, Beaumont, and Freeport is classified by the US Geological Survey (USGS) as urban development, in varying intensities determined by the amount of paved ground surface; areas where the ground surface are entirely paved are considered high intensity (Figure 3A, page 9). Areas south and west of Houston, and between Houston and Beaumont, are predominantly classified as hay pasture (Figure 3B) or as cultivated crops (Figure 3C). Areas of forested (Figure 3D) and scrub-shrub (Figure 3E) land cover are predominately found northeast of Houston, in the Pineywoods and Big Thicket ecoregion. Herbaceous land cover that has not been converted to agriculture (Figure 3F) is rare and fragmented, making it difficult to discern in USGS land cover data.

A variety of and use change models have been developed using tools and knowledge from biophysical and socioeconomic disciplines (Veldkamp and Verburg 2004). However, models which examine the effects of land use change specifically on vegetation are still being developed. Previous assessments of vegetation in South Tyrol, Italy, a mountainous environment, indicated that changes are linked to land use changes, which are linked to transportation and access (Tasser and Tappeiner 2002). The purpose of this study is to assess how anthropogenic land use changes have specifically affected the vegetation in southeast Texas, a low-elevation environment with a significantly different history of settlement and development from South Tyrol. It was hypothesized that land use had resulted in the loss of the grassland ecosystem described by Stephen F. Austin. A secondary purpose of this study is to ascertain the level of effort necessary for ecological restoration in the region.

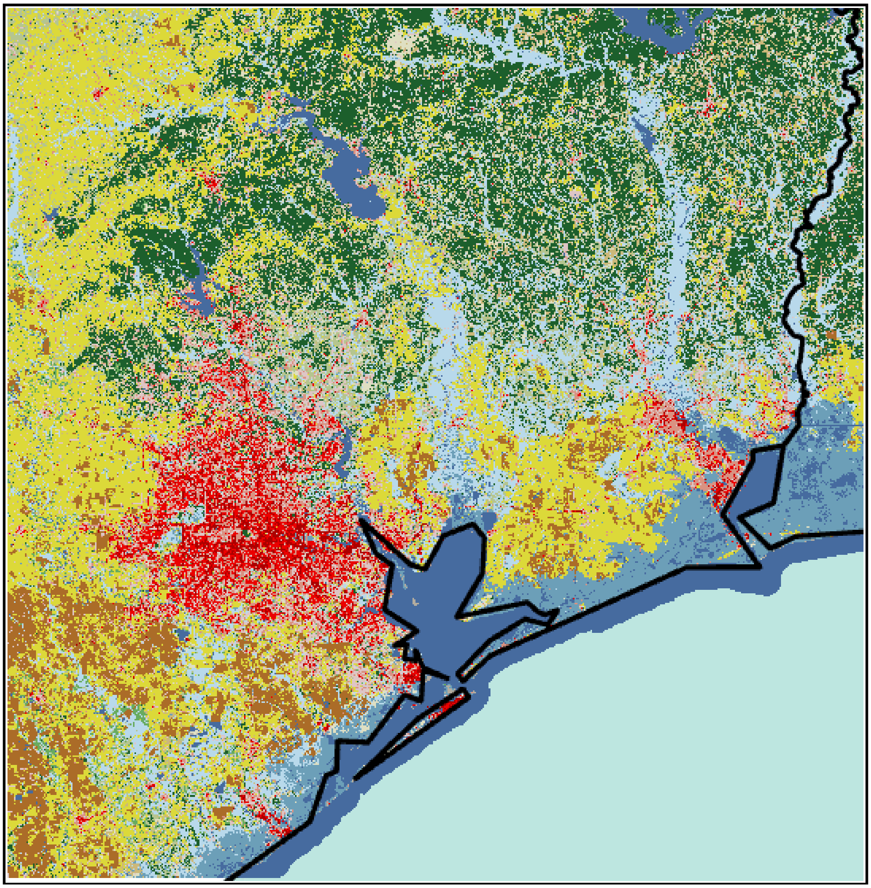

Figure 2. Land cover in the study area as classified by the United States Geological Survey. Areas in red represent developed/urbanized land; areas in green represent forests; areas in pale blue and teal represent wetlands; areas in yellow represent hayfields and pastures; areas in brown represent cultivated row crops (MRLC 2022). Source: United States Geological Survey, National Land Cover Database 2016.

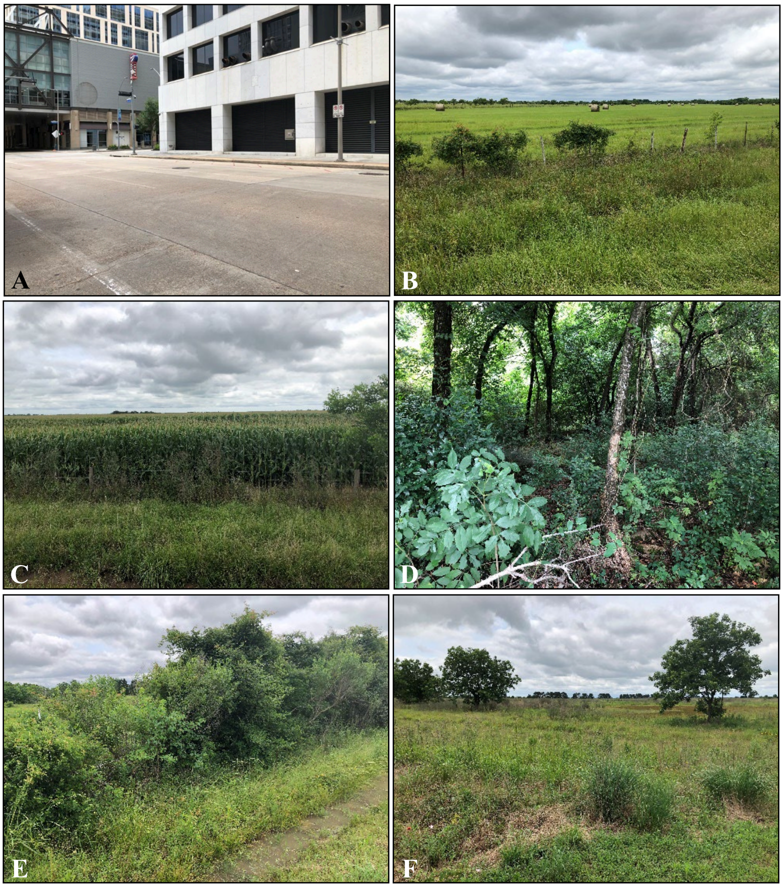

Figure 3. Dominant land cover types in present-day southeast Texas. A. Entirely paved ground surface. B. Hay pasture. C. Cultivated crops. D. Forest. E. Scrubland. F. Herbaceous land cover that has not been converted to agriculture. All photographs were taken by the author from publicly-accessible areas in May 2022.

