Transportation Consortium of South-Central States

Tran-SET

*Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation*

# Evaluation and Enhancement of Carbon Sequestration Potential of Existing Vegetation along Roadsides

**Project No. 18HSTSA01**

**Lead University: University of Texas at San Antonio**

**Final Report**

**August 2019**

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PI: Vikram Kapoor https://orcid.org/0000-0002-7159-0883
Co-PI: Jeffrey T. Hutchinson https://orcid.org/0000-0003-2122-7485
Co-PI: Samer Dessouky https://orcid.org/0000-0002-6799-6805

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**16. Abstract**

The objectives of this study were to evaluate the vegetative composition and carbon sequestration potential of vegetation along a major roadway in Texas. Soil and vegetation were evaluated along IH-35 within Bexar County for composition and carbon content. Three 20 m transects were placed at each site and percent vegetative cover was estimated and above ground plant biomass, and soil was collected from three 0.25 $m^2$ subplots along each transect. Plant and soil samples were analyzed for carbon content. Two non-native grasses, bermudagrass and King Ranch bluestem, were the dominant cover at all sites accounting for > 90% coverage at several sites. Native plants were rare with only one species, western ragweed, accounting for > 5% mean coverage at all sites. Carbon content of plant species was highest for bermudagrass (699 kg C $ha^{-1}$) and King Ranch bluestem (401 kg C $ha^{-1}$), and 6 of 7 sites contained significantly more carbon in non-native plants compared to native plants. The highest native plant carbon content was western ragweed with an average of 15 kg C $ha^{-1}$. Mean soil carbon content ranged from 3.1 to 6.9 kg C $m^{3\ -1}$ among the sites, and significantly ($P < 0.05$) greater amounts of carbon were recorded in the upper 0-10 cm compared to the 10-20 cm. The photosynthesis rates of Bermudagrass were significantly greater than rates recorded for King Ranch bluestem indicating the former species is highly adapted to hot semi-arid climate of central Texas, but King Ranch bluestem may gain a competitive advantage along roadways during the spring, fall and periods of increased precipitation. The total available area for the vegetation along the IH-35 highway in Bexar County is estimated to be approximately 81.7 ha (201.5 acres). We suggest the area between sites 5 and 6 (25.1 ha; 62 acres) are ideal locations for carbon sequestration using native plant communities including those with larger diameter woody stems such as trees.

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# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| $^oF$ | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | $^oC$ |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |

## APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| $^oC$ | Celsius | 1.8C+32 | Fahrenheit | $^oF$ |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

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# ACRONYMS, ABBREVIATIONS, AND SYMBOLS

| | |
|---|---|
| BG | Bermudagrass |
| C | Carbon |
| $CO_2$ | Carbon dioxide |
| DOT | Department of Transportation |
| GHG | Greenhouse gases |
| Gt | Gigaton |
| IH-35 | Interstate Highway 35 |
| KRB | King Ranch Bluestem |
| NHS | National Highway System |
| ROW | Right of Way |
| SIC | Soil Inorganic Carbon |
| SOC | Soil Organic Carbon |
| FHWA | Federal Highway Administration |
| TxDOT | Texas Department of Transportation |

## EXECUTIVE SUMMARY

Atmospheric $CO_2$ is regulated by plants and soil with plants absorbing $CO_2$ and soils storing carbon for various periods of time dependent on disturbance. Highway corridors are surrounded by vegetative cover which has the potential to sequester and store $CO_2$. In this study, we evaluated the carbon content of soils and plant species along six grassy strips adjacent to IH-35 and one strip along SH-1604 in San Antonio, Bexar County, Texas. The results of this study indicate that grassy stripes and swales along IH-35 in Bexar County are dominated by two non-native grass species, King Ranch bluestem (*Bothriochloa ischaemum*) and bermudagrass (*Cynadon dactylon*). Mean native species coverage averaged < 5% and the highest native species coverage was 33.3% for western ragweed. The mean percent coverage of King Ranch bluestem and bermudagrass was 40.2 and 38.2 % of the total vegetation cover for all seven study sites. No native grass was documented with a mean coverage > 5%. Species richness was low to moderate at the seven sites and ranged from 9 to 25 species. Simpson's Index of Diversity ranged from 0.20 (low diversity) to 0.81 (high diversity) indicating that 2 or 3 species were dominant at each site. A similar pattern was observed with evenness values which ranged 0.08 to 0.41 indicating that only a 1 to 3 species accounted for total vegetation cover and other species were rare.

Carbon content was highly variable based on 95% confidence intervals for leaf litter, vegetation, and soil. The carbon content in leaf litter accounted for 2497 kg C $ha^{-1}$ based on the means for all seven sites, which was greater than the carbon content in vegetation by ca. 50%. The mean carbon content in vegetation was 1282 kg C $ha^{-1}$ for all seven sites. The total carbon content of non-native plants was significantly greater ($P < 0.05$) compared to native plants at 6 of the 7 sites evaluated. In four sites, vegetation coverage was >85% and comprised of Bermudagrass and/or King Ranch bluestem. The large variation in the carbon content is possibly due to the age of vegetation, management practices such as mowing, and disturbance patterns. The mean carbon content of the soil was estimated to be 5.0 kg C $m^{3\ -1}$ but ranged from 3.1 to 6.9 kg C $m^{2\ -1}$. Additional research is needed to evaluate the carbon content of native vegetation and associated soils along roadways that have not been planted with non-native grasses. Carbon content was significantly greater ($P < 0.05$) in the upper 0-10 cm (3.1 kg C $m^{3\ -1}$) of the soil compared to the soil layer 10-20 cm (1.9 kg C $m^{3\ -1}$) below the surface. Many of sites evaluated contained fill material and was comprised of pebbles and gravel which may account for the low carbon content in the lower 10-20 cm of the soil.

Photosynthesis light curve responses were significantly greater ($P < 0.0001$) for bermudagrass compared to King Ranch bluestem indicating that bermudagrass may be more adaptable to hot semi-arid climate of central Texas. In addition, the quantum yield efficiency and maximum photosynthesis rate were higher for bermudagrass compared to King Ranch bluestem. These results may indicate that bermudagrass is a more efficient competitor over King Ranch bluestem during the summer months when temperatures are warmer and often exceed 35 °C.

The total available area for the vegetation along the IH-35 highway in Bexar County is estimated to be approximately 81.7 ha (201.5 acres). We suggest the area between sites 5 and 6 (25.1 ha; 62 acres) are ideal locations for carbon sequestration using native plant communities including those with larger diameter woody stems such as trees.

## 1. INTRODUCTION

Roadway corridors are anthropogenic ecosystems that are typically seeded or sodded with fast-growing, rhizomatous non-native grasses. In semi-arid regions such as Texas, low precipitation further limits plant growth and many species enter dormancy during periods of low precipitation. The United States Federal Highway Administration (FHWA) estimates that grasses make up 44% or 900,000 ha of the right-of-ways *(1)*. Texas is estimated to have ca. 22,370 km of roadways in the National Highway System *(2)* along with thousands more kilometers of local and state maintained roadways.

Since the industrial revolution, there has been a drastic increase of greenhouse gases (GHG) in the atmosphere, particularly carbon dioxide ($CO_2$). Prior to the industrial revolution the mean atmospheric $CO_2$ level was approximately 280 ppm, and as of August 2018 the mean $CO_2$ level was 407 ppm *(8)*. Increasing levels of $CO_2$ are largely caused by anthropogenic sources – specifically the combustion of fossil fuels *(9)*. The global ramifications of climate change are being presented at progressively higher instances – be it extreme weather, heat related illnesses, or food shortages *(10)*. Climate change will only be exacerbated with increasing human population, land use change, and an apathetic view of changing individual lifestyles *(10, 11)*.

