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## **Riparian Forest Carbon Offset Quantification: Summary of 2015 Results**

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### **INTRODUCTION**

One of the goals of the Watershed Protection Department (WPD)'s Riparian Zone Restoration (RZR) program is to increase urban riparian forest cover through the implementation of protected Grow Zones on public lands. The recovery of these previously mowed or otherwise degraded areas allows for increased carbon sequestration as woody trees and shrubs increase in size and areal coverage. Both passive and active management are used in Grow Zones to encourage the growth and establishment of native tree species.

Healthy riparian forests provide a variety of ecological functions (Simpson et al. 2013). Tree roots filter stormwater, removing its pollutants and improving water quality. Increased infiltration contributes to groundwater recharge thus slowing the peak flow of stormwater runoff into creeks and reducing streambank erosion and downstream flooding. Riparian forests also provide habitat and food for wildlife, and help mitigate the urban heat island effect by providing shade. Trees that shade the creek lower the evaporation rates and reduce water temperatures, providing more hospitable conditions for aquatic life. Additionally, trees play an important role in mediating climate change by capturing atmospheric carbon and storing it as organic carbon biomass.

The purpose of this study is to develop and test a repeatable methodology for quantifying increased carbon storage provided by restoration at RZR project sites. Although WPD's Riparian Functional Assessment method annually tracks vegetative succession and several other measures of ecological function (Duncan 2012; Duncan and Richter 2012), a protocol for quantifying the amount of carbon sequestration resulting from existing and newly established trees within Grow Zones is lacking. The U.S. Forest Service's Forest Inventory and Assessment (FIA) program has developed an extensive set of species-specific allometric equations that can be used to compute tree volume, biomass, and carbon mass by identifying each tree to species, measuring tree height and diameter, and estimating the amount of volume missing/rotten and (if dead) the decay class (Domke et al. 2011; Woodall et al. 2011; Harmon et al. 2013; O'Connell et al. 2014). The resulting carbon estimates will provide a baseline for the extent and condition of existing Grow Zone sequestration, in order to determine future carbon accrual beyond this baseline.

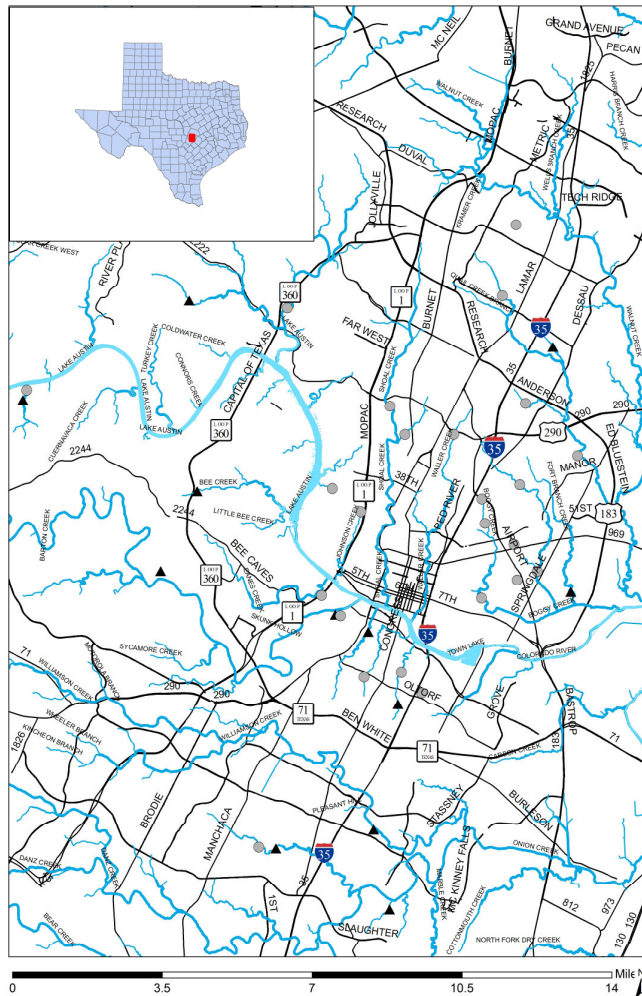
Project objectives include: 1) Develop a repeatable methodology appropriate for quantifying carbon stocks in standing trees of Austin's urban riparian forest systems. 2) Monitor and track the carbon sequestration occurring at WPD Grow Zone locations. 3) Develop a reliable measure of average carbon sequestration per unit area in order to extrapolate city-wide carbon stocks as a result of WPD Grow Zone locations.

Preliminary results following one year of data collection are presented, along with minor modifications of the sampling protocol for subsequent years.

## METHODS

Data collection for the initial phase of this project took place in November 2013 at 8 field sites, each with 4 plots. In autumn 2015, it was decided to streamline field efforts by combining Carbon Offset data collection with Riparian Functional Assessment (RFA) data collection, beginning in spring 2015.

RFA sites are classified as either reference sites, representing relatively undisturbed urban forest areas, or degraded sites, representing areas that have been highly altered by human activities such as mowing. This framework allows the reference sites to serve as a measure against which restoration progress in Grow Zones can be compared. As many degraded sites are Grow Zones, this study will also provide carbon sequestration data specific to these and other Riparian Zone Restoration (RZR) sites. Each year, RFA data are collected at all of the 12 RFA reference sites, and half of the RFA degraded sites (12 on even years and 12 on odd years, as of 2015). See **Figure 1** for a map of all RFA sites.



**Figure 1:** Map showing location of RFA degraded sites sampled in even and odd years (gray dots), and RFA reference sites (black triangles).