Methods

A study area was established for this study, defined as the land area contained by the following 18 Texas counties, alphabetized (numbers correspond to those used in Figure 4): 1. Brazoria, 2. Chambers, 3. Fort Bend, 4. Galveston, 5. Grimes, 6. Hardin, 7. Harris, 8. Jasper, 9. Jefferson, 10. Liberty, 11. Montgomery, 12. Newton, 13. Orange, 14. Polk, 15. San Jacinto, 16. Tyler, 17. Walker, and 18. Waller (Figure 4). These counties were selected because they are located predominantly within the same ecoregion defined by TPWD

(2019) and they collectively contain a wide variety of land uses including urban development, agriculture, and lands reserved for conservation such as the W. G. Jones State Forest and the Big Thicket National Preserve. In addition to county lines, the study area is also defined by natural boundaries including the Sabine River in the east, the San Bernard River in the west, the edge of the Gulf Coast Aquifer in the north (TWDB 2006) and the Gulf of Mexico in the south and southeast.

Figure 4. Map of Texas (United States of America), with counties included in the study (refer to text above). Source: No machine-readable author provided. Norman Einstein assumed (based on copyright claims). https://commons.wikimedia.org/wiki/File:Texas_counties_blank_map.png . Except scale, numbers and words were added by TF.

Scientific literature was reviewed for three land uses that were expected to be the main causes of changes in the plant communities, such as agriculture, urbanization/development, and fire, including 29 peer-reviewed scientific and engineering papers, 7 government reports, and 12 historical articles. Additional information was obtained from articles in local news sources, industry newsletters and blogs, as well as non-governmental organizations.

Agriculture was examined because it results in habitat fragmentation, carries with it the potential to introduce non-native species to the landscape, and may involve the eradication of rodents and lagomorphs which play a crucial role in the dispersal of small seeds (Godó et al. 2022). The agricultural methods of both Native Americans and white settlers was analyzed. Logging was also examined, and for the purposes of this study it is included as a form of agriculture. Urbanization and development (i.e., paving over the soil surface) was examined because the construction of buildings and roadways necessarily entails the removal of vegetation that is in the construction right-of-way, and because it too results in habitat fragmentation (Swenson and Franklin 2000). Fire was the third land use examined because fire is known to play a key role in the structure and species composition of an ecosystem (Mutch 1970, Waldrop et al. 1992, Bond et al. 2003). The year 1821 was chosen for the "baseline" state of southeast Texas' vegetation as this is the earliest year in which detailed descriptions of the region's vegetation (Austin 1904) were found.

Historical records including maps, botanical surveys and agricultural inventories were reviewed to determine when major shifts in the three land uses occurred, and what changes in the surrounding vegetation came about afterward. Primary sources such as Austin's journal were used wherever possible, as these provide the most direct observations. The land uses of Native American tribes in the study area, which was primarily inhabited by the Karankawa, was reviewed as these practices would give insight into the reasons why the landscape looked the way it did when European and white American explorers arrived to make their observations. Close attention was paid to agricultural or other practices (e.g., hunting) that would have required maintenance of the ecosystem or resulted in modifications to it, such as controlled burns. The Texas Almanac, first published in 1857, was reviewed as its contents included an inventory of agriculture in the state. Further historical information was obtained from the Handbook of Texas Online, an online publication of the Texas State Historical Association.

Geographic Information Systems (GIS) data were obtained from USGS and from the ArcGIS Living Atlas of the World, a collection of maps, applications and data layers maintained by the Esri organization. GIS data from USGS included the National Land Cover Database (NLCD) and the NLCD Land Cover Change Index. The NLCD categorizes land cover and land cover change at a 30-meter resolution in 16 classes.

Information from Houston-area news publications and nonprofit organizations, as well as public agencies, was compiled to assess the possibility, problems, and potential solutions for efforts to return the study area's vegetation to a native state.

Results

Changes in land use that had effects on the vegetation of southeast Texas can be sorted into three broad categories: Agriculture, Urbanization/ Development, and Fire. These land uses, and the changes they underwent over the 19th and 20th Centuries, are discussed in detail below.

Agriculture

This category can itself be broken down into two sub-categories: ranching and farming, the latter of which is accomplished through row crops. In order to understand how the landscape observed in 1821 came to be, it is necessary to first understand what land use practices might have been at work before European-American settlement. The Native Americans did not leave detailed written records of their agricultural methods, therefore, the impact and influence they might have had on the ecology of southeast Texas must be discerned as accurately as possible using the evidence available (Weatherford 1991). Most of this evidence comes from the recorded observations of European-American settlers and missionaries (Texas Beyond History 2019).

Four tribes of Native Americans dominated southeast Texas in the days before white settlement: the Karankawa, the Atakapa, the Bidais and the Caddo (Moore 1999). The Karankawa and Atakapas were nomadic tribes who obtained food by hunting, fishing, and gathering, although the Atakapas are recorded to have had some settled communities (Couser 2010). Exact population numbers for the Karankawa cannot be obtained, but their numbers were much reduced by the early 19th century due to disease and armed conflict with the Spanish (Lipscomb 2016). The Atakapas had all but died out by 1807 as a result of the diseases which swept the New World (Couser 2010). Of the Bidais, little is known; the tribe was so ravaged by the same diseases which struck the Atakapa that many of the Bidais were absorbed into the Atakapas and Caddos by the time that white observers could make written descriptions of their culture (Campbell 2010).

The Caddo were the most sedentary of the four tribes. For the most part they lived in settlements of grass and cane houses, but they also built town-sized mounds to serve as their civic-ceremonial centers (Perttula 2010). By the 14th century they had developed a sophisticated economy based on horticulture and trade (Texas Beyond History 2019). They cultivated several crops, chief among them being corn, as well as multiple species of beans, squash, sunflower, and tubers. Some wild plants were also gathered for food, with these being mainly nuts (pecan, hickory, etc.) and berries, persimmon, plums, and grapes. For meat, the Caddo relied on hunting. They had numerous prey species including rabbits, turkeys, the occasional buffalo and even bear, but the most important prey species for food and materials was the white-tailed deer, *Odocoileus virginianus*

(Zimmermann, 1780) (Cervidae) (Texas Beyond History 2019). *Odocoileus virginianus* is an adaptable animal that can thrive in a variety of habitats but is often considered an edge species as it prefers to live in environments with a mixture of open grass, hardwood forest and brushy areas (Smith 1991).

Within the study area, the Caddo had the smallest presence, with their communities being present only in the northernmost counties being examined in this study (Moore 1999). The hunter-gatherer tribes would therefore have had the greatest direct effect on the ecology of southeast Texas.