There is a growing interest in the potential for roadside vegetation and soils to capture and store carbon. Emissions of $CO_2$ generated from combustion of fossil fuel comprises roughly 80 percent of the anthropogenic greenhouse gases contributing to global climate change. There are greater than 482,800 km of roadways and 23.8 registered motor vehicles in Texas, and 5494 km of highway and 1.5 million registered vehicles in Bexar County *(3)*. Transportation accounts for 34% of total $CO_2$ emissions *(4)*. Carbon sequestration is one method of reducing carbon dioxide levels in the atmosphere, and it can be accomplished biotically by vegetation and soil. A Florida Department of Transportation study valued carbon capture and storage at $157-363 million along highways using a conservative price for carbon *(5)*. Other studies reported that high vegetation species and diversity in grasslands resulted in greater carbon sequestration than low diversity grasslands *(6, 7)*. In addition, biomass production during carbon storage has the potential to provide biofuel through plantation of bioenergy crops in degraded roadside soils. Other ecological advantages of roadside vegetation include improved water quality, and erosion control, which is particularly important during flooding events as seen in the recent case of Hurricane Harvey.

Plants absorb $CO_2$ along roadways which is used in photosynthesis and the carbon molecule is synthesized into multiple compounds. These compounds are stored in above and below ground biomass. Carbon from senescent plants and their parts is returned to the atmosphere through decomposition or incorporated into the soil profile by microorganisms. In addition to carbon sequestration, roadside vegetation provides other benefits such as reducing air and noise pollution, slowing down and trapping sediment, and uptake of nutrients and metals. Limited information is known about the carbon pools associated with leaf litter, soils, and plant species along IH-35 in San Antonio, Texas.

Carbon sequestration by plants is one method to mitigate increasing $CO_2$ levels. Carbon sequestration refers to the process of atmospheric $CO_2$ being captured by plants and stored indefinitely in the carbon pool *(10)*. There are two main carbon pools – the oceanic pool and the terrestrial pool. Oceans are estimated to store 39,000 Gigaton (Gt) of carbon (C), and terrestrial systems are estimated to store 3,100 Gt of C. Additionally, the atmosphere is estimated to store 760 Gt of C *(12)*. The terrestrial pool can be divided into the biotic pool, which stores approximately 560 Pg, and the pedologic (soil) pool, which stores approximately 2,500 Gt *(13)*. The pedologic pool can be subdivided into the soil organic carbon (SOC) pool, and the soil inorganic carbon (SIC) pool *(12)*. The biotic pool consists of all above ground biomass, below ground biomass, and leaf litter *(14)*. The biotic pool is the smallest pool, but is important because nearly all SOC found in the soil is derived from the breakdown of senescent plants and the release of root exudates rich in carbon compounds *(15)*.

In 2015 the transportation sector accounted for 25.81% of total $CO_2$ emissions in the United States, second to the electrical sector at 26.66% *(16)*. In 2010, FHWA developed the Carbon Sequestration Pilot Program *(17)*. The purpose of this program is to estimate the capacity of the right-of way (ROW) along the National Highway System (NHS) to sequester carbon, and to estimate the amount of carbon currently being sequestered based on land cover. According to the FHWA, Texas has nearly 119,137 ha (294,394 ac) of unpaved ROW, which is estimated to capture 472,642 metric tons C/acre/year. At $10 per ton of $CO_2$, this could provide the state of Texas, assuming the land is owned by the Texas Department of Transportation (TxDOT), nearly $15 million gross *(17)*.

Two invasive grasses, *Bothriochloa ischaemum* var. *songarica* (King Ranch bluestem, KRB) and *Cynodon dactylon* (bermudagrass, BG) have become dominate in many lawns and roadsides of the South Central Texas region. King Ranch bluestem is an Old World bluestem native to Eurasia, and was first introduced in Texas in the 1930s *(18)*. The introduction of BG first occurred in 1751 and is thought to be native to southeastern Africa *(19)*. King Ranch bluestem and bermudagrass have historically been and continue to be planted on roadsides due to their rapid establishment and effective erosion control *(18, 20)*. Both species are known to out compete native species due to their rapid growth *(18, 19)*. Species diversity on average is lower when an invasive species becomes established in a region, but despite lowered diversity there is a net increase in primary productivity *(21)*.

This study aims to conduct a baseline assessment of carbon sequestration potential of existing vegetation along a Texas highway (as a model Region 6 road network) and evaluating different management techniques to take remedial measures for improving carbon sequestration capability along existing roadside infrastructure.

## 2. OBJECTIVES

The main objective of this project is to evaluate and enhance the carbon sequestration potential and other ecosystem service provided by roadside vegetation. This study is especially important for roadsides in highly polluted zones such as those affected by heavy vehicular traffic and industries. Therefore, due to heavy traffic and close proximity to UTSA, we will evaluate carbon sequestration along Interstate-35 (I-35) within Bexar County for this study.

The technical objectives of this study are:

1. Conduct literature review on existing methodologies for carbon sequestration assessment along the roadside in order to establish a scientific methodology for assessing carbon sequestration potential of existing vegetation and soils along Texas highways.
2. Perform baseline assessment of the current carbon being captured along I-35 roadside using multiple parameters such as roadside acreage, current plantation practices (grasses, shrubs, and trees), and soil and plant carbon content.
3. Evaluate the potential of existing roadside infrastructure for increasing carbon sequestration by assessing available roadside acreage, optimizing plant choices for maximum carbon storage and biofuel production, and evaluating holistic land management practices.

# 3. LITERATURE REVIEW

The FHWA estimated carbon sequestration potential based on five land types: grassland, woody, grassland/woody mix, and shrubs. Grasslands comprise nearly 890,308 ha (2.2 million ac) of ROWs in the U.S. *(17)* and are composed of mixtures of native and non-native species of vegetation. Limited research exists that compares the carbon sequestration potential of the dominant non-native grasses in Texas, specifically KRB and BG. There is also a lack of research estimating the carbon pools associated with soils and vegetation found along Texas ROWs in Bexar County. Carbon sequestration along the roadsides can be measured according to different approaches which will be described in the following sections.

## 3.1. Carbon in Soil and Vegetation

The Carbon Sequestration Pilot Program (CSPP) was established in 2008 by the FHWA to assess the cost-effectiveness and feasibility of implementing programs designed to sequester carbon along roadways. The CSPP identified available right-of-way and used a literature value of 0.17 kg C $m^{-2}$ $yr^{-1}$ to represent the grassed vegetation within the ROW. This rate is three times the rate of carbon sequestration for other grasslands 0.054 kg C $m^{-2}$ $yr^{-1}$ *(22)*. In another study, *(23)* measured the sequestered carbon by the soil. They chose 20 sites containing vegetation strips and grouped them into very young, young, medium and old age bins if their ages were between 0 and 5 years, 6 to 15 years, 16 to 25 years and 26 to 38 years old, respectively. After removing the initial layer of the vegetation and thatch, an AMS hammer corer, was used to capture an intact soil core *(24)*. The cores were then grouped and sieved to less than 2mm. a subsample was taken from the 2 mm fine fraction, and further ground to less than 250 µm and analyzed for total carbon. It was measured at the NCSU Environmental and Agricultural Testing Services (EATS) lab through dry combustion at 550°C with a Perkin-Elmer 2400 CHN Elemental Analyzer *(25)*.

In another study, *(26)* measured the amount of the carbon that has been carried out based on the amount of standing woody biomass of trees on the roadsides of Vadora City. Initially the trees were sampled by the quadrate method. Quadrates of size 20m × 20m were taken at different roadsides and at the same time measurements of Girth at Breast Height (GBH) (cm) and Basal Area ($m^2$) for different trees were taken *(27)* Based on these values standing woody biomass (T/ha) *(27)* and carbon sequestration rate of trees (T/ha) *(27)* were calculated.

According to *(28)* at each site, a quadrat of 400 $m^2$ was positioned in the area between the edge of the road and the fence separating the road from the adjacent property. Within each quadrat, all woody plants (trees and shrubs) were counted and assigned to one of five classes; seedling (< 1 m tall), DBH <10 cm (DBH =diameter at breast height), DBH 10-20 cm, DBH 20-40 cm or DBH >40cm. Samples of the surface 30 mm of the soil were collected from the four corners and centers of both paired quadrats at each site, bulked, and thoroughly mixed for laboratory analyses. Soils were air dried and passed through a 2 mm sieve to remove any large stones and debris. The organic carbon content was determined using the modified Walkley-Black method *(29)* with two replicate samples per quadrat. Percentage organic carbon was converted to total carbon (t $ha^{-1}$) using unpublished bulk density data and values collected at some of the survey sites with a soil corer of diameter 4 7 mm and depth 20 mm. Total aboveground biomass of trees was calculated using algorithms for Eucalyptus spp. woodland trees *(33)* and Callitris spp. *(30)* which relate stem diameter at breast height (DBH) to total tree biomass. Total carbon in the vegetation was calculated by multiplying biomass by a factor of 0.5 (see *(31, 32)*). Root biomass was estimated on the basis of 0.25 of aboveground vegetation biomass after *(33)*.

