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16. Abstract

Carbon footprints, carbon credits and associated carbon sequestration techniques are rapidly becoming part of how environmental mitigation business is conducted, not only in Texas but globally. Terrestrial carbon sequestration is the general term used for the capture and long-term storage of carbon dioxide. For a transportation facility, this occurs through the natural processes of the roadside vegetation and soil. Texas has a state-maintained highway system of approximately 80,000 linear miles of roadway with more than 1.1 million acres of right-of-way, not including the street systems of cities, towns and local communities. The majority of these roadways have supporting vegetation within their rights-of-way that usually consists of various combinations of grasses, shrubs and trees. Roadside carbon sequestration measurement practices typically rely on modeling and in-situ measurements. This project conducted initial testing to develop a method for quantifying plant and soil carbon sequestration capabilities under the controlled conditions of the Texas Transportation Institute's Environmental and Emissions Research Facility (EERF). Plants and soil were subjected to heavy-duty truck emissions over a six week period. Samples were analyzed for changes in carbon and nitrogen content over time. Due to the plant injury that occurred during testing, the sequestration capabilities of these plant materials and soils were inconclusive. A comparison of samples taken over the course of the study indicated that the desired results may have been accomplished had the initial exposure in the EERF been reduced to a more moderate level. Modifications to this technique for future research on specific soils and plant materials may help identify plant and soil combinations to maximize roadside carbon sequestration.

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Development and Validation of a Testing Protocol for Carbon Sequestration Using a Controlled Environment

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DISCLAIMER

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EXECUTIVE SUMMARY

Carbon footprints, carbon credits and associated carbon sequestration techniques are rapidly becoming part of how environmental mitigation business is conducted, not only in the United States but globally. State departments of transportation across the country are looking to the roadsides as an opportunity for carbon sequestration and biomass production for alternative fuels.

The overall goal of this research is to develop a testing method or protocol to quantify the ability of vegetation and soil to sequester carbon in a full-scale, controlled laboratory using the chamber of the Environmental and Emissions Research Facility (EERF) located at Texas A&M University's Riverside Campus. The plants and soil chosen for this research are typical of Texas roadsides and hardy for an urban environment:

- Dwarf yaupon holly (yaupon), *Ilex vomitoria* 'Nana.'
- Texas sage (sage), *Leucophyllum frutescens*.
- Elbon rye grass (elbon), *Secale cereale* 'Elbon.'
- Bermudagrass (bermuda), *Cynodon dactylon.*

The study conducted experiments in the EERF chamber using the exhaust from a 2006 Freightliner heavy-duty truck as a source of emissions introduced to the plant materials and soil. The initial test protocol called for a vehicle run time of 20 minutes twice daily. Plants were subjected to 18 hours of artificial grow lights and watered approximately every three days. After approximately one week of exposure to high concentrations of pollutants, the plant material showed signs of rapid decline. Each of the plant types and respective soils clearly demonstrated the effects of high concentrations of nitrogen monoxide (NO), nitrogen dioxide (NO_2) and carbon monoxide (CO). The emissions level was reduced to 20 minutes every other day for the remainder of the study.

Plant and soil samples were collected before testing on March 24, 2011, as a baseline. Subsequent samples were collected the week of April 4, 2011, and after removal from the chamber on May 2, 2011. The sample data were analyzed for changes over time in the amount of total nitrogen (N) and carbon (C) content in each plant's stems, leaves, roots and soil.

Due to the plant injury that occurred during testing, the sequestration capabilities of these plant materials and soils were inconclusive. A comparison of samples taken over the course of the study indicated that the desired results may have been accomplished had the initial exposure in the chamber been reduced to a more moderate level. The results of this study were also inconclusive for determining a relationship between N and C relative to the collected samples.

Recommendations for future research include the investigation of the effects different emission levels have on plant health to determine a level that represents an urban roadside environment and is suitable for prolonged exposure with minimal plant damage. Also, research should examine different plant materials and soils to determine performance capabilities for maximizing carbon sequestration on roadside applications.

INTRODUCTION

BACKGROUND

State departments of transportation (DOTs) across the country are facing the challenges of meeting environmental goals for reduction of greenhouse gas (GHG) emissions and declining budgets for transportation programs and infrastructure, with limited ability to raise additional revenue. The combined result compels these agencies to look at creative and unconventional means to use the National Highway System's (NHS's) 5 million acres of unpaved right-of-way to meet these goals. Texas roadways account for more than 1.1 million acres of right-of-way, not including the street systems of cities, towns and local communities. Carbon footprints, carbon credits and associated carbon sequestration techniques are rapidly becoming part of how environmental mitigation business is conducted, not only in the United States but globally. DOTs are looking to the roadsides as an opportunity for carbon sequestration and biomass production for alternative fuels.

The carbon footprint (the total set of GHG emissions resulting from activities of an organization, event or product, usually expressed in terms of the amount of carbon dioxide [CO_2] or its equivalent of other GHGs emitted) of a transportation system is being scrutinized more closely by federal, state and local agencies, not only for environmental impacts but also for potential economic opportunities. Historically, carbon sequestration has been assessed from an agricultural or forestry perspective. It is only within recent years that the vast quantity of land owned, operated and maintained by transportation agencies has been considered in the equation of carbon sequestration, carbon credits, carbon trading and biomass production. These roadway systems have miles of supporting vegetation within their rights-of-way that usually consists of various combinations of grasses, shrubs and trees. This vegetation has historically been overlooked from a carbon sequestration standpoint but is now beginning to be considered. With these new opportunities come issues for DOTs in implementing new programs.

Recent research conducted by the Federal Highway Administration (FHWA) and the John A. Volpe National Transportation Systems Center, *Carbon Sequestration Pilot Program: Estimated Land Available for Carbon Sequestration in the National Highway System* (CSPP), assessed whether roadside carbon sequestration efforts through modified maintenance and management practices are appropriate and feasible for DOTs. Some of the logic behind this research stems from ecosystem service, defined as the inherent functions of natural ecosystems that benefit human populations at little or no additional cost, i.e., the roadside. These functions include flood storage, water quality treatment, carbon sequestration, provision of wildlife habitat, genetic diversity and landscape diversity. According to FHWA, "Since DOTs must retain unused buffers in their right-of-way (ROW) for safety, operations, and maintenance purposes, FHWA recognized that an opportunity might exist to shape the future of a burgeoning ecosystem service market." The CSPP also demonstrated the "ecological, economic, and political uncertainties" that lie ahead for initializing biological carbon sequestration programs for DOTs *(1)*.

Transportation facilities and the roadsides relate to the carbon cycle in their ability to sequester carbon where the soil, vegetation and associated water quality facilities are the carbon sinks. Carbon sequestration is the general term that is commonly used to describe the capture and long-term storage of carbon dioxide. The carbon cycle is the basic process responsible for terrestrial carbon sequestration, which would generally apply to carbon capture from roadside vegetation. Carbon is exchanged through a biogeochemical cycle that occurs among the biosphere (the sum of all ecosystems), geosphere (rock), pedosphere (soil), hydrosphere (water) and atmosphere (air) as shown in Figure 1.

There are five major carbon sequestration methods, sinks or reservoirs in this exchange cycle where carbon is captured and stored until it is released through physical or chemical disturbance. These include:

- Soil (soil sequestration).
- Forests and other vegetation (plant sequestration).
- Underground geological formations (geosequestration).
- Ocean (ocean sequestration).
- Chemical reactions to form inorganic carbonates (mineral carbonation).

