Riparian Productivity in the Brazos, Guadalupe, and Trinity River Basins, Texas

Final Report

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1. Introduction

The current study is the initial phase of a three-basin six-site effort to refine the analysis of river discharge versus riparian forest productivity. This report primarily concerns two study sites (Hearne and Navasota) on the middle Brazos River in Texas. At the study sites, correlations among incremental tree-core measurements and an array of river-flow metrics are measured using multiple-regression statistics, in order to determine the statistical power of the flow-productivity relationship. The management objective is a more ecological development of environmental-flow prescriptions, to conserve riparian forest and other floodplain fish and wildlife habitats.

Within the study reach that includes the Hearne and Navasota sites, the floodplain is mostly 5-10 km wide, except when confined by resistant outcrops where it narrows to less than five km wide (Heitmuller 2014). As discussed in the other TCS riparian reports for the middle and lower Brazos River (Hayes 2016a and 2016b), flow regulation decreases with distance below Waco, due to the absence of additional reservoirs. Thus, flow variability is progressively restored to a relatively natural regime on the middle and lower Brazos River.

Largely due to agricultural land uses, remnant riparian forests along the middle Brazos River mostly occupy the active meander belt, which generally extends no more than a few hundred meters both sides of the river centerline. The forests are relatively protected from human disturbance within the meander belt, which is unsuitable for agriculture by being too wet and prone to frequent fluvial disturbance. These are the riparian forests in which tree cores were sampled to measure riparian productivity, as described below.

Figure 1 summarizes key aspects of the primary species-flow guilds within riparian forests of the lower and middle Brazos River study reach, which include lower swamp (streamside), upper swamp (between first and second levees), seasonally flooded forest (low flats and backwater areas), and temporarily flooded forest (high flats). The figure describes the guilds in terms of relative elevation, common tree species, and hydroperiod requirements (hydrologic regime, flood frequency, and growing season inundation).

The six study sites (out of a total of nine project sites) selected for the three-basin flow versus riparian productivity assessment within the guilds are mapped in Figure 2. Examples of the black willow lower-swamp and black willow-box elder upper-swamp flow guilds are shown in Figures 3 and 4, respectively. To convey the dynamic nature of the flow guilds, a backwater slough at the San Felipe site is shown before (Figure 5) and at the initiation (Figure 6) of the winter 2018-2019 flood. Like all but one (San Felipe) of the nine overall TPWD-TWDB-TCS riparian study sites, the Hearne and Navasota sites discussed in this report are installed on private lands, which facilitates siting flexibility and public outreach. The ongoing decline of riparian habitats on private lands poses serious threats to downstream resources, including aquatic and terrestrial habitats, and the quantity and quality of stream flow (King et al. 2009).

The overall project combines ongoing measurements of flow-productivity relationships, with prior analyses of riparian habitat inundation at the river-reach scale and site-level forest plot inventories, in order to address what Mahoney and Rood (1998) called the greatest challenge: regional floodplain conservation. With three dendroecological study sites, including the two addressed in this report, the overall riparian study on the middle and lower Brazos River (MLBR) encompasses six riparian study sites and approximately 180 river miles. This coordinated effort aims to refine environmental flows to conserve thousands of hectares of rapidly declining riparian and floodplain habitats on the MLBR study reach. At this scale, floodplain vegetation, fish, and wildlife may be sustained at the population level.

2. River Flow and Riparian Forest Productivity

Floodplain sustainability depends upon connectivity with the river, a naturally variable flow regime that maintains both low and high flows, and enough area to foster geomorphic processes and significant ecosystem services (Opperman et al. 2010). When hydrology is relatively undisturbed, riparian forests are among the most productive ecosystems, with primary production exceeding 1000 $g/m^2/y$ (Conner et al. 1990). Their high species diversity and flow subsidies maintain high primary and secondary production (Bayley 1995). Once river sediments settle out, the relatively clear waters deposited in the riparian and bottomland habitats by overbank flows initiate higher levels of both primary and secondary production than is possible in the river channel. Riparian forest productivity peaks with annual floods in winter and early spring (Conner et al. 1990).

Incremental tree growth in temperate regions is not as climatically sensitive, that is, as closely correlated with climate, as growth data from semiarid regions (Phipps 1982). Smith et al. (2013), when researching connections between tree growth and inundation, showed that river flow and related soil moisture variables impacted tree growth more than climate. Within Cache River riparian forests in Arkansas, intensive hydrologic studies revealed that river discharge accounted for more than 90% of the annual water budget (Walton et al. 1996). These and other studies reveal that, when compared to stream flow, groundwater, precipitation, and evapotranspiration are insignificant contributions to the riparian-forest water budgets in temperate areas.

Competitive interactions among tree species complicate the relationship between forest productivity and variable river flow. Hydric tree species, physiologically attuned to wet conditions, are more limited by dry conditions than more xeric (dry-site) trees (Phipps1982). Reduced growth of dominant tree species on bottomland sites during drought is due to their low drought tolerance and/or shallow root systems. Abrams et al. (1998) measured differences in species impact during drought according to site, with tree species adapted to the wettest and driest sites more adversely impacted by drought than intermediate sites. Golet et al. (1993) also measured reduced rates of tree growth, when stressed by either drier or wetter conditions than normal. Interestingly, Anderson and Mitsch (2008) measured a similar parabolic curve of tree growth relative to inundation, which showed an intermediate optimum of frequency and/or duration of inundation, when the flood subsidy outweighed the stress of too little or too much water.

Species responses to flood regime can be subtle. A higher frequency of floods may either directly increase riparian forest growth rates or indirectly do so by impeding less flood-adapted competitors. Thus, floods later in the growing season have the added benefit of excluding competition from invading upland species that are more vulnerable after leaf out, which boosts the productivity of riparian hardwood forests over the long term. In addition to variable flows, riparian forest composition depends upon the location within the floodplain mosaic of geomorphology, soils, and available plant species. Dale and Ware (2004) point out that species adaptations to the season of flooding and whether flooding is by moving or stagnant water may be as important as frequency and duration of inundation.

3. Methods

The overall study quantifies environmental flows needed to conserve and restore declining riparian habitats in Texas. The relationship between riparian forest productivity and historical river flows is examined by developing tree-ring chronologies for target riparian tree species. Techniques are developed to refine productivity-flow relationships through the application of productivity indices, cumulative flow metrics, and multiple-regression statistics. Figure 2 is a map of the subset of six ongoing TCS-TPWD-TWDB riparian monitoring sites selected for the current three-basin flow-productivity study. Study-site codes:

Site Code:	**Description:**
LGR-N	Lower Guadalupe River, Nursery Site
LBR-S	Lower Brazos River, San Felipe Site (SFASP)
MBR-H	Middle Brazos River, Hearne Site
MBR-N	Middle Brazos River, Navasota Site
MTR-B	Middle Trinity River, Palestine Site B (BLBWMA)
MTR-C	Middle Trinity River, Palestine Site C (BLBWMA)

3.1. Field Methods

To construct a master chronology for analytical purposes, the coring of 30-40 trees is generally required for each species at each site, order to analyze a minimum of 20 usable cores for each species. One increment core (5.1 mm diameter) is sampled from the south side of each tree at the standard diameter-at-breast-height (DBH, 1.37 m). Three primary tree species are selected per site, each of which will ideally be represented by 30 or more usable cores at a given study site.

Tree selection is important, in order to reduce high sample variance in riparian habitats due to complex subsurface, hydrological, and biological factors. Fritts and Swetnam (1989) stress that replicate trees within each target flow guild must be sampled very carefully to minimize any differences in the ring patterns due to inadvertent interference in the control factor, which in this study is the guild-defined hydroperiod. Sampled microsites and cored trees must be skillfully selected, in order to achieve sufficient statistical power to assess the connection between flow and riparian forest productivity.

Dominant or co-dominant open-grown trees without significant structural defects are cored in each of three homogeneous microsites (species-flow guilds) per site, in order to decrease variance associated with elevations, soils, and hydrological regimes. Sampled trees are carefully selected to avoid disease and decay, large broken branches, partially or wholly overtopping canopies, indications of prior overtopping such as deformed branches and tops, and adjacent canopy openings due to the death of a dominant or co-dominant tree.

3.1.1. Equipment

Before going into the field, it is necessary to gather the equipment that will be needed for sampling. The basic tools for dendrochronological fieldwork include at least two increment borers, straws in which cores are stored, map tube for holding cores and straws, diameter tape, permanent markers (sharpie), push rod for clearing wood stuck in a borer, sharpening kit (with a small wedge stone and a cone sharpening stone) to sharpen dull or chipped increment borers, global positioning system (GPS), digital camera, flagging to label cored trees, and field data sheets.

3.1.2. Tree Coring

One usable core per tree is sufficient when the objective is to compare tree rings with environmental (climate or flow) variables (Cook, 1985; Cook et al., 2000). However, in this study, two or more cores are taken from one tree, whenever the dating between cores needs to be checked or the initial core is unusable due to wood defects or other issues.

Depending on availability, approximately 30 trees are initially cored per species, in order to determine the resulting statistical power (EPS, expressed population signal, from ARSTAN). If necessary, in order to enhance common signal strength (percent common variance), additional trees will be cored. Note that the recommended threshold value for EPS is 0.80 or higher (Cook et al., 2004; Speer, 2010).

To start coring, the increment borer is pushed into a crack in the bark of the tree while turning the handle in a clockwise direction. The crack in the bark gives a starting place and allows one to avoid coring through a thicker area of bark. Starting a borer is an easy process in softwoods but can be exceedingly difficult in hardwood trees. To aid in starting a borer in hardwood trees, one can use an increment borer starter, which consists of a metal plate that can be positioned against chest and a shaft that fits into the opening on the increment borer at the handle. This allows one to push with chest while turning the borer by hand. The starter also makes sure that coring is done straight into the tree, perpendicular to the angle of the stem.

Coring a tree is often painstaking due to the resistance to turning the increment borer. If the borer starts to turn easily, it is likely that the borer hits a pocket of rot in the tree and is at risk of getting stuck. At this time, coring should be stopped and both the core and borer should be removed from the tree. If, on the other hand, it becomes very difficult to turn the borer, the core may be twisting up inside the shaft and may result the borer being jammed. As such, coring should be stopped.

When a desired length of the stem is cored (usually a little over half-way through just beyond the pith center), a core extractor (also called spoon) is inserted into the shaft of the increment borer and is forced to pinch into the end of the core. The increment borer is then turned in the counter-clockwise direction, allowing the core to be extracted by pulling the spoon out of the borer shaft. At this point, the core is placed into a straw to protect it and maintain the proper order of any wood fragments that come out of the increment borer. Before placing the core into the straw, one end of the straw should be sealed with masking tape. The spoon should be removed only far enough out of the shaft to slide the exposed core into the straw. It is recommended to pinch down the end of the straw and to close plastic straws using masking tape. The straw is then labeled with the site designation, species code, and tree number. Once the cores are neatly packaged in a straw, they are placed in a map tube to protect them from breakage or getting lost.

When removing from the tree, the borer is turned in a counterclockwise direction. The borer should gradually come out of the tree as it is turned. A borer may become stuck in a tree if left too long because the wood that was pushed out of the way will relax back on the shaft of the borer. If this occurs, a sharp backward jerking force is applied on the borer while turning the borer counterclockwise so that the spiral threads of the borer bite back into the wood of the tree. Occasionally the wood-core may become stuck inside the shaft. The best way to remove it is to insert a push-rod at the tip of the borer and clean the wood stuck in the borer. It is often recommended to insert a wooden plug with wood glue into the bore hole.

3.2. Pre-Measurement Protocols

Pre-measurement laboratory work includes drying, mounting, sanding and chemically treating the cores.

3.2.1. Core Drying and Mounting

Tree cores are removed from straws within three days to commence drying, so as to avoid warping and mildew. Drying is the first step to prepare tree cores before gluing them to mounts. Cores are air dried for approximately 24 hours, after careful removal from straws, so that all pieces are obtained in the proper sequence, while noting the pith and outside ends. If the core is broken during collection, care should be taken so that the broken pieces are oriented correctly (i.e. bark and pith are rightly positioned), while drying and then mounting.