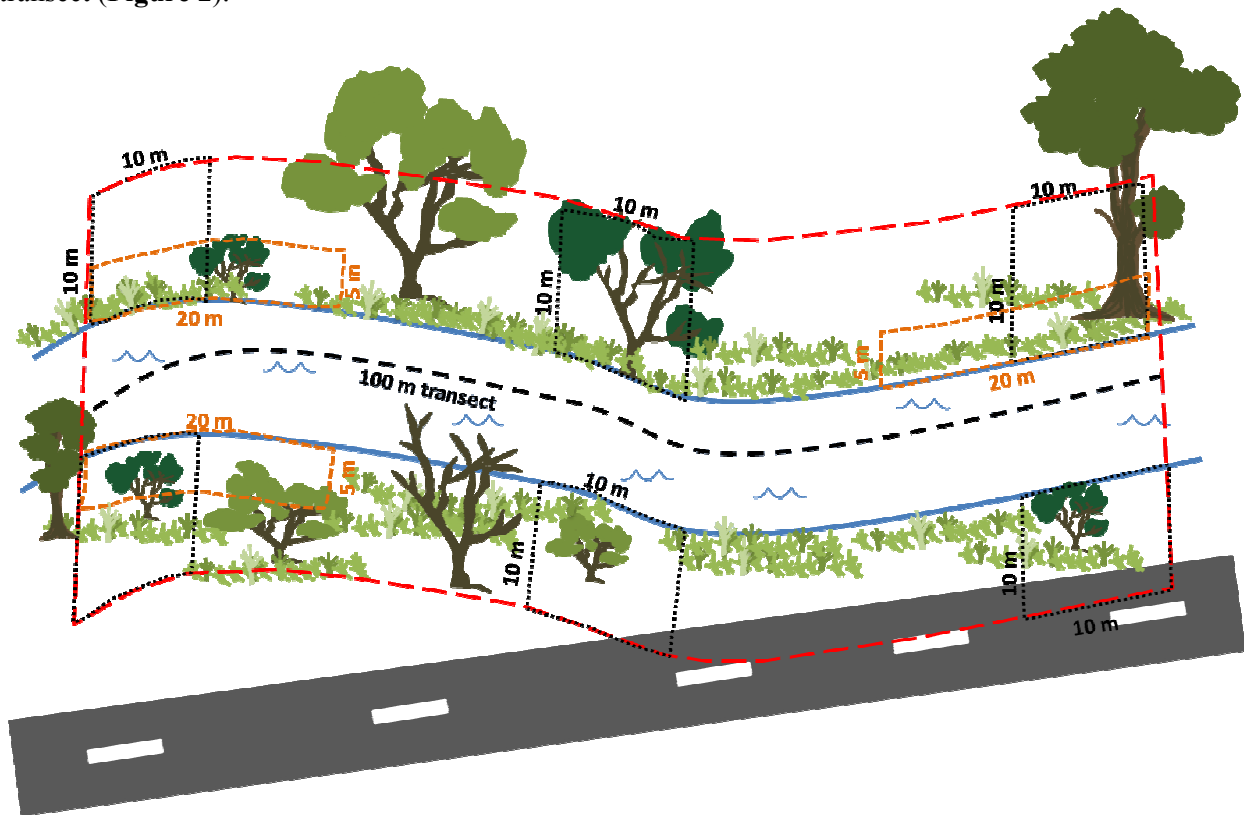
Carbon Offset (CO) data were collected from all 12 of the RFA reference sites in 2015, in order to establish a single, snapshot estimate of the amount and variation of carbon storage that restored sites might be expected to achieve. We also collected CO data in 2015 from the 12 odd-year RFA degraded sites (**Appendix 1**). Because it is possible for both reference and degraded conditions to exist within a single RFA site (for example, if some of the plots in a reference site get mowed), the vegetative condition was recorded at the individual CO plot level for this study. Additional CO sampling is planned in 2017 and 2019 for odd-year degraded sites, and in 2016, 2018, and 2020 for even-year degraded sites; this will provide estimates of how carbon storage in riparian forests changes over a 4-year period.

**Plot Design**

Each RFA site consists of a 100-m transect (parallel to the creek centerline), with a total of six 10m x 10m plots, laid out at 0m-10m, 45m-55m, and 90m-100m on both right and left banks, where “right bank (RB)” and “left bank (LB)” are designated by facing downstream.

At each RFA site, three CO plots were selected prior to fieldwork (generally 10m RB, 50m LB, and 90m LB), with adjustments as necessary if field conditions did not match all the plot criteria: 1) The riparian zone was at least 5 m (16.4 ft.) wide, 2) The plot did not contain significant artificial structures (bridges, concrete, etc.), and 3) The terrain was not too hazardous to work in (steep, etc.). All 2015 sites had at least three plots that fit these criteria.

The CO plot boundaries were oriented to start at bankfull, running 5 meters perpendicular and 20 meters parallel to the stream, thus extending from 0 m - 20 m, 40 m - 60 m, and/or 80 m – 100 m along the creek transect (**Figure 2**).



**Figure 2:** Example of three selected CO plots (dashed orange lines) located within the selected RFA sampling site (dotted red line). RFA sample plots are shown in black squares.

### ***Plot Sampling***

Within each 5m x 20m (100-m<sup>2</sup>, 0.02 acre) CO plot, live and standing dead trees were measured. Small shrubs and woody vines were not measured, since only tree species are currently proposed for carbon sequestration measurement. U.S. Forest Service’s Forest Inventory and Analysis (FIA) program does not define the difference between “tree” and “shrub” (U.S. Forest Service 2014); for our surveys we included all woody species whose mature height is 4.6 m (15 ft.) or greater (USDA NRCS 2014). We included only native species, since management plans often target non-native species for removal. See **Appendix 2** for a list of all native trees previously documented in RFA studies.

### ***Tree Measurements***

Tree measurements followed the standards established by the U.S. Forest Service’s Forest Inventory and Analysis (FIA) program (U.S. Forest Service 2014). All FIA equations for tree volume and biomass depend on the data being entered in U.S. customary units (inches and feet), rather than metric units (Woodall et al. 2011). Our field measurements were recorded in metric units, and then converted into U.S. customary units for computations. Biomass and carbon mass results in pounds were then converted to kilograms and metric tonnes for reporting. Forest carbon stocks are customarily reported in metric tonnes per hectare (International Panel on Climate Change 2006; U.S. Environmental Protection Agency 2012).

Many western North American woodland tree species have multiple stems and are very slow growing, thus the allometric growth formulas are very different for woodland species than for timber species (Woodall et al. 2011). In the Austin area, species designated as “woodland” (Woodall et al. 2011) include *Juniperus ashei* (Ashe juniper), *Acacia farnesiana* (sweet acacia), *Prosopis glandulosa* (honey mesquite), and *Condalia hookeri* (bluewood). All other non-woodland tree species are considered “timber” species (Domke et al. 2011). For timber species, each trunk is measured as a separate individual, whereas woodland multi-stemmed trees are measured as a single individual.

The method of measuring tree characteristics differs for timber versus woodland tree species. We only collected data from trees and large shrubs that meet the following minimum criteria:

<u>Species Type</u>	<u>Status</u>	<u>Height</u>	<u>Cumulative DBH</u>
Timber	Living	1.4 m (4.5 ft.)	2.5 cm (1 in.)
	Dead	1.4 m (4.5 ft.)	12.7 cm (5 in.) leaning < 45 degrees from vertical

<u>Species Type</u>	<u>Height</u>	<u>Diameter at 0.3 m height</u>
Woodland	Living/Dead	0.3 m (1 ft.) 2.5 cm (1 in.)