A mathematical model for Native American populations in this period, proposed by Winterhalder et al. (1988), takes this into consideration by using different parameters to calculate an environment's carrying capacity for hunter-gatherers who inhabit it. Essentially, this equilibrium occurs when the rate at which people acquire a food source that equals or exceeds the rate at which that food source provides enough energy that the people can just survive. Winterhalder's model identifies a preferred food source as one that provides the greatest energy gained for the least energy expended in acquiring it - but human ingenuity can reduce the amount of energy expended. Humans have a history of altering their environment in order to improve the efficiency of gaining energy, and the Native Americans were no different. Many tribes altered the vegetation around their living spaces to create conditions that would attract their favored prey, and one of the main tools that they used for this purpose was fire (Weatherford 1991). It is therefore likely that all four tribes used fire as a tool for agricultural and hunting purposes, and this will be discussed in greater detail later.

Details of each tribe's agricultural practices were obtained from articles published by the Texas State Historical Association (Couser 2010, Lipscomb 2016). A band of Karankawa, which consisted of around thirty to forty individuals, would rarely stay on a single campsite for more than a few weeks. Their movement was seasonal, dictated by the availability of prey species including those hunted by the Caddo, but their proximity to the Gulf of Mexico afforded the Karankawa access to a variety of fish, shellfish, and turtles as well (Lipscomb 2010). The Atakapa, who lived to the northeast, did not have access to the barrier islands through which the Karankawa migrated and so their diet included less fish and shellfish, but they made up for this by including alligator, *Alligator mississippiensis* (Daudin, 1802), in their prey species (Couser 2010).

With the advent of European-American settlement came the practices of row crops and ranching, which are sufficiently different from indigenous agriculture that they can produce effects to the soils, fauna, and hydrology of an area (Anderson and Moratto 1996). Habitat fragmentation causes a peculiar time-delayed stress on surrounding plant communities referred to as extinction debt. In temperate-to-humid grasslands fragmented by agriculture, extinction debt is estimated to be approximately 40% of current species, meaning that a grassland fragmented by row crops can be expected to lose 40% of its species richness if conditions remain constant (Helm et al. 2006).

Ranching in Texas expanded quickly. Although it does not record how many individual ranches and farms were in Texas at the time, the first edition of the Texas Almanac (1857) records that in 1850 there were a total of 750,352 horses and cattle in the state; in 1855 that number had increased to 1,603,146. It is noteworthy, however, that the almanac describes this increase as occurring in the western counties:

> *Horses have increased from 89,223 in 1850, to 17,444 in 1855, or nearly 100 per cent. Eight counties, seven of which are in the Eastern portion of the State, show a decrease in this stock during the five years. This arises from the want of grass in Eastern Texas, the horses having been removed to the western prairies. To the same cause is to be attributed the decrease of Cattle, which occurs in twenty counties in the State, all in the Eastern counties, except Colorado.*
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> ...
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> *The above statement shows a most astonishing result, considering that only twenty years have passed since Texas was literally an uncultivated waste (Texas Almanac, 1857).*

The pattern described by this passage of the almanac still holds in the study area today. The NLCD maps (Figure 2) classifies much of the southern and western portions of the study area as hay pasture, while forest and shrub/scrub land dominate the north and northeast. The second paragraph quoted from the almanac is notable as it suggests a lack of significant ranch land or row crops in the state before 1837.

Agriculture may indirectly affect the species composition of surrounding natural ecosystems (Anderson and Moratto 1996). Ranching originally made use of native grasses for forage; however today *Cynodon dactylon* (Lehmann) Persoon (Poaceae) is cultivated in many ranches (Crudney et al. 2007). This grass is not native to North America but was described as an important grass as early as 1807 due to its value as forage; although native animals can eat it, it can also become weedy if not properly managed (NRCS 2000). Other exotic plants introduced to Texas through the agriculture industry include *Eleusine indica* (Lehmann) Gaertner (Poaceae), which entered the state during a drought in

1996, by being included in bales of hay that were imported to Texas (Rector 2006). More problematic species introduced by agriculture are *Dichanthium annulatum* (Forsskål) Stapf (Poaceae) and *Bothriochloa ischaemum* (Lehmann) Keng (Poaceae) (Simmons et al. 2007).

Another invasive plant which was probably introduced through agriculture is *Triadica sebifera* Small (Euphorbiaceae), commonly known as Chinese tallow tree (NRCS 2000). Originally introduced in 1776 in by Benjamin Franklin (Randall and Marinelli 1996), this medium-sized tree was cultivated in China for centuries as a seed-oil crop and was cultivated in America as a source of tallow for candle-making. Although *T. sebifera* has also been maintained as an ornamental, the fact that it was cultivated in orchards suggests an agricultural origin in America. *T. sebifera* is considered by the US Department of Agriculture (USDA) as the most successful invader in southwestern Louisiana (USDA 2000). USDA expects one of two scenarios to occur in Texas woodlands dominated by *T. sebifera*: a stable exotic vegetation type, or a climax community of native woody species (NRCS 2000).

Texas' logging industry appears to have had a limited presence in the study area, which is not surprising as the journal passages that Stephen F. Austin wrote as he passed through included multiple variations of the phrase, "timber scarce, but sufficient." (Austin 1904) As logging necessarily involves the take of plants from a plant community, however, the industry must be investigated for this study to be complete. The US Forest Service (USFS) is a part of the United States Department of Agriculture, and the timber industry occasionally uses practices similar to farming (Carsan and Holding 2006), so logging is included in this study as a form of agriculture.

The first recorded sawmill in Texas appeared in Nacogdoches County in 1829. From there, a lack of reliable roads and other means of transportation besides rivers prevented logging from growing as an industry (Texas Beyond History 2004). By 1880, however, a network of railways provided transportation to every part of East Texas, with Houston serving as a major hub (see Figure 4). This led to a period referred to by historians as the "bonanza," which lasted for approximately fifty years. The Great Depression devastated the lumber industry in Texas as it devastated so many other industries, but even before that, logging in Texas was on the decline as many companies had cut-over the land where they operated (Maxwell 2012).