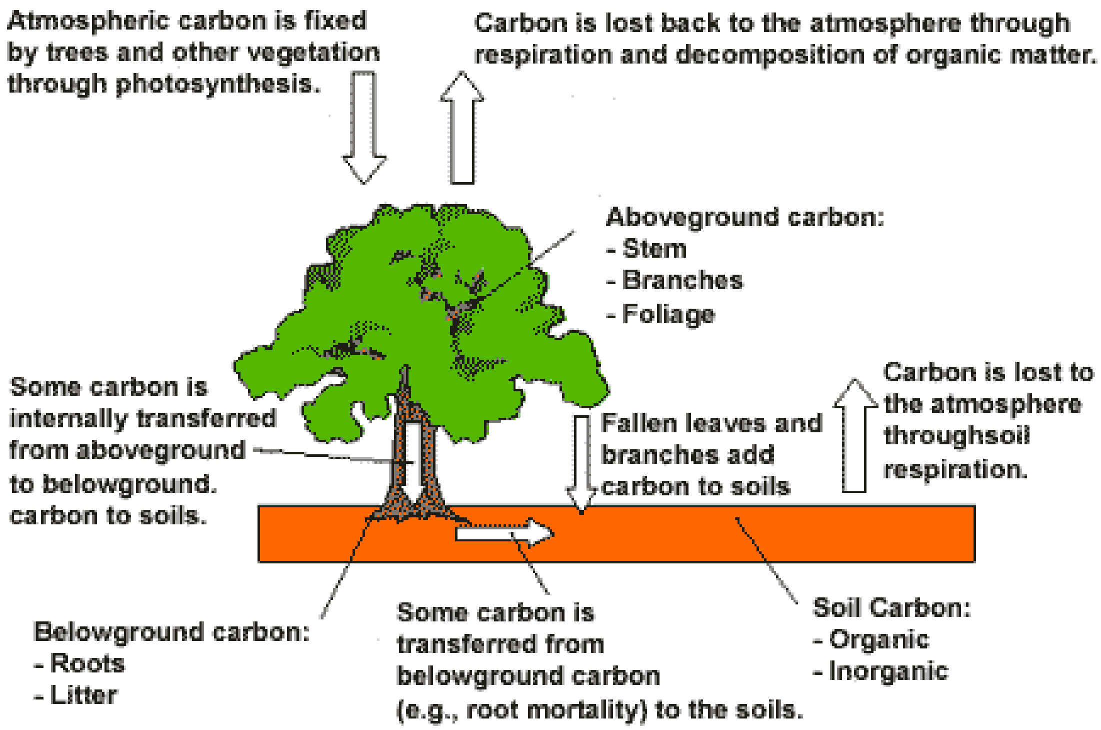


Figure 1. Carbon Sequestration Cycle (*2*).

Carbon has two phases in the carbon cycle: gaseous and solid. Its gaseous phase is mostly in the form of CO_2, but it can also be found in compounds like methane and carbon monoxide. Carbon dioxide can be taken out of the atmosphere by photosynthesis in plants, which converts the carbon into a solid form (sugars or carbohydrates), which can then be stored or put back into the air during respiration. Photosynthesis combines CO_2, water and sunlight to form glucose and release oxygen (Figure 2). Carbon is stored when the amount of photosynthesis exceeds the rate of plant respiration. It can also be removed from the atmosphere by being absorbed by water, where it becomes available to water plants for photosynthesis, as well as being available to form compounds such as calcium carbonate or to be put back into the atmosphere when the water temperature rises.

$$6CO_2 + 6H_2O + \text{Light} \longrightarrow C_6H_{12}O_6 + 6O_2$$

$$\text{Carbon Dioxide} + \text{Water} + \text{Light} \longrightarrow \text{Sugar} + \text{Oxygen}$$

Figure 2. Overall Formula for Photosynthesis.

The focus on CO_2 is due to its global effect. The environmental impact of CO_2 is generally similar, no matter the global position, because it mixes quickly with the surrounding air. This means that the location of the emitter is irrelevant from a climate change perspective, “a ton of CO_2 (or its equivalent in another GHG) reduced in the United States and a ton sequestered in another nation would have the same result on the atmospheric concentration of GHGs” *(3).* This cannot be said for pollutants such as sulfur dioxide (SO_2) or nitric oxide (NO_X), where the local or regional impact is dependent upon where they are released. This accounts for the widespread global emphasis on CO_2 sequestration as an environmental solution and marketable commodity.

Carbon credits and offsets are a relatively new form of trade within the global marketplace and are rapidly becoming a viable commodity. The basic unit of trade is 1 metric ton of CO_2 equivalent (tCO_2e). The carbon market trades emissions under cap-and-trade schemes or with credits that pay for or offset GHG reductions, and are the most popular way to regulate CO_2 and other emissions. The basic concept relies on a cap for allowable emissions. Those members exceeding the set goal can purchase credits, and those with surplus can sell or trade credits. Carbon trading can be either mandatory or voluntary.

The Chicago Climate Exchange (CCX) operates North America’s only cap-and-trade system for all six GHGs, involving a voluntary but legally binding commitment of its members to meet annual GHG emission reduction targets. CCX has developed the only existing carbon sequestration offset protocols resulting in emissions credit exchanges in the United States. The protocols, likely to apply to right-of-way management in the United States, are the CCX Forestry *(4),* Grassland *(5)* and Rangeland *(6)* protocols last updated in 2009. CCX launched the Chicago Climate Exchange Offsets Registry Program in 2011 to register verified emission reductions. These emission reductions are based on the protocols established by CCX. While the new CCX program plans to leverage existing protocols, the details and program rules will be modified given stakeholder input *(7)*.

One of the issues facing DOTs in implementing carbon credit trading lies in the bylaws of exchanges such as CCX. Currently, if a DOT wishes to join CCX, all state agencies have to be included. There is no established protocol consistent with the characteristics and practices related to the NHS rights-of-way and state transportation agencies.

DOTs may face some obstacles in deciding how best to use the NHS rights-of-way. The 2007 report from the U.S. Congressional Budget Office, *The Potential for Carbon Sequestration in the United States,* brings to light a point of conflict when it states that when deciding "whether to engage in sequestration activities, landowners would consider two types of costs: direct costs and opportunity costs. Direct costs are those associated with the activity itself—the cost of planting trees, for example. Opportunity costs are the forgone returns associated with alternative uses of the land that the owner did not choose—for instance, land used to grow trees cannot also be used to grow biofuel crops" *(8)*.

RESEARCH OBJECTIVES

The overall goals of this research are to develop a testing method or protocol to quantify the ability of vegetation and soil to sequester carbon in a full-scale, controlled laboratory environment. The analysis of this research includes the following:

- Reviewing literature as related to relevant carbon sequestration studies with a focus on laboratory or controlled-environment research and testing methods.
- Developing and conducting a controlled laboratory protocol for quantifying plant and soil carbon sequestration capabilities using the Environmental and Emissions Research Facility (EERF) located at Texas A&M University's Riverside Campus.
- Analyzing results to determine whether the protocol achieved the goals and recommend modifications as necessary for future use.

LITERATURE REVIEW

Terrestrial carbon sequestration is defined as either the net removal of CO_2 from the atmosphere or the prevention of CO_2 net emissions from the terrestrial ecosystems into the atmosphere. Enhancing the natural processes that remove CO_2 from the atmosphere is thought to be one of the most cost-effective means of reducing atmospheric levels of CO_2. There are two fundamental approaches to sequestering carbon in terrestrial ecosystems:

- Protect the ecosystems that store carbon.
- Manipulate the ecosystems to increase and/or maintain sequestered carbon *(9)*.