**Timber Species: Diameter at Breast Height (DBH) Measurement** - In the United States, DBH is defined as the average stem diameter, outside bark, at 1.4 m (4.5 ft.) above the ground on the high side of the tree. For consistent measurement, the diameter tape must be level and pulled taut. For trees with swellings, deformities, or branches that occur at 1.4 m (4.5 ft.) above the ground, the DBH is measured above the irregularity, where the normal stem shape ceases to be affected. DBH measurements for timber species with multiple trunks followed USFS 2014 protocol.

### **Woodland Species: Diameter at Root Collar (DRC) Measurement**

Many western woodland tree species, such as Ashe juniper and mesquite, have multiple stems and are very slow growing. Clumps of stems with a single crown and common above-ground root stock are measured as a single tree (U.S. Forest Service 2014). For these species, Diameter at Root Collar (DRC) is measured at the ground line or stem root collar, whichever is higher.

For a single-stemmed woodland tree, the DRC is equal to the single diameter measured, to the nearest centimeter. For a multi-stemmed woodland tree, DRC is computed as the square root of the sum of the squared stem diameters.

$$\text{DRC} = \text{SQRT} [\text{SUM} (\text{stem diameter}^2)]$$

Height Measurement - Total height for all measured trees was recorded to the nearest 0.1 m (4 in.). For shorter trees, total tree height was measured directly, with the use of a stadia telescoping rod or tape measure. For taller trees, we used a) range-finder or measuring tape to measure distance to tree, and clinometer to estimate the height as a percent of that distance, or b) visual estimates of tree height based on known-height metrics.

#### Tree Status

*Live:* Trees were considered alive if they had any living parts (leaves, buds, or cambium) at or above the diameter measurement (DBH or DRC) (U.S. Forest Service 2014).

*Dead:* To be counted as a standing dead tree (U.S. Forest Service 2014), dead timber trees were required to

- 1) have a diameter of at least 12.7 cm (5.0 in.),
- 2) have a bole of unbroken length of at least 1.4 m (4.5 ft.), and
- 3) lean less than 45 degrees from vertical.

For woodland species with multiple stems, a dead tree was considered standing as long as at least 1/3 of the volume is still attached or upright (not including cut or removed volume). For woodland species with single stems to qualify as a standing dead tree (U.S. Forest Service 2014), dead trees were required to

- 1) have a diameter of at least 12.7 cm (5.0 in.),
- 2) have an unbroken length of at least 0.3 m (1.0 ft.), and
- 3) lean less than 45 degrees from vertical.

Dead standing trees did not have to be self-supported. They may have been supported by other trees, branches, or their crown (U.S. Forest Service 2014).

#### Rotten and Missing Volume:

For live and dead trees  $\geq 12.7$  cm (5 in.) DBH or DRC, we recorded the percentage of rotten and missing volume on the merchantable bole/portion of the tree (from a 0.3 m (1 ft.) stump to a 10 cm (4 in.) diameter top) to the nearest 5 percent. For woodland species, the merchantable portion is between the point of DRC measurement to a 4 cm (1.5 in.) diameter top (U.S. Forest Service 2014).

For live saplings  $< 12.7$  cm (5 in.) DBH or DRC, we recorded the percent of rotten and missing whole-sapling volume, to the nearest 5 percent.

#### Decay Class:

For all standing dead trees, we used **Table 1** to categorize the tree by decay class.

**Table 1:** Standing woody debris decay class descriptions (U.S. Forest Service 2014).

Decay class stage (code)	Limbs and branches	Top	% Bark Remaining	Sapwood presence and condition *	Heartwood condition *
1	All present	Pointed	100	Intact; sound, incipient decay, hard, original color	Sound, hard, original color
2	Few limbs, no fine branches	May be broken	Variable	Sloughing; advanced decay, fibrous, firm to soft, light brown	Sound at base, incipient decay in outer edge of upper bole, hard, light to reddish brown
3	Limb stubs only	Broken	Variable	Sloughing; fibrous, soft, light to reddish brown	Incipient decay at base, advanced decay throughout upper bole, fibrous, hard to firm, reddish brown
4	Few or no stubs	Broken	Variable	Sloughing; cubical, soft, reddish to dark brown	Advanced decay at base, sloughing from upper bole, fibrous to cubical, soft, dark reddish brown
5	None	Broken	Less than 20	Gone	Sloughing, cubical, soft, dark brown, OR fibrous, very soft, dark reddish brown, encased in hardened shell

\* Characteristics are for Douglas-fir. Dead trees of other species may vary somewhat. Use this only as a guide.

### Calculations

Computations followed the standards established by the U.S. Forest Service's Forest Inventory and Analysis (FIA) program. For trees of timber species having DBH  $\geq 12.7$  cm (5 in.), FIA estimates tree biomass using the Component Ratio Method (Zhou and Hemstrom 2009; O'Connell et al. 2014).

### Analysis

The number of trees, number of species, and amount of carbon stored per 100 m<sup>2</sup> plot was compared between reference and degraded conditions through separate t-tests using Bayesian methods, in particular the MCMC procedure in SAS version 9.4. The number of trees and number of species are discrete counts and were modeled using a Poisson distribution, while the amount of carbon was modeled using a lognormal distribution. A lognormal distribution is described as a distribution which will lead to a normal distribution if the logarithm of the parameter is computed, and is a common distribution in environmental parameters. If a parameter is continuous with a positive distribution and a long tail, which fits the description of the carbon distribution, then a lognormal distribution can be used to fit the data and will lead to better parameter estimates when compared to a normal distribution (McGill et al. 2006). Results from all three analyses were taken from a MCMC run of 10,000 iterations following a burn-in period of 5,000 iterations. Uninformed priors with model parameters containing wide variances were used as assumptions when building the models.

Model output using the lognormal distribution contains log-transformed values, thus the back transformations of the mean and standard error for the amount of carbon stored per 100 m<sup>2</sup> were computed according to SAS 9.4's User's Guide formulas:

$$E[Y] = \exp \{ \mu \} \sqrt{\omega}$$

$$\text{Var}[Y]=\exp \{2\mu\} \omega(\omega-1)$$

$$\omega=\exp \{\sigma^2\}$$

Where  $\sigma$  is the standard error of the lognormal model,  $\mu$  is the mean of the lognormal model,  $E[Y]$  is the mean of the back transformed model, and the square root of  $\text{Var}[Y]$  is the standard error of the back transformed model. The 95% credible interval was also calculated for the number of trees, number of species, and amount of carbon stored per 100 m<sup>2</sup>.