Once the core is dried, it is mounted on a machined wood mount (Figure 7). The mounts have a half circular groove to securely receive cores. Before mounting the core, all of the information written on the straw during core collection (tree species, tree number, and collection site) is copied on to the mount with permanent marker. Water soluble white glue is used to mount the cores, so that, if necessary, cores can be removed from the mount and remounted. It is important to mount the core with a cross sectional view facing up to make sure the ring boundaries are conspicuous after sanding. Once the core is glued to the mount, heavy weights can be used to hold the cores in place as the glue dries. Alternatively, string tightly ties the core to the mount every 0.5-1 cm. The glued core-mount should set for at least twelve hours, before the core is sanded.

3.2.2. Sanding Cores

When the glue is dry and the core is aligned straight on the groove, the core needs to be sanded with progressively finer sandpaper: ANSI 120, 220, 320, 400, 600, 800. The first sanding grit is used to flatten the core surface for subsequent polishing and takes the longest. The progressive sequence of finer grits is meant to create a surface so that each individual ring of the cross sectional view can be clearly seen under a microscope. A belt sander with a flat top is often used for sanding cores, but be extremely careful not to apply any pressure that may destroy the core.

When using a belt sander, one should invert it so that the belt faces up, and clamp the sander handle to the table. This creates a flat, stable surface on which the cores are sanded. Changing the angle of the core is good practice between sanding grits (sanding along the length of the sander then switching to a 45 degree angle from the axis of the sander), so as to see and remove the coarse marks left, if any, from the previous belt. In the next level of finer sanding, sandpaper of 1000, 1500, 2000 grit followed by lamb's wool provide a finer polish to the finished surface. Repeated visual examination of the core helps determine when the core has been sanded enough.

Care should be taken not to sand so that too much of the core surface is removed. About half of the core should be left when all sanding is done, so that the widest (full diameter) core area remains to analyze under the microscope. The final polish on the cross sectional view is most important for allowing the proper identification of ring boundaries. Sometimes rings on a dry surface are difficult to visualize, in this case the surface can be gently soaked to clearly reveal the rings.

3.2.3. Chemical Treatment

Tree rings on a core that do not standout after sanding are treated using a specialized chemical solution, which is made by dissolving one gram of phloroglucinol crystals in 100cc of 95% ethyl alcohol within a graduated glass cylinder (Forestry Suppliers, Inc., 2008). First, cores are soaked in the phloroglucinol solution for one minute, then taken out of the cylinder and the excess solution is allowed to drip off into the cylinder. In the next step, cores are placed in an approximately 38% HCl acid solution in a second graduated glass cylinder, until they begin to turn red. Finally, cores are washed in water and open-air dried. This process allows the rings to become more evident as the cores dry. Personal protective equipment is used at all times during chemical treatment of cores, including nitrile gloves and protective eyewear.

3.3. Tree-Ring Measurement and Quality Control

3.3.1 Cross-Dating

Prepared cores are now ready for cross-dating and ring measurements. Most dendroecology projects require ring width measurement for a quantitative analysis of tree growth and productivity in comparison with environmental data, such as historical flow events. The synchrony of incremental tree growth is the basis for dendrochronology, including among our target riparian species within the same species-flow guilds.

In the arid southwestern United States, Fritts and Swetnam (1989) noted that 60-80% and 50-70% of ring-width variance is shared by trees of the same species and different species, respectively, in a given region. Covariance of ring-width pattern is due to shared annual and interannual variations in local environmental factors, such as river discharge, which control the physiology of ring growth. In the current study, cross-dating of tree cores applies this synchrony to confirm tree-ring dates within a flow-guild set of tree cores for a given species.

During correlations among river-flow and forest-productivity data, the precise dating of tree rings is of paramount importance. Both visual and computer-assisted cross-dating techniques are utilized, with the goal of assigning precise calendar dates to each annual ring, as required to relate tree growth to the environment. However, visual cross-dating is an essential learned skill that must be applied prior to ring-width measurements and the program COFECHA (explained later) that provides statistical validation of the visual cross-dating.

Careful visual and graphical cross-dating, including skeleton plots, list method, and marker rings, is as important as statistical methods, during riparian productivity analyses, since the variable-flow regime (false and missing rings, etc.) requires accurate and repeatable cross-dating. The process may begin by marking a visual ring count of the decades on the wood. If marking cores, use very small marks on one side of the core, in order to maintain maximum ring visibility.

Dendrochronologists may apply several visual analysis techniques to cross-date tree rings such as skeleton plotting, list method, and memorization method (Speer, 2010), but for the particular purpose of our research the following explains the list method for measuring and dating tree rings in hardwood species. The list method begins with inspection from the outside of the tree (bark side), since the coring date is known. The dendrochronologist first determines marker rings that are consistently narrow or have identifiable characteristics, and are consistent between different trees. S/he then counts back the rings from the bark to the pith, marking calendar years on the core. Each narrow ring is noted, with the date of each written in a vertical list under the sample identification (species, tree number, and site). Once the researcher has done this for five to ten cores, s/he goes back to the lists and determines which rings are consistently narrow between samples. Once a list of these marker rings is developed, the analyst can use these marker rings to more quickly date the rest of the samples.

3.3.2 Velmex TA Measurement System

Many ring-width measuring systems are available that can be used to obtain accurate measurements of tree ring widths (Speer 2010). Most of these systems have a stage which moves with rotation of a lead screw or by an optical linear encoder. These systems include the Bannister Measuring Stage, the Measurechron, the Henson Measuring Stage, the Zahn Measuring Stage, the LinTab Measuring System, and the Velmex Measuring System. All of these systems are used in conjunction with a stereo-zoom microscope supported by a boom stand.

The Velmex TA system used by TCS has a movable stage that is advanced by a lead screw connected to a handle, but an optical linear encoder actually determines the exact location of the stage and measures its position to an accuracy of 0.001 mm. The microscope has a crosshair reticle in one of the eye pieces and this crosshair is lined up with a ring boundary, so that the vertical hair is tangent to the curve of the ring boundary. Measurements are then made along a core perpendicular to the ring boundary. As a core approaches the pith, it often shows much curvature at the center, so that the position of the core must be adjusted between each measurement, in order to stay perpendicular to the previous ring boundary.

3.3.3 Dendrochronological Software Applications

Appendix C details the stepwise protocols for the three primary software applications used during this research project for tree-core measurements (MeasureJ2X), cross-dating (COFECHA), and chronology development and quality control (ARSTAN). To integrate measurements in the computer-assisted Velmex TA system, the recommended program is MeasureJ2X. Initial quality control of ring dates following visual cross-dating is provided by COFECHA, which statistically creates a post-measurement chronology. The much more powerful ARSTAN program is then applied to COFECHA output to build site-level chronologies. In ARSTAN, additional standardization techniques maximize the signal of interest and remove noise from the final chronology. The program fits a curve to the tree-ring measurements from each core, divides the ring width by the modeled curve value, and averages the resultant index for each core to create a tree-level index. The program then averages the tree indices to develop a stand-level chronology that includes the final ring-width measurements.

3.4. Flow-Productivity Analyses

The overall research objective is to identify the most significant flow-productivity relationships that can be derived from river-gage and tree-core data.

3.4.1 Flow Metrics: Mean Discharge and Overbank Events

Despite the many variables that may impact riparian productivity, such as the temporal distribution of precipitation, air temperature, and evapotranspiration, the strongest correlation with the incremental growth of riparian trees is with river flow in temperate regions, as confirmed by many researchers reviewed by Crockett et al. (2010). The link between flow and tree-ring chronologies is particularly strong, since other variables that influence tree growth are intimately linked to flow. For example, rainfall is directly connected to flow, and both air temperature and solar radiation vary according to rainfall.

Cumulative flow metrics (mean discharge volume and the number of days with overbank flows) include annual total, growing season, critical reproductive period, each three-month season, and each month. The initial number of monthly totals was increased to twelve, in order to more closely examine significant flow-productivity responses identified during spring through fall. Growing season (Texas State Climatologist 2004), critical reproductive period, and seasons are defined as:

Seasonal Name	**Period**
Total	Whole Year
Reproductive Critical	February - April
Growing Season - Hearne	Mar 9-Nov 19
Growing Season - Navasota	Mar 1-Dec 4
Winter	December (previous year) - February
Spring	March - May
Summer	June - August
Fall	September - October

Following discussions with among TWDB, TPWD, and TCS staff, an overbank flow was defined as the mean daily discharge that inundates 80% extent of box elder and cottonwood, along the TCS monitoring transects. This definition may best correspond to the initiation of overbank flows, important for riparian and low-elevation-floodplain forest conservation. TWDB then extrapolated the corresponding flow rates for the Highbank (08098290) and Hempstead

(08111500) stream gages for the 1992-2016 timeframe of the tree productivity chronologies. The resulting overbank stage elevations at the Hearne and Navasota riparian sites are 82.85m and 52.8m, respectively. Therefore, the overbank flow rates at the Hearne and Navasota sites are 34,000 cfs and 49,000 cfs, respectively. Since daily mean discharge is unavailable for Navasota (gage # 8111500) during 09/30/88 – 09/30/00, the Navasota overbank tally is limited to 10/01/00 through 12/31/16.

3.4.2 Tree Species Productivity

For correlation with flow metrics, mean riparian productivity chronologies are processed for each of the site-species combinations. The mean chronologies are created by further standardizing and merging of the final ring-width measurements. In this manner, the sensitivity of productivity data to abiotic factors is enhanced, by minimizing temporal changes in biotic sensitivity due to growth and competition. When analyzing tree-ring chronologies, the natural progression of growth produces successively smaller tree rings as trees age. This age-growth effect thus reduces sensitivity to environmental variables in the tree-ring record, including river flow. In addition, the growth of relatively shade-intolerant species, such as our riparian study species, is influenced by the competitive status of each tree, which is primarily determined by the degree of canopy overlap. Standardization of ring widths removes age-growth effects, and merging individual tree chronologies into a mean collection chronology eliminates competition interference with the growth of individual trees. In this manner, the increased sensitivity of tree-growth data to environmental factors strengthens flow-productivity regression analyses.

For the TCS productivity analyses, the first step for standardizing ring-width measurements discards the first ten annual rings of each tree chronology from further analysis, in order to reduce the juvenile growth effect. For each tree core, tree ring widths are then standardized to remove other age effects on growth. Each individual tree chronology is standardized to a mean value of one, by calculating an annual ring-width index (RWI) equal to the yearly measured growth value for each core divided by the average annual growth rate for that core (minus the first ten years. This removes the age-growth effect. Individual-tree outliers were not removed prior to creating these mean RWI values. The high variability of the individual-tree data is typical, due to the complexity of below- and above-ground environments especially in floodplains. This is why researchers standardize and average productivity data (Phipps 1982).

The basic unit for dendroclimatic and dendroecological research has been the mean chronology, obtained by averaging data from several individual trees from a single species at a single collection site (Phipps 1982). Merging data of the samples into a mean chronology weights the mean chronology in favor of the variance in common among samples. In this study, individual tree chronologies are merged into mean chronologies for each of the six species and site combinations, in order to eliminate competition interference with the growth of individual trees. This is accomplished by averaging the annual RWI values for a given species and site, for all years in which there are at least 20 RWI values. In this approach, the standardization and merging of ring-width measurements enhances the sensitivity of productivity to flow, by minimizing temporal changes in biotic sensitivity due to growth and competition. Sensitivity on a year-by-year basis is the very feature of a tree ring record that is most important for research. What is not wanted are changes or shifts in sensitivity (Phipps 1982).

3.4.3 Flow-Productivity Correlations

A broad-brush exploratory approach, based on multiple linear regressions, initiated this refinement of environmental flows for riparian habitats. The relative predictive strength of the various relationships between tree growth and streamflow are measured using the Spearman correlation coefficient rho during linear regressions. In order to determine the annual period(s) of flow with increased benefit to forest productivity, annual incremental growth data (RWI) are correlated via multiple linear regressions with cumulative totals for flow volumes and overbank flow frequencies for each site.