## 3.2. Aerial Photography

In one study *(34)* used the aerial photographs and used the ArcGIS software for the image interpretation. Moreover, the vegetation along the roadsides were categorized as occupied, forested area and afforestation potential regions. Occupied areas included buildings, river stretches and crossroads. Forested areas were the areas which were forested within the roadside and finally, afforested potential regions included areas suitable for afforestation activities. The area for each region was calculated based on the ArcGIS software analysis. Occupancy rate was defined as the sum of the forested and occupied areas divided by the sum of the total area. The amount of fixed carbon by each type of vegetation over the mentioned period was estimated by the average of the increase of carbon, considering the species studied by *(35)*. Finally, the potential of the roadsides vegetation for sequestering carbon was estimated by multiplying the increment of carbon for the future period of time by available area for vegetation.

## 3.3. Measuring Air Quality and Air Fluxes Directly

The exchange of carbon between the atmosphere and terrestrial ecosystems can be measured by several methods, including eddy-covariance and various chamber-based systems, each with their own advantages and disadvantages *(36, 37)*.

According to a report for the New Mexico Department of Transportation *(38)*, vegetative canopy and basal cover were monitored throughout the growing season from all test plots. Monitoring vegetation cover varied by season, with more intensive monitoring during the fall. Five to ten 0.25-square-meter ($m^2$) quadrats were placed systematically along the sites. Quantitative vegetation data (e.g., canopy and basal cover) were measured by growth-form (i.e., grass, forb, shrub) and the dominant species within each quadrat was recorded. Surface $CO_2$ flux was measured using a portable LiCor Model 8100A™ survey $CO_2$ flux chamber system.

The eddy covariance technique offers a number of advantages including: non-invasive observations, the ability to measure flux continuously at high temporal resolution (typically half-hourly) over long time scales (decades), and the ability to synthesize multiple measurement sites into global databases *(39)*.

In one study, *(40)* measured the $CO_2$ fluxes at 1.35 m above the ground using an eddy covariance system. In another study *(41)*, Atmospheric carbon dioxide concentration ($CO_2$, ppm) was monitored at sites using a $CO_2$ gas analyzer EGM–1 (PP Systems, UK). Measurements were carried out at 1 m from the soil level, at a distance of 2 m from traffic, from 8:00 to 11:00 a.m. (peak hours) *(42)*, in three following sampling days per month with the same weather conditions, during the study period. Traffic density (cars $min^{-1}$) was monitored at the same time of $CO_2$ concentration measurements in each of the considered sites. Simple regression analysis was carried out to evaluate the relationship between $CO_2$ concentration and traffic density.

According to the *(43)* report on Roadside Vegetation and Soils on Federal Lands, to estimate potential carbon capture within the Road Effect Zone (REZ), they utilized empirical observations of net $CO_2$ exchange from a global network of eddy covariance towers arrayed according to functional vegetation types. These flux tower networks (e.g., AmeriFlux, Agriflux) have provided continuous data collection of ecosystem exchanges of carbon (e.g., net ecosystem exchange), between terrestrial ecosystems and the atmosphere since 1992 *(44)*.

Moreover, according to a review study by the *(45)*, Observations from a single eddy covariance flux tower are not sufficient to determine the influence of vegetation on the net neighborhood-scale $CO_2$ flux. A few studies have therefore conducted simultaneous eddy covariance flux measurements over neighborhoods with different land cover characteristics within the same metropolitan area (e.g., see *(46–48)*).

Another method is measuring the air quality parameters on site. For example *(49)* did the air pollution monitoring using instrumented vehicular platforms - one mobile electric vehicle (Li-Ion Motors Corp), and two stationary vehicles with on-board battery supply. One parked sports utility vehicle, and one parked van with a mast allowing for sampling at heights up to 7 m. Two sampling sessions were conducted for each of the sites – in the early fall and then again in the late fall/winter – to observe the impact of reduced leaf coverage on near-road air pollution. One of the two stationary vehicles was parked before the vegetated area along the roadside and the other after the area of interest. The vehicles were equipped with CO analyzer and three-dimensional (3D) ultrasonic anemometers monitoring wind speed and direction. During sampling, the two stationary vehicles remained with their engines off and used battery-supplied power for the instrumentation during the 2–3h daily sampling period. The mobile electric vehicle – the sampling platform that provided data of primary focus for analyses to follow – recorded real-time air quality parameters and location data while being repeatedly driven on a specified route.

# 4. METHODOLOGY

## 4.1. Study Area

The study area was within Bexar County, Texas, USA and included a total of seven sites (Figure 1). Six sites were along IH-35 through San Antonio and an additional site was adjacent to SH-1604 (Table 1). Many sites in the downtown area of San Antonio were unsafe for researchers, and sites focused on locations northeast and southeast of the downtown area. The study sites were all sites that were vegetated and safely accessible. Sampling occurred 15 m away from roadways to ensure the safety of researchers. All study sites are managed by the Texas Department of Transportation.

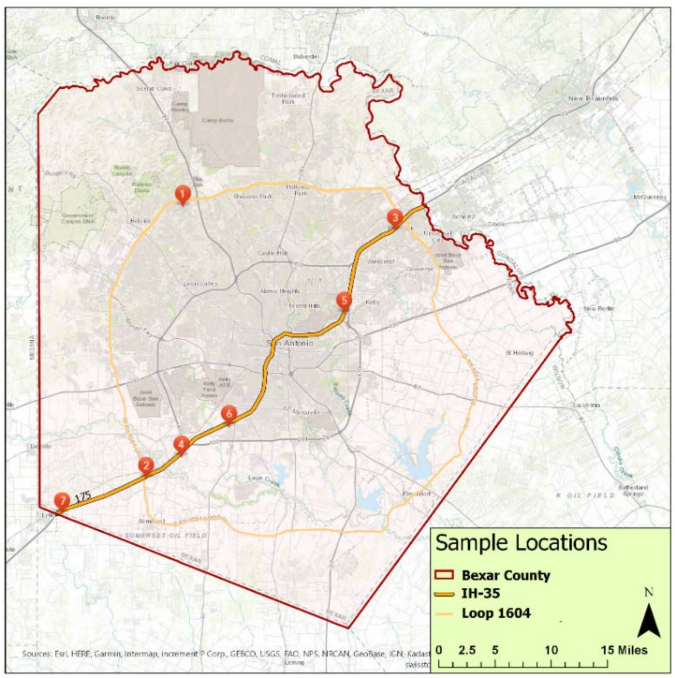


**Figure 1. Site locations. All sites are adjacent to IH-35, and within Bexar County, Texas. The sites were chosen based on safety concerns and the presence of vegetation, rather than fill material.**

**Table 1. Coordinates and reference locations of the seven sites surveyed.**

| Site | Coordinates | Reference location |
|---|---|---|
| 1 | 29.588015, -98.616740 | N Loop 1604 W and UTSA |
| 2 | 29.280913, -98.664163 | W Loop 1604 S and I-35 S |
| 3 | 29.561193, -98.342836 | I-35 S and Livingway Christian Church |
| 4 | 29.308457, -98.618410 | I-35 S and Fischer Road |
| 5 | 29.472060, -98.405490 | Between NE Loop 410 and N PanAm Expressway |
| 6 | 29.342361, -98.553657 | I-35 S and Poteet Jourdanton Freeway |
| 7 | 29.241329, -98.773312 | I-35 N and Rolling Meadow Dr (near Lytle, Texas) |

## 4.2. Site Evaluation

Six sites were surveyed from May to August 2018 along IH-35 and one site along SH-1604 in Bexar County. Three 20 m line transects were randomly established at each site, and percent vegetative cover by species was estimated along each line using the methods of *(48)* (Figure 2). Vegetation along each line was classified by species and the total distance of each species was taken along the line. The total distance of each species along the line was divided by 20 to estimate percent cover. At each site, the three line transects were combined as one composite sample. Three 0.25 $m^2$ were randomly placed along each transect and all above ground biomass, including leaf litter, was clipped and bagged by species (Figure 3). Two 20 cm soil cores were extracted with a hand-held auger from each plot and separated as the top portion (0-10 cm) and lower portion (10.1-20 cm).