## RESULTS

### Sampling Efforts:

Visits to the 24 sites for 2015 data collection took place on 13 days between March 18 and April 14. Site visits were combined with RFA data collection, in order to minimize the amount of travel time spent driving and hiking to the same sites and the associated carbon footprint of the studies.

The combined RFA & CO daily teams consisted of 4 people: 2 people to collect CO data and help collect RFA data if/when CO was complete; and 2 people to assist with laying out all RFA and CO plots and collect RFA data.

The mileage for the combined RFA&CO sampling routes was estimated using Google Maps (Google Inc. 2015) as a total of 207.3 miles. Fieldwork was primarily conducted in the 2015 Chevy Equinox AWD, which gets an estimated 17 miles per gallon using E85 fuel (U.S. Department of Energy 2015a). This gives an estimate of 12.2 gallons of E85 fuel for the combined RFA and CO studies. This value was entered in the Flex Fuel Cost Calculator (U.S. Department of Energy 2015b) to give an estimate of 152 lbs. (68 kg) of CO<sub>2</sub> emissions for the combined studies; half can thus be attributed to the Carbon Offset study this year. Future years of this study will only collect CO data from degraded sites (not reference), thus future emissions assigned to the CO study will be lower in those years.

There was no simple way to separately keep track of the proportion of field time spent exclusively on collecting CO data because time-consuming data on soil parameters were collected at some, but not all, of the RFA sites.

### Technique Refinements:

The method of measuring height was the component that took the most time, especially at the beginning of the study. We discarded the idea of using a stadia rod after the first day, due to the difficulty of erecting the staff into thick tree canopy and dragging a long pole from tree to tree. The clinometer + digital range finder and clinometer + tape measure methods both had their drawbacks. The rangefinder was unable to be used when there was vegetation between the observer and the target tree trunk – this occurred frequently. The tape measure was sometimes difficult to deploy in a straight line across intervening terrain and vegetation.

Visual estimation proved to be the most rapid method to estimate tree height. The observer stood at a distance away from the tree, and used the second person's height as a yardstick against which to estimate the overall height of the tree. The results of this method were checked upon multiple instances against estimates by several observers, clinometer + tape, and clinometer + rangefinder, and were found to be comparable and consistent.

As seen in highlighted cells of **Appendix 1**, the *a priori* expectations of vegetative condition of plots did not always match *in situ* conditions. Two of the RFA sites that were otherwise reference condition had some CO plots that had been either mowed or thinned. One of the sites classified for RFA as degraded

was only degraded condition on one of the two banks. We maintained our original *a priori* plot selection scheme, rather than adjusting for actual field conditions (however, see Discussion section).

#### Data Analysis:

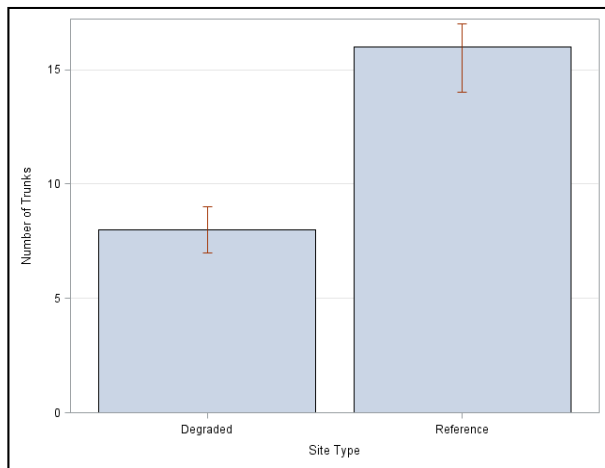
Overall at the 24 sites, we collected CO data for 769 trees. One degraded site had no trees large enough to sample within any of the 3 plots. We planned to sample 3 plots each at 12 degraded and 12 reference sites for a total of 36 degraded and 36 reference plots; however, actual plot conditions (e.g. initially categorized as reference but with evidence of mowing) resulted in sampling of 37 degraded and 35 reference CO plots (**Appendix 1**).

#### *Number of trees per plot*

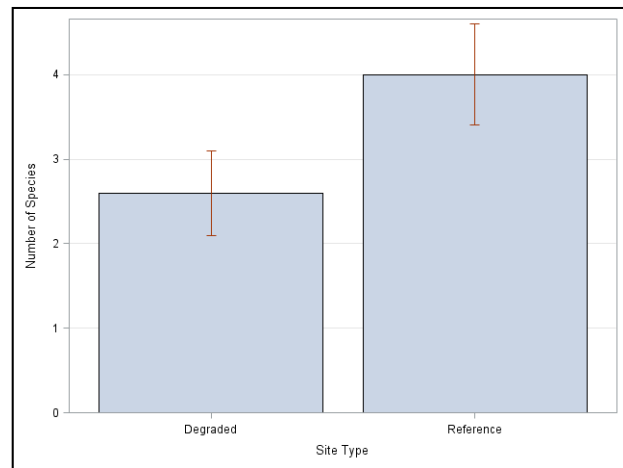
The 35 reference plots had 573 trees, compared to 196 trees in the 37 degraded plots. Dead trees constituted 27/573 (4.7%) of all trees in reference plots, and 7/196 (3.6%) of all trees in degraded plots. The median number of trees per plot was 3 trees in degraded and 12 trees in reference plots. The model estimate of the mean (and 95% Credible Interval) number of trees per plot was 7.67 (6.71 - 8.66) for degraded and 15.68 (14.43 - 16.97) for reference plots (**Figure 3**). Based on the t-test using Bayesian methods, there is a 1.0 probability that the mean number of trees is higher in reference sites than degraded.

#### *Number of species per plot*

The model estimate of the mean (and 95% CI) number of species per plot was 2.56 (2.08 - 3.06) for degraded and 4.00 (3.40 - 4.63) for reference plots (**Figure 4**). Based on the t-test using Bayesian methods, there is a 1.0 probability that the mean number of species is higher in reference sites than degraded.