Many prior researchers show that annual tree growth usually best correlates to current + prior year (two-year) water availability, not current or prior year alone. A lag of one or more years in the growth effect is often observed following the trigger flow interval, which increases tree-growth variance (Fritts and Swetnam 1989). As reviewed in Stromberg and Patten (1990) and Anderson and Mitsch (2008), many dendroecological studies have found that soil-moisture conditions from the prior growing season strongly impact incremental tree growth in the following year. Anderson and Mitsch (2008) found annual tree growth significantly correlated only to two-year flood data, due to significant growth occurring early in the growing season, which depends on carbon fixed in the prior year. However, Stromberg and Patton (1990) documented a significant correlation between riparian tree growth and both annual and prior-year flow volumes. Otherwise, Mitsch and Rust (1984) and Mitsch et al. (1979) correlated 5-year averages of riparian tree growth with the number of flood events during the corresponding 5-year periods. Their two reasons for using the five-year average growth measures were to include growth effects lagging behind annual flow and flood measurements, and to diminish possible errors due to missing or double ring counting.

To encompass the variety of potential lag effects, the current analysis includes single- and multiple-year measures of flow volumes, flood events, and riparian productivity. The following four basic methods of regression analysis are used to assess cumulative totals for flow metrics and productivity data (RWI) in this study:

1. One year: RWI (Year i) vs Flow (Year i)
2. Two year: RWI (Year i) vs Flow (Year i + Year i -1)
3. Three year: RWI (Year i + Year i -1) vs Flow (Year i + Year i -1+ Year i -2)
4. Five-year: RWI (Year i + Year i -1 + Year i -2 + Year i -3 + Year i-4) vs
   Flow (Year i + Year i -1 + Year i -2 + Year i -3 + Year i-4)

Utilizing the above four regression frameworks, a Python-Excel application (Python Version 2.7) was created to assess RWI relationships with the above seasonal and monthly cumulative flow metrics. Statistical analyses were completed using the SciPy package (Oliphant 2007) in Python Version 2.7 (Python Software Foundation, available at http://www.python.org). The variables were inconsistently normal using the normality test scipy.stats.normaltest (https://docs.scipy.org/doc/scipy/reference/generated/scipy.stats.normaltest.html) (D’Agostino 1971, D’Agostino and Pearson 1973). Therefore, the non-parametric Spearman Rank Correlation was used, scipy.stats.spearmanr, with correlation tested at an alpha value (significance level) of 0.05 (https://docs.scipy.org/doc/scipy/reference/generated/scipy.stats.spearmanr.html).

4. Results

4.1 Flow Metrics

Current-year seasonal flow volumes (ac-ft) are presented for Hearne (Figure 10, 1992-2016) and Navasota (Figure 11, 2001-2016). At Hearne, the highest and lowest total annual flow volumes occur in 1992 and 2014, respectively, while at Navasota the highest and lowest cumulative flow flows occur in 2007 and 2011, respectively. The most serious drought (2011-2014) during the period of the productivity chronologies is evident at both sites, though, of course, the more downstream site, Navasota, always has significantly higher mean discharge. Other significant drought years are 2006 and both sites, and 1999 at Hearne. Current-year seasonal flow volumes are highest in the spring and growing season at both sites, with lowest flow volumes occurring in fall and summer at Hearne and in fall and winter at Navasota.

As discussed, two-year (current + prior) seasonal flow volumes often correlate better with tree productivity, compared to current-year volumes. These two-year flow data are graphed in Figures 12 (Hearne) and 13 (Navasota). At the Hearne and Navasota sites, the highest and lowest cumulative two-year mean discharge volume were in 2015-2016 and 2013-2014, respectively.

On a monthly basis, both current-year and two-year monthly flow volume averages are largest in March at Hearne and in May at Navasota, during the respective site timeframes. At these sites, the smallest current-year and two-year monthly volumes happen in August and September.

4.2 Species Productivity

Tree-core measurements and productivity indices (RWI) were completed for target species (black willow, box elder, and hackberry) at the Hearne and Navasota sites. Of the 30-45 trees cored per species at each study site, only 22-38 usable cores were then able to be measured per species due to structural and other defects (Table 2). The species chronologies for the RWI productivity indices for the two sites are depicted side by side for comparison in Figure 14 (box elder), Figure 15 (black willow), and Figure 16 (sugarberry).

Though no data outliers were removed, the synchrony within intervals of one to two years between the two sites in each species' annual productivity response to environmental variables is visually apparent. All tree species appear to react to annual environmental change, such as drought and high-flow years. The range of RWI values are similar for the three study species. However, black willow RWI values indicate this species to most frequently exhibit a strong response to seasonal and monthly measures of mean discharge volume (see Tables 4, 6, and 7), possibly due to black willow distribution being nearest the main river channel.

4.3. Correlations: River Discharge and Species Productivity

Tables 4-9 summarize the correlation results that are central to this ecological refinement of flow-productivity relationships, in order to develop environmental flows for riparian sustainability. A spreadsheet (BH&BN.FlowChrono_SpearmanStatsOutput.12-24-18) is available to provide more detailed correlation results. However, the summary tables present sufficient detail to assess the statistical strength of the many flow-productivity relationships, including Spearman's correlation coefficient rho, p-values (significance), sample size, and analytical time frame (years) for each data point.

In the correlation tables, color coding of cells denotes correlation strength. Blue and red identify significant correlations for discharge trends and species-specific flow-productivity relationships, respectively. The color coding in the tables and study criteria for determining strength of correlation/relationship are as follows:

Color coding: Red: species productivity, Blue: discharge.
Color border & fill, bold font: Very strong correlation (rho $\geq |0.70|$, p-value ≤ 0.05)
Color border, no fill, bold font: Strong correlation ($0.70 > |\text{rho}| \geq 0.50$, p-value ≤ 0.05)
No color, bold font: Moderate correlation ($0.50 > |\text{rho}| \geq 0.30$, p-value ≤ 0.05)

Strength of relationship: Value of rho, p-value ≤ 0.05
Very Strong: -1.00 to -0.70 or 0.70 to 1.00
Strong: -0.69 to -0.50 or 0.50 to 0.69
Moderate: -0.49 to -0.30 or 0.30 to 0.49
Weak: -0.29 to -0.10 or 0.10 to 0.29

For each of the basic four basic regression categories (Section 3.4.3), the row in the tables that is labeled “Year” provides the correlation statistics for the river flow trend during the full period of analysis. For example, in Table 4, winter discharge volumes during winter for the two-year (current + prior) category at Hearne show a strong decline throughout 1992-2016 (rho = -0.52, p-value = 0.0078, n = 25).

4.3.1. Black Willow

Mean Discharge: Of the three target species (box elder, black willow, and sugarberry) in this field study, black willow productivity is most benefitted by mean river discharge, when measured either seasonally (Table 4) or monthly (Tables 6-7), at both the Hearne (mean daily discharge) and Navasota (mean monthly discharge) research sites. On a seasonal basis, black willow’s most positive and most consistent response to both current-year and multiple-year cumulative discharge is during the summer (Hearne, rho: 0.80-0.87, p-value: 0.0025-0.0096, n: 8-9; Navasota, rho: 0.64-0.84, p-value: 0.0001-0.0026, n: 12-16). The species’ flow-productivity response to current-year mean discharge is strongest in summer at both sites (Hearne, rho: 0.87, p-value: 0.0025, n: 9; Navasota, rho: 0.84, p-value: 0.0001, n: 16). The current-year and multiple-year flow-productivity responses of black willow are also very strong (Hearne) to strong (Navasota) for annual total, growing season, and spring discharge totals (Table 4).

Correlations of black willow productivity with cumulative monthly discharge data (Tables 6-7) affirm the above seasonal results. The summer months of June and August include the strongest current-year flow-productivity correlations, Hearne: August (rho: 0.90, p-value: 0.0009, n: 9) and Navasota: June (rho: 0.85, p-value: 0.0001, n: 16).

When accounting for possible lag effects, correlations of multiple-year monthly cumulative discharge (current + prior year, current + two years) with annual productivity (Tables 6-7) are also strong to very strong during late spring and summer (Hearne: May-August, Navasota: May-July). At Navasota, five-year cumulative flow-productivity correlations for black willow [RWI (Year i + Year i -1 + Year i -2 + Year i -3 + Year i-4) vs Flow (Year i + Year i -1 + Year i -2 + Year i -3 + Year i-4)] are very strong for two months each season of winter, spring, and summer, but not fall. No correlations occurred among five-year seasonal or monthly data at Hearne, possibly due to the lower sample number (n = 6), compared to Navasota (n = 12).

Overbank Events: Black willow growth is uncorrelated with any seasonal totals for overbank events at both sites (Table 5). However, at Hearne two-year and three-year cumulative overbank frequencies are very strongly correlated (rho $\geq$ 0.82, p-value $\leq$ 0.0117) with increased incremental growth of black willow in May (2008-2016). At Navasota, there unfortunately are no data for monthly overbank events that coincide with measured black willow chronologies, due to the paucity of USGS mean daily discharge data at the site.

4.3.2. Box Elder

Mean Discharge: In contrast with the strong response of flow-acclimated black willow, box elder is the least responsive target species to mean discharge. At both Hearne and Navasota, no significant correlations between seasonal flow metrics and productivity are measured for box elder (Table 4).

When box elder productivity is compared to monthly cumulative discharge (Tables 6-7), three significant correlations are detected. At Hearne, current-year discharge results in a strong positive correlation (rho: 0.64, p-value: 0.0191, n: 13) with annual growth in June, while five-year discharge exhibits a very strong negative correlation in February (rho: -0.70, p-value: 0.0251, n: 10). At Navasota, three-year cumulative flow in February also has a strong negative influence on box elder productivity (rho: -0.60, p-value: 0.0287, n: 14).

Overbank Events: Seasonal correlations of box elder growth with overbank event frequency differ according to study site (Table 5). At Hearne, the seasonal correlations reveal a strong current-year growth increase (rho = 0.60, p-value = 0.0293, $n/n_0 = 5/13$) for box elder during 2004-2016, relative to the annual event total. The three-year (current + prior 2 years) cumulative number of events is also strongly correlated with increased box elder growth in the fall (rho = 0.61, p-value = 0.0335, $n/n_0 = 4/12$) at Hearne. On the other hand, an increased number of overbank events during two-year (current + prior year) discharge in the reproductive-critical and spring seasons at Navasota is very strongly associated (rho = -0.83, p-value = 0.0418, $n/n_0 = 2/7$) with reduced box elder growth.

4.3.3. Sugarberry

Mean Discharge: Based on mean daily discharge data, neither seasonal nor monthly flow-productivity correlations occur for sugarberry at the Hearne study site. On the other hand, during seasonal correlations at Navasota (Table 4), where only mean monthly discharge data are available during 2001-2016, annual sugarberry productivity is significantly enhanced with current-year discharge in winter (rho = 0.58, p-value = 0.0249, n = 16). A strong correlation also occurs with multiple-year cumulative discharge (current + prior year, current + two years) in winter, spring, and summer (Table 4). Most notably, five-year flow-productivity correlations are very strong or strong for Navasota sugarberry every season of the year, with winter mean discharge again having the strongest impact (rho = 0.95, p-value < 0.0001, n = 12).

Monthly flow-productivity correlations at Navasota (Tables 6-7) support the importance of winter discharge for sugarberry. Current-year correlations are strong for December and February, while two- and three-year correlations are very strong or strong during January and December. Two- and three-year correlations for sugarberry are also strong during July and August. Additionally, March is strongly correlated in the three-year timeframe. Still, the five-year flow-productivity correlations are stronger, with December, January and March very strong, and August and November strong (Tables 6-7).

At the Navasota site, flow-productivity correlations based on mean daily discharge data are limited, since full-year mean daily discharge data for Navasota are only available before the year 2000. RWI data for black willow and box elder at the site are not correlated with pre-2000 mean daily discharge, likely due to the small number (n) of usable tree chronologies for that period. However, nine sugarberry chronologies are available 1992-2000, resulting in productivity correlations with current-year mean daily discharge. These seasonal correlations for Navasota sugarberry were positive and very strong for annual total discharge (rho = 0.71, p-value = 0.0465, n = 9), and for the reproductive-critical (rho = 0.81, p-value = 0.0149, n = 9) and winter (rho = 0.86, p-value = 0.0065, n = 9) seasons. Monthly correlations based on mean daily discharge data for Navasota are also significant. During the winter months (December-February) and April, current-year flow-productivity correlations are very strong and positive for sugarberry (rho: 0.74-0.93, p-value: 0.0009-0.0366, n: 9). Possibly due to smaller sample sizes (n), multiple-year flow-productivity data based on mean daily discharge at Navasota are not correlated.