**Figure 2. UTSA students measuring vegetation coverage along IH-35 using the line transect method.**

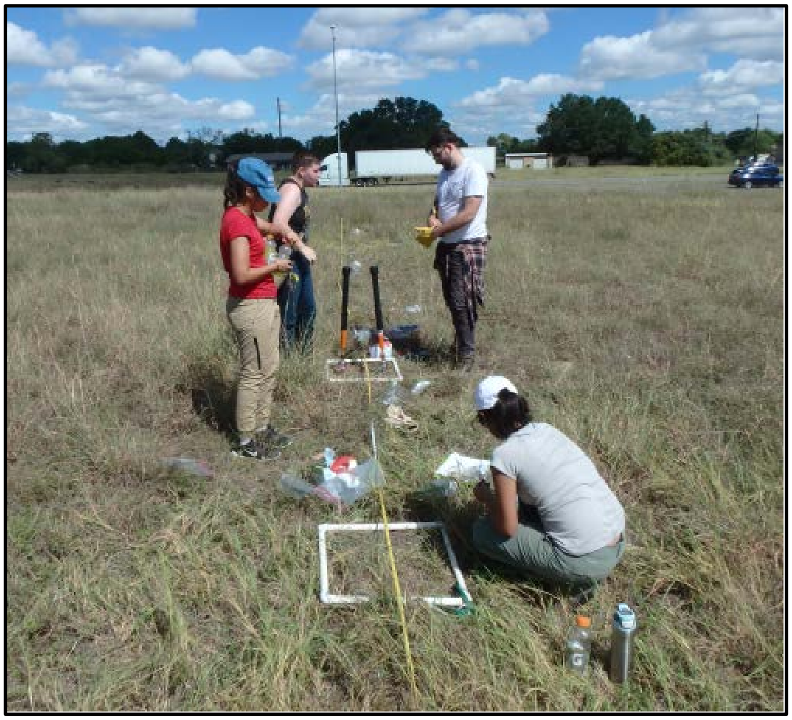

**Figure 3. Vegetation cover was recorded for each plant species along a 20 m transect line and two 20 cm soils cores were taken from three 0.25 m$^2$ plot. Within each 0.25 m$^2$ plots, plants were clipped at soil level and separated by species to examine carbon content.**

## 4.3. Lab Evaluation

Carbon content of soil, plants, and leaf litter was estimated with the loss-on-ignition method *(50)*. Plant samples were air dried for 24 hours, and then oven dried at 115°C for 72 hours and weighed. Soil samples were air dried for 48 hours, sieved to 2.0 mm, and then oven dried at 115°C for 48 hours. After oven drying, soil samples were weighed to the nearest 0.001 g and placed into a muffle furnace at 360°C for 4 hours, the samples were then weighed to the nearest 0.001 g. Soil and plant carbon content was determined using the following equations *(51, 52)*:

$$Soil\ carbon\ content = \frac{soil\ dry\ weigh}{1.724} \quad [1]$$

$$Plant\ carbon\ content = plant\ dry\ weigh * \ 0.427 \quad [2]$$

Photosynthesis measurements were taken on the dominant grasses documented from line transects with a portable infrared gas analyzer (LI-6400 Portable Photosynthesis System). The light curves were created using a 400 µmol gas flow rate and photosynthetically active radiation (PAR) levels of 0, 5, 10, 25, 50, 100, 200, 400, 600, 800, 1000, 1200, 1600, and 2000 µmol/m$^2$/s. Photosynthesis response curves were developed from the mean of four measurements per plant to determine which plants are more efficient in absorbing $CO_2$ under ambient conditions at varying light intensities. Means and standard errors were calculated for quantum yield efficiency ($QY$), maximum photosynthesis rate ($A_{\max}$), light saturation point ($L_{sp}$), light compensation point ($L_{cp}$), and dark respiration rate ($R_d$). Quantum yield efficiency is equal to the ratio of photons absorbed to molecules reacted and provides information on which plant species are most efficient in their absorption of $CO_2$. The maximum photosynthesis rate describes the rate at which a plant can absorb $CO_2$. Light saturation point refers to the irradiance level at which photosynthesis no longer increases with increasing light levels. Light compensation point refers to the point at which photosynthesis equals respiration. At levels above the light compensation point, there is a gain in $CO_2$ within the plant. Dark respiration accounts for respiration rate of plants in the absence of light.

**Figure 4. Soil samples being sieved and sorted in the lab for analysis of carbon content.**

## 4.4. Data Analysis

Descriptive statistics (means and standard errors) were calculated for all variables in SigmPlot. Data was analyzed with Student t-tests ($P < 0.05$) for differences between carbon content between top (0-10 cm) and lower (10-20 cm) soil depths, mean carbon content of native and non-native vegetation at each site, and photosynthesis rates between the two dominant non-native grasses. Differences in the light curve response between bermudagrass and King Ranch bluestem was analyzed with a repeated measures ANOVA. Photosynthesis values for each light reading were combined into one composite sample for each species and plotted using the non-linear regression Equation 3.

$$y = a(1 - b^x) \qquad [3]$$

Species richness patterns were determined by counting the number of plant species that intersected each transect line. Species richness if the total number of species documented at each site. Species evenness patterns were determined using the methods of *(53)*. Species evenness refers to the proportion of each species at each site and takes into account species richness and diversity. Evenness values close to 0 indicate a single species is dominant at the site, while values close to 1 indicate that multiple species occur at the site in similar proportions. Evenness patterns were calculated as defined in Equation 4.

$$E = 1/DS \qquad [4]$$

where:
E = Species evenness;
D = Simpson’s Index; and
S = Species richness.

$$D = \Sigma\,[(n/N)^2] \qquad [5]$$

where:
$n$ = the total number of a single species; and
$N$ = the total number of all species.

The three lines on each site were averaged to obtain the mean species richness and evenness.

Simpson's Index of Diversity was calculated as 1 - D.

# 5. ANALYSIS AND FINDINGS

## 5.1. Vegetation Surveys

The results of this study indicate that grassy stripes along IH-35 in Bexar County are dominated by two non-native grass species, King Ranch bluestem (*Bothriochloa ischaemum*) and bermudagrass (*Cynadon dactylon*) (Table 2). The three non-native grass species documented bermudagrass, King Ranch bluestem, Johnsongrass, all of which are invasive in Texas and form monocultures. The mean percent coverage of KRB and BG was 40.2 and 38.2 % of the total vegetation cover for all seven study sites. Native plant coverage was low at all sites, and shrubs and trees were very rare. Two native herbaceous species, common ragweed and Texas frog-fruit, comprised 33.3 and 13.6% coverage, respectively at single sites but most native species coverage was less than 5%. Western ragweed was the only native plant documented that accounted for > 5% coverage combing the cover data from all seven sites. Only 16 plant species (three non-native and 13 native species) were documented in two or more of the study sites (Table 3). A total of 55 species were observed among the seven sites indicating overall low species richness along roadways (Appendix A).