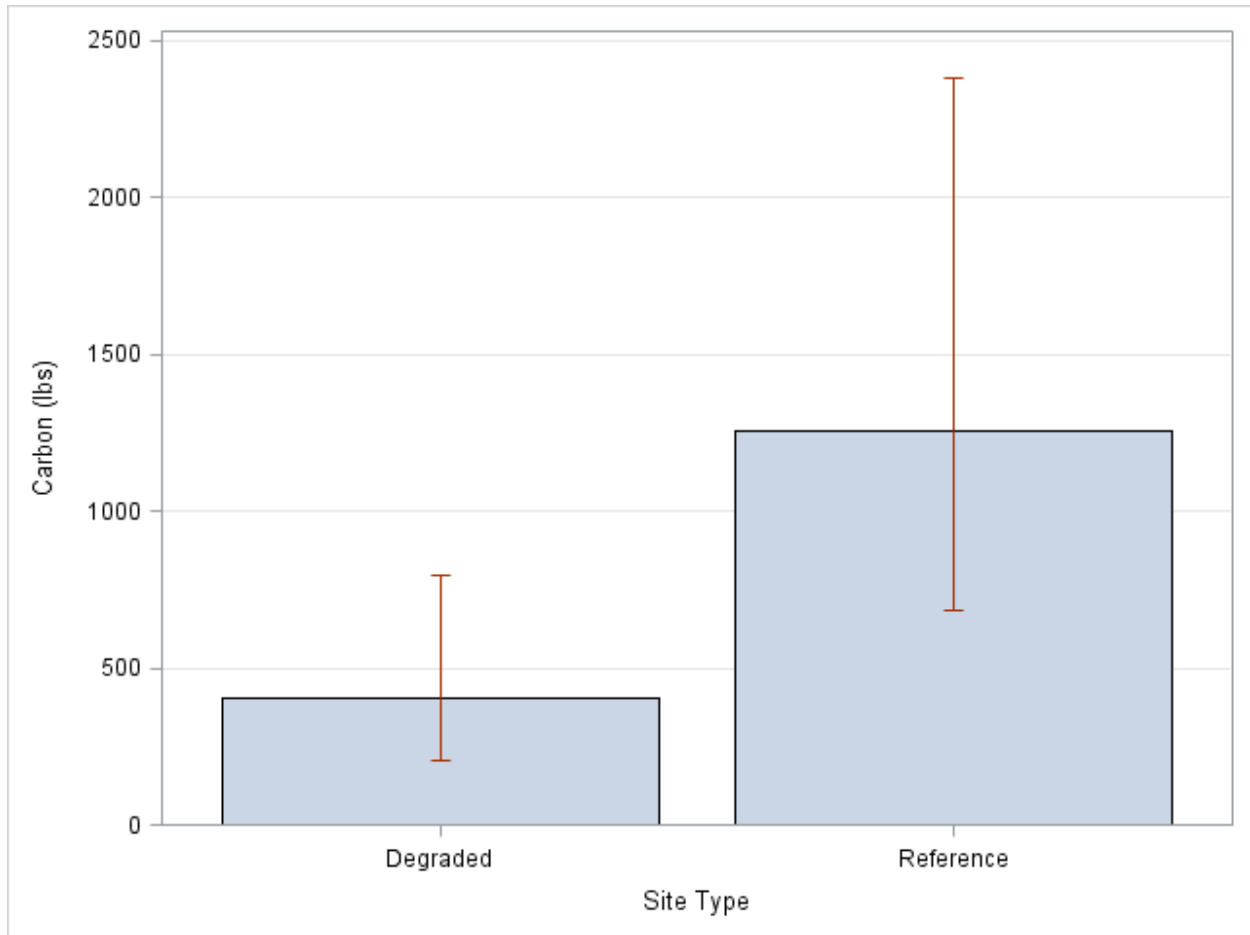
**Figure 3:** Mean number of native trees and shrub individuals per 100 m<sup>2</sup> in degraded and reference plots. Bars indicate 95% Credible Intervals.



**Figure 4:** Mean number of native tree and shrub species per 100 m<sup>2</sup> in degraded and reference plots. Bars indicate Bayesian 95% Credible Intervals.

#### *Mass of carbon per plot*

The model estimate of the mean (and 95% CI) carbon mass per plot was 402.19 (205.47 - 794.97) lbs. for degraded and 1254.55 (684.46 - 2384.27) lbs. for reference plots (**Figure 5**). As it is customary to report carbon mass in metric tonnes of carbon per hectare, these results were converted. Degraded sites had an estimated mean 18.24 tC/ha (9.32 - 36.06), while reference sites had an estimated mean 56.91 tC/ha (31.05 - 108.15). Based on the t-test using Bayesian methods, there is a 0.9922 probability that the mean carbon mass stored in reference plots is higher than in degraded plots.



**Figure 5:** Mean lbs. of carbon stored by native trees and shrubs per 100 m<sup>2</sup> in degraded and reference plots. Bars indicate Bayesian 95% Credible Intervals.

## DISCUSSION

### *Summary of Sampling Results*

Compared to degraded sites, reference sites had approximately twice as many trees, one and a half times more species, and over three times more carbon mass.

Our calculation of reference sites sequestering 56.91 (31.05 – 108.15) tC/ha is near the estimate of 48.7 tC/ha for average storage of carbon by trees in Texas (Birdsey 1992).

Our surveys included only carbon sequestered in forest tree biomass; it does not include other carbon pools (down woody debris, forest floor, understory biomass, and soil).

Reforestation in Grow Zones (“degraded” sites) is a result of both passive and active management to promote the succession of native woody tree and shrub species. Passive management relies on natural recruitment, and is a relatively slow process, whereas active management activities include seedling planting, and the removal of nonnative species. Because new seedlings require some time to become established and begin putting on substantial biomass, the process of sequestering carbon is a slow one, with substantial accumulation of carbon occurring at a forest age of 10-50 years (Zhang et al. 2012). Carbon storage increases considerably with forest age (time since disturbance) (Birdsey et al. 2006).

The 2015 sampling of reference and odd-year degraded sites, when combined with the 2016 sampling of odd-year degraded sites, will constitute a baseline assessment of carbon stocks for the studied areas. This will allow future evaluations of how management activities are affecting carbon sequestration in the degraded sites. Grow Zones, most of them in the initial stages of forest succession, have the potential to sequester about three times more carbon than they currently store thus supporting the City of Austin goals to reduce our carbon footprint.

#### *Protocol Changes for Subsequent Years*

In general, tree heights will be estimated visually. At the beginning of the CO fieldwork, each observer will practice visually estimating tree heights in an area free of obstructions, so that assessments can be calibrated against stadia rod, clinometer and tape measure, and/or clinometer and rangefinder results.

All subsequent years' sampling will take place in degraded vegetative condition plots. When choosing plots for sampling, if an *a priori* selected CO plot actually has reference conditions, a different plot will be chosen (if available).

## **REFERENCES**

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Birdsey R. 1992. Carbon storage and accumulation in United States forest ecosystems. Gen. Tech. Rep. WO-59, U.S. Dep. Agric. For. Serv. Washingt. Off.:51.