Overbank Events: At Hearne, no significant seasonal or monthly correlations occur between overbank events and sugarberry growth. However, seasonal sugarberry productivity relative to current-year overbank event frequency is very strongly enhanced (rho ≥ 0.73, p-value ≤ 0.0387) during the reproductive-critical, winter, and spring seasons during 1992-2000 at Navasota (Table 5). In similar fashion, sugarberry growth at Navasota has a very strong positive correlation (rho ≥ 0.73, p-value ≤ 0.0387, $n/n_0 = 2/9$) with current-year overbank event totals during February and March.

5. Discussion

5.1 Background

Research examining the relationship between riparian forest productivity and river flow supports the importance of correlating two-year cumulative flow (current and prior) with riparian forest productivity. Though current-year flooding affects growth, stored energy resulting from flooding during the prior growing season is vital, since stem growth occurs early in the growing season. For example, Broadfoot (1967) measured a 50% increase in the radial growth of several riparian tree species, after flooding during the prior dormant season. And in central Pennsylvania, Abrams et al (1998) deduced that, compared to upland species, riparian tree species are more likely to have above-average growth during drought years and below-average growth the year after drought, due to the lag effect between water availability and its effect on tree growth.

Anderson and Mitsch (2008) measured significant positive correlations between number of high-flood discharge days over the preceding two-year period (Year i + Year i -1) with basal area increment (BAI, $cm^2/year$) during both the current-year (Year i) and preceding two-year period (Year i + Year i -1). The BAI decline lagged one year after a low-discharge year. Anderson and Mitsch (2008) also found a statistically significant link between higher annual tree productivity and increased flood duration in bottomland hardwood systems, but only when examined over a combined two-year period. Though flood frequency and flood duration are often correlated, the number of flood events is only a rough measure of bottomland water status, since riparian inundation and soil saturation persist for many days after disconnection with the river.

A systematic examination of the extent of the flow-productivity lag effect has not been an objective during other research. However, in an alluvial bald cypress swamp in Illinois, Mitsch et al. (1979) did find a significant positive relationship between 5-year average growth of bald cypress and the number of floods during the corresponding period, which they attributed to phosphorus input during floods. Broadfoot and Williston (1973) measured increased stress and mortality in riparian forest four years after a flood, where sedimentation exceeds three inches or standing water persists in depressions.

Increasing the timeframe of flow-productivity research not only addresses lag effects, but also extends the correlation analysis to include more incremental growth data and more seasonal and monthly inter- and intra-annual variations in single- and multiple-year measures of flow volumes and flood peaks. A larger number of low and high flow events, and tree chronologies, likely increases the statistical power of correlations. For example, Disalvo and Hart (2002) failed to find significant correlations between river flow and cottonwood growth, likely due to the short five-year extent of their research.

Therefore, the current study, which explores various refinements to the flow-productivity relationship, incorporates a comprehensive approach that measures four different timeframes of productivity-discharge effects, 1-year, 2-year, 3-year, and 5-Year, as defined in Section 3.5. Interestingly, the 5-year timeframe often produces the strongest correlations in this study, indicating the lag time may be much longer than previously assumed, when measuring the response of riparian forest productivity to water input from the adjacent river.

5.2. Flow-Productivity Relationships

5.2.1. Black willow

Mean Discharge: At both sites, seasonal correlation statistics for essentially all cumulative measures of mean discharge identify spring and summer discharge as providing the strongest boost for black willow productivity (Table 4). Other significant positive relationships of flow with black willow productivity include total annual and growing-season cumulative discharge. Monthly cumulative discharge April through August is also strongly or very strongly associated with enhanced black willow growth at both Hearne and Navasota (Tables 6-7).

During their multiple regression analysis of cottonwood growth, Reily and Johnson (1982) also found streamflow early in the growing season to be the most important growth stimulus during a natural flow regime. Broadfoot and Williston (1973) found that the augmentation of diameter growth of riparian hardwoods by spring floods is chiefly caused by increased water availability and the water table rising into the rooting zone later in the growing season. Riparian tree species exhibit a vernal growth pattern, in which maximum growth occurs in the early growing season when flood water is normally available, then ceases when soils dry in the middle of summer. Spring floods may effectively extend the growing season for riparian species.

Overbank Events: At Hearne, a mid-summer rise in the number of overbank events during May very strongly correlates with accelerated black willow growth, like the species' consistently positive relationship with spring and summer discharge (Table 8). Since black willow seedlings survived continuous floods lasting up to two growing seasons, Broadfoot and Williston (1973) classified black willow as a very flood-tolerant species. Again based on the relative tolerance of seedlings to soil saturation, Hosner and Boyce (1962) classified black willow as among the species most adapted to inundation. Superior flood tolerance likely allows black willow to outcompete less tolerant competitors during mid-summer floods, increasing black willow dominance and therefore productivity over time.

Spring floods are more beneficial than summer floods, since cool water holds more oxygen and dormant roots require less oxygen. Even if floods persist through July, flood-tolerant species such as black willow, and species that leaf out late, such as green ash, overcup oak, and water hickory, will not be adversely affected (Broadfoot and Williston 1973).

5.2.2. Box elder

Mean Discharge: Flow-productivity correlations for box elder are complicated by both positive and negative associations depending on time timeframe and site. At Hearne, cumulative current-year discharge in both summer and June is strongly correlated with increased box elder growth (Tables 4 and 6). However, at both Hearne and Navasota, winter discharge totals in February have either a very strong (5-year total, Hearne) or a strong (3-year total, Navasota) negative relationship with box elder growth (Table 6).

Due its dominance within the more elevated locations associated with the first and second levees in the current study sites, beyond the reach of upland runoff, the Hearne correlation results indicate box elder growth may depend on higher flows during the drier summer months. Though the scope of the current study is larger in terms of numbers of sites and replicate samples, the dependence by box elder on summer overbank events is supported by Reily and Johnson (1982), who also used multiple linear regression analyses to correlate river flow and box elder growth. Downstream from the Garrison Dam on the Missouri River in North Dakota, they used tree cores to detect a significant decrease in the growth of box elder, American elm, and green ash. Lower productivity was correlated with a lower water table and absence spring overbank flooding following dam construction. Species on higher flats in the floodplain without access to upland runoff, including box elder and American elm, declined the most.

The significantly adverse effect of three- and five-year totals for February discharge on box elder productivity measured in this study may be due to the limited tolerance of the species to soil saturation. Hosner and Boyce (1962) and Broadfoot and Williston (1973) labeled box elder as only intermediate in flood tolerance, based on its limited tolerance of soil saturation.

Overbank Events: Like with discharge metrics, box elder productivity exhibits similarly convoluted relationships with overbank flows. Significant correlations only occur at Hearne, where annual current-year discharge totals, and multi-year overbank-event totals in fall (five-year) and October (two-, three-, and five-year), all have either strongly or very strongly positive interactions with box elder growth (rho ≥ 0.60, *p-value* ≤ 0.0335) (Tables 5 and 8-9). The relatively high-elevation positon of the species atop the first and second levees may increase its growth response to overbank flows later in the growing season.

Reily and Johnson (1982) determined box elder to be among the species whose incremental growth is most dependent on frequent floods, due to their preference for higher floodplain terraces isolated from upland runoff. Spanning a 14-year period, Anderson and Mitsch (2008) measured annual basal area increments (BAI) for 42 dominant trees, including ten species. Box elder, 45% of the cored trees, exerted the most influence on the results. A significant positive relationship between the number of days of high-flood discharge and annual BAI was measured, only when discharge was measured in two-year increments, not single-year increments.

Like the February discharge results at Hearne, box elder relationships with overbank events at Hearne in the cooler seasons (reproduction-critical, spring, February-April) are very strongly negative (rho = -0.83, *p-value* = 0.0418) (Tables 5 and 8-9). As with discharge, its intermediate flood tolerance may increase the stress of saturated soil conditions during the cooler portions of the year.

In response to reduced flood frequency, Reily and Johnson (1982) determined box elder to be among the species experiencing the steepest drop in incremental growth when overbank flows are reduced in frequency, due to their preference for higher floodplain terraces isolated from upland runoff. Among common species in the current study areas, Broadfoot and Williston (1973) determined box elder and sycamore seedlings to be only moderately flood tolerant.

Box elder has a complex response to the timing of discharge and overbank flows. As a general rule, the more limiting an environmental factor is to growth, the more directly variations in that factor may be correlated with variations in growth (Phipps 1982). In this manner, box elder productivity depends upon higher summer discharge and increased overbank events in the fall. However, increased mean discharge in winter and more frequent overbank flows in spring reduce box elder growth.

5.2.3. Sugarberry

Mean Discharge: The only correlations of sugarberry productivity with discharge happen at Navasota, where its productivity is strongly promoted by current-year discharge in winter and two-year discharge in both winter and summer. Most of the other multiple-year cumulative metrics for discharge at the site are either strongly or very strongly correlated with increased sugarberry growth during every season (Table 4). In similar fashion, annual sugarberry growth is strongly correlated with current-year discharge in February and December, and with two-year discharge totals for January, July, and August (Tables 6-7). Three- and five-year discharge totals for January, March, July, August, November, and December are also strongly or very strongly correlated with accelerated sugarberry growth.

Grissino-Mayer (1993) identifies sugarberry as a species “of no or little importance in tree-ring research.” However, the present study successfully developed growth chronologies for this species that showed significant responses to mean discharge and inundation. Seasonal and monthly measures of current-year and two-year cumulative discharge, spanning both winter and summer, have a strong positive correlation with sugarberry growth. The growth stimulus connected to three- and five-year cumulative discharge during these two seasons is even stronger.

Overbank Events: Sugarberry annual productivity at Navasota is very strongly related to current-year totals for overbank events during the reproductive-critical, winter, and spring seasons. The only other significant correlation between overbank events and sugarberry growth is moderately strong and occurs at Hearne for five-year cumulative event totals during the month of May.

Hosner and Boyce (1962) classified sugarberry as flood intolerant, due to the adverse impact of saturated soil conditions on the species. However, the present study showed sugarberry growth to be very strongly increased during the same year as early season floods. The species appears to benefit from increased water availability, which extends the normally most productive portion of the growing season. Smith et al. (2013) described a similar effect caused by the average timing of flood events later in the year, which was the only variable that significantly increased the annual growth of all four of their studied tree species, including sugarberry. In this manner, flood frequency provided the strongest hydrologic stimulus for the combined growth of the four tree species.

6. Conclusion

During this beginning phase of refining environmental flows to be more responsive to riparian habitat maintenance, the chief accomplishment was the development of an analytical framework. Individual-tree responses to inundation are highly variable even within the same tree species, depending upon age, canopy position, tree health, elevation, soil, and microtopography. The computation of ring-width indices (RWI, Section 3.4.2) reduces within-species variability and enhances the flow signal by compensating for competition and growth influences on the flow-productivity relationships among species and sites. As a result, the early correlation results appear conclusive, since regression statistics are too significant for them to have occurred by chance and findings are generally verified by other research. However, completing the dendroecological research at the other four riparian sites will increase replication, and both confirm and expand initial results (Fritts and Swetnam 1989).

As a more sustainable alternative to the ranking of water uses according to their specified importance, Richter (2010) proposes the Sustainability Boundary Approach, which defines limits on the cumulative impact of all water uses and related land uses. Sustainability is achieved by managing the quantity and scheduling of overall water use and river flow within quantifiable limits placed upon the alteration of the natural flow regime. In this manner, environmental flows, including often neglected high flow events, are better conserved for socioeconomic and ecosystem services (Richter 2010). The seasonal and monthly measures of flow volumes and overbank flow events, used in the current flow-productivity correlation analyses, may assist in establishing sustainable limits on cumulative water use.

6.1. Environmental Flows Based on Riparian Flow-Productivity Relationships

As a more sustainable alternative to the ranking of water uses according to their specified importance, Richter (2010) proposes the Sustainability Boundary Approach, which defines limits on the cumulative impact of all water uses and related land uses. Sustainability is achieved by managing the quantity and scheduling of overall water use and river flow within quantifiable limits placed upon the alteration of the natural flow regime. In this manner, environmental flows, including often neglected high flow events, are better conserved for socioeconomic and ecosystem services (Richter 2010). The seasonal and monthly measures of flow volumes used in the current flow-productivity analysis may help establish sustainable limits on cumulative water use.