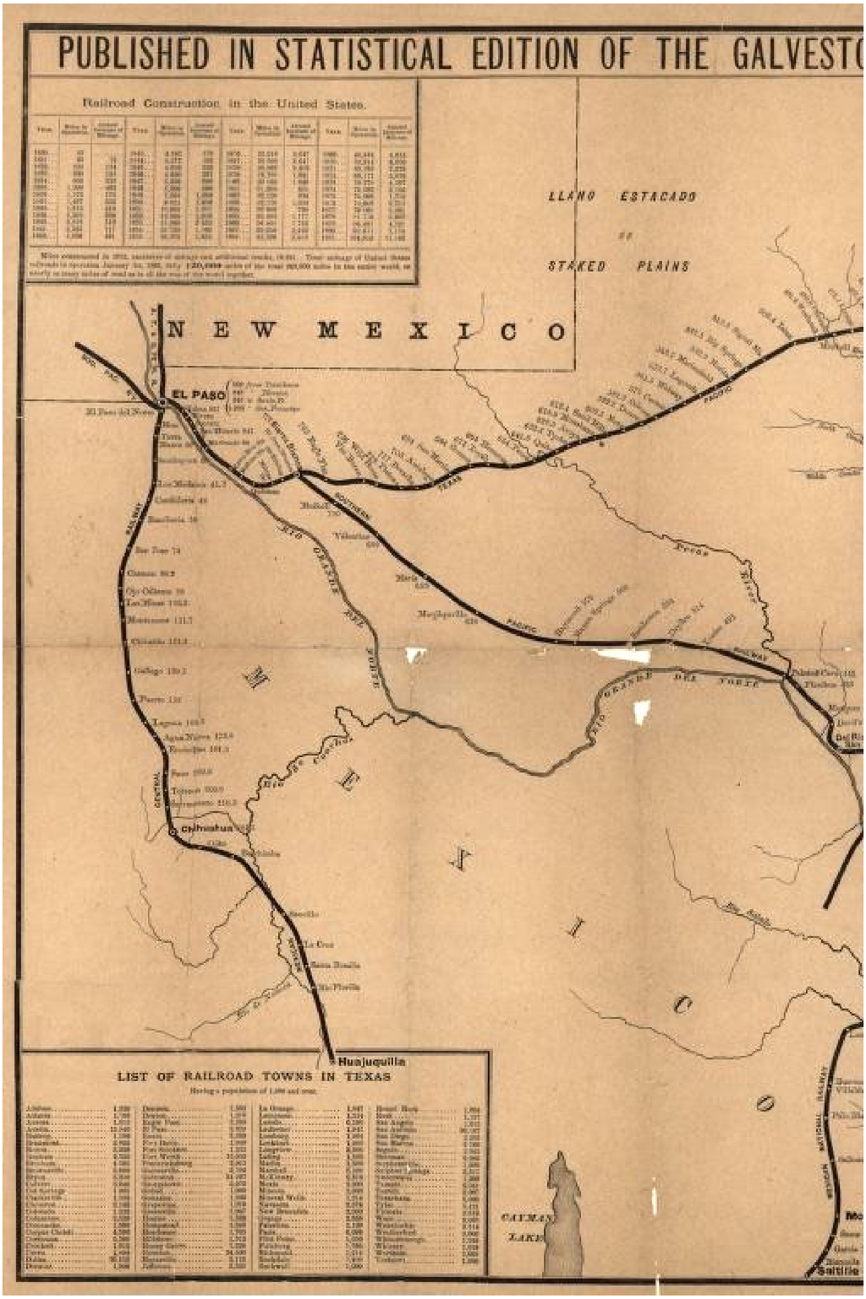
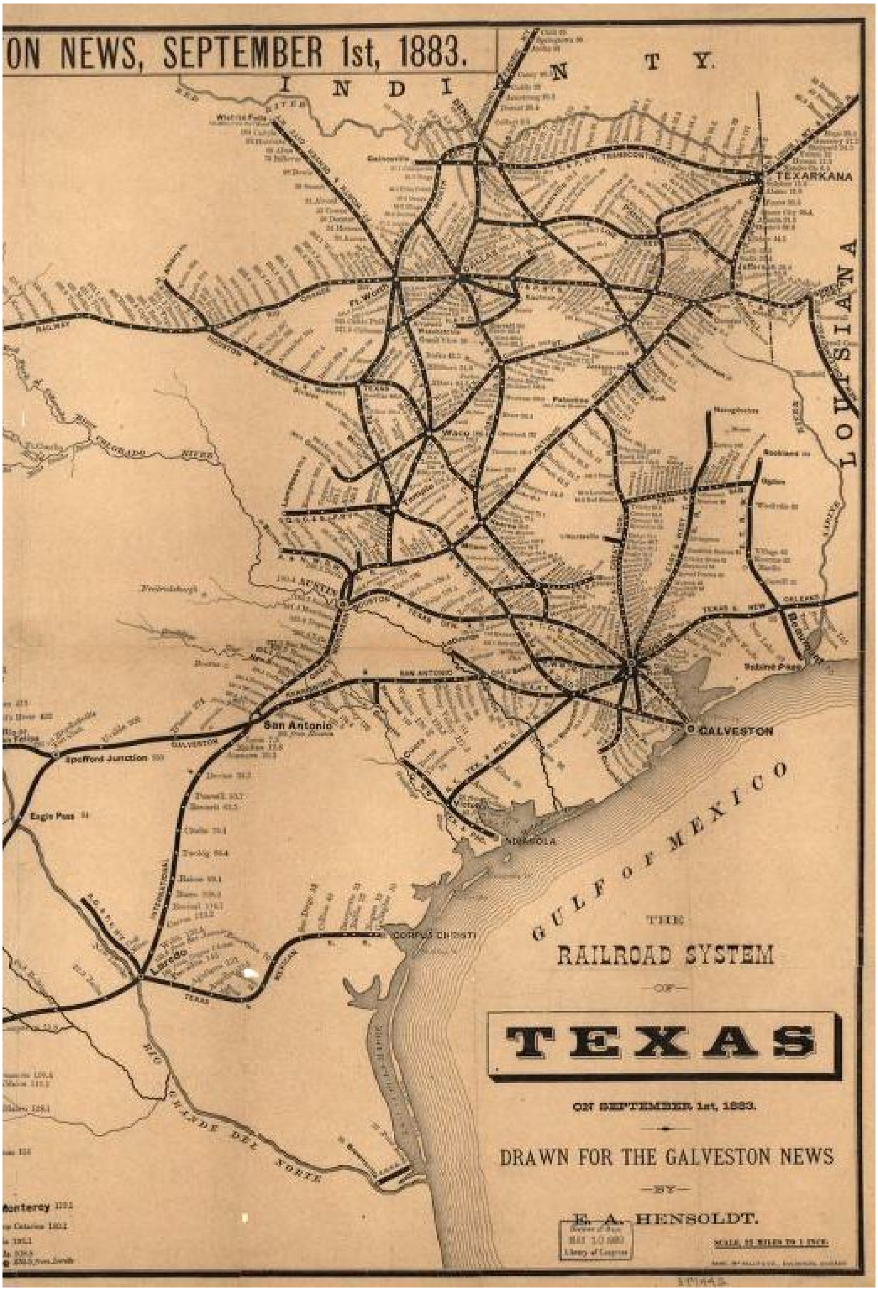


Figure 5. The railroad system of Texas on September 1st, 1883. Source: Library of



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Urbanization and development

In this study, “development” refers to the paving of an unpaved area of land, regardless of prior or future use. In this definition, development occurs in the construction of buildings and roadways. Houston, Galveston, and Beaumont are the largest urban areas in the study area (Data USA 2019).