Birdsey R, Pregitzer K, Lucier A. 2006. Forest Carbon Management in the United States. J. Environ. Qual. 35:1461–1469.

Domke GM, Woodall CW, Smith JE. 2011. Accounting for density reduction and structural loss in standing dead trees: Implications for forest biomass and carbon stock estimates in the United States. Carbon Balance Manag. 6:14. [accessed 2014 Dec 1].  
<http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3283479&tool=pmcentrez&rendertype=abstract>

Duncan A. 2012. A functional approach to riparian restoration. SR-12-05. Austin (TX): City of Austin, Watershed Protection Department (Short Report).

Duncan A, Richter A. 2012. Sapling survival assessment: prioritizing native tree species to use in riparian zone restoration in the city of Austin, Texas. SR-12-11. Austin (TX): City of Austin, Watershed Protection Department (Short Report).

Google Inc. 2015. Google Maps. [accessed 2015 Aug 10]. <https://www.google.com/maps/>

Harmon ME, Fasth B, Woodall CW, Sexton J. 2013. Carbon concentration of standing and downed woody detritus: Effects of tree taxa, decay class, position, and tissue type. For. Ecol. Manage. 291:259–267. [accessed 2014 Dec 15]. <http://linkinghub.elsevier.com/retrieve/pii/S0378112712007220>

International Panel on Climate Change. 2006. Chapter 4 forest land 2006. In: IPCC Guidelines for National Greenhouse Gas Inventories. International Panel on Climate Change. p. 4.1–4.83.

McGill BJ, Mayr BA, Weiser MD. 2006. Empirical evaluation of neutral theory. Ecology 87:1411–1423.

O'Connell BM, LaPoint EB, Turner JA, Ridley T, Pugh SA, Wilson AM, Waddell KL, Conkling BL. 2014. The Forest Inventory and Analysis Database: Database Description and User Guide for Phase 2 (version 6.0.1). U.S. Department of Agriculture, Forest Service.

Simpson H, Taylor III E, Li Y, Barber B. 2013. Texas Statewide Assessment of Forest Ecosystem Services: A Comprehensive Analysis of the Regulating and Cultural Services Provided by Texas Forests. College Station (TX): Texas A&M Forest Service.

U.S. Department of Energy. 2015a. Fuel economy of 2015 Chevrolet vehicles. Fuel Econ. Guid. [accessed 2015 Aug 10]. <http://www.fueleconomy.gov/feg/bymake/Chevrolet2015.shtml>

U.S. Department of Energy. 2015b. Ethanol Vehicle Emissions. Altern. Fuels Data Cent. [accessed 2015 Aug 11]. [http://www.afdc.energy.gov/vehicles/flexible\\_fuel\\_emissions.html](http://www.afdc.energy.gov/vehicles/flexible_fuel_emissions.html)

U.S. Environmental Protection Agency. 2012. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2010. Washington, D.C.: U.S. Environmental Protection Agency.

U.S. Forest Service. 2014. Forest Inventory and Analysis National Core Field Guide: Volume 1: Field Data Collection Procedures for Phase 2 Plots. U.S. Forest Service.

USDA NRCS. 2014. The PLANTS Database. The Plants Database.

Woodall CW, Heath LS, Domke GM, Nichols MC. 2011. Methods and Equations for Estimating Aboveground Volume, Biomass, and Carbon for Trees in the U. S. Forest Inventory , 2010. General Te. U.S. Department of Agriculture, Forest Service, Northern Research Station.

Zhang F, Chen JM, Pan Y, Birdsey R a., Shen S, Ju W, He L. 2012. Attributing carbon changes in conterminous U.S. forests to disturbance and non-disturbance factors from 1901 to 2010. J. Geophys. Res. Biogeosciences 117:1–18.

Zhou X, Hemstrom MA. 2009. Estimating Aboveground Tree Biomass on Forest Land in the Pacific Northwest: A Comparison of Approaches. Research P. Portland, Oregon: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

**APPENDIX 1:** Carbon Offset plots sampled in 2015. The Plot Vegetative Condition column identifies the condition as found during field work. Plots that were identified *a priori* with a different expected condition (reference or degraded) to the one actually found during field work are color coded.

<b>FSDB Site</b>	<b>Plot Name</b>	<b>Plot Vegetative Condition</b>	<b>Drainage Area Range</b>	<b>Years</b>
11149	Barton @ Key West from Cape Coral(10mRB)	Reference	0-64	2015 only
11152	Barton @ Key West from Cape Coral(50mLB)	Reference	0-64	2015 only
11153	Barton @ Key West from Cape Coral(90mRB)	Reference	0-64	2015 only
11180	Barton Creek Ephemeral 3(10mLB)	Reference	0-64	2015 only
11182	Barton Creek Ephemeral 3(50mLB)	Reference	0-64	2015 only
11183	Barton Creek Ephemeral 3(90mRB)	Reference	0-64	2015 only
11168	Barton Creek Trib @ Lund and Robert E. Lee(10mLB)	Degraded	0-64	odd
11170	Barton Creek Trib @ Lund and Robert E. Lee(50mLB)	Degraded	0-64	odd
11171	Barton Creek Trib @ Lund and Robert E. Lee(90mRB)	Degraded	0-64	odd
11221	Bee Creek DS Loop 360(10mRB)	Reference	65-320	2015 only
11224	Bee Creek DS Loop 360(50mLB)	Reference	65-320	2015 only
11226	Bee Creek DS Loop 360(90mLB)	Reference	65-320	2015 only
11286	Blunn Creek @ Rosedale(10mLB)	Degraded	321-640	odd
11288	Blunn Creek @ Rosedale(50mLB)	Degraded	321-640	odd
11289	Blunn Creek @ Rosedale(90mRB)	Degraded	321-640	odd
11279	Blunn Creek US of Cow Trough Spring(10mRB)	Reference	65-320	2015 only
11282	Blunn Creek US of Cow Trough Spring(50mLB)	Reference	65-320	2015 only
11284	Blunn Creek US of Cow Trough Spring(90mLB)	Reference	65-320	2015 only
11267	Boggy @ Willowbrook Huisache Crossing(10mRB)	Degraded	65-320	odd
11269	Boggy @ Willowbrook Huisache Crossing(50mRB)	Degraded	65-320	odd
11272	Boggy @ Willowbrook Huisache Crossing(90mLB)	Degraded	65-320	odd
11186	Boggy Creek @ 10th St(10mLB)	Degraded	641-1280	odd
11188	Boggy Creek @ 10th St(50mLB)	Degraded	641-1280	odd
11190	Boggy Creek @ 10th St(90mLB)	Degraded	641-1280	odd
11197	Boggy Creek @ Airport(10mRB)	Degraded	65-320	odd
11199	Boggy Creek @ Airport(50mRB)	Degraded	65-320	odd
11200	Boggy Creek @ Airport(50mLB)	Degraded	65-320	odd
11209	Bull Creek @ Bull District Park (Lakewood Dr)(10mRB)	Degraded	641-1280	odd
11212	Bull Creek @ Bull District Park (Lakewood Dr)(50mLB)	Degraded	641-1280	odd
11211	Bull Creek @ Bull District Park (Lakewood Dr)(50mRB)	Degraded	641-1280	odd
11227	Commons Ford Trib US Bridge @ Commons Ford Ranch(10mRB)	Reference	641-1280	2015 only
11230	Commons Ford Trib US Bridge @ Commons Ford Ranch(50mLB)	Reference	641-1280	2015 only
11229	Commons Ford Trib US Bridge @ Commons Ford Ranch(50mRB)	Reference	641-1280	2015 only
11174	Eanes @ Zilker Disc Golf(10mLB)	Degraded	0-64	odd