6.1.1. River Discharge

The overall results provide strong support of the importance of higher mean discharge during summer in promoting riparian productivity.

Black willow: This important riparian species receives the largest boost in productivity from increased summer mean discharge, though spring discharge is also important.

Box elder: Higher mid-summer flows are most beneficial to box elder productivity, while late winter discharge (February) is significantly detrimental this species’ growth.

Sugarberry: Productivity is notably enhanced by increased mean discharge during winter, with summer discharge also important.

6.1.2. Overbank Events

Black willow: Increasing the number of overbank events in May is particularly associated with higher black willow productivity.

Box elder: Increasing overbank events in the fall and reducing such events in the spring provide a strong impetus to accelerated box elder growth.

Sugarberry: Sugarberry productivity is promoted by overbank events during winter, with spring events also beneficial.

6.2. Recommendations

Many peer-reviewed papers recommend an integrated approach for sustaining riparian habitats. Despite the emerging understanding of the flow requirements of riparian vegetation, instream flow methodologies remain biased towards the needs of fish and other aquatic biota, even though vegetation sustains fish and wildlife, along with many crucial ecosystem and societal services. The flow requirements of riparian vegetation are likely greater than those of fisheries (Stromberg and Patton 1990), so that environmental flows to sustain the entire riparian ecosystem over the long term must be integrated with those of fisheries. Based on their research experience and literature review, Opperman et al. (2010) conclude that large-scale riparian conservation also requires its linkage with important environmental services, like flood risk reduction, especially in the face of climate change.

1. In order to encompass the diversity of altered flow regimes and consequent riparian impacts, the current dendroecological research (Brazos, Guadalupe, and Trinity basins) should be extended to additional river basins. Candidate basins with ongoing studies focused on riparian environmental flows include the San Antonio and Cypress-Caddo basins. The latter basin

includes a paired-watershed long-term forest monitoring network, utilizing the same tree-layer sampling design as the TPWD-TWDB-TCS riparian sites.

2. The impact of flow on tree growth is mediated by soil moisture, so that distance from the river and elevation relative to groundwater should ideally both be determined for each cored tree. However, since sampled trees were selected within riparian flow guilds of similar hydroperiod and surface elevation, a representative well for monitoring groundwater could alternatively be installed in each sampled flow guild, in order to link river discharge, groundwater elevation, and soil moisture availability.

3. Long-term forest plot and quadrat monitoring is important to measure how non-growth responses, such as regeneration, succession, and mortality, vary according to river discharge. In addition to tree growth and mortality rates, Stromberg and Patton (1990) conclude that environmental flow prescriptions should emphasize sustainability, i.e., reproductive output and seedling establishment, within riparian forests impacted by flow limitations. Long-term riparian plot monitoring should continue, as a necessary component of flow-productivity research.

4. To guide proactive water management, species-specific monitoring should be implemented to focus on the most flow-responsive riparian tree species, which are either decreasing or increasing within the Brazos river basin. Black willow should be included due to being the assessed dominant species most benefitted by higher flows. Eastern cottonwood and green ash should be monitored due to their high mortality and low regeneration along the middle Brazos River. In order to better understand its complex relationship with mean discharge and overbank flows, box elder warrants further study. Sugarberry, identified by Duke (2011) as an indicator of riparian forests degraded by floodplain desiccation, should be monitored due to its apparent expansion along the Brazos River.

7. References

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Appendix A: Tables

Table 1. USGS Stream Gages: Three-Basin Riparian Productivity Research
Brazos, Guadalupe, and Trinity River Basins, Texas

USGS Gage_ID	Name	Data Link	Available Data	County	Site Data Availability	Stream Distance: gage to study sites (mi) *	Application
8098290	BR nr Highbank, TX	08098290 Brazos Rv nr Highbank, TX	10/1/65-pres	Falls	BH (full)	BH: 23.8 mi DS	BH flow vs prod
8110200	BR at Washington, TX	08110200 Brazos Rv at Washington, TX	11/1/65-3/15/87	Brazos / Washington	BN (pre 1987)	BN: 2.56 mi US	BN flow vs prod
8111500	BR nr Hempstead, TX	08111500 Brazos Rv nr Hempstead, TX	10/1/38-pres	Waller / Washington	BN (except pre 1987), BS (full)	BN: 36.46 mi US, BS: 43.5 mi DS	BN flow vs prod, Daily mean discharge unavailable 09/30/88-09/30/00.
8114000	BR at Richmond, TX	08114000 Brazos Rv at Richmond, TX	1/1/1903-pres	Fort Bend	BW & BS (full)	BS: 60.6 mi US, BW: 32.34 mi US	BS flow vs prod
8176500	GR at Victoria, TX	08176500 Guadalupe Rv at Victoria, TX	12/1/1934-pres	Victoria	GN & GV (full)		GN & GV flow vs prod
8065000	TR nr Palestine, TX	08065000 Trinity Rv nr Oakwood, TX	10/1/1923-pres	Anderson	TP (full)	TP: mi US	TP flow vs prod

*US: upstream, DS: downstream; BH: Hearne, BN: Navasota, BS: San Felipe, GN: Nursery, GV: Victoria, TP: Palestine

Table 2. Completed Tree-Core Field Samples: Black Willow, Box Elder, and Sugarberry
Hearne, Navasota and San Felipe Study Sites

Study Site	Species	Flow Guild	Geomorphic Position	# Usable Cores
Hearne	Black Willow	lower swamp	crest and upper inside slope of first levee	25
	Box Elder	upper swamp	swale between first and second levees	38
	Sugarberry	temporarily flooded forest	floodplain flat beyond second levee	22
Navasota	Black Willow	lower swamp	crest and upper inside slope of first levee	29
	Box Elder	upper swamp	swale between first and second levees	26
	Sugarberry	temporarily flooded forest	elevated meander-belt flat beyond second levee	35
San Felipe *	Black Willow	lower swamp	swale between first and second levees	29
	Sugarberry	temporarily flooded forest	elevated meander-belt flat beyond second levee	26

* Fall-Winter 2018 flood prevented completion of sycamore sample (21 tree cores collected and measured)

Table 3. Master Chronologies: Annual Ring-Width Index
Hearne and Navasota Study Sites: Black Willow, Box Elder, and Sugarberry

Site & Species*	Sample Size		Master Chronologies: Annual Ring-Width Index (RWI)																								
	Trees	n	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
BHAN	38	20-38													1.00	0.94	0.96	1.13	0.74	0.67	0.85	0.69	0.91	0.95	1.20	1.32	1.57
BHSN	25	20-25																	1.33	0.96	1.06	0.77	0.84	0.79	0.97	1.10	1.23
BHCL	22	20-22	1.15	1.02	1.06	0.99	0.78	1.01	1.11	0.74	1.15	1.16	1.01	0.81	0.84	0.92	1.01	1.26	1.04	0.88	1.12	0.83	0.87	1.01	1.37	0.98	0.91
BNAN	26	20-26			1.19	1.28	0.99	0.76	0.81	0.96	0.93	1.29	1.73	1.07	0.78	0.86	0.80	1.00	1.08	0.86	0.81	1.02	0.78	0.89	1.11	0.94	1.13
BNSN	29	22-29								1.14	1.02	1.08	1.07	0.87	1.17	0.92	0.94	1.14	0.99	0.68	1.00	0.69	0.68	0.72	1.04	1.31	1.59
BNCL	35	21-35	0.94	0.60	0.46	0.60	0.58	0.89	0.61	0.63	0.79	1.44	1.65	1.77	1.52	1.37	1.04	1.26	1.37	0.88	0.85	0.40	0.94	0.73	1.24	0.89	1.13

* BH: Brazos-Hearne, BN: Brazos-Navasota

AN: Box Elder (*Acer negundo*), CL: Sugarberry (*Celtis laevigata*), SN: Black Willow (*Salix nigra*)

Table 4. Seasonal Correlations: Mean Discharge and Species Productivity
Hearne and Navasota Riparian Study Sites, Middle Brazos River, Texas

SEASONAL CORRELATIONS: MEAN DISCHARGE			n	Years	Total			Growing Season			Reprod. Critical			Winter			Spring			Summer			Fall		
					rho	pval	n	rho	pval	n	rho	pval	n	rho	pval	n	rho	pval	n	rho	pval	n	rho	pval	n
Brazos-Hearne Mean Daily Discharge	Current Year	Year	25	1992-2016	-0.19	0.3650	25	-0.09	0.6714	25	-0.32	0.1180	25	-0.39	0.0560	25	-0.19	0.3710	25	-0.20	0.3397	25	0.05	0.8181	25
		box elder	13	2004-2016	0.41	0.1680	13	0.38	0.2014	13	0.07	0.8166	13	0.15	0.6286	13	0.39	0.1876	13	**0.63**	**0.0205**	**13**	0.11	0.7208	13
		black willow	9	2008-2016	0.55	0.1250	9	0.62	0.0769	9	0.57	0.1116	9	0.27	0.4879	9	**0.70**	**0.0358**	**9**	**0.87**	**0.0025**	**9**	0.03	0.9322	9
		sugarberry	25	1992-2016	0.20	0.3454	25	0.24	0.2574	25	0.20	0.3474	25	0.06	0.7757	25	0.26	0.2094	25	0.30	0.1462	25	0.07	0.7506	25
	Current + Prior Year	Year	25	1992-2016	-0.25	0.2222	25	-0.16	0.4317	25	**-0.46**	**0.0200**	**25**	**-0.52**	**0.0078**	**25**	**-0.42**	**0.0366**	**25**	-0.19	0.3512	25	0.12	0.5753	25
		box elder	13	2004-2016	0.21	0.4936	13	0.18	0.5656	13	-0.38	0.1944	13	-0.02	0.9432	13	0.03	0.9290	13	0.37	0.2086	13	0.04	0.9007	13
		black willow	9	2008-2016	**0.70**	**0.0358**	**9**	**0.70**	**0.0358**	**9**	0.02	0.9661	9	-0.17	0.6682	9	0.55	0.1250	9	**0.80**	**0.0096**	**9**	0.43	0.2440	9
		sugarberry	25	1992-2016	0.12	0.5803	25	0.11	0.5981	25	0.11	0.5956	25	-0.12	0.5528	25	0.17	0.4080	25	0.13	0.5332	25	-0.14	0.5188	25
	Current + Prior 2 Yrs	Year	25	1992-2016	**-0.42**	**0.0355**	**25**	-0.24	0.2386	25	**-0.65**	**0.0004**	**25**	**-0.59**	**0.0017**	**25**	**-0.61**	**0.0012**	**25**	-0.19	0.3670	25	0.15	0.4788	25
		box elder	13	2004-2016	0.19	0.5567	12	0.08	0.8122	12	-0.38	0.2262	12	0.20	0.5419	12	-0.15	0.6488	12	0.36	0.2551	12	-0.36	0.2453	12
		black willow	9	2008-2016	**0.90**	**0.0020**	**8**	**0.93**	**0.0009**	**8**	-0.21	0.6103	8	-0.10	0.8225	8	0.57	0.1390	8	**0.86**	**0.0065**	**8**	0.45	0.2604	8
		sugarberry	25	1992-2016	0.03	0.8845	24	0.13	0.5599	24	-0.12	0.5682	24	-0.31	0.1422	24	-0.03	0.8845	24	0.16	0.4527	24	-0.18	0.4070	24
	Current + Prior 4 Yrs	Year	25	1992-2016	**-0.45**	**0.0377**	**22**	-0.04	0.8555	22	**-0.75**	**0.0001**	**22**	**-0.86**	**<0.0001**	**22**	**-0.63**	**0.0016**	**22**	0.03	0.8909	22	**0.44**	**0.0417**	**22**
		box elder	13	2004-2016	0.32	0.3655	10	0.30	0.4047	10	-0.60	0.0667	10	-0.02	0.9602	10	0.10	0.7770	10	0.28	0.4250	10	-0.61	0.0600	10
		black willow	9	2008-2016	0.14	0.7872	6	0.14	0.7872	6	-0.09	0.8717	6	0.60	0.2080	6	0.09	0.8717	6	0.20	0.7040	6	-0.43	0.3965	6
		sugarberry	25	1992-2016	0.00	0.9901	22	0.18	0.4225	22	-0.17	0.4374	22	-0.39	0.0691	22	-0.02	0.9304	22	0.20	0.3738	22	-0.12	0.5974	22
Brazos-Navasota Mean Monthly Discharge	Current Year	Year	16	2001-2016	-0.34	0.2160	16	-0.28	0.3147	16	-0.41	0.1247	16	**-0.55**	**0.0351**	**16**	-0.22	0.4354	16	-0.28	0.3083	16	-0.23	0.4126	16
		box elder	16	2001-2016	-0.06	0.8199	16	-0.13	0.6571	16	-0.15	0.5848	16	0.10	0.7134	16	-0.10	0.7325	16	0.13	0.6387	16	-0.07	0.8003	16
		black willow	16	2001-2016	**0.68**	**0.0058**	**16**	**0.62**	**0.0141**	**16**	0.27	0.3344	16	0.36	0.1866	16	**0.63**	**0.0121**	**16**	**0.84**	**0.0001**	**16**	0.51	0.0537	16
		sugarberry	16	2001-2016	0.36	0.1819	16	0.27	0.3344	16	0.36	0.1866	16	**0.58**	**0.0249**	**16**	0.35	0.1961	16	0.49	0.0620	16	0.16	0.5585	16
	Current + Prior Year	Year	16	2001-2016	-0.47	0.0880	15	-0.42	0.1351	15	**-0.67**	**0.0081**	**15**	**-0.81**	**0.0005**	**15**	-0.33	0.2531	15	-0.44	0.1138	15	-0.40	0.1590	15
		box elder	16	2001-2016	0.16	0.5733	15	0.18	0.5426	15	-0.01	0.9703	15	0.09	0.7708	15	0.16	0.5838	15	0.25	0.3919	15	0.03	0.9228	15
		black willow	16	2001-2016	**0.56**	**0.0389**	**15**	**0.53**	**0.0492**	**15**	0.07	0.8054	15	0.06	0.8286	15	0.52	0.0562	15	**0.64**	**0.0138**	**15**	**0.55**	**0.0408**	**15**
		sugarberry	16	2001-2016	0.47	0.0880	15	0.44	0.1138	15	0.31	0.2809	15	**0.55**	**0.0428**	**15**	0.31	0.2882	15	**0.56**	**0.0353**	**15**	0.33	0.2531	15
	Current + Prior 2 Yrs	Year	16	2001-2016	**-0.68**	**0.0112**	**14**	-0.51	0.0743	14	**-0.69**	**0.0087**	**14**	**-0.87**	**0.0001**	**14**	**-0.68**	**0.0112**	**14**	-0.41	0.1618	14	-0.34	0.2629	14
		box elder	16	2001-2016	0.02	0.9574	14	0.15	0.6158	14	-0.35	0.2387	14	-0.30	0.3249	14	0.08	0.8028	14	0.25	0.4048	14	0.21	0.4821	14
		black willow	16	2001-2016	0.52	0.0673	14	**0.57**	**0.0438**	**14**	-0.01	0.9716	14	0.20	0.5053	14	0.38	0.2014	14	**0.65**	**0.0153**	**14**	0.28	0.3538	14
		sugarberry	16	2001-2016	**0.68**	**0.0103**	**14**	**0.60**	**0.0287**	**14**	0.37	0.2159	14	**0.60**	**0.0287**	**14**	**0.64**	**0.0191**	**14**	**0.58**	**0.0390**	**14**	0.37	0.2086	14
	Current + Prior 4 Yrs	Year	16	2001-2016	**-0.74**	**0.0098**	**12**	-0.60	0.0510	12	**-0.85**	**0.0010**	**12**	**-0.97**	**<0.0001**	**12**	**-0.76**	**0.0062**	**12**	**-0.61**	**0.0467**	**12**	**-0.75**	**0.0073**	**12**
		box elder	16	2001-2016	-0.03	0.9366	12	-0.15	0.6696	12	0.07	0.8317	12	0.31	0.3550	12	-0.06	0.8525	12	-0.10	0.7699	12	0.26	0.4334	12
		black willow	16	2001-2016	**0.88**	**0.0003**	**12**	**0.77**	**0.0053**	**12**	**0.72**	**0.0128**	**12**	**0.87**	**0.0005**	**12**	**0.86**	**0.0006**	**12**	**0.81**	**0.0026**	**12**	**0.68**	**0.0208**	**12**
		sugarberry	16	2001-2016	**0.77**	**0.0053**	**12**	**0.64**	**0.0353**	**12**	**0.79**	**0.0037**	**12**	**0.95**	**<0.0001**	**12**	**0.78**	**0.0045**	**12**	**0.66**	**0.0260**	**12**	**0.74**	**0.0098**	**12**