Historically, much of the measurement data regarding terrestrial carbon sequestration focused on land use types and/or changes in these land uses and the estimated changes in their sequestration rates:

- Agricultural land management to include biomass production.
- Forests to include agroforestry applications.
- Wetlands and peat bogs.
- Perennial grasslands.
- Urban applications.

Transportation agency rights-of-way encompass many of these vegetation/soil types. Changes in transportation facilities can be an integral part of changes in surrounding land uses.

The right-of-way is typically considered and designed as part of the transportation facility used to stabilize the roadbed and discharge stormwater. However, many transportation agencies now face decisions regarding roadside management that may include carbon sequestration and biomass production. The millions of acres of vegetated rights-of-way across the country hold great potential for new management techniques to maximize vegetation's potential beyond stormwater conveyance.

CARBON SEQUESTRATION VERSUS BIOMASS PRODUCTION

Both carbon sequestration and biomass production are relatively new concepts for roadside management. Ironically, the plants with the most promise for carbon sequestration are also the most promising for biomass production. These plants use C_4 carbon fixation (4-carbon molecule). These species are known to use less water and fix more carbon than their counterparts. Plants include many species used in biomass production such as maize, sugar cane, millet and sorghum. This adds another layer of complexity to the decisions of transportation agencies in adopting carbon sequestration and/or biomass production programs. These decisions are coupled with the tremendously varied rights-of-way across the United States with respect to soil composition, slope, climate and other landscape variables.

MEASUREMENT AND MODELING

The total amount of carbon present in vegetation and soil is generally referred to as the carbon stock. The total carbon is usually calculated through sample analysis or biomass estimates. The terrestrial carbon sequestration rate for a given area is typically reported in units of metric tons of carbon or CO_2 per acre per year. There are several methods used to try to calculate a given ecosystem's ability to capture and retain atmospheric CO_2:

- Direct methods:
  - Field and laboratory measurement—Samples are analyzed for the total carbon content of above- and belowground biomass and respective soils.
  - Micrometeorological measurement—CO_2 exchanges between the atmosphere and the plant/soil surface are measured using tower eddy covariance *(10)*.
- Indirect methods:
  - Accounting with databases.
  - Remote sensing.
  - Inelastic neutron scattering (INS).
  - Mid-/near-infrared spectroscopy (MIR/NIR).
  - Laser-induced breakdown spectroscopy (LIBS).
  - Simulation/modeling—Numerous models exist that use complex mathematical models of transfers of C between plants, soils and the atmosphere based on known or estimated relationships. These models estimate carbon sequestration rates using varied scenarios that include different types of land uses and changes in land uses over time *(11)*.

Laboratory measurement techniques and scales differ throughout the literature. Nothing was found in the literature regarding full-scale, controlled-environment laboratory measurement using vehicle emissions. The majority of open- and closed-chamber, flask or laboratory research conducted measured the amount of soil-respired CO_2 occurring over time using specific plant materials and soils.

METHODOLOGY

RESEARCH DESIGN SUMMARY

The research for this project was conducted at two Texas Transportation Institute (TTI) facilities located in the Riverside Campus of Texas A&M University in Bryan, Texas:

- Hydraulics, Sedimentation and Erosion Control Laboratory (HSECL)—The laboratory was established in 1990 to provide the transportation industry with a research program for stormwater quality improvement, erosion control, sediment control and vegetation establishment.
- Environmental and Emissions Research Facility—Opened January 2010, this is the largest drive-in environmental and emissions testing chamber in the country and the only one based at a university that can conduct tests using a full tractor-trailer or bus.

Using previous background material and information obtained from literature, the following underlying questions drove this study:

- Can we adequately synthesize the conditions necessary for plant and soil processes for carbon sequestration in the controlled environment of the EERF?
- Will the selected emission level and exposure time for testing in the EERF provide sufficient data for analysis?
- How will the plants respond to selected exposure to emissions in a controlled environment?
- How can the methodology be improved for further testing?

TEST BED ESTABLISHMENT AND TRANSPORT

The initial concept for this research project was to use plant material grown over the previous two years as bioretention cells (cells) at the HSECL. These cells were part of phase one of Texas Department of Transportation Project 0-5949, *Bioretention for Stormwater Quality Improvement in Texas: Pilot Experiments (12).* The five cells consisted of different types of vegetation—including shrubs and grass species (native and non-native)—and no vegetation as the control. The soil and plant material content of the cells established above- and belowground biomass, which was ideal for use in the study. However, discussion of the logistics associated with transporting the containers compelled the development of another approach. The size and weight of the cells, made from modified small trash dumpsters, prohibited their use in this project because they required specialized equipment (a large forklift) each time the cells needed to be moved for any reason (see Figure 3).

Figure 3. Bioretention Cells.

The alternative to the cells consisted of using existing test beds at the HSECL to conduct the test trials for this project. These beds are smaller (1.5 ft wide, 0.75 ft deep and 15 ft long), are primarily used for testing channel lining materials, and can be moved using the HSECL's existing equipment. Because of the logistics of this project and the ease of transporting these smaller test beds, this proved to be the best approach for this project. Four beds were filled with a sandy loam topsoil mixture from north Burleson County, Texas. The beds were planted on December 21, 2010, with the materials listed below, and placed in the HSECL greenhouse (see Figure 4):

- Bed 1—six Dwarf yaupon holly (yaupon), *Ilex vomitoria* 'Nana.'
- Bed 2—six Texas sage (sage), *Leucophyllum frutescens.*

- Bed 3—Elbon rye grass (elbon), *Secale cereale* ‘Elbon.’
- Bed 4—Bermudagrass (bermuda), *Cynodon dactylon.*

Figure 4. Left: Beds in HSECL Greenhouse;
Right: Elbon Rye Grass at Two Weeks of Growth.

These selected plant types, except elbon rye grass, are typical of Texas highway landscape development and are considered to be hardy enough for the harsh urban roadside environment. Elbon was chosen because it is a commonly planted Texas cool-season cereal rye that has quick growth and fast green-up characteristics.

The four test beds were grown in the HSECL greenhouse for three months to establish above- and below-ground biomass. Plants were watered and maintained to maximize growth and healthy establishment prior to transport to the EERF chamber for testing.

There were two main issues that needed to be resolved in order to move to the next phase of the project in the controlled environment of the EERF chamber:

- Maintaining photosynthesis during testing.
- Transporting the test beds without compromising the plant material.

The solution was to place the four beds on a flatbed trailer and mount lights above the beds. Two 1000 W (average 1161 FC) high-pressure sodium full-spectrum grow lights, with deep reflector light ballasts, were mounted at 6 ft above the beds to ensure that photosynthesis continued at an optimum level as shown in Figure 5. Placement on the trailer enabled the research team to easily transport the test beds with minimal disturbance. The test bed trailer was transported to the EERF on March 24, 2011.

Figure 5. Test Beds on Trailer Ready for Transport to the EERF March, 24, 2011.

IN-CHAMBER TESTING AT THE EERF

The EERF chamber is capable of sustaining a controlled environment and introducing specific air mixtures to simulate roadside environments. The facility has the following technical specifications:

- Temperature range: −13 °F to +131 °F (−25 °C to +55 °C).
- Relative humidity range: up to 70 percent at 104 °F (40 °C).
- Dimensions: 75 ft × 23 ft × 22 ft (capable of holding a tractor-trailer or bus).
- Other equipment: solar loading lights and wind simulator fans (Figure 6).