**Table 2. Percent cover and mean of seven sites for the dominant vegetation sampled.**

| Species | Site | | | | | | | Mean |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
| *Bothriochloa ischaemum* * | 79.0 | | 58.9 | 91.1 | | | 52.3 | 40.2 |
| *Cynodon dactylon* * | | 100.0 | 24.0 | | 98.1 | 16.2 | 28.8 | 38.2 |
| *Ambrosia artemisiifolia* | | 2.4 | | | | 33.3 | | 5.1 |
| *Echinocloa crus-galli* * | | | | | 33.0 | | | 4.7 |
| *Sorghum halepense* * | | | | | 3.1 | 25.9 | | 4.1 |
| *Neptunia lutea* | | 7.6 | | 7.3 | | | | 2.1 |
| *Phyla nodiflora* | | | | | | | 13.6 | 1.9 |
| *Pseudognaphalium obtusifolium* | 4.3 | | | | | | | 0.6 |
| *Ratibida columnifera* | | | 2.5 | | | | | 0.4 |
| Other species | 16.7 | 2.8 | 6.3 | 17.3 | 6.8 | 37.3 | 50.4 | 19.7 |

**Indicates non-native species*

Species richness was low to moderate at the seven sites and ranged from 9 to 25 species (Table 4). Simpson’s Index of Diversity which gives emphasis to dominate species ranged from 0.20 (low diversity) to 0.81 (high diversity) indicating that 2 or 3 species were dominant at each site. A similar pattern was observed with evenness values which ranged 0.08 to 0.41 indicating that only a few species accounted for total vegetation cover and other species were rare. *In situ* competitive studies on roadside vegetative areas are needed to determine native grasses capable of competing with non-natives along roadways and developing xeric landscaping protocols.

## 5.2. Plant and Soil Carbon Content

Carbon content was highly variable based on confidence 95% confidence intervals for leaf litter, vegetation, and soil (Table 5). The carbon content in leaf litter accounted for 2497 kg C $ha^{-1}$ based on the means for all seven sites, which was greater than the carbon content in vegetation by ca. 50%. The high carbon content in leaf litter among all sites may indicate that vegetative strips examined in this study may be serving as a source of $CO_2$ rather than a sink. The mean carbon content in vegetation was 1282 kg C $ha^{-1}$ for all seven sites. The large variation in the carbon content is due to multiple variables such as soil type, management practices such as mowing, and disturbance patterns among the sites. The mean carbon content of the soil was estimated to be 5.0 kg C $m^{2\ -1}$ but ranged from 3.1 to 6.9 kg C $m^{2\ -1}$. Additional research is needed to evaluate the carbon content of native vegetation and associated soils along roadways that have not been planted with non-native grasses.

**Table 3. Dominant vegetation species documented that occurred at ≥ 2 sites along I-35 in Bexar County, Texas. *Cynodon dactylon* and *Bothriochloa ischaemum* occurred at five of the six sites.**

| Species | Common Name | Site | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| *Ambrosia artemisiifolia* | Western ragweed | | x | | | | x | |
| *Asclepias oenotheroides* | Side-cluster Milkweed | | x | | | | | x |
| *Bothriochloa ischaemum** | King Ranch Bluestem | x | x | x | x | | x | x |
| *Bouteloua curtipendula* | Sideoats grama | | | x | | | | x |
| *Croton spp.* | Croton | x | | | | | | x |
| *Cynodon dactylon** | Bermudagrass | | x | x | x | x | x | x |
| *Gaillardia pulchella* | Indian blanket | x | | | | | | x |
| *Merremia dissecta* | Alamo vine | | | x | | | x | |
| *Neptunia lutea* | Yellow Puff | | | | x | x | | |
| *Oenothera spp.* | Gaura | | x | x | x | | x | |
| *Phyllanthus polygonoides* | Smartweed leaf-flower | | | x | x | | | x |
| *Ratibida columnifera* | Mexican Hat | x | x | x | | | x | |
| *Sida cordifolia* | Sida | | | x | | | x | x |
| *Solanum elaeagnifolium* | Silverleaf nightshade | x | x | | | | x | |
| *Sorghum halepense** | Johnson grass | | x | x | x | x | x | |
| *Verbena halei* | Texas vervain | x | | x | | | | |

**Represents a non-native species*

**Table 4. Plant richness and diversity Indices for the six sites surveyed.**

| Parameter | Site | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Species richness | 21 | 13 | 25 | 12 | 9 | 13 | 21 |
| Simpson's Index of Diversity | 0.41 | 0.53 | 0.29 | 0.20 | 0.46 | 0.81 | 0.80 |
| Evenness | 0.08 | 0.16 | 0.06 | 0.10 | 0.20 | 0.41 | 0.23 |

**Table 5. Mean carbon content, standard error, and 95% confidence limits of leaf litter, vegetation, and soils for all seven sites combined.**

| Variable | Mean (Carbon Content) | SE | 95% CI |
|---|---|---|---|
| Leaf litter (kg C $ha^{-1}$) | 2497 | 865 | 1440 - 3555 |
| Vegetation (kg C $ha^{-1}$) | 1282 | 387 | 808 - 1756 |
| Soil 0-20 cm (kg C $m^{3\ -1}$) | 5.0 | 1.6 | 3.1 - 6.9 |

There were significant differences between carbon content in the top 10 cm compared to layer 10-20 cm below the surface (Figure 5). The upper 10 cm of soil contained 3.1 kg C $m^{3\ -1}$ while the lower 10-20 cm contained 1.9 kg C $m^{3\ -1}$. Many of the sites evaluated contained fill material and was comprised of pebbles and gravel which may account for the low carbon content in the lower 10-20 cm of soil.

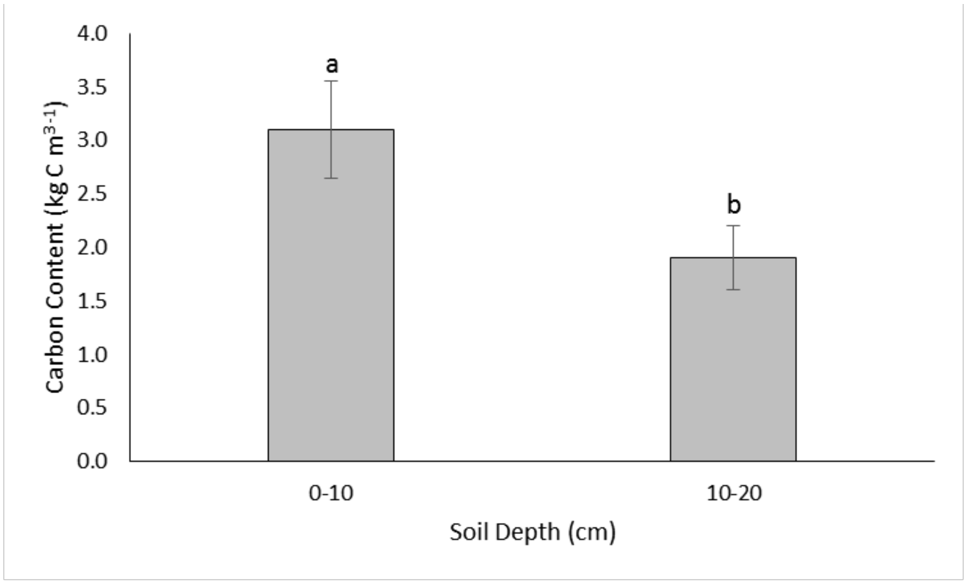


**Figure 5. Mean soil carbon content (kg C $m^{3\ -1}$) for all sites in the top 0 to 10 cm and 10 to 20 cm of the upper soil profile. Different letters represent significant differences at P < 0.0001 based on Student's t-test. Error bars represent standard deviation.**

The total carbon content of non-native plants was significantly greater ($P < 0.05$) compared to native plants at 6 of the 7 sites evaluated (Figure 6). The vegetation at sites 2, 3, 4, and 5 were dominated by Bermudagrass and/or King Ranch bluestem comprising >85% vegetation coverage. The highest carbon content was from Site 4 which was comprised of >91% coverage of King Ranch bluestem.