Legend **rho:** Spearman's correlation coefficient, **pval:** *p*-value, **n_0 / n:** ratio of non-zero sample size (n_0) to total Sample size (n), with sample size = # of years or annual species RWI chronologies. Color and other table symbols are explained, and seasons defined, in Section 4.1.

Table 5. January-June Monthly Correlations: Mean Discharge Volume and Species Productivity
Hearne and Navasota Riparian Study Sites, Middle Brazos River, Texas

MONTHLY CORRELATIONS: MEAN DISCHARGE					**January**			**February**			**March**			**April**			**May**			**June**		
Riparian Productivity vs Flow			**n**	**Period**	**rho**	**pval**	**n**	**rho**	**pval**	**n**	**rho**	**pval**	**n**	**rho**	**pval**	**n**	**rho**	**pval**	**n**	**rho**	**pval**	**n**
Brazos-Hearne Mean Daily Discharge	**Current Year**	**Year**	25	1992-2016	-0.36	0.0738	25	-0.39	0.0534	25	-0.26	0.2066	25	-0.20	0.3378	25	-0.07	0.7423	25	-0.10	0.6396	25
		box elder	13	2004-2016	0.23	0.4593	13	-0.12	0.6940	13	0.20	0.5053	13	0.16	0.6031	13	0.51	0.0743	13	**0.64**	**0.0191**	**13**
		black willow	9	2008-2016	0.03	0.9322	9	0.15	0.7001	9	0.63	0.0671	9	**0.70**	**0.0358**	**9**	**0.83**	**0.0053**	**9**	**0.75**	**0.0199**	**9**
		sugarberry	25	1992-2016	0.09	0.6768	25	-0.01	0.9796	25	0.18	0.3831	25	0.19	0.3610	25	0.39	0.0519	25	0.34	0.0932	25
	Current + Prior Year	**Year**	25	1992-2016	**-0.59**	**0.0018**	**25**	**-0.54**	**0.0054**	**25**	**-0.46**	**0.0217**	**25**	-0.36	0.0813	25	-0.17	0.4038	25	-0.18	0.3851	25
		box elder	13	2004-2016	0.08	0.7890	13	-0.42	0.1497	13	-0.11	0.7208	13	-0.29	0.3344	13	0.18	0.5533	13	0.37	0.2159	13
		black willow	9	2008-2016	0.10	0.7980	9	-0.50	0.1705	9	-0.13	0.7324	9	0.42	0.2646	9	**0.85**	**0.0037**	**9**	**0.68**	**0.0424**	**9**
		sugarberry	25	1992-2016	-0.11	0.5879	25	0.02	0.9099	25	0.07	0.7230	25	0.09	0.6822	25	0.06	0.7841	25	0.12	0.5828	25
	Current + Prior 2 Years	**Year**	25	1992-2016	**-0.75**	**<0.0001**	**25**	**-0.61**	**0.0012**	**25**	**-0.64**	**0.0006**	**25**	**-0.47**	**0.0186**	**25**	-0.31	0.1275	25	-0.16	0.4538	25
		box elder	13	2004-2016	0.17	0.6021	12	-0.40	0.1993	12	0.16	0.6175	12	-0.48	0.1121	12	0.15	0.6331	12	0.45	0.1377	12
		black willow	9	2008-2016	-0.02	0.9554	8	-0.69	0.0580	8	-0.31	0.4556	8	0.38	0.3518	8	**0.93**	**0.0009**	**8**	**0.83**	**0.0102**	**8**
		sugarberry	25	1992-2016	-0.19	0.3728	24	-0.25	0.2396	24	-0.03	0.8941	24	-0.11	0.5989	24	0.01	0.9550	24	0.16	0.4502	24
	Current + Prior 4 Years	**Year**	25	1992-2016	**-0.84**	**<0.0001**	**22**	**-0.70**	**0.0003**	**22**	**-0.80**	**0.0000**	**22**	**-0.50**	**0.0188**	**22**	-0.25	0.2683	22	0.03	0.8988	22
		box elder	13	2004-2016	0.20	0.5796	10	**-0.70**	**0.0251**	**10**	-0.19	0.6032	10	-0.27	0.4458	10	0.39	0.2600	10	0.39	0.2600	10
		black willow	9	2008-2016	-0.26	0.6228	6	0.14	0.7872	6	0.54	0.2657	6	-0.09	0.8717	6	0.14	0.7872	6	0.20	0.7040	6
		sugarberry	25	1992-2016	-0.21	0.3548	22	-0.39	0.0754	22	-0.22	0.3260	22	-0.07	0.7588	22	0.06	0.7779	22	0.17	0.4374	22
Brazos-Navasota Mean Monthly Discharge	**Current Year**	**Year**	16	2001-2016	-0.41	0.1283	16	**-0.54**	**0.0396**	**16**	-0.38	0.1598	16	-0.38	0.1684	16	-0.06	0.8298	16	-0.16	0.5760	16
		box elder	16	2001-2016	0.25	0.3760	16	-0.11	0.7039	16	-0.10	0.7229	16	-0.09	0.7517	16	-0.01	0.9798	16	0.11	0.6945	16
		black willow	16	2001-2016	0.48	0.0687	16	0.23	0.4051	16	0.28	0.3083	16	0.46	0.0867	16	**0.76**	**0.0010**	**16**	**0.85**	**0.0001**	**16**
		sugarberry	16	2001-2016	0.43	0.1077	16	**0.52**	**0.0462**	**16**	0.42	0.1212	16	0.34	0.2212	16	0.24	0.3904	16	0.40	0.1435	16
	Current + Prior Year	**Year**	16	2001-2016	**-0.65**	**0.0114**	**15**	-0.45	0.1098	15	**-0.59**	**0.0260**	**15**	**-0.54**	**0.0470**	**15**	-0.08	0.7938	15	-0.14	0.6369	15
		box elder	16	2001-2016	0.36	0.2026	15	-0.30	0.3030	15	-0.17	0.5630	15	0.26	0.3748	15	0.15	0.6048	15	0.25	0.3833	15
		black willow	16	2001-2016	0.43	0.1263	15	-0.26	0.3664	15	0.02	0.9346	15	0.12	0.6806	15	**0.61**	**0.0197**	**15**	**0.68**	**0.0070**	**15**
		sugarberry	16	2001-2016	**0.66**	**0.0100**	**15**	-0.02	0.9346	15	0.35	0.2145	15	0.36	0.2085	15	0.18	0.5426	15	0.30	0.3030	15
	Current + Prior 2 Years	**Year**	16	2001-2016	**-0.76**	**0.0027**	**14**	-0.37	0.2086	14	**-0.75**	**0.0030**	**14**	-0.52	0.0707	14	-0.21	0.4936	14	-0.29	0.3344	14
		box elder	16	2001-2016	0.18	0.5533	14	**-0.60**	**0.0287**	**14**	-0.24	0.4262	14	0.19	0.5411	14	0.16	0.5905	14	0.25	0.4154	14
		black willow	16	2001-2016	**0.57**	**0.0438**	**14**	-0.25	0.4154	14	0.07	0.8166	14	-0.01	0.9858	14	**0.56**	**0.0463**	**14**	**0.74**	**0.0037**	**14**
		sugarberry	16	2001-2016	**0.76**	**0.0024**	**14**	-0.04	0.8866	14	**0.57**	**0.0438**	**14**	0.32	0.2799	14	0.38	0.2014	14	0.53	0.0607	14
	Current + Prior 4 Years	**Year**	16	2001-2016	**-0.83**	**0.0017**	**12**	-0.54	0.0890	12	**-0.91**	**0.0001**	**12**	-0.49	0.1252	12	-0.42	0.2006	12	-0.35	0.2981	12
		box elder	16	2001-2016	0.17	0.6115	12	0.18	0.5926	12	0.07	0.8317	12	-0.15	0.6696	12	-0.18	0.5926	12	-0.09	0.7904	12
		black willow	16	2001-2016	**0.91**	**0.0001**	**12**	0.20	0.5554	12	**0.79**	**0.0037**	**12**	0.52	0.1025	12	**0.70**	**0.0165**	**12**	**0.69**	**0.0186**	**12**
		sugarberry	16	2001-2016	**0.86**	**0.0006**	**12**	0.45	0.1697	12	**0.89**	**0.0002**	**12**	0.45	0.1601	12	0.49	0.1252	12	0.45	0.1601	12

Legend **n:** total sample size (# of years or annual species RWI chronologies), **rho:** Spearman's correlation coefficient, **pval:** *p*-value. Color and other table coding are explained in Section 4.1.