<b>FSDB Site</b>	<b>Plot Name</b>	<b>Plot Vegetative Condition</b>	<b>Drainage Area Range</b>	<b>Years</b>
11176	Eanes @ Zilker Disc Golf(50mLB)	Degraded	0-64	odd
11177	Eanes @ Zilker Disc Golf(90mRB)	Degraded	0-64	odd
11192	Fort Branch @ Tura Lane LISI 1(10mLB)	Reference	641-1280	2015 only
11191	Fort Branch @ Tura Lane LISI 1(10mRB)	Reference	641-1280	2015 only
11195	Fort Branch @ Tura Lane LISI 1(90mRB)	Reference	641-1280	2015 only
11257	Johnson Creek in Tarrytown Park(10mRB)	Degraded	65-320	odd
11260	Johnson Creek in Tarrytown Park(50mLB)	Degraded	65-320	odd
11259	Johnson Creek in Tarrytown Park(50mRB)	Degraded	65-320	odd
11203	Little Walnut Creek @ Dottie Jordan Park(10mRB)	Degraded	641-1280	odd
11206	Little Walnut Creek @ Dottie Jordan Park(50mLB)	Degraded	641-1280	odd
11207	Little Walnut Creek @ Dottie Jordan Park(90mRB)	Degraded	641-1280	odd
11155	Little Walnut Creek Upstream of Mearns Meadow(10mRB)	Degraded	321-640	odd
11157	Little Walnut Creek Upstream of Mearns Meadow(50mRB)	Degraded	321-640	odd
11159	Little Walnut Creek Upstream of Mearns Meadow(90mRB)	Degraded	321-640	odd
11161	Little Walnut Trib @ Gus Garcia Park(10mRB)	Reference	321-640	2015 only
11164	Little Walnut Trib @ Gus Garcia Park(50mLB)	Reference	321-640	2015 only
11165	Little Walnut Trib @ Gus Garcia Park(90mRB)	Reference	321-640	2015 only
11261	Oak Springs Trib Downstream of Tillery Street(10mRB)	Degraded	0-64	odd
11263	Oak Springs Trib Downstream of Tillery Street(50mRB)	Degraded	0-64	odd
11266	Oak Springs Trib Downstream of Tillery Street(90mLB)	Degraded	0-64	odd
11240	Onion Creek @ Nuckols and Thaxton(10mLB)	Reference	65-320	2015 only
11241	Onion Creek @ Nuckols and Thaxton(50mRB)	Reference	65-320	2015 only
11244	Onion Creek @ Nuckols and Thaxton(90mLB)	Reference	65-320	2015 only
11246	South Boggy @ Dittmar Park near Strickland(10mLB)	Degraded	321-640	odd
11248	South Boggy @ Dittmar Park near Strickland(50m LB)	Degraded	321-640	odd
11249	South Boggy @ Dittmar Park near Strickland(90mRB)	Reference	321-640	odd
11252	South Boggy near Latteridge Almondsbury(10mLB)	Reference	321-640	2015 only
11251	South Boggy near Latteridge Almondsbury(10mRB)	Reference	321-640	2015 only
11256	South Boggy near Latteridge Almondsbury(90mLB)	Degraded	321-640	2015 only
11273	West Bouldin Creek in West Bouldin (10mRB)	Reference	641-1280	2015 only
11276	West Bouldin Creek in West Bouldin (50mLB)	Reference	641-1280	2015 only
11275	West Bouldin Creek in West Bouldin (50mRB)	Reference	641-1280	2015 only
11216	West Bull @ Long Canyon and Standing Rock(10mLB)	Reference	321-640	2015 only
11217	West Bull @ Long Canyon and Standing Rock(50mRB)	Reference	321-640	2015 only
11220	West Bull @ Long Canyon and Standing Rock(90mLB)	Degraded	321-640	2015 only
11233	Williamson Creek @ Wagon Bed Trl(10mRB)	Reference	0-64	2015 only
11235	Williamson Creek @ Wagon Bed Trl(50mRB)	Reference	0-64	2015 only
11238	Williamson Creek @ Wagon Bed Trl(90mLB)	Reference	0-64	2015 only