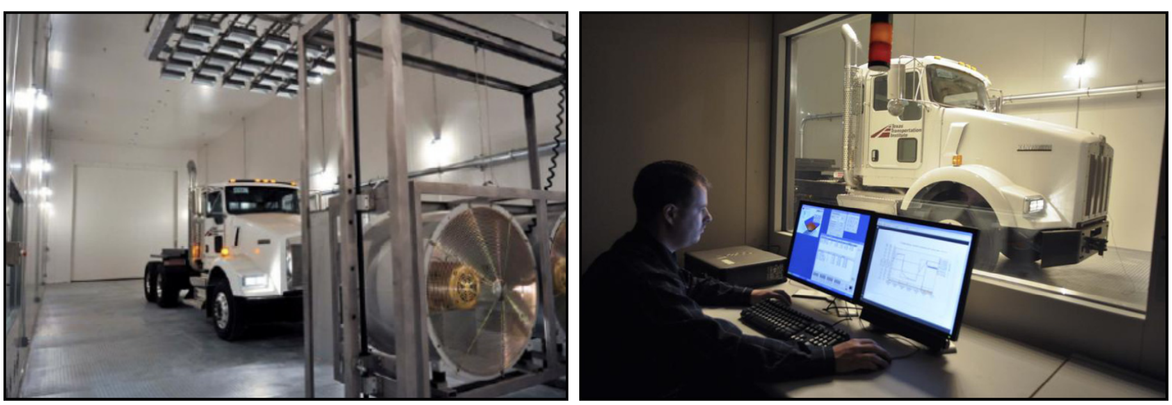


Figure 6. Left: EERF Chamber Interior;
Right: View into Chamber from Monitor and Control Room.

The EERF is a relatively new facility that typically tests new vehicles, components and automotive products—as well as many other products—for their durability under severe temperature, humidity and other weather-like conditions. Prior to this project, the chamber had never been used for any research regarding plant materials, particularly a project that required containment of emission to ascertain plant reactions and carbon sequestration capabilities. The testing was performed by bringing the plants into the test chamber, along with a source of emissions. The source of the emissions was a 2006 Freightliner heavy-duty truck.

The research team had to determine the following:

- Emission levels necessary to simulate an ultra-urban environment with high constituent levels.
- The vehicle run-time necessary to achieve desired pollutant levels.
- Chamber containment levels to maximize exposure for plant materials.
- The resident time of the test beds in the chamber.

Initial Test Protocol

The first round of testing began on March 30, 2011. The initial testing protocol consisted of the following:

- Place the test beds in the EERF chamber.
- Run the vehicle for 20 minutes with direct emissions discharge into the closed EERF chamber to reach a level equivalent to a heavily polluted area, i.e., a congested urban roadside.
- Monitor the levels of nitrogen monoxide (NO), nitrogen dioxide (NO_2) and carbon monoxide (CO).
- Run the vehicle as described above twice daily.
- Keep the chamber closed with minimal entry and disturbance to maximize exposure.
- Provide 18 hours of grow lights over the plant material to ensure adequate photosynthesis (Figure 7).
- Remove the plant material from the chamber for watering as necessary, approximately twice weekly.

- Monitor plant vigor and health over the exposure period, and modify emissions level as required.

Figure 7. Left: Grow Lights over Test Beds without Emissions in Chamber; Right: Chamber with Emissions on March 30, 2011.

Modifications to Test Protocol

This chamber had not previously been used in a manner that subjected anything living, i.e., plant material, to sustained emission levels that simulate a very contaminated urban roadside environment. The plant material was monitored in the chamber to determine responses to the sustained emissions exposure. Going into the research, it was uncertain as to how well the chamber would contain the specified air content and not dissipate or leak. The chamber remained closed, except for necessary entry for monitoring and maintenance, to retain the emissions for maximum exposure. The containment of the chamber exceeded expectations as shown in the right photo in Figure 7. The concentration of CO in the chamber was measured in parts per million (ppm) over the first few days of operation. The concentrations remained consistent at an average range of 25 to 40 ppm as shown in Figure 8. Once a steady level was achieved, the CO concentration in the chamber dropped only 4 to 5 ppm over the duration of the daily test period. After one week the cumulative effects of running the vehicle twice daily for 20 minutes put the plant material in rapid decline. This deleterious effect on the plant materials compelled the research team to step back and reevaluate the procedure. The vehicle run time was reduced to 20 minutes every other day for the remainder of the study.

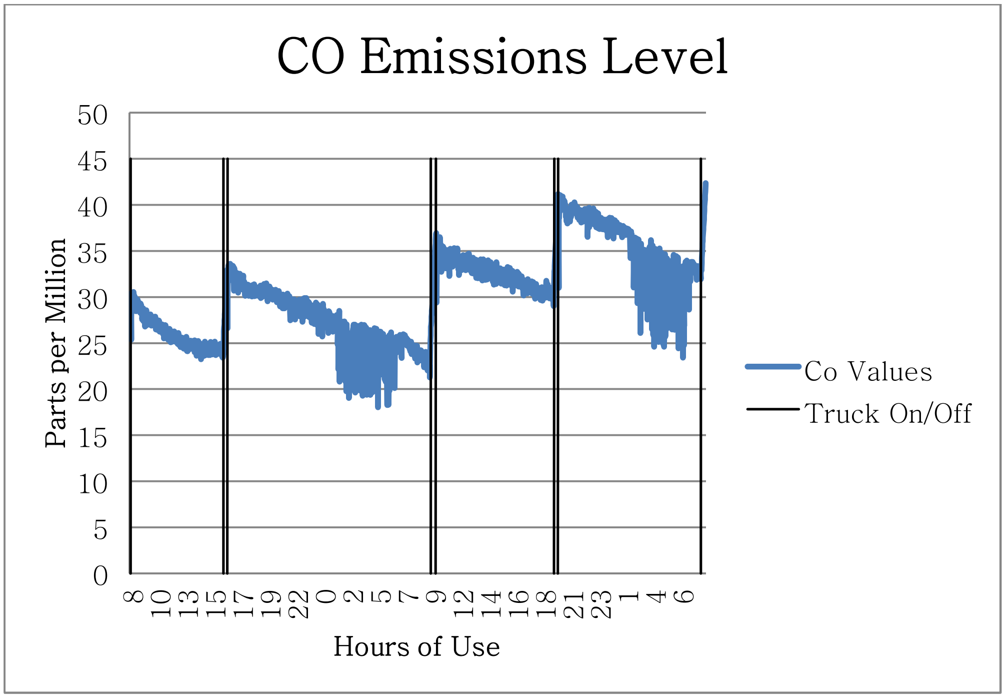


Figure 8. CO Concentrations in the EERF Chamber.

Plant Material Responses

Examination of the plant material on April 4, 2011, showed signs of significant stress and decline. This observation was noted only six days after introducing the plants into the test chamber. When viewing the plants, there was obvious physical injury that had occurred from continual exposure to the vehicle emissions. Typical air pollutants can cause cell metabolism disruption such as membrane damage, respiration and photosynthesis, leaf injury and loss, and reduced growth and reproduction. Damage from specific pollutants present is as follows:

- Ozone: speckles of brown spots on the flat areas of the leaf between the veins.
- Sulfur dioxide: larger bleached-looking areas. Injury is localized, and uninjured areas usually recover.
- Nitrogen dioxide: irregular brown or white collapsed lesions on intercostal tissue and near the leaf edge.
- Ammonia: unnatural green appearance with tissue drying out *(13, 14)*.