Table 6. July-December Monthly Correlations: Mean Discharge Volume and Species Productivity
Hearne and Navasota Riparian Study Sites, Middle Brazos River, Texas

MONTHLY CORRELATIONS: MEAN DISCHARGE					**July**			**August**			**September**			**October**			**November**			**December**		
Riparian Productivity vs Flow			**n**	**Period**	**rho**	**pval**	**n**	**rho**	**pval**	**n**	**rho**	**pval**	**n**	**rho**	**pval**	**n**	**rho**	**pval**	**n**	**rho**	**pval**	**n**
Brazos-Hearne **Mean Daily Discharge**	**Current Year**	**Year**	25	1992-2016	-0.22	0.2976	25	-0.34	0.1012	25	-0.19	0.3710	25	0.06	0.7841	25	-0.15	0.4765	25	**-0.41**	**0.0393**	**25**
		box elder	13	2004-2016	0.55	0.0518	13	0.37	0.2159	13	0.07	0.8305	13	-0.16	0.6031	13	0.11	0.7208	13	-0.10	0.7343	13
		black willow	9	2008-2016	0.50	0.1705	9	**0.90**	**0.0009**	**9**	0.27	0.4879	9	-0.13	0.7324	9	0.07	0.8647	9	0.47	0.2054	9
		sugarberry	25	1992-2016	0.15	0.4605	25	0.19	0.3750	25	0.02	0.9128	25	-0.05	0.8096	25	0.02	0.9186	25	-0.02	0.9157	25
	Current + Prior Year	**Year**	25	1992-2016	-0.14	0.5116	25	**-0.45**	**0.0257**	**25**	-0.15	0.4881	25	0.33	0.1037	25	-0.07	0.7534	25	**-0.56**	**0.0034**	**25**
		box elder	13	2004-2016	0.29	0.3344	13	-0.03	0.9290	13	-0.40	0.1809	13	0.07	0.8166	13	0.25	0.4048	13	0.03	0.9149	13
		black willow	9	2008-2016	**0.75**	**0.0199**	**9**	**0.68**	**0.0424**	**9**	0.03	0.9322	9	0.22	0.5755	9	0.35	0.3558	9	-0.10	0.7980	9
		sugarberry	25	1992-2016	0.09	0.6714	25	-0.03	0.9012	25	-0.03	0.8983	25	-0.19	0.3571	25	-0.12	0.5703	25	-0.15	0.4742	25
	Current + Prior 2 Years	**Year**	25	1992-2016	-0.08	0.6930	25	**-0.47**	**0.0169**	**25**	0.01	0.9505	25	0.29	0.1574	25	-0.04	0.8494	25	**-0.61**	**0.0012**	**25**
		box elder	13	2004-2016	0.20	0.5273	12	0.03	0.9312	12	-0.56	0.0586	12	-0.33	0.2969	12	0.24	0.4433	12	0.17	0.5868	12
		black willow	9	2008-2016	**0.90**	**0.0020**	**8**	0.64	0.0856	8	-0.26	0.5309	8	0.52	0.1827	8	**0.71**	**0.0465**	**8**	0.14	0.7358	8
		sugarberry	25	1992-2016	0.10	0.6420	24	-0.18	0.4070	24	-0.18	0.4023	24	-0.20	0.3574	24	-0.18	0.4093	24	-0.27	0.1997	24
	Current + Prior 4 Years	**Year**	25	1992-2016	0.07	0.7702	22	**-0.60**	**0.0031**	**22**	0.21	0.3442	22	**0.59**	**0.0040**	**22**	-0.07	0.7511	22	**-0.66**	**0.0008**	**22**
		box elder	13	2004-2016	-0.03	0.9338	10	-0.12	0.7514	10	-0.44	0.2004	10	-0.49	0.1497	10	0.37	0.2931	10	0.08	0.8287	10
		black willow	9	2008-2016	-0.31	0.5441	6	-0.09	0.8717	6	-0.37	0.4685	6	-0.43	0.3965	6	0.14	0.7872	6	0.43	0.3965	6
		sugarberry	25	1992-2016	0.23	0.3085	22	-0.27	0.2316	22	0.07	0.7549	22	-0.05	0.8281	22	-0.30	0.1718	22	-0.29	0.1874	22
Brazos-Navasota **Mean Monthly Discharge**	**Current Year**	**Year**	16	2001-2016	-0.24	0.3977	16	-0.35	0.1961	16	-0.39	0.1515	16	-0.31	0.2655	16	-0.15	0.5848	15	**-0.53**	**0.0428**	**16**
		box elder	16	2001-2016	0.07	0.8003	16	-0.03	0.9095	16	-0.06	0.8199	16	-0.09	0.7420	16	0.14	0.6115	15	0.46	0.0839	16
		black willow	16	2001-2016	**0.78**	**0.0006**	**16**	**0.55**	**0.0323**	**16**	0.43	0.1110	16	0.21	0.4588	16	**0.54**	**0.0396**	**15**	0.39	0.1475	16
		sugarberry	16	2001-2016	0.42	0.1212	16	0.37	0.1728	16	0.30	0.2773	16	0.20	0.4668	16	0.22	0.4277	15	**0.66**	**0.0073**	**16**
	Current + Prior Year	**Year**	16	2001-2016	-0.41	0.1443	15	**-0.62**	**0.0186**	**15**	-0.45	0.1022	15	-0.46	0.0949	15	-0.24	0.4006	14	**-0.68**	**0.0070**	**15**
		box elder	16	2001-2016	0.31	0.2738	15	0.04	0.8873	15	0.22	0.4549	15	-0.05	0.8755	15	0.13	0.6696	14	0.11	0.7028	15
		black willow	16	2001-2016	**0.71**	**0.0048**	**15**	0.42	0.1351	15	0.21	0.4643	15	0.31	0.2882	15	**0.54**	**0.0449**	**14**	0.18	0.5426	15
		sugarberry	16	2001-2016	**0.58**	**0.0304**	**15**	**0.56**	**0.0353**	**15**	0.17	0.5528	15	0.27	0.3581	15	0.36	0.2026	14	0.51	0.0612	15
	Current + Prior 2 Years	**Year**	16	2001-2016	**-0.56**	**0.0463**	**14**	**-0.63**	**0.0220**	**14**	-0.30	0.3249	14	-0.46	0.1173	14	-0.36	0.2309	13	**-0.77**	**0.0021**	**14**
		box elder	16	2001-2016	0.13	0.6808	14	0.02	0.9432	14	0.10	0.7343	14	0.10	0.7343	14	-0.06	0.8445	13	-0.25	0.4048	14
		black willow	16	2001-2016	0.52	0.0673	14	0.49	0.0899	14	-0.03	0.9290	14	0.02	0.9574	14	0.41	0.1618	13	0.40	0.1809	14
		sugarberry	16	2001-2016	**0.63**	**0.0220**	**14**	**0.64**	**0.0178**	**14**	0.05	0.8725	14	0.22	0.4706	14	0.49	0.0899	13	**0.60**	**0.0306**	**14**
	Current + Prior 4 Years	**Year**	16	2001-2016	**-0.56**	**0.0710**	**12**	**-0.61**	**0.0467**	**12**	-0.35	0.2981	12	-0.27	0.4171	12	-0.55	0.0767	11	**-0.91**	**0.0001**	**12**
		box elder	16	2001-2016	-0.09	0.7904	12	-0.12	0.7293	12	-0.22	0.5192	12	-0.19	0.5739	12	0.31	0.3550	11	0.31	0.3550	12
		black willow	16	2001-2016	**0.79**	**0.0037**	**12**	**0.77**	**0.0053**	**12**	0.39	0.2345	12	0.06	0.8525	12	0.59	0.0556	11	**0.82**	**0.0021**	**12**
		sugarberry	16	2001-2016	0.60	0.0510	12	**0.65**	**0.0320**	**12**	0.29	0.3855	12	0.18	0.5926	12	**0.61**	**0.0467**	**11**	**0.89**	**0.0021**	**12**

Legend — **n:** total sample size (# of years or annual species RWI chronologies), **rho:** Spearman's correlation coefficient, **pval:** *p*-value. Color and other table coding are explained in Section 4.1.

Table 7. January-June Monthly Correlations: Overbank Event Frequency and Species Productivity
Hearne and Navasota Riparian Study Sites, Middle Brazos River, Texas