**APPENDIX 2:** Central Texas trees and tall shrubs previously documented in Riparian Functional Assessment study plots.

Family	COMMON NAME	GENUS	SPECIES	USDA Code	FSDB #	Mature Height (ft)	Texas native
Fabaceae	sweet acacia	<i>Acacia</i>	<i>farnesiana</i>	ACFA	6564	20	native
Fabaceae	catclaw acacia	<i>Acacia</i>	<i>greggii</i>	ACGR	6637	20	native
Aceraceae	boxelder	<i>Acer</i>	<i>negundo</i>	ACNE2	5903	60	native
Hippocastanaceae	Texas buckeye	<i>Aesculus</i>	<i>glabra</i>	AEGLA	6647	25	native
Hippocastanaceae	red buckeye	<i>Aesculus</i>	<i>pavia</i>	AEPAP	6631	40	native
Fabaceae	false indigo bush	<i>Amorpha</i>	<i>fruticosa</i>	AMFR	5893	15	native
Juglandaceae	pecan	<i>Carya</i>	<i>illinoensis</i>	CAIL2	5945	120	native
Juglandaceae	black hickory	<i>Carya</i>	<i>texana</i>	CATE9		40	native
Bignoniaceae	southern catalpa	<i>Catalpa</i>	<i>bignonioides</i>	CABI8		66	native
Ulmaceae	sugarberry	<i>Celtis</i>	<i>laevigata</i>	CELA	5952	80	native
Ulmaceae	hackberry	<i>Celtis</i>	<i>occidentalis</i>	CEOC	6621	60	native
Rubiaceae	common buttonbush	<i>Cephalanthus</i>	<i>occidentalis</i>	CEOC2	5955	15	native
Fabaceae	eastern redbud	<i>Cercis</i>	<i>canadensis</i>	CECAT	6636	20	native
Bignoniaceae	desert willow	<i>Chilopsis</i>	<i>linearis</i>	CHLI2		25	native
Rhamnaceae	Bluewood	<i>Condalia</i>	<i>hookeri</i>	COHO	6653	30	native
Cornaceae	roughleaf dogwood	<i>Cornus</i>	<i>drummondii</i>	CODR	5972	20	native
Anacardiaceae	smoketree	<i>Cotinus</i>	<i>obovatus</i>	COOB2		30	native
Ebenaceae	Texas persimmon	<i>Diospyros</i>	<i>texana</i>	DITE3	5993	15	native
Boraginaceae	Anacua knockaway	<i>Ehretia</i>	<i>anacua</i>	EHAN		45	native
Oleaceae	stretchberry	<i>Forestiera</i>	<i>pubescens</i>	FOPU2	6020	15	native
Rhamnaceae	Carolina buckthorn	<i>Frangula</i>	<i>caroliniana</i>	FRCA13	6119	20	native
Oleaceae	Texas ash	<i>Fraxinus</i>	<i>albicans</i>	FRAL3	6024	45	native
Oleaceae	green ash	<i>Fraxinus</i>	<i>pennsylvanica</i>	FRPE	6023	80	native
Garryaceae	Lindheimer's silktassel	<i>Garrya</i>	<i>ovata</i>	GAOVL	6228	18	native
Leguminosae	honeylocust	<i>Gleditsia</i>	<i>triacanthos</i>	GLTR	6030	70	native
Aquifoliaceae	possumhaw	<i>Ilex</i>	<i>decidua</i>	ILDE	5894	33	native
Aquifoliaceae	yaupon	<i>Ilex</i>	<i>vomitorea</i>	ILVO	6034	25	native
Juglandaceae	black walnut	<i>Juglans</i>	<i>nigra</i>	JUNI	6038	100	native
Cupressaceae	Ashe juniper	<i>Juniperus</i>	<i>ashei</i>	JUAS	6040	30	native
Cupressaceae	eastern redcedar	<i>Juniperus</i>	<i>virginiana</i>	JUVI	6042	40	native
Fabaceae	littleleaf leadtree	<i>Leucaena</i>	<i>retusa</i>	LERE3	6051	25	native
Moraceae	Osage-orange	<i>Maclura</i>	<i>pomifera</i>	MAPO	6056	35	native
Moraceae	red mulberry	<i>Morus</i>	<i>rubra</i>	MORU2	6064	70	native

<b>Family</b>	<b>COMMON_NAME</b>	<b>GENUS</b>	<b>SPECIES</b>	<b>USDA Code</b>	<b>FSDB #</b>	<b>Mature Height (ft)</b>	<b>Texas native</b>
Fabaceae	Jerusalem thorn	<i>Parkinsonia</i>	<i>aculeata</i>	PAAC3	6652	15	native
Platanaceae	American sycamore	<i>Platanus</i>	<i>occidentalis</i>	PLOC	6087	100	native
Salicaceae	eastern cottonwood	<i>Populus</i>	<i>deltoides</i>	PODE3	6093	190	native
Leguminosae	honey mesquite	<i>Prosopis</i>	<i>glandulosa</i>	PRGL2	6096	30	native
Rosaceae	Carolina laurelcherry	<i>Prunus</i>	<i>caroliniana</i>	PRCA	6632	36	native
Rosaceae	Mexican plum	<i>Prunus</i>	<i>mexicana</i>	PRME	6100	35	native
Rosaceae	black cherry	<i>Prunus</i>	<i>serotina</i>	PRSE2	6101	80	native
Rosaceae	chokecherry	<i>Prunus</i>	<i>virginiana</i>	PRVI		25	native
Rutaceae	common hoptree	<i>Ptelea</i>	<i>trifoliata</i>	PTTR	6103	25	native
Fagaceae	Buckley oak	<i>Quercus</i>	<i>buckleyi</i>	QUBU2	6106	50	native
Fagaceae	Texas live oak	<i>Quercus</i>	<i>fusiformis</i>	QUFU	6107	40	native
Fagaceae	bur oak	<i>Quercus</i>	<i>macrocarpa</i>	QUMA2	6625	100	native
Fagaceae	chinkapin oak	<i>Quercus</i>	<i>muehlenbergii</i>	QUMU	6624	110	native
Fagaceae	Shumard oak	<i>Quercus</i>	<i>shumardii</i>	QUSH		100	native
Fagaceae	post oak	<i>Quercus</i>	<i>stellata</i>	QUST	6627	60	native
Fagaceae	Texas red oak	<i>Quercus</i>	<i>texana</i>	QUTE	6116	110	native
Anacardiaceae	prairie sumac	<i>Rhus</i>	<i>lanceolata</i>	RHLA3		20	native
Leguminosae	black locust	<i>Robinia</i>	<i>pseudoacacia</i>	ROPS		60	native
Salicaceae	black willow	<i>Salix</i>	<i>nigra</i>	SANI	6136	100	native
Sapindaceae	western soapberry	<i>Sapindus</i>	<i>saponaria</i>	SASAD	6144	20	native
Sapotaceae	gum bully	<i>Sideroxylon</i>	<i>lanuginosum</i>	SILA20	6623	48	native
Fabaceae	mescal bean	<i>Sophora</i>	<i>secundiflora</i>	SOSE3	6644	15	native
Fabaceae	Eve's necklacepod	<i>Styphnolobium</i>	<i>affine</i>	STAF4	6645	30	native
Cupressaceae	bald cypress	<i>Taxodium</i>	<i>distichum</i>	TADI2	6172	130	native
Ulmaceae	American elm	<i>Ulmus</i>	<i>americana</i>	ULAM	6185	120	native
Ulmaceae	cedar elm	<i>Ulmus</i>	<i>crassifolia</i>	ULCR	6186	90	native
Caprifoliaceae	rusty blackhaw	<i>Viburnum</i>	<i>rufidulum</i>	VIRU	6191	18	native
Rutaceae	common pricklyash	<i>Zanthoxylum</i>	<i>americanum</i>	ZAAM	6667	25	native