The sage and yaupon plants presented leaf injury and loss. The symptoms included damage that may be attributed to excessive exposure to NO_2 as explained above. The elbon and bermuda also presented signs of stress but much less than the shrubs. Figures 9 through 12 show the damaged plants.

Figure 9. Sage in Decline after Exposure.

Figure 10. Yaupon in Decline after Exposure.

Figure 11. Elbon and Bermuda Showing Signs of Stress.

Figure 12. Test Beds in EERF Chamber on April 4, 2011.

The researchers collected Sample 2 from the plant materials and respective soil the week of April 4, 2011. Plants remained in the chamber, and testing continued at a reduced emissions level. By April 18, 2011, the yaupon and sage were already recovering and producing new leaf growth as shown in Figure 13. The grasses continued to show signs of stress but were alive and green.

The elbon and bermuda were still in decline on April 27, 2011, and did not ever completely recover from their exposure in the chamber as shown in Figure 14. However, the yaupon and sage were recovering and still growing new leaves through the end of the chamber testing period.

The plants were kept in the EERF chamber for six weeks. They were removed on May 2, 2011.

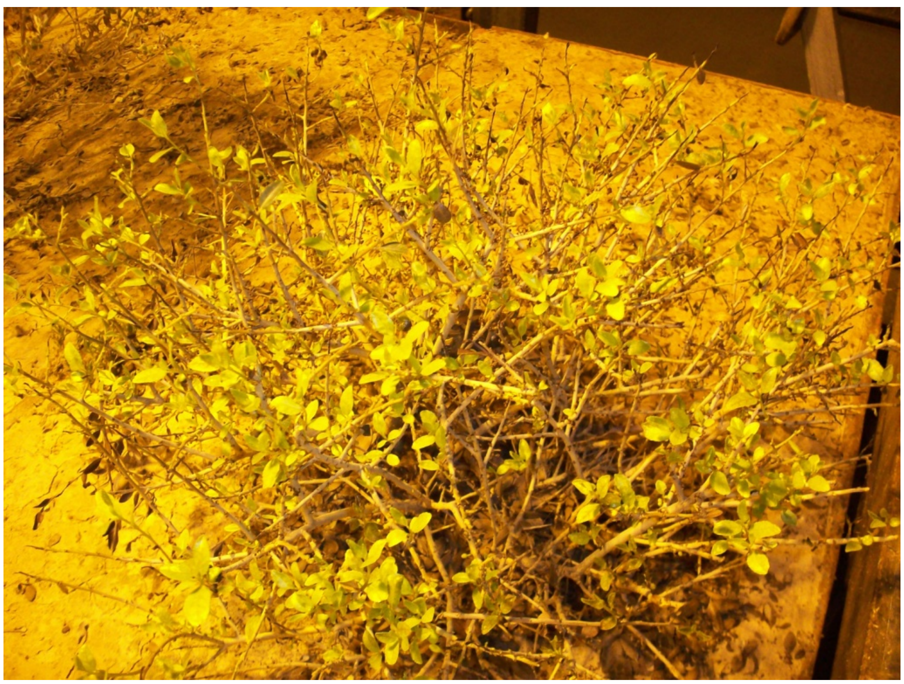


Figure 13. New Leaf Growth on Yaupon on April 18, 2011.

Figure 14. Plant Material after Four Weeks in Chamber. Left: Grasses in Decline; Right: New Growth on Shrubs.

GATHERING AND ANALYZING DATA

Data were gathered for this study by taking samples from the stems, leaves, roots and soil for each type of plant material used. The first sample of each type of plant and soil was obtained prior to the test bed placement in the EERF on March 24, 2011. This is the baseline condition for the project. The samples were sent to the Texas AgriLife Extension Service Soil, Forage and Water Testing Laboratory located at Texas A&M University. The laboratory determined the total nitrogen and carbon content for the stems, leaves, roots and soil. The soil was air-dried at 65 °C (149 °F) overnight and ground with a flail-type soil crusher, and then run through a 2 mm sieve. The final sample is everything that passed through the 2 mm sieve. The plant samples were air-dried at 65 °C (149 °F) overnight and ground with a Udy cyclone grinder to pass through a 0.5 mm screen. Total carbon and nitrogen were determined using an Elementar C/N Max. The C/N Max is a combustion-type CN analyzer. Citations for the current methods can be found at the AgriLife Extension Service Soil, Forage and Water Testing Laboratory website at http://soiltesting.tamu.edu/webpages/swftlmethods1209.html.

Subsequent samples were collected the week of April 4, 2011, and the week of May 3, 2011. The data were analyzed for change over time in the amount of total nitrogen and carbon content in each plant's stems, leaves, roots and soil.

The decision to collect nitrogen data was based on the relationship between soil nitrogen and carbon sequestration capabilities. The researchers wanted to determine if there was any significant relationship within the collected samples over the short duration of the project. Much research and controversy exist over the positive contribution of nitrogen in plant growth and the potentially negative effects of nitrogen (i.e., fertilizers) entering the remaining ecosystem.

EVALUATION OF RESULTS AND DISCUSSION

The researchers collected samples at three time periods during this project. Each time samples were taken, three distinct samples—leaves and stems, roots, and soil from the test bed—were taken for each type of plant used in this research:

- Sample 1 was collected on March 24, 2011, before placement in the EERF.
- Sample 2 was collected the week of April 4, 2011, after signs of plant decline.
- Sample 3 was collected the week of May 3, 2011, at the end of six weeks in the EERF.

The samples were analyzed for their total nitrogen and carbon content. Sample 1 served as the baseline for comparison of the changes that occurred in the plants and soil over time. The data compared individual plant and soil performance by comparing total carbon and total nitrogen content between Sample 1 and Sample 2, Sample 2 and Sample 3, and Sample 1 and Sample 3.

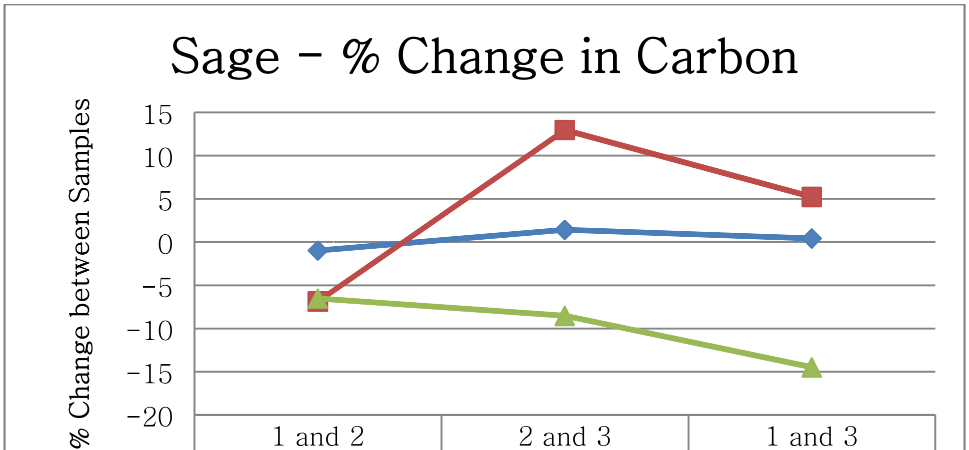
CARBON RESULTS

Texas Sage, *Leucophyllum frutescens*

The results for the carbon content show the sage with the greatest positive change in capturing carbon with an increase of more than 0.43 percent for the stems and leaves. Figure 15 demonstrates the change in the sage stems and leaves (S&L) and the effects of the decrease in emissions exposure after Sample 2 collection. The roots showed an increase of 5.23 percent.