Houston was founded in 1836 and served as the original capital of the Republic of Texas until 1839 (Houston Visitors Bureau 2019). Development occurred immediately and rapidly. Flat terrain and the presence of several meandering waterways meant that the Houston area was, and still is, rife with wetlands. Despite these seemingly inhospitable surroundings, Houston developed soon, and rapidly. The new city was well positioned to be a hub for trade going to and coming from the port in Galveston, and by 1844 both steamboats and railroads carried the goods of this trade (Houston Visitors Bureau 2019). In 1873 Houston was the city where “eleven railroads meet the sea,” and a hub for the Texas and Pacific Railway.

By 1870 Galveston was the largest city in Texas, but after it was devastated by the hurricane of 1900 Galveston’s population declined precipitously. This was partially due to the deaths inflicted by the hurricane and partially due to a newfound aversion to living in a city which now had a reputation for risk (McComb 2019). Galveston’s loss became Houston’s gain; in 1910 Houston successfully lobbied the federal government to help fund the widening of Buffalo Bayou, the city’s waterway to the Gulf of Mexico, so that it could be traversed by larger ships. The discovery of nearby oil sources in 1901 ensured that Houston would be a major center of economic activity (Houston Visitors Bureau 2019).

Historically, Houston has experienced a great degree of urban sprawl, as seen in its large population - approximately 6.89 million in the greater metropolitan area (Data USA 2019) - and comparatively low population density (Maciag 2017). An illustration of this can be observed in the NLCD (Figure 2); lighter shades of red indicate less intense urbanization and the area in and around Houston shows few areas of the highest intensity. This has implications for habitat fragmentation, as Houston’s sprawl has manifested itself in a collection of small cities that require a network of roadways to connect them, and each new roadway built in a previously undeveloped area fragments the habitat of that area.

The development of roadways is known to fragment the habitat of animals, and this may indirectly affect the species composition of nearby plant communities (Anderson and Moratto 1996). Rodents are a common disperser of tree seeds, including acorns. The seed dispersal effectiveness of rodents declines in proximity to a road; the average distance which rodents carry acorns is reduced by 40.9% to 60.9% within 200 meters of a road (Wenwen et al. 2019).

This would have the effect of diminishing the dispersal and recruitment of oak species within the vicinity of a roadway network. Eleven species of oak are found in the study area (Marks and Harcombe 1981), and their diminished dispersal would create a competitive advantage for the aforementioned *T. sebifera*, whose seeds are dispersed mainly by birds and water (NRCS 2000) and therefore less affected by habitat fragmentation.

Houston has no zoning laws - the only major city in North America to lack them - with land use instead being regulated by the city, as well as by private groups and community associations, through other means (The Kinder Institute for Urban Research 2020). For the city government, this includes regulations on roadway and parking lot sizes. Under Houston law, major thoroughfares must have an unobstructed right-of-way for traffic no less than 100 feet in width, while more minor thoroughfares must be between 50 and 60 feet in length. This is wider than the national average; most American urban streets are 35 feet wide or narrower. Parking lot sizes are required to have a minimum size depending on the number of residents or customers that an establishment is built to serve. For example, apartment complexes must have 1.3 parking spaces per resident, and bars must have 10 parking spaces for every 1,000 square feet of gross floor space (Qian 2010). The ecological effects of this policy are quite negative to native plant species; the above-average amount of paved ground surface reduces the amount of urban microhabitats in which displaced vegetation might otherwise survive, and most microhabitats that remain would be dominated by species adapted to rocky outcrops (Lundholm and Marlin 2006). Southeast Texas does not have very many rocky outcrops, its landscape having been formed by flooding from the Gulf of Mexico and the rivers which flow through it. These rivers - the Sabine, the San Jacinto, the Brazos, the San Bernard, and their tributaries - all have meandering drainage patterns which indicate an absence of rocky substrate (Earle 2019). Source populations for plants adapted to rocky outcrops, if they were present at all in 1821, are therefore likely to have been small and unlikely to send many seeds to colonize paved land surface in the study area.

Non-governmental regulations are enabled by Texas state law, specifically that which relates to homeowners associations (City of Houston 2019). Homeowners associations, which can be founded before homes are even built in an area, are empowered to enact deed restrictions and ordinances which regulate landscaping and other land use activities. The City of Houston's Planning and Development Department works within this system by allowing for an entity which it labels a "super neighborhood." A super neighborhood is a geographically designated area of vegetation that share common physical characteristics, identities, or infrastructure. A council, elected from the area's residents and stakeholders, serves as a forum to identify issues facing the super neighborhood and implement projects to address them (City of Houston 2019).

For super neighborhoods, the means of regulation begin by drafting a Super Neighborhood Action Plan for land use within the boundaries of the neighborhood. This can include schools and housing, but also environmental issues as well. Entities and people which do not comply with the Action Plan are subject to legal protests and civil lawsuits filed by the super neighborhood's council (City of Houston 2019). This method of enforcement has produced few meaningful consequences for those whose land use deviates from a Super Neighborhood Action Plan (Qian 2010).

Houston, however, does not have jurisdiction over the entire study area. Local regulations vary from one incorporated city to the next, and even among unincorporated areas that receive services from Municipal Utility Districts (Kim and Ellis 2009). The result of this is a variance among the community structure of habitat fragments that exists within each municipality, as explained by Jinki Kim and Christopher D. Ellis (2009) in their comparison study of neighborhoods in northern Houston and The Woodlands, a master-planned community to Houston's north (Figure 1). The Woodlands is not an incorporated city but is a special-purpose district - a legal entity created by an act of the Texas Legislature which allows for a local governing body to levy regulations. Among the landscaping regulations that The Woodlands imposes is a stipulation that lawns adjacent to the street must contain no more than 60% grass cover (with the species of grass not being specified); the remaining 40% or more must be covered by other plants - trees, shrubs, flowers, etc. (Kim and Ellis 2009). No tree wider than 15 centimeters at breast height may be removed from a property without the approval of The Woodlands' Development Standard Committee. Meanwhile, the regulations dictated to the neighborhoods of North Houston say only that weeds and grass must be cut in a "sanitary, healthful and attractive manner." Both areas were developed beginning in the early 1970s and have very similar socio-economic characteristics with regards to population density, rate of educational attainment and median income. They have similar ecological characteristics as well, being located in the same vegetation type, TPWD-defined ecoregion (Pine-Hardwood) and watershed boundary (the Walnut Creek-Spring Creek Watershed) (Kim and Ellis 2009).

Kim and Ellis (2009) used aerial photography and a land cover classification system with three categories (trees, grass, and developed area) to analyze how these land use regulations affected the ecological landscape structure in each jurisdiction, in three time periods: before development, immediately after development, and after enough time had passed for ecological structures to mature. They found that The Woodlands had 88% of its original amount of forest cover in the third time period, compared with 73% for North

Houston (Kim and Ellis 2009). They also analyzed six other metrics of forest habitat fragmentation and found only one that showed no significant difference between the two communities - the mean distance from one patch of forest habitat to another. In all other metrics which Kim and Ellis (2009) used to measure forest habitat fragmentation, The Woodlands, with its exacting land use regulations, showed less fragmentation. They further found that re-growth of trees, by itself, cannot overcome differences in regulatory environment - not only does North Houston have more forest habitat fragmentation now, but it will continue to have it (Kim and Ellis 2009).