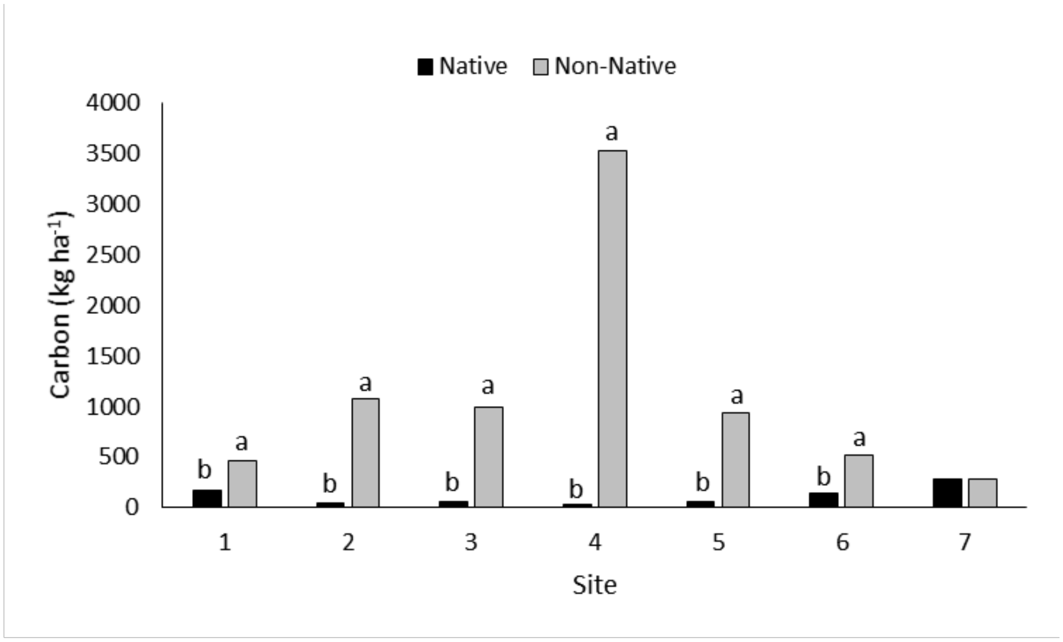


**Figure 6. Mean carbon content of native and non-native plant species at each site. Different letters between native and non-native plants at each site represent significant differences at P < 0.0001 based on Student's t-test.**

The dominant non-native grass species accounted for the greatest amount of carbon content combing the means of each species for all seven sites (Table 6). The carbon content of bermudagrass and King Ranch bluestem were 10 to 17 fold higher than the other plant species. Two native grasses, Carolina jointgrass and silver bluestem, were rare but warrant further studies as native grasses suitable for re-vegetating disturbed areas along roadways.

## 5.3. Photosynthesis Efficiency of Roadside Vegetation

Analysis of the photosynthesis light curve response of bermudagrass and King Ranch bluestem was significantly greater ($P < 0.0001$) for bermudagrass compared to King Ranch bluestem based on a repeated measures ANOVA (Figure 7). Non-linear regression equations based on light response curves were $y = 30.9\ (1\text{-}0.997^{X})$ ($R^2 = 0.98$, $P < 0.001$) and $y = 16.4\ (1\text{-}0.997^{X})$ ($R^2 = 0.92$, $P < 0.0001$) for bermudagrass and King Ranch bluestem, respectively. The results indicate that bermudagrass may be more adaptable to hot summer temperatures found in Texas allowing it thrive in the compacted soils typical of roadsides. In addition, the quantum yield efficiency and maximum photosynthesis rate were higher for bermudagrass compared to King Ranch bluestem indicating bermudagrass is more efficient in uptake of carbon during the summer months when temperatures are warmer and often exceed 35 °C (Table 7).

**Table 6. Mean carbon content (kg ha$^{-1}$) of the 12 most common plants documented during the study.**

| Species | Common Name | Mean Carbon Content (kg ha$^{-1}$) |
|---|---|---|
| *Cynodon dactylon* * | Bermudagrass | 699 |
| *Bothriochloa ischaemum* * | King Ranch bluestem | 401 |
| *Sorghum halepense* * | Johnson grass | 40 |
| *Echinochloa crus-galli* * | Common barnyard grass | 19 |
| *Ambrosia artemisiifolia* | Common ragweed | 15 |
| *Coelorachis cylindrica* | Carolina jointgrass | 12 |
| *Juniperus ashei* | Ashe Juniper | 10 |
| *Bothriochloa laguroides* | Silver bluestem | 10 |
| *Phyla nodiflora* | Texas frogfruit | 9 |
| *Opuntia engelmannii* | Texas prickly pear cactus | 9 |
| *Pennisetum spp.* * | Fountaingrass | 8 |
| *Scolochloa festucacea* | Spangletop | 5 |

**Indicates non-native species*

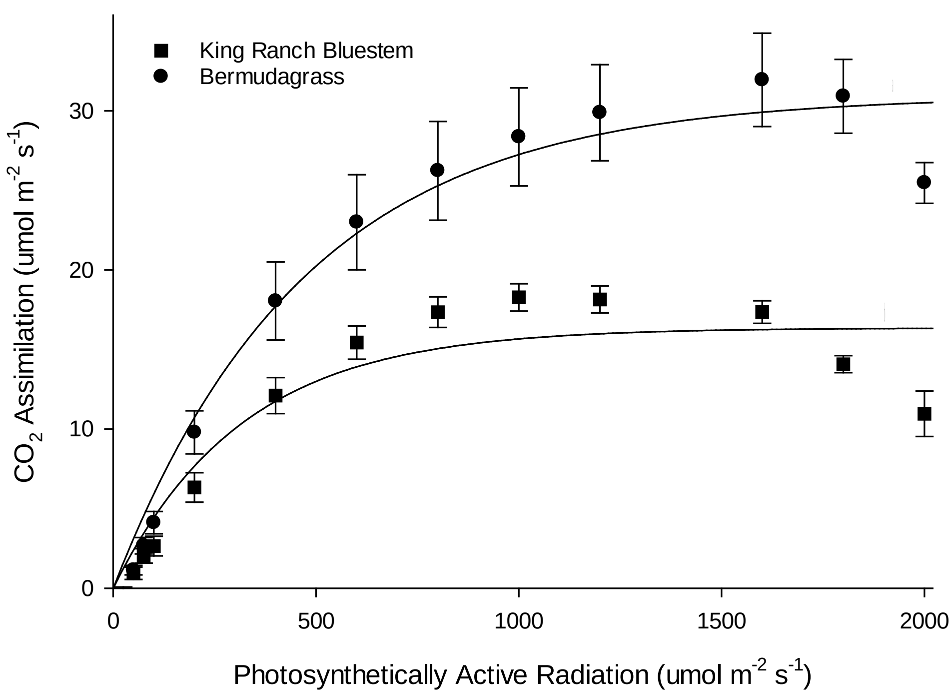


**Figure 7. Modeled light response curve (black lines) for $CO_2$ assimilation to increasing light levels for King Ranch bluestem (n = 4) and bermudagrass (n = 4). Symbols represent mean recorded values and bars represent standard error. Different letters represent significant differences ($P < 0.05$) based on a repeated measures ANOVA.**

**Table 7. The mean (standard error) maximum net photosynthetic rates quantum yield efficiency (*QY*; µmol $CO_2$ $m^{-2}$ $s^{-1}$ / µmol $m^{-2}$ $s^{-1}$), maximum photosynthesis rate ($A_{max}$; µmol $CO_2$ $m^{-2}$ $s^{-1}$), light compensation point ($L_{cp}$; µmol $m^{-2}$ $s^{-1}$), light saturation point ($L_{sat}$; µmol $m^{-2}$ $s^{-1}$), and dark respiration rate ($R_d$; µmol $CO_2$ $m^{-2}$ $s^{-1}$) for bermudagrass and King Ranch bluestem.**

| Parameter[1] | Bermudagrass | King Ranch Bluestem |
|---|---|---|
| QY (µmol $CO_2$ $m^{-2}$ $s^{-1}$)/(µmol $m^{-2}$ $s^{-1}$) | 0.06 (0.01) [a] | 0.03 (0.005) [b] |
| $A_{max}$ (µmol $CO_2$ $m^{-2}$ $s^{-1}$) | 33.2 (1.9) [a] | 16.9 (1.1) [b] |
| $L_{cp}$ (µmol $CO_2$ $m^{-2}$ $s^{-1}$) | 33.9 (1.7) [ns] | 28.9 (1.8) [ns] |
| $L_{sat}$ (µmol $CO_2$ $m^{-2}$ $s^{-1}$) | 589 (41.2) [ns] | 529 (32.8) [ns] |
| $R_d$ (µmol $CO_2$ $CO_2$ $m^{-2}$ $s^{-1}$) | -0.98 (0.25) [a] | -2.03 (0.85) [a] |

[1]*Different letters in rows represent significant differences at P < 0.05 based on Student's t-test*

## 5.4. Roadside Acreage

The GIS files of the streets of the city of San Antonio were downloaded from the sanantonio.gov website and edited using ArcMap software. The IH-35 highway was selected from the attribute table of the file and a 75 foot was created on both sides of IH-35 highway. The buffered layer was exported to Google Earth Pro software to create a polygon. After making the polygons and creating the available area of the vegetation along IH-35, the Google Earth file was exported to ArcMap to calculate the area of each polygon. The calculated area in the ArcMap was then exported to an Excel file and the total available area between each of the two consecutive sites was calculated (Table 8). It should be noted that frontage roads were not considered in these calculations since the available area for vegetation is very limited. Moreover, in many cases, the available vegetation area around the frontage roads are on private property.