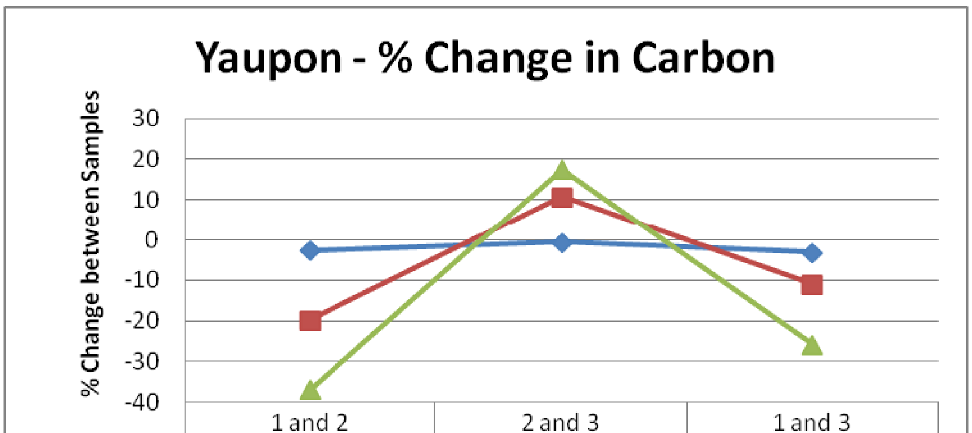
Dwarf Yaupon Holly, *Ilex vomitoria* 'Nana'

The soil carbon content for the yaupon showed the greatest increase between Samples 1 and 2 and the greatest decline after Sample 2 as shown in Figure 16. Even with as much leaf injury and loss suffered during the first week of exposure in the chamber, the stems and leaves seemed to remain fairly constant throughout the study with an overall reduction in carbon content of approximately 3 percent.



	1 and 2	2 and 3	1 and 3
S&L	-0.97	1.42	0.43
Roots	-6.86	12.98	5.23
Soil	-6.52	-8.53	-14.49

Figure 15. Percent Change in Sage Carbon Content.



	1 and 2	2 and 3	1 and 3
S&L	-2.52	-0.58	-3.08
Roots	-19.67	10.71	-10.99
Soil	-36.81	17.48	-25.77

Figure 16. Percent Change in Yaupon Carbon Content.

Elbon Rye Grass, *Secale cereale* 'Elbon'

The elbon rye grass, *Secale cereale* 'Elbon,' showed a decrease in the amount of carbon held in the stems and leaves of more than 3 percent. The soil showed a decrease of more than 6 percent (Figure 17).

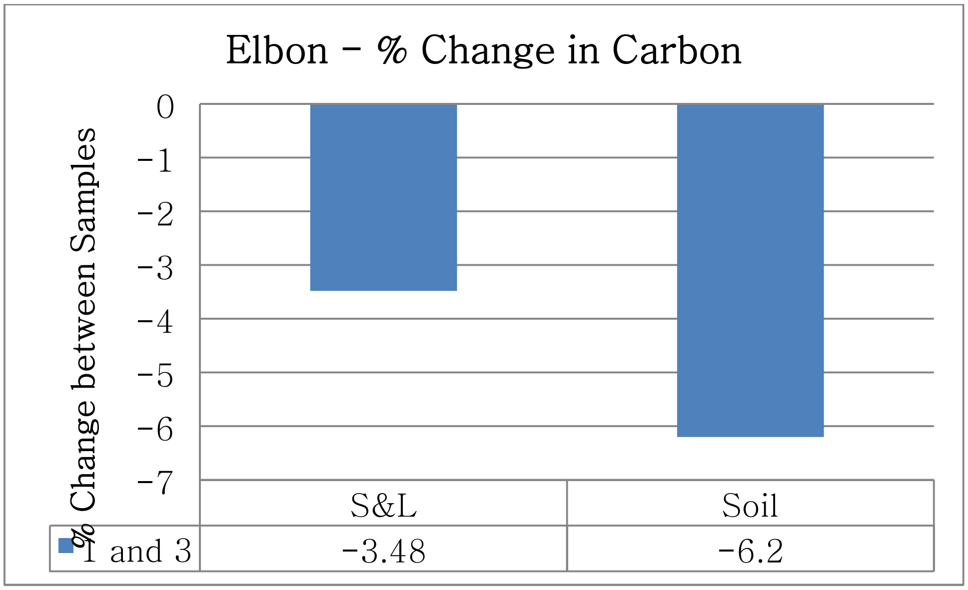


Figure 17. Percent Change in Elbon Carbon Content.

Bermudagrass, *Cynodon dactylon*

The only other plant resulting in increased carbon content was the soil of the bermudagrass, *Cynodon dactylon.* The soil from the bermuda samples showed an overall increase of more than 11 percent (Figure 18). The stems and leaves had a decrease of approximately 2.5 percent. This type of grass is commonly found on roadsides as part of seed mixtures used by the Texas Department of Transportation. However, annual cereal rye grasses such as elbon are not typically used by transportation agencies as permanent vegetative cover.

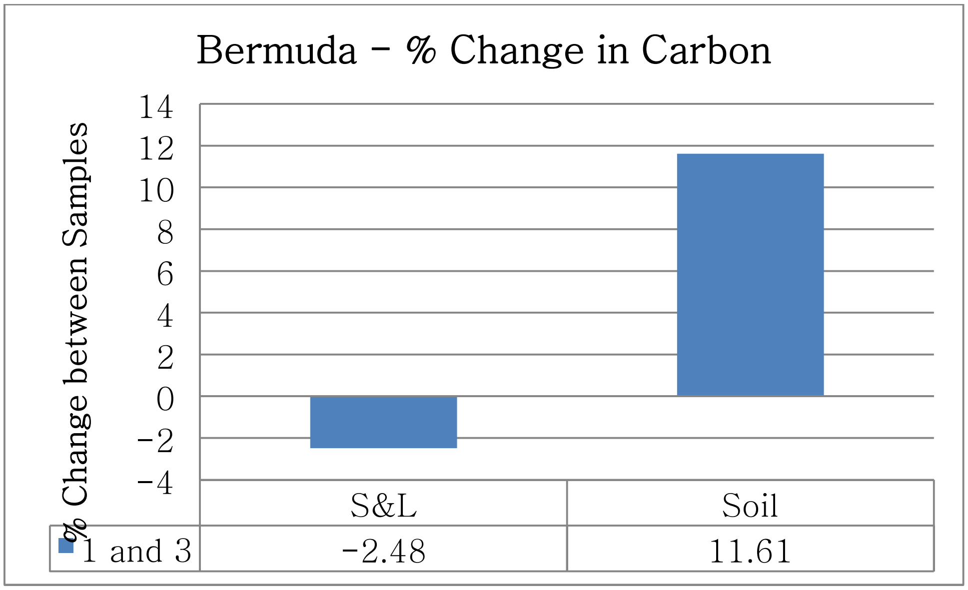


Figure 18. Percent Change in Bermuda Carbon Content.