Ironically, this environmental ethos that The Woodlands maintains also maintains a plant community that did not exist in a state of nature, or as close to a state of nature as can be determined given current knowledge of pre-contact Native Americans. Wooded areas in The Woodlands show an abundance of pine, with a thick understory of shrubs, and the vegetation has few open areas that resemble the untamed grasslands of Stephen F. Austin's observation. The persistence of this plant community is also supported by development-induced changes in weather patterns.

Urbanization and development have consequences for an ecosystem that go beyond habitat fragmentation. As more and more land surface is paved over, the reflection of solar radiation back into the atmosphere eventually produces the urban heat island effect (UHI). Steven Burian and J. Marshall Shepherd (2005) studied diurnal rainfall patterns in Houston across two time periods: 1940-1958, before the city was large enough to have had a significant UHI on the surrounding area; and 1984-1999, after Houston became a major metropolitan area. Areas that were downwind of Houston's UHI - north and northeast of the metropolitan area - recorded 30% more rainfall during an average warm season in the 1984-99 time period than they did in the 1940-58 time period (Burian and Shepherd 2005). This is significant, as an increase in precipitation intensity can increase the growth of woody plants and decrease the growth of grasses (Kulmatiski and Beard, 2013). The data presented in the NLCD supports the hypothesis that this is indeed what has happened, as the areas north and northeast of Houston are dominated by the forest and scrub-shrub land cover categories (Figure 2).

Like agriculture, urbanization can introduce invasive species to an ecosystem. Economic factors have been shown to play a role in the probability of a species becoming invasive - the more frequently a species appears in nursery markets, and the lower its price, the more likely it is to disperse into natural ecosystems (Dehnen-Schmutz et al. 2007). An example of this in the study area is *Ligustrum sinense*, Loureiro (Oleaceae), a shrub native to China, which was introduced in the United States in 1852 as an ornamental shrub (NRCS 2000). Although it is not widespread in the Big Thicket (Marks and

Harcombe 1981) it is nonetheless present in unmaintained wooded areas. Another example is *Rosa bracteata* Wendland (Rosaceae), imported to North America in 1850 to serve as both an ornamental and as a fence line hedge (Dehnen-Schmutz et al. 2007).

Fire suppression

Fire is crucial for the development of grassland biomes, even more crucial than rainfall patterns (Bond at aal. 2003). The landscapes of grass and pine described by early European explorers can only be maintained by prolonged periods of regular burning (Waldrop et al. 1992). It is known that Native Americans used fire for a variety of purposes, including the deliberate modification of landscapes to create habitat for their preferred game species and the facilitation of travel through forests. They also used fire to cultivate plants which they used for specific purposes (food, medicine, materiel). A lack of archeological data prevents us from knowing how often native peoples set these fires, or what specific techniques some tribes used. Sadly, this data gap extends to the Caddo, Karankawa, Atakapas, and Bidais. What can be determined is the average fire return interval (Frost 1998, see below) and the average seasonal variations of these fires. Kevin C. Ryan et al. (2013) used historical records to determine the main historical fire seasons of seven areas in the continental United States. Southeast Texas was not among them, but in northern Florida, which has a similar climate, the historical fire season was found to have begun in May and lasted until August or early September.

Cecil Frost (1998) approximated the fire return intervals of landscapes across the United States by compiling fire history studies and examining a map of land surface forms. The results of his research indicate that the pre-settlement fire return interval for the study area was 1 to 3 years (Frost 1998).

The frequency of fires declined along with Native American populations after European contact (Frost 1998). This period also coincides with the Little Ice Age. With the lower temperatures and greater humidity, the landscapes of North America became less fire-prone, and this may have influenced European settlers' thoughts about how often fires ought to occur in their new country (Ryan et al. 2013). The decline of fire frequency may be a factor in the movement of agricultural activity through the study area, as described in the 1857 Texas Almanac. A grassland which experiences a prolonged period without fire will see an increase in shrub cover, and herbaceous cover is negatively correlated with woody plant cover (Archer 1990). In addition to changes in plant community structure, the exclusion of fire from a previously fire-prone ecosystem results in changes to ecosystem composition and function (Ryan et al. 2013).

Federal wildland fire policy may not necessarily have been mirrored in state or local governments; however, it is unlikely that federal policy would deviate significantly from the prevailing attitudes and customs of the day and so in the absence of records of policies enacted by the state of Texas and the major town in the study area federal policy regarding fire was assumed to be similar. Research by Ryan et al. (2013) supports this notion.

Federal fire policy began in 1896 with the establishment of the national parks and the need for a policy to manage the ecosystems within them. In 1891 Gifford Pinchot became the first head of the USFS, tasked with managing reserves of forest land as a long-term resource (Stephens and Ruth 2005). His policy toward fire was suppression, although some foresters supported the idea of prescribed fire. During the tenure of Henry Graves, the second head of the USFS, the subject of using controlled fires for ecosystem health was still a matter of spirited debate within the USFS. In 1924 an experiment was conducted in an attempt to re-create the controlled fires set by Native Americans, but the interpretation of the collected evidence was to support a rigorous policy of fire suppression (Stephens and Ruth 2005).

By 1935, it was the policy of the USFS to suppress every wildland fire by 10 a.m. the day after it was reported (Forest History Society 2019). This began to change after USFS ranger Robert W. Mutch (1970) published his hypothesis, since supported by experimentation, that certain ecosystems and plant species are adapted to burn. Since 1995, federal policy has been amended to integrate fire into land and resource management plans (Stephens and Ruth 2005). Prescribed burns are a part of TPWD's land management practices today (TPWD 2019). However, a re-introduction of regular fire onto privately owned land is inhibited by several factors: a lack of knowledge and familiarity in prescribed burns, a lack of resources, such as time, money, and equipment, as well as concerns about liability (Diaz et al. 2015); efforts to overcome these limitations will be discussed later.

In southeast Texas, one of the plant species that has benefited from the absence of fire is *Baccharis halimifolia* Linnaeus (Asteraceae), a shrub. A study by Allain and Grace (2001) demonstrated that *B. halimifolia* can lose almost half of its population density after a single burn; however, the rate at which this shrub recovers after fire is not yet known. Grace et al. (2005) analyzed results of multiple studies which suggest that burning does not reduce *B. halimifolia*'s abundance for very long. The spread of *B. halimifolia* is notable as it exhibits many traits of an invasive species, and in fact has been declared invasive by environmental authorities in the European Union (Calleja et al. 2019).