**Table 8. The estimated area and distance between sites sampled for carbon along the IH-35 corridor in San Antonio, Texas.**

| Area Between Sites | Area (ha) | Distance (km) |
|---|---|---|
| From site 1 to site 2 | 10.5 | 12.9 |
| From site 2 to Downtown | 9.1 | 8.0 |
| From Downtown to site 3 | 11.5 | 8.8 |
| From site 3 to site 4 | 16.0 | 7.2 |
| From site 4 to site 5 | 9.5 | 5.6 |
| From site 5 to site 6 | 25.1 | 11.3 |

The available area for vegetation increases south of downtown San Antonio concurrently with decreasing population density. The Downtown area is located between sites 2 and 3. It starts at the IH-35 and IH-37 intersection and continues to I-35 and I-10 intersection. Since there is limited vegetated areas present in the downtown area, the available area between these two sites is divided before and after downtown. The area between sites 5 and 6 is the most effective area to sequester carbon since site 6 is located outside of the SH-1604 loop and in a semi-urban/rural surrounding with large buffer zones for vegetation. The available area is a more important factor for the carbon sequestration compared to the distance between sites. The total available area for the vegetation along the IH-35 highway in Bexar County is estimated to be approximately 81.7 ha (201.5 acres). We suggest the area between sites 5 and 6 (25.1 ha; 62 acres) are ideal locations for carbon sequestration using native plant communities including those with larger diameter woody stems such as trees.

We estimated a total carbon sequestration budget of 1,126,866 kg C within the area (81.7 ha) sampled along IH-35 (Table 9). A greater amount of carbon was sequestered in the top 20 cm of the soil compared to leaf litter and above-ground vegetation, and leaf litter contained more carbon than above-ground vegetation. The majority (ca. 95%) of the area sampled was grass and forb vegetation that is regularly mowed. Few trees are present because of safety issues regarding driver visibility, but many of the larger right-of-ways south of downtown could be planted with long-lived trees such as live oaks to sequester a greater amount of carbon in the future.

**Table 9. Location, area (hectares), and the amount (kg) of carbon sequestered at each site and total for leaf litter, vegetation (above ground), soil (top 20 cm) along the IH-35 corridor in San Antonio, Texas.**

| **Location (Site)** | **Hectares** | **Carbon (kg)** | | |
|---|---|---|---|---|
| | | **Leaf Litter** | **Vegetation** | **Soil (Top 20 cm)** |
| Site 1 to 2 | 10.5 | 26,284 | 13,495 | 105,263 |
| Site 2 to downtown | 9.1 | 22,746 | 11,678 | 91,093 |
| Downtown to 3 | 11.5 | 28,811 | 14,792 | 115,385 |
| Site 3 to 4 | 16.0 | 39,932 | 20,502 | 159,919 |
| Site 4 to 5 | 9.5 | 23,757 | 12,197 | 95,141 |
| Site 5 to 6 | 25.1 | 62,678 | 32,180 | 251,012 |
| Total | 81.7 | 204,208 | 104,844 | 817,814 |
| **Grand Total** | | 1,126,866 | | |

Soils located in arid regions have low concentrations of carbon due to infrequent precipitation and decreased microbial activity *(54)*. In New Mexico, soil carbon was strongly correlated with precipitation *(55)*. The results of this study may represent minimal estimates of carbon due to minimal precipitation during the summer sampling period. Pulses of carbon sequestration may occur during precipitation events. Other factors that may limit carbon sequestration along IH-35 include soil compaction and low organic matter. An assessment of soil and plant carbon content is affected by environmental variability that includes precipitation and temperature, and different soil types. In semi-arid regions such as Texas, carbon sequestration is likely a pulsed event dependent on precipitation and vegetation diversity. Increased plant species richness and diversity along roadways may result in greater annual carbon sequestration. As $CO_2$ levels increase, it is unclear if $C_3$ plants will become more productive than $C_4$ plants *(56)*. Roadsides with a mixed diversity of $C_3$, $C_4$, cool and warm season species would be more efficient at carbon sequestration on a year round basis. $C_3$ plants initially fix $CO_2$ into a three-acid compound and are most efficient at photosynthesis in temperate, cooler climates. In $C_3$ plants, oxygen competes with $CO_2$ at the binding site of the enzyme rubisco and photosynthesis is less efficient under hot environmental conditions. $C_4$ plants are more efficient in fixing CO2 and utilize two CO2 fixing mechanisms. When $CO_2$ diffuses into $C_4$ plants, it is initially fixed in the mesophyll cells into a 4 carbon compound by the enzyme PEP-carboxylase which has no affinity for oxygen. The four carbon compound is then shuttled into the bundle-sheath cells where it is fixed into sugars. $C_4$ plants are more photosynthetically efficient in tropical and arid climates, and account for many agricultural crops and grassland species.

Warm season grasses generally have a higher root to shoot ratio comprised of greater fine root densities than cool season grasses *(57, 58)* and the continual senescence of fine roots incorporates greater carbon into soil profile *(59)*. Bermudagrass and King Ranch bluestem are warm season grasses that go dormant for 3-4 months in South-Central Texas, limiting soil carbon sequestration in the winter. Bermudagrass is a stoloniferous and rhizomatous species which translocate more carbon into multiple roots along nodes. King Ranch bluestem is a clump grass with shallow roots, spreads by short stolons, and occurs in high densities. Conversely, cool season grasses and forbs are important along roadways carbon sequestration, trapping sediment and preventing erosion during the cooler months in South-Central Texas.

In this study, bermudagrass was more efficient in $CO_2$ assimilation at higher light compared to King Ranch bluestem. Quantum efficiency, $CO_2$ saturated assimilation, light compensation, and light saturation rates were greater for bermudagrass compared to King Ranch bluestem. Based on the respiration rate, bermudagrass experiences minimal photorespiration and has a greater tolerance to higher irradiances and temperatures than King Ranch bluestem. Several warm season native grasses occurred in the study sites but coverage was less than 5%. These native species included little bluestem (*Schizachyrium scoparium*), side oats gamma (*Bouteloua curtipendula*), buffalograss (*Buchloe dactyloides*), silver bluestem (*Bothriochloa laguroides*), white tridens (*Tridens albescens*), and purple threeawn (*Artistida purpurea*). Comparisons of native to non-native grasses will provide insight on native species capable of competing with non-native grasses. In disturbed and compacted roadside soils, carbon may be a limiting factor in native plants becoming established or non-native species are more efficient at atmospheric $CO_2$ intake giving them a competitive advantage. Carbon soil content in an undisturbed Central Texas prairies containing a mix of native and nonnative species was greater than improved grasslands and agricultural sites *(60)*. In disturbed and compacted roadside soils, carbon may be a limiting factor in native plants becoming established. In highly disturbed soils along roadways, it may take decades for the soil carbon content to increase its carbon storage capacity. Consequently, many roadside corridors may be well below their capacity to store carbon.