Carbon Content Data Comparisons

The carbon content data for all of the samples collected are shown in Table 1. It is unfortunate that the plants suffered injury from exposure during the first week of testing. The increase between Sample 1 and Sample 2 shown by the sage stems and leaves demonstrated the plant's potential ability to sequester carbon. Even with damage to the plant, the sage stems' and leaves' carbon content continued to rise. One might presuppose from these data that a sustained lower emission level from the beginning of the study may have produced a greater rate of sequestration over time, not only for the sage but for all of the plants and soils used in this study.

From the data collected on carbon content for soil, the point of emission-level reduction only had a positive effect on the bermuda carbon content soil data. Surprisingly, the yaupon soil demonstrated the greatest negative impact of high exposure. The grasses in general performed better than the shrubs for soil sequestration. The sage plants had the only net positive for carbon content for samples from stems, leaves and roots.

Table 1. Data for Carbon Content from All Samples.

Changes in Percent Carbon						
Sample Type	Plant	Samples		% Change 1→2	% Change 2→3	% Change 1→3
Stems & Leaves	Yaupon	1	49.92	−2.52	−0.58	−3.08
		2	48.66			
		3	48.38			
	Sage	1	48.49	−0.97	1.42	0.43
		2	48.02			
		3	48.7			
	Bermuda	1	44.37	—	—	−2.48
		2	—*			
		3	43.27			
	Elbon	1	44.6	—	—	−3.48
		2	—			
		3	43.05			
Roots	Yaupon	1	47.13	−19.67	10.71	−10.99
		2	37.86			
		3	41.95			
	Sage	1	46.97	−6.86	12.98	5.23
		2	43.75			
		3	49.43			
Soil	Yaupon	1	1.63	−36.81	17.48	−25.77
		2	1.03			
		3	1.21			
	Sage	1	1.38	−6.52	−8.53	−14.49
		2	1.29			
		3	1.18			
	Bermuda	1	1.12	—	—	11.61
		2	—			
		3	1.25			
	Elbon	1	1.29	—	—	−6.2
		2	—			
		3	1.21			
*— indicates no samples were collected						

NITROGEN RESULTS

Similar patterns between samples demonstrated in carbon content were shown in the nitrogen samples with a reduction in emissions level in the EERF chamber. Changes in plant and soil performance were apparent in each of the four plants at this point in the study.

Texas Sage, *Leucophyllum frutescens*

Data for total nitrogen content showed an overall increase of almost 48 percent in the stems and leaves of the sage plants. Figure 19 shows the decline in nitrogen content of the sage roots with high emission exposure and the content increase when emission levels were decreased. In contrast to the carbon content samples, the nitrogen content in the soil had a steady increase the first week in the chamber and a decrease when emission levels were reduced.

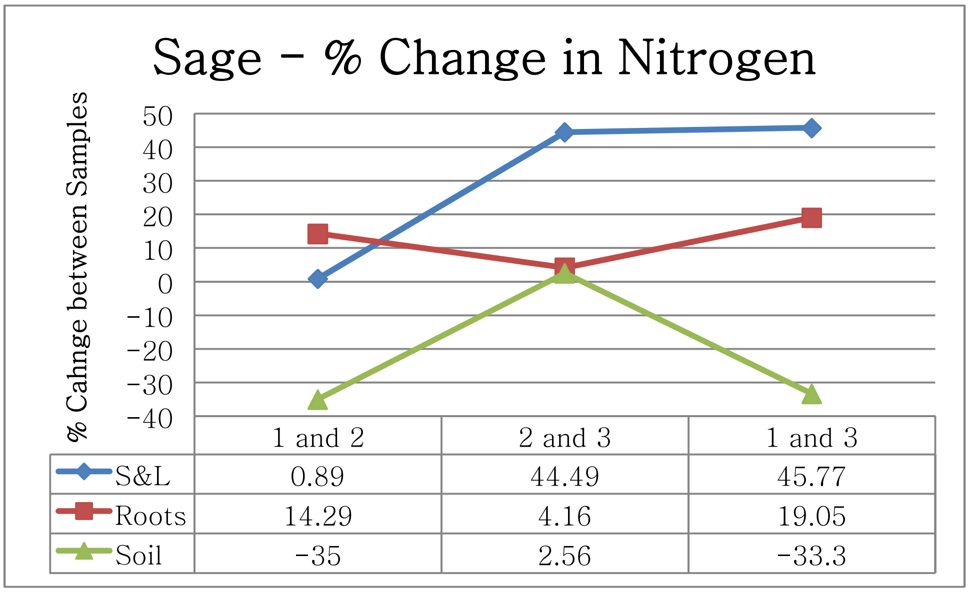


Figure 19. Nitrogen Content of Sage Samples.

Dwarf Yaupon Holly, *Ilex vomitoria* 'Nana'

The yaupon had the greatest increase between Sample 1 and Sample 2 with an increase of more than 130 percent and an overall increase of 77 percent. As with the carbon content samples, the change occurred as the emission level decreased. The nitrogen content of all samples decreased from Sample 2 collection.

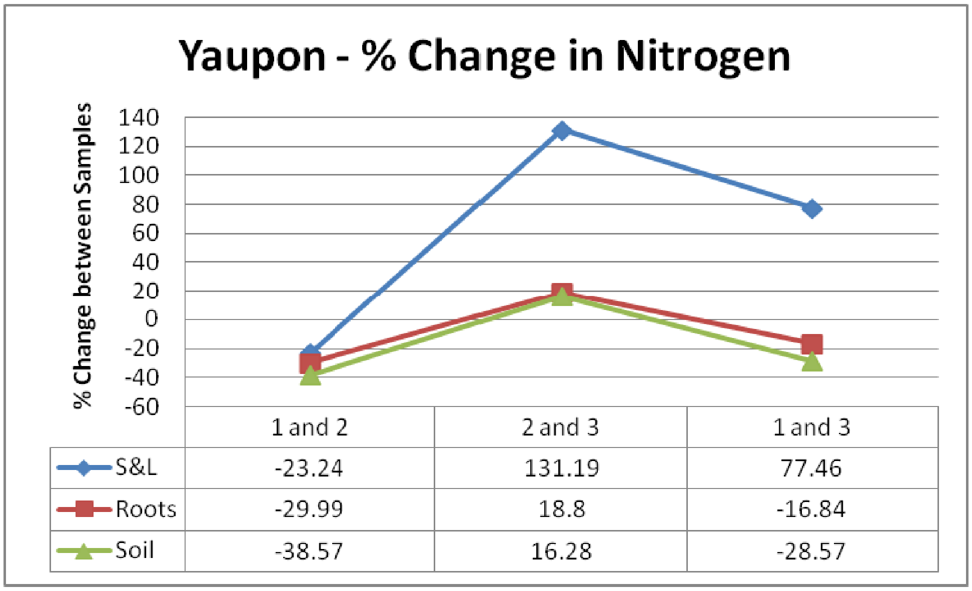


Figure 20. Nitrogen Content of Yaupon Samples.

Elbon Rye Grass, *Secale cereale* 'Elbon'

The elbon showed an increase in nitrogen content for stems, leaves and soil (Figure 21).