Discussion

An analysis of the results

The trend among the plant communities of southeast Texas is one of a conversion from prairies to one of three other types: forest, urban and pasture. That the northern and northeastern regions of the study area were converted to forest is not surprising. According to Stephen F. Austin's journal (1821), timber was plentiful in areas north of the study area and would thereby provide a source population for the migration of woody species. In addition to the change in plant community structure, these forests also display a change in species composition from the 1821 baseline. Austin wrote of oak, pecan, and hickory, and made no mention of pine. Marks and Harcombe (1981) observed *Pinus* species in ten out of the eleven habitat types of the Big Thicket, with a mean basal area of up to 10.2 square meters per hectare. They did not find a single stand in the Big Thicket which contained a significant amount of pecan, *Carya illinoinensis* Koch (Juglandaceae), and only observed hickory, *Carya tomentosa* Nuttall (Juglandaceae), in limited quantities in mixed oak-pine forests. Although the reasons for this decline are not clear, given the species' economic value, it is possible that they were overharvested during the logging bonanza of the late 19th and early 20th centuries. Austin made no record of the extent of shrubs in his journal, as he was concerned with economic value rather than ecological value - i.e., wood that could produce logs and boards. However, he did occasionally write down where he saw trees that he thought held little economic value. Post oak, *Quercus stellata* Wangenheim (Fagaceae), was the species of which he complained most often (Austin 1904). Such entries are rare, and this suggests that shrub/scrub environments were not common in 1821.

Urbanization and development can be expected to continue as the Houston-The Woodlands-Sugar Land metropolitan area recorded a 1.77% increase in population in 2016, and a 3.39% increase in median household income (Data USA 2019). These trends are favorable to continued development as they enable people to build and buy more new homes. Trees raise a home's property value (Wolf 2007), which provides an incentive to homeowners to maintain mature trees, which can then act as a source population for their species to spread into herbaceous areas not already converted to forest or scrub-shrub.

Pastures may not represent a change in community structure, but many of these pastures contain non-native forage species, especially *C. dactylon, D. annulatum* and *B. ischaemum*. Like *C. dactylon*, *D. annulatum* and *B. ischaemum* were imported to Texas as cattle forage but have proven to be much more capable of out-competing native grasses (Simmons et al. 2007). Ranch lands may also eventually convert to wooded habitat, as grazing is a selective disturbance which often leaves woody species like *B. halimifolia* untouched. Prescribed burns are rare in Texas, as mentioned previously, due to a lack of resources, knowledge, familiarity, and protection from liability (Diaz et al. 2015).

The Gulf Coast prairies are not the only landscape to see a conversion from grassland to forest. Archer (1990) determined that similar changes had occurred in the savannahs of south Texas, and as with this study, he concluded that the beginnings of this conversion coincided with the arrival of European-style agriculture to the region.

Rainfall patterns alone cannot adequately explain the change in vegetation in southeast Texas as the Pineywoods receives an annual average of 35 to 60 inches of rainfall (889 - 1524 mm) while the prairies along the coast receive 20 to 50 inches (508 - 1270 mm, Landers, Jr. 1987). Likewise, changes in temperature are not known to have such a drastic effect on plant communities as seen in the study area - which, based on the Texas State Historical Association's records (Maxwell 2012), appears to have begun before industrialization increased CO_2 concentrations in the atmosphere to a degree sufficient to raise global temperatures. It is therefore likely that the conversion of Gulf Coast Prairies to the Big Thicket is the result of changes in land use.

Quantifying the degree to which one category of land use has affected the environment is difficult, as none of them occurs in isolation. Urban areas require agriculture to support them and so development will not occur far from agricultural areas; likewise farms and ranches are found near towns or highways as this makes it easier to transport crops and livestock to market. Both of these land uses result in habitat fragmentation and have the capacity to introduce invasive plant species to an area. However, a review of scientific literature suggests that species introduced to a landscape as row crops generally do not escape to become invasive in natural ecosystems, as most articles on the subject detail the damage caused to agriculture by invasive species (Randall and Marinelli 1996, Rector 2006, Dehnen-Schmutz et al. 2007). Logging, which is considered a form of agriculture for the purposes of this study, might be expected to work against the grassland-to-forest conversion but only if it is pursued by means of clear-cutting.

However, of the three major land uses studied, fire suppression must be considered the prime suspect (Grace et al. 2005). Throughout the early decades of the 20th century, societal and legal forces pushed fire policy toward suppression above all other goals, whether that policy was enacted at the federal or state level, and even among private landowners (Ryan et al. 2013). Previous research conducted in other ecosystems has shown that the absence of fire can, by itself, convert a grassland to a forest and/or shrubland. This can be observed in the aforementioned spread of *B. halimifolia*, which as previously stated, is not adapted to regular burnings (Allain and Grace 2001).

Can the prairies be restored?

Less than 1 percent of the Gulf Coast Prairie remains in the state observed and recorded by Stephen F. Austin in 1821 (TNC 2023); however, there is a new interest in restoring that prairie. Motives for this restoration include improving quail habitat so that the species is once more abundant enough to hunt, as well as the emotional experience of walking around in a landscape that was there when the Karankawa still dwelt in the region. Organizations like the Wildlife Habitat Federation, the Nature Conservancy, and the Coastal Prairie Conservancy work to achieve this goal, by working on lands that they own (TNC 2023, CPC 2023) and by encouraging and aiding private landowners to restore their own lands (WHF 2019).

Due to the valued ecosystem services that trees provide, the coastal prairie likely could only be restored in limited areas of urban and suburban southeast Texas. Trees increase the value of the property on which they stand (Wolf 2007), and their shade provides residents with relief from the region's notoriously hot summers, which are exacerbated for urban residents by the UHI effect (Burian and Shepherd 2005). Regulations which promote the presence of native species may be acceptable to the populace if they are given clear guidance to help them identify the native species (e.g., *Quercus virginiana* Miller (Fagaceae) and *C. illinoinensis*) and the most troublesome non-native species (e.g., *T. sebifera*). This will be difficult in Houston, with its *laissez-faire* regulatory environment, but other jurisdictions may have more flexibility under their governing charters. The planting of native grasses might be encouraged outside of regulation by emphasizing the fact that their adaptations to the local climate result in a reduced need for maintenance. In southeast Texas, the ideal species for this include *Buchloe dactyloides* (Nuttall) Engelmann (Poaceae), *Bouteloua curtipendula* (Michaux) Torrey (Poaceae), *Distichlis spicata* Green (Poaceae) and *Stenotaphrum secundatum* (Walter) Kuntze (Poaceae) (Johnson 2000). *Stenotaphrum secundatum* is already a popular turf grass in humid subtropical areas like southeast Texas, and *Q. virginiana* and *Pinus taeda* Blanco (Pinaceae) are commonly seen in Houston as shade trees (Kim and Ellis 2009). These three species could be presented to the public as examples of the benefits of native species, an introduction to a pitch for greater biological diversity in urban areas.