Non-native grasses were the dominant plant cover along IH-35 in San Antonio. No signs of erosion were observed at any study site indicating the current vegetation cover is effective at preventing damage to roadway infrastructure. Due to safety issues with driver visibility, low growing grasses and forbs are the only options for many roadways. Our results indicate that grasses can sequester between 808 to 1756 kg C $ha^{-1}$ in San Antonio, Texas. The two dominant non-native grasses documented in this study can theoretically sequester up to 123 kg $CO_2$ $ha^{-1}$ during maximum sunlight conditions from 10 AM to 2 PM. In addition, soil carbon content along IH-35 in San Antonio ranged between 3.1 to 6.9 kg C $m^{3\ -1}$. The variation in the soil carbon content is likely due to site and disturbance age which was unknown for the study sites. Moreover, in semi-arid areas like San Antonio, carbon sequestration will be variable seasonally due to irregular precipitation and temperature. Carbon in soils is due to net primary productivity, inputs of organic matter, soil moisture, and temperature *(61)*. We recommend that native grasses be evaluated as options for planting along roadways. In theory, native plants within a region have evolved to climate patterns and are expected to be more resilient and resistant to long periods of droughts and short intense periods of inundation, thus providing greater carbon sequestration on an annual basis. Low-growing evergreen shrubs < 1 m and cool season grasses planted may compensate for the loss of carbon sequestration from warm season plants that go dormant during the winter months. For additional carbon sequestration in the vicinity of roadways, the planting of trees in ruderal sites off roadways and in large medians where safety is not an issue will result in increased carbon sequestration and long-term storage compared to perennial grasses and forbs. Vegetated roadways are one component in the overall solution to sequester greater amount of carbon. Additional studies are needed to evaluate the mowing patterns, changes in microbial communities, and carbon sequestration and storage along roadways.

## 6. CONCLUSIONS

The results of this study found that two non-native grasses, bermudagrass and King Ranch bluestem, accounted for the dominate plant coverage in vegetative strips along IH-35 and an adjacent strip on SH-1604 in San Antonio, Bexar County, Texas. Mean native plant coverages for each species documented were < 5% at all sites and native grasses were rare. Total vegetation carbon content averaged 1282 kg C $ha^{-1}$ among all sites. Vegetation carbon content was significantly higher ($P < 0.0001$) in 6 of the 7 sites sampled for non-native species compared to native species. Mean soil carbon content for all sites was 5.0 kg C $m^{3\ -1}$ and ranged from 3.1 to 6.9 kg C $m^{3\ -1}$. Soil carbon content was significantly greater in the upper 10 cm of the soil profile compare to soil carbon in the lower 10-20 cm. Leaf litter carbon content averaged 2497 kg C $ha^{-1}$ among all sites sampled indicating that vegetative strips along roadways in Bexar County, Texas may be a source of $CO_2$ rather than a sink. It is unknown if the carbon content of leaf litter is stored in the soil or diffused into the atmosphere. Roadside vegetated areas may require decades of minimal disturbance not including mowing to develop soil organic matter content in the upper soil profile capable of supporting greater plant diversity. Additional research is needed to evaluate the carbon content of native vegetation and associated soils along roadways that are not dominated with non-native grass coverage. *In* and *ex situ* competitive studies are needed to elucidate native xeric grasses and forbs capable of competing with non-native grasses along roadways. Development of native xeric landscaping protocols along roadways are needed that maximize carbon sequestration and storage, while promoting native species. Roadside vegetation with a mixed diversity of $C_3$, $C_4$, and cool and warm season species would result in more efficient at carbon sequestration on a year round basis.

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## APPENDIX A: LIST OF PLANT SPECIES DOCUMENTED AT EACH SITE

**Table A1. List of plant species documented at each site during the study. This list excludes 14 specimens of seedlings or non-flowering plants that could not be identified.**

| Species | Common Name | Site | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| *Abutilon fruticosum* | Texas Indian mallow | x | | | | | | |
| *Acacia greggii var. wrightii* | Wright acacia | x | | | | | | |
| *Agalinis heterophylla* | Prairie Agalinus | | | | | | | x |
| *Ambrosia artemisiifolia* | Common ragweed | | | x | x | | x | |
| *Aristida purpurea* | Wiregrass | | | | | | | x |
| *Asclepias oenotheroides* | Side-cluster Milkweed | | x | | | | | x |
| *Bothriochloa ischaemum* * | King Ranch bluestem | x | x | x | x | | x | x |
| *Bothriochloa laguroides* | Silver bluestem | | | | | | | x |
| *Bouteloua curtipendula* | Sideoats grama | | | x | | | | x |
| *Bromus catharticus* * | Rescuegrass | | | | x | | | |
| *Calyptocarpus vialis* * | Straggler Daisy | | | x | | | | |
| *Carex planostachys* | Cedar Sedge | x | | | | | | |
| *Cenchrus spinifex* | Coastal sandbur | | | | | | | x |
| *Chamaecrista fasciculata* | Partridge pea | | | | | | | x |
| *Chloris virgata* | Showy Chloris | | | | | x | | |
| *Coelorachis cylindrica* | Carolina jointgrass | | | | | | | x |
| *Convolvulus equitans* | Texas Bindweed | | | x | | | | |
| *Croton spp.* | Croton | x | | | | | | x |
| *Cynodon dactylon* * | Bermudagrass | | x | x | x | x | x | x |
| *Echinochloa crus-galli* * | Common barnyard grass | | | | | x | | |
| *Euphorbia nutans* | Eyebane | | | | | x | | |
| *Froelichia gracilis* | Slender snakecotton | | | | | | | x |
| *Gaillardia pulchella* | Indian blanket | x | | | | | | x |
| *Gaura spp.* | Gaura | | x | x | x | | | |
| *Glandularia bipinnatifida* | Prairie verbena | x | | | | | | |
| *Hydrocotyle spp.* | Dollarweed | | | | | | | x |
| *Juniperus ashei* | Ashe Juniper | x | | | | | | |
| *Malva parviflora* | Cheeseweed | | | x | | | | |
| *Merremia dissecta* | Alamo vine | | | x | | | x | |
| *Mimosa borealis* | Pink mimosa | | | x | | | | |
| *Mimosa microphylla* | Littleleaf Sensitive Briar | | | x | | | | |
| *Neptunia lutea* | Yellow-puff | | | | x | x | | |
| *Oenothera curtiflora* | Velvetweed | | | x | | | | |
| *Oenothera suffrutescens* | Scarlet gaura | | | | | | x | |
| *Opuntia engelmannii* | Texas prickly pear | x | | | | | | |
| *Oxalis spp.* | Oxalis | | | x | | | | |

| Species | Common Name | Site | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| *Paspalum spp.* | Paspalum | | | | x | | | |
| *Pennisetum spp.* * | Fountaingrass | | | | | | | x |
| *Phyla nodiflora* | Texas frogfruit | | | | | | | x |
| *Phyllanthus polygonoides* | Smartweed leaf-flower | | x | x | x | | | x |
| *Plantago rhodosperma* | Red-seeded Plantain | | x | | | | | |
| *Prosopis glandulosa* | Honey mesquite | | | x | | | | |
| *Pseudognaphalium obtusifolium* | Rabbit tobacco | x | | | | | | |
| *Quercus fusiformis* | Escarpment live oak | x | | | | | | |
| *Ratibida columnifera* | Mexican Hat | x | x | x | | | x | |
| *Ruellia spp.* | Wild Petunia | | x | x | | | x | |
| *Salsola kali* * | Russian thistle | | | | | x | | |
| *Scolochloa festucacea* | Spangletop | | | | | x | | |
| *Setaria scheelei* | Southwestern bristlegrass | | | | | | x | |
| *Sida cordifolia* | Heart-leaf sida | | | | | | | |
| *Sida spp.* | Sida | | | x | | | x | x |
| *Solanum dimidiatum* | Western horsenettle | | | x | | | | |
| *Solanum elaeagnifolium* | Silverleaf nightshade | x | x | | x | | x | |
| *Sorghum halepense* * | Johnson grass | | x | x | x | x | x | |
| *Sphaeralcea spp.* | Globemallow | | | x | | | | |
| *Thymophylla pentachaeta* | Parralena | | | | | | | x |
| *Tragia betonicifolia* | Betonyleaf noseburn | x | | | | | | |
| *Vachellia farnesiana* | Huisache | | | | | | | x |
| *Verbena halei* | Texas vervain | x | | x | | | | |
| *Vicia ludoviciana* | Deer pea vetch | x | | | | | | |
| *Wedelia hispida* | Zexmenia | x | | | | | | |
| **Total Species per Site** | | 18 | 10 | 22 | 11 | 8 | 11 | 20 |