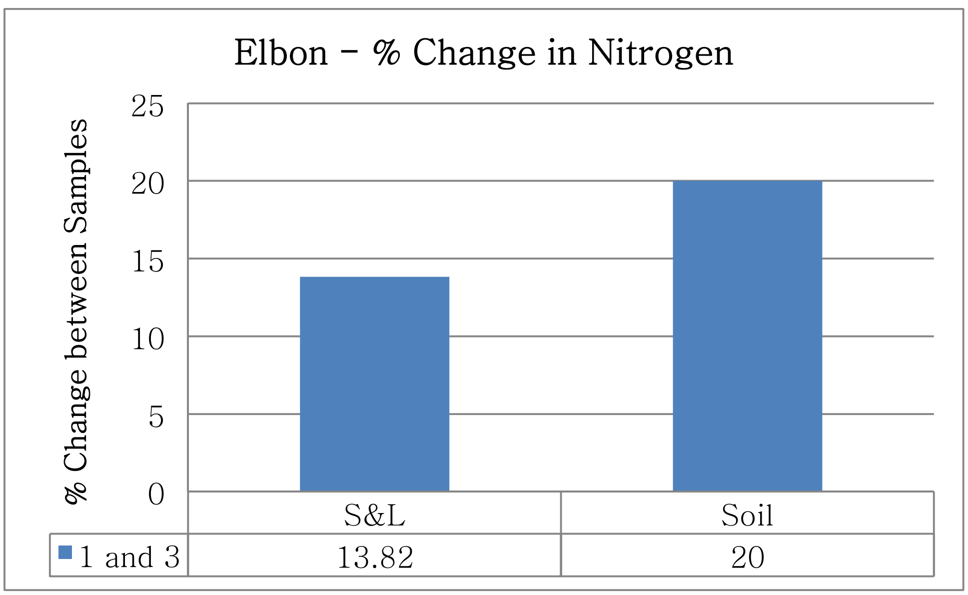


Figure 21. Nitrogen Content of Elbon Samples.

Bermudagrass, *Cynodon dactylon*

The bermuda showed an overall increase of approximately 55 percent for the stems and leaves. The soil had a decrease of 20 percent (Figure 22).

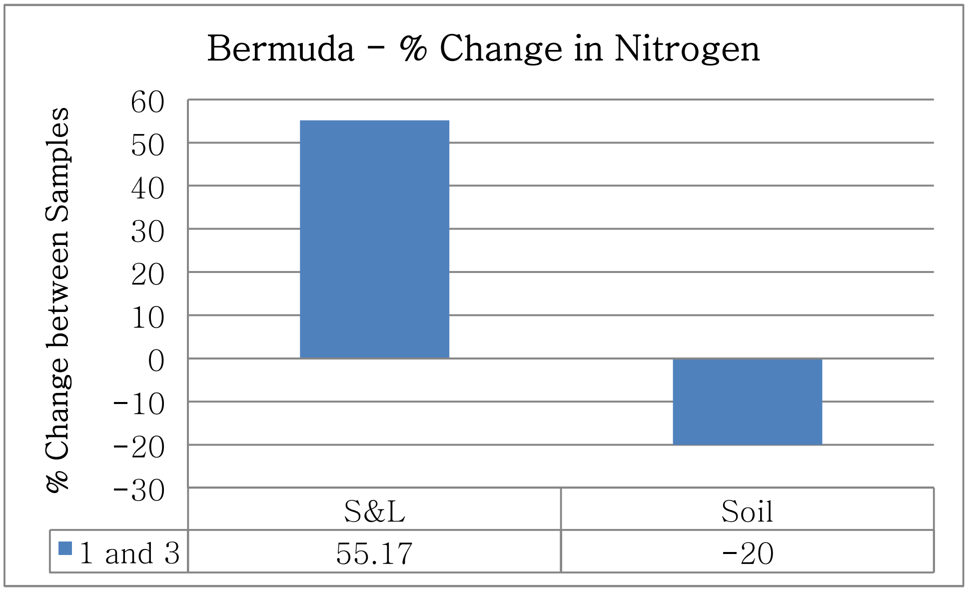


Figure 22. Nitrogen Content of Bermuda Samples.

The nitrogen content data for all of the samples collected are shown in Table 2. For the stems and leaves sampled, all plants showed increased nitrogen content by the end of the study. From the data collected on nitrogen content for soil, the elbon was the only sample that had an increase in nitrogen content over the duration of the study.

Table 2. Data for Nitrogen Content from All Samples.

Results for Percent Nitrogen						
Sample Type	Plant	Samples		% Change 1→2	% Change 2→3	% Change 1→3
Stems & Leaves	Yaupon	1	1.42	−23.24	131.19	77.46
		2	1.09			
		3	2.52			
	Sage	1	2.25	0.89	44.49	45.77
		2	2.27			
		3	3.28			
	Bermuda	1	1.45	—	—	55.17
		2	—*			
		3	2.25			
	Elbon	1	1.23	—	—	13.82
		2	—			
		3	1.4			
Roots	Yaupon	1	1.9	−29.99	18.8	−16.84
		2	1.33			
		3	1.58			
	Sage	1	1.05	14.29	4.16	19.05
		2	1.2			
		3	1.25			
Soil	Yaupon	1	0.07	−38.57	16.28	−28.57
		2	0.043			
		3	0.05			
	Sage	1	0.06	−35	2.56	−33.3
		2	0.039			
		3	0.04			
	Bermuda	1	0.05	—	—	−20
		2	—			
		3	0.04			
	Elbon	1	0.05	—	—	19.99
		2	—			
		3	0.06			
*— indicates no samples were collected						

CONCLUSIONS

SUMMARY OF FINDINGS

This study provides an assessment of the developed test protocol as an effective tool for quantifying plant and soil carbon sequestration capabilities using a full-scale, controlled laboratory environment. The plants and soil chosen for this research are typical of Texas roadsides and hardy for an urban environment:

- Dwarf yaupon holly (yaupon), *Ilex vomitoria* 'Nana.'
- Texas sage (sage), *Leucophyllum frutescens.*
- Elbon rye grass (elbon), *Secale cereale* 'Elbon.'
- Bermudagrass (bermuda), *Cynodon dactylon.*
- Sandy loam topsoil mixture from north Burleson County, Texas.

The study conducted experiments in the EERF chamber using the exhaust from a 2006 Freightliner heavy-duty truck as a source of emissions introduced to the plant materials and soil. The EERF had never been used for any research involving live plant materials and soil, and there were several unanswered questions going forward. The initial test protocol called for a vehicle run time of 20 minutes twice daily. The researchers were uncertain as to how much of the emissions the chamber would contain and what level of emissions exposure would get the desired results. Over the course of the testing, it became apparent that the protocol developed for this study required modification. Plant health became a major concern. After approximately one week of exposure to high concentrations of pollutants, the plant material showed signs of rapid decline. Each of the plant types and respective soils clearly demonstrated the effects of high concentrations of NO, NO_2 and CO. The emissions level was reduced to once daily for 20 minutes every other day.

Due to the plant injury that occurred over the course of testing, the sequestration capabilities of these plant materials and soils were inconclusive. A comparison of samples taken over the course of the study indicated that the desired results may have been accomplished had the initial exposure in the chamber been reduced to more moderate levels. The results of this study were also inconclusive for determining a relationship between carbon and nitrogen relative to the collected samples.

FUTURE RESEARCH

Future research recommendations are as follows:

- Investigate the effects different emission levels have on plant health to determine a level that represents an urban roadside environment and is suitable for prolonged exposure with minimal plant damage.
- Investigate different plant materials and soils to determine performance capabilities for maximizing carbon sequestration on roadside applications.

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