It may yet be possible to restore all undeveloped regions of the study area to something which resembles the 1821 baseline, however there are a few obstacles which must first be overcome if this is to happen. First, the populace of the Houston-The Woodlands-Sugar Land metropolitan area must know what the native landscape looked like. Photography did not exist in 1821 and landscape paintings of the area that would become Houston are scarce. Mr. Austin's journal must therefore suffice as the blueprint. Multiple nonprofit organizations maintain a "pocket prairies" program (Figure 6) wherein plots of native grasses and forbs are planted in urban areas where local residents can see a small piece of what the landscape of southeast Texas once looked like. The Memorial Park Conservancy, which manages one of the largest and most popular parks in Houston, has published its Master Plan 2015 which lays out a vision for the renovation of Memorial Park. This renovation includes the establishment of plots of native prairie, Big Thicket vegetation and the ecotones between them (MPC 2015), which will offer Houstonians an accessible presentation of what to plant on their lawns. Widespread adoption of native species for landscaping will provide source populations that could spread outward from urban areas in the event of a disturbance outside of town. Another example of using native plants as part of the city landscape is shown in Figure 7.

Figure 6. Brays Bayou Pocket Prairie in Houston, co-sponsored by Houston Audubon and Citizens League for Environmental Action Now. Photograph taken by the author.

A second obstacle is the suppression and removal of invasive species. Preventing the introduction and spread of invasive species in the first place is highly desirable (Simmons et al. 2007); this would best be achieved through a comprehensive social outreach and education program, as human activity is a key vector of the introduction of non-native species which can alter fire regimes (Fusco et al. 2020).

Figure 7. Memorial Park in Houston. Photo taken from the "living bridge" walkway over Memorial Drive. Coastal prairie native plants can be seen in the foreground and the skyline of downtown Houston can be seen in the background. Photo taken by the author on the morning of May 29, 2023.

Three methods are most commonly used to control invasive plant species on a wide scale: manual and mechanical removal, herbicide, and prescribed fire. A fourth method, biological control through mixed-species grazing, is highly effective for restoring grasslands in the Great Plains when employed in combination with prescribed fire (Wilcox et al 2022). Manual and mechanical removal have the benefit of being well understood by the populace, but cutting plants and removing their remains may not be sufficient to control some species. *T. sebifera* and *B. halimifolia* - which is native to southeast Texas but exhibits traits of an invader - (Grace et al. 2005 and Calleja et al. 2019) can only be controlled by cutting if an herbicide is applied to the stump, while mowing seems to have no effect at all on the spread of *B. ischaemum* (Simmons et al. 2007). Herbicide can be effective on all species if applied correctly and at the proper time of year but may not promote the growth of native vegetation (Kettenring and Adams 2011).

As mentioned previously, the widespread adoption of using fire to control invasive species and restore the prairie is limited by Texans' lack of familiarity, knowledge, and resources, as well as the liability risks that come with it. The establishment of a prescribed burn cooperative would alleviate all three of these limitations by providing individual members with the resources - education, funding, and fire crew personnel - to employ fire safely and effectively as a land management tool (Tidwell et al. 2013).

The landscape that Stephen F. Austin saw was shaped by fire and, even though the Native Americans were gone, Austin knew this well enough to arrange for swathes of his new colony to be regularly burned (Grace et al. 2005). The limitations of the adoption of prescribed burning must therefore be confronted. Texans' lack of knowledge and familiarity can be addressed by way of a public awareness campaign. The Wildlife Habitat Federation offers help to landowners who wish to use prescribed burns (WHF 2019), and together with local media reporting the organization's success stories this could prove to be critical, as Texas has few public lands where an agency such as TPWD may let its scientists conduct prescribed burns (TPWD 2019). Private landowners must be told and shown the benefits of the old fire regime, which include increased forage for cattle and increased habitat for quail, a popular game species. Ranchers should be encouraged to adopt mixed-species grazing by herding goats as well as cattle, as was done in western regions of Texas up until the 1960s, as mixed-species grazing has been shown to be effective at suppressing the spread of woody species (Wilcox et al. 2022). Other stakeholders, such as environmentally-conscious residents of the greater Houston area, may be enticed to push for more prescribed burns as a way to save the habitat of the endangered Attwater's prairie chicken, *Tympanuchus cupido attwateri* Bendire, 1893 (Phasianidae).

A lack of resources is a more difficult problem to solve. The survey analyzed by Diaz et al. (2015) used a definition of "resources" that included time, money, and equipment. Although a lack of equipment can be partly addressed through public outreach initiatives which educate landowners and stakeholders about what equipment is needed and where and how to obtain it, a lack of time is more troublesome, especially because the timing of a prescribed burn is critical to determining the success or failure of its intended goals. *Bothriochloa ischaemum,* for example, will easily grow back into a burned area if the fire occurs at the wrong time of year (Simmons et al. 2007). Public outreach can tell landowners when the best time is to burn, but it cannot give them the opportunity to burn when that time occurs. They must create that opportunity for themselves, if they can, and it would appear that they often do not, or cannot as Ryan et al. (2013) found that modern prescribed burning seasons in the continental United States rarely coincide with the fire seasons that occurred before modern times. Money is the most difficult resource to address in the event of a shortage. The knowledge to conduct a prescribed burn is highly specialized (Lashmet 2017), and thus those who possess it are in a position to command a high price for their services. Organizations like the Wildlife Habitat Federation and Texas A&M AgriLife extension offer outreach and technical advice (WHF 2019), but they too are limited by their resources of personnel, time, and money.

The final and most difficult obstacle to overcome is liability (Lashmet 2017). Even if a controlled burn were to be conducted entirely within the confines of a fuel break, the wind could carry embers through the air to start a spot fire on the property of someone who was not involved with - and therefore not prepared for - the burn. Were this hypothetical spot fire to burn the pasture on which a neighboring rancher planned to move his cattle - or even worse, if the fire killed his cattle - the monetary damages from the ensuing lawsuit could be enormous. Texas adheres to a standard of ordinary negligence when it comes to controlled burns, meaning that the state imposes liability if the burner fails to exercise reasonable care under the circumstances. An exception is made for prescribed burns on agricultural land conducted by, or under the supervision of, a qualified prescribed burn manager (Lashmet 2017). This may offer hope for southeast Texas' prairies, as much of the study area is covered by ranch land (see Figure 2). The northern and northeastern areas present more of a challenge. Not only is there less agriculture in this area, but there is also more fuel for a fire to burn, which raises the risk of the fire escaping from the burn managers' control.

Although these obstacles are formidable, they are not insurmountable. The prairies that Stephen F. Austin first encountered in 1821 can be brought back. It would require an extensive long-term plan to include outreach, education, funding, changes to regulations and most importantly, a collective will from the residents of southeast Texas, but all of these things are possible. Patience and steady effort will eventually pay off.

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