MONTHLY CORRELATIONS: OVERBANK EVENT FREQUENCY					**January**			**February**			**March**			**April**			**May**			**June**		
Riparian Productivity vs Flow			**n**	**Period**	**rho**	**pval**	**n_0 / n**	**rho**	**pval**	**n_0 / n**	**rho**	**pval**	**n_0 / n**	**rho**	**pval**	**n_0 / n**	**rho**	**pval**	**n_0 / n**	**rho**	**pval**	**n_0 / n**
Brazos-Hearne Mean Daily Discharge	**Current Year**	**Year**	25	1992-2016	-0.34	0.0967	1/25	-0.38	0.0580	2/25	0.20	0.3419	3/25	ND	ND	0/25	0.28	0.1761	2/25	0.08	0.6865	1/25
		box elder	13	2004-2016	ND	ND	0/13	ND	ND	0/13	0.23	0.4539	2/13	ND	ND	0/13	0.45	0.1271	2/13	0.23	0.4467	1/13
		black willow	9	2008-2016	ND	ND	0/9	ND	ND	0/9	0.10	0.7910	2/9	ND	ND	0/9	0.27	0.4758	1/9	ND	ND	0/9
		sugarberry	25	1992-2016	0.23	0.2764	1/25	0.14	0.5179	2/25	-0.21	0.3027	3/25	ND	ND	0/25	0.17	0.4031	2/25	0.31	0.1297	1/25
	Current + Prior Year	**Year**	25	1992-2016	**-0.47**	**0.0177**	**2/25**	**-0.53**	**0.0064**	**4/25**	0.17	0.4247	5/25	ND	ND	0/25	**0.43**	**0.0307**	**4/25**	0.14	0.4949	2/25
		box elder	13	2004-2016	ND	ND	0/13	ND	ND	0/13	0.20	0.5228	3/13	ND	ND	0/13	0.36	0.2309	4/13	-0.06	0.8533	2/13
		black willow	9	2008-2016	ND	ND	0/9	ND	ND	0/9	-0.18	0.6382	3/9	ND	ND	0/9	**0.84**	**0.0049**	**3/9**	0.55	0.1269	1/9
		sugarberry	25	1992-2016	0.22	0.2797	2/25	0.23	0.2604	4/25	-0.08	0.7216	5/25	ND	ND	0/25	0.13	0.5254	4/25	0.31	0.1359	2/25
	Current + Prior 2 Years	**Year**	25	1992-2016	**-0.56**	**0.0034**	**3/25**	**-0.63**	**0.0007**	**6/25**	0.16	0.4338	7/25	ND	ND	0/25	0.30	0.1487	6/25	0.20	0.3260	3/25
		box elder	13	2004-2016	ND	ND	0/12	ND	ND	0/12	0.26	0.4218	4/12	ND	ND	0/12	0.16	0.6158	5/12	-0.20	0.5434	3/12
		black willow	9	2008-2016	ND	ND	0/8	ND	ND	0/8	-0.44	0.2797	4/8	ND	ND	0/8	**0.82**	**0.0117**	**3/8**	0.41	0.3100	1/8
		sugarberry	25	1992-2016	0.22	0.3066	2/24	-0.01	0.9750	5/24	-0.21	0.3261	7/24	ND	ND	0/24	0.32	0.1255	5/24	0.26	0.2127	3/24
	Current + Prior 4 Years	**Year**	25	1992-2016	**-0.50**	**0.0182**	**2/22**	**-0.77**	**<0.0001**	**7/22**	-0.04	0.8682	10/22	ND	ND	0/22	**0.52**	**0.0124**	**7/22**	0.30	0.1762	5/22
		box elder	13	2004-2016	ND	ND	0/10	ND	ND	0/10	0.30	0.3972	5/10	ND	ND	0/10	0.07	0.8567	7/10	-0.17	0.6305	5/10
		black willow	9	2008-2016	ND	ND	0/6	ND	ND	0/6	0.68	0.1404	5/6	ND	ND	0/6	-0.31	0.5518	3/6	-0.65	0.1583	1/6
		sugarberry	25	1992-2016	-0.22	0.3156	2/22	-0.25	0.2700	7/22	-0.05	0.8162	10/22	ND	ND	0/22	**0.44**	**0.0383**	**7/22**	0.35	0.1098	5/22
Brazos-Navasota Mean Daily Discharge	**Current Year**	**Year**	9	1992-2000	-0.22	0.6036	2/9	-0.33	0.4287	2/9	-0.17	0.6848	2/9	0.25	0.5546	1/9	ND	ND	0/9	ND	ND	0/9
		box elder	7	1994-2000	-0.39	0.4411	1/7	-0.65	0.1583	1/7	-0.65	0.1583	1/7	-0.65	0.1583	1/7	ND	ND	0/7	ND	ND	0/7
		sugarberry	9	1992-2000	0.55	0.1619	2/9	**0.76**	**0.0274**	**2/9**	**0.73**	**0.0387**	**2/9**	0.41	0.3100	1/9	ND	ND	0/9	ND	ND	0/9
	Current + Prior Year	**Year**	9	1992-2000	-0.32	0.4408	4/9	-0.46	0.2481	4/9	0.05	0.9037	4/9	0.50	0.2029	2/9	ND	ND	0/9	ND	ND	0/9
		box elder	7	1994-2000	-0.41	0.4144	2/7	**-0.83**	**0.0418**	**2/7**	**-0.83**	**0.0418**	**2/7**	**-0.83**	**0.0418**	**2/7**	ND	ND	0/7	ND	ND	0/7
		sugarberry	9	1992-2000	0.47	0.2371	4/9	0.49	0.2192	4/9	0.54	0.1671	4/9	0.38	0.3559	2/9	ND	ND	0/9	ND	ND	0/9
	Current + Prior 2 Years	**Year**	9	1992-2000	-0.39	0.3832	5/8	-0.38	0.4032	5/8	0.64	0.1196	5/8	**0.87**	**0.0117**	**3/8**	ND	ND	0/8	ND	ND	0/8
		box elder	7	1994-2000	-0.58	0.3081	3/6	-0.87	0.0577	3/6	-0.87	0.0577	3/6	-0.87	0.0577	3/6	ND	ND	0/6	ND	ND	0/6
		sugarberry	9	1992-2000	0.30	0.5142	5/8	0.28	0.5379	5/8	0.51	0.2420	5/8	0.43	0.3318	3/8	ND	ND	0/8	ND	ND	0/8
	Current + Prior 4 Years	**Year**	9	1992-2000	-0.67	0.2189	5/6	-0.87	0.0577	6/6	0.87	0.0577	6/6	0.87	0.0577	4/6	ND	ND	0/6	ND	ND	0/6
		box elder	7	1994-2000	0.87	0.3333	3/4	ID	ID	4/4	ID	ID	4/4	ID	ID	4/4	ND	ND	0/4	ND	ND	0/4
		sugarberry	9	1992-2000	-0.21	0.7406	5/6	-0.29	0.6376	6/6	0.29	0.6376	6/6	0.29	0.6376	4/6	ND	ND	0/6	ND	ND	0/6

Legend **rho:** Spearman's correlation coefficient, **pval:** *p*-value, **n_0 / n:** ratio of non-zero sample size (n_0) to total sample size (n), with sample size = # of years or annual species RWI chronologies. Color and other table symbols are explained, and seasons defined, in Section 4.1.

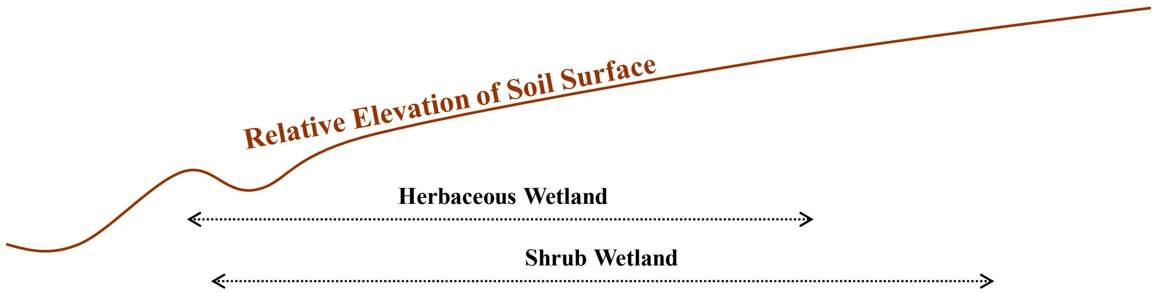
Table 8. July-December Monthly Correlations: Overbank Event Frequency and Species Productivity
Hearne and Navasota Riparian Study Sites, Middle Brazos River, Texas

MONTHLY CORRELATIONS: OVERBANK EVENT FREQUENCY					**July**			**August**			**September**			**October**			**November**			**December**		
Riparian Productivity vs Flow			**n**	**Period**	**rho**	**pval**	**n_0 / n**	**rho**	**pval**	**n_0 / n**	**rho**	**pval**	**n_0 / n**	**rho**	**pval**	**n_0 / n**	**rho**	**pval**	**n_0 / n**	**rho**	**pval**	**n_0 / n**
Brazos-Hearne Mean Daily Discharge	**Current Year**	**Year**	25	1992-2016	0.08	0.6865	1/25	ND	ND	0/25	ND	ND	0/25	0.31	0.1297	1/25	0.22	0.3004	2/25	-0.29	0.1535	2/25
		box elder	13	2004-2016	0.23	0.4467	1/13	ND	ND	0/13	ND	ND	0/13	0.39	0.1930	1/13	0.38	0.1947	2/13	ND	ND	0/13
		black willow	9	2008-2016	ND	ND	0/9	ND	ND	0/9	ND	ND	0/9	0.27	0.4758	1/9	0.27	0.4758	1/9	ND	ND	0/9
		sugarberry	25	1992-2016	0.31	0.1297	1/25	ND	ND	0/25	ND	ND	0/25	-0.08	0.6865	1/25	-0.23	0.2713	2/25	0.21	0.3156	2/25
	Current + Prior Year	**Year**	25	1992-2016	0.14	0.4949	2/25	ND	ND	0/25	ND	ND	0/25	**0.47**	**0.0177**	**2/25**	0.34	0.1014	4/25	**-0.42**	**0.0386**	**4/25**
		box elder	13	2004-2016	-0.06	0.8533	2/13	ND	ND	0/13	ND	ND	0/13	**0.63**	**0.0219**	**2/13**	0.46	0.1153	4/13	ND	ND	0/13
		black willow	9	2008-2016	0.55	0.1269	1/9	ND	ND	0/9	ND	ND	0/9	0.52	0.1536	2/9	0.52	0.1536	2/9	ND	ND	0/9
		sugarberry	25	1992-2016	0.31	0.1359	2/25	ND	ND	0/25	ND	ND	0/25	-0.16	0.4346	2/25	-0.31	0.1365	4/25	0.07	0.7462	4/25
	Current + Prior 2 Years	**Year**	25	1992-2016	0.20	0.3260	3/25	ND	ND	0/25	ND	ND	0/25	**0.47**	**0.0177**	**2/25**	0.32	0.1145	5/25	**-0.51**	**0.0093**	**6/25**
		box elder	13	2004-2016	-0.20	0.5434	3/12	ND	ND	0/12	ND	ND	0/12	**0.65**	**0.0228**	**2/12**	0.54	0.0730	4/12	ND	ND	0/12
		black willow	9	2008-2016	0.41	0.3100	1/8	ND	ND	0/8	ND	ND	0/8	0.63	0.0941	2/8	0.63	0.0941	2/8	ND	ND	0/8
		sugarberry	25	1992-2016	0.26	0.2127	3/24	ND	ND	0/24	ND	ND	0/24	0.15	0.4770	2/24	-0.25	0.2334	5/24	0.00	0.9886	5/24
	Current + Prior 4 Years	**Year**	25	1992-2016	0.30	0.1762	5/22	ND	ND	0/22	ND	ND	0/22	**0.50**	**0.0182**	**2/22**	0.28	0.2146	7/22	**-0.48**	**0.0254**	**7/22**
		box elder	13	2004-2016	-0.17	0.6305	5/10	ND	ND	0/10	ND	ND	0/10	**0.70**	**0.0253**	**2/10**	0.36	0.3100	4/10	ND	ND	0/10
		black willow	9	2008-2016	-0.65	0.1583	1/6	ND	ND	0/6	ND	ND	0/6	0.41	0.4144	2/6	0.41	0.4144	2/6	ND	ND	0/6
		sugarberry	25	1992-2016	0.35	0.1098	5/22	ND	ND	0/22	ND	ND	0/22	0.22	0.3156	2/22	-0.13	0.5512	7/22	-0.27	0.2230	7/22
Brazos-Navasota Mean Daily Discharge	**Current Year**	**Year**	9	1992-2000	ND	ND	0/9	ND	ND	0/9	ND	ND	0/9	0.19	0.6574	2/8	0.41	0.3100	1/8	-0.58	0.1340	1/9
		box elder	7	1994-2000	ND	ND	0/7	ND	ND	0/7	ND	ND	0/7	-0.10	0.8484	2/6	-0.39	0.4411	1/6	ND	ND	0/7
		sugarberry	9	1992-2000	ND	ND	0/9	ND	ND	0/9	ND	ND	0/9	-0.31	0.4523	2/8	0.08	0.8461	1/8	0.58	0.1340	1/9
	Current + Prior Year	**Year**	9	1992-2000	ND	ND	0/9	ND	ND	0/9	ND	ND	0/9	0.62	0.1030	4/8	**0.76**	**0.0300**	**2/8**	**-0.76**	**0.0300**	**9/9**
		box elder	7	1994-2000	ND	ND	0/7	ND	ND	0/7	ND	ND	0/7	0.00	1.0000	4/6	-0.41	0.4144	2/6	ID	ID	7/7
		sugarberry	9	1992-2000	ND	ND	0/9	ND	ND	0/9	ND	ND	0/9	-0.05	0.9037	4/8	0.25	0.5472	2/8	0.25	0.5472	9/9
	Current + Prior 2 Years	**Year**	9	1992-2000	ND	ND	0/8	ND	ND	0/8	ND	ND	0/8	0.66	0.1056	5/7	**0.79**	**0.0343**	**2/7**	**-0.79**	**0.0343**	**8/8**
		box elder	7	1994-2000	ND	ND	0/6	ND	ND	0/6	ND	ND	0/6	-0.26	0.6684	4/5	-0.58	0.3081	2/5	ID	ID	6/6
		sugarberry	9	1992-2000	ND	ND	0/8	ND	ND	0/8	ND	ND	0/8	-0.19	0.6849	5/7	0.32	0.4896	2/7	0.00	1.0000	8/8
	Current + Prior 4 Years	**Year**	9	1992-2000	ND	ND	0/6	ND	ND	0/6	ND	ND	0/6	0.78	0.1176	5/5	0.87	0.0577	2/5	-0.87	0.0577	6/6
		box elder	7	1994-2000	ND	ND	0/4	ND	ND	0/4	ND	ND	0/4	1.00	0.0000	3/3	0.87	0.3333	2/3	ID	ID	4/4
		sugarberry	9	1992-2000	ND	ND	0/6	ND	ND	0/6	ND	ND	0/6	0.45	0.4502	5/5	0.58	0.3081	2/5	-0.29	0.6376	6/6

Legend: **rho:** Spearman’s correlation coefficient, **pval:** *p*-value, **n_0 / n:** ratio of non-zero sample size (n_0) to total sample size (n), with sample size = # of years or annual species RWI chronologies. Color and other table symbols are explained, and seasons defined, in Section 4.1.

Appendix B: Figures

Figure 1. Riparian Species-Flow Guilds, Middle and Lower Brazos River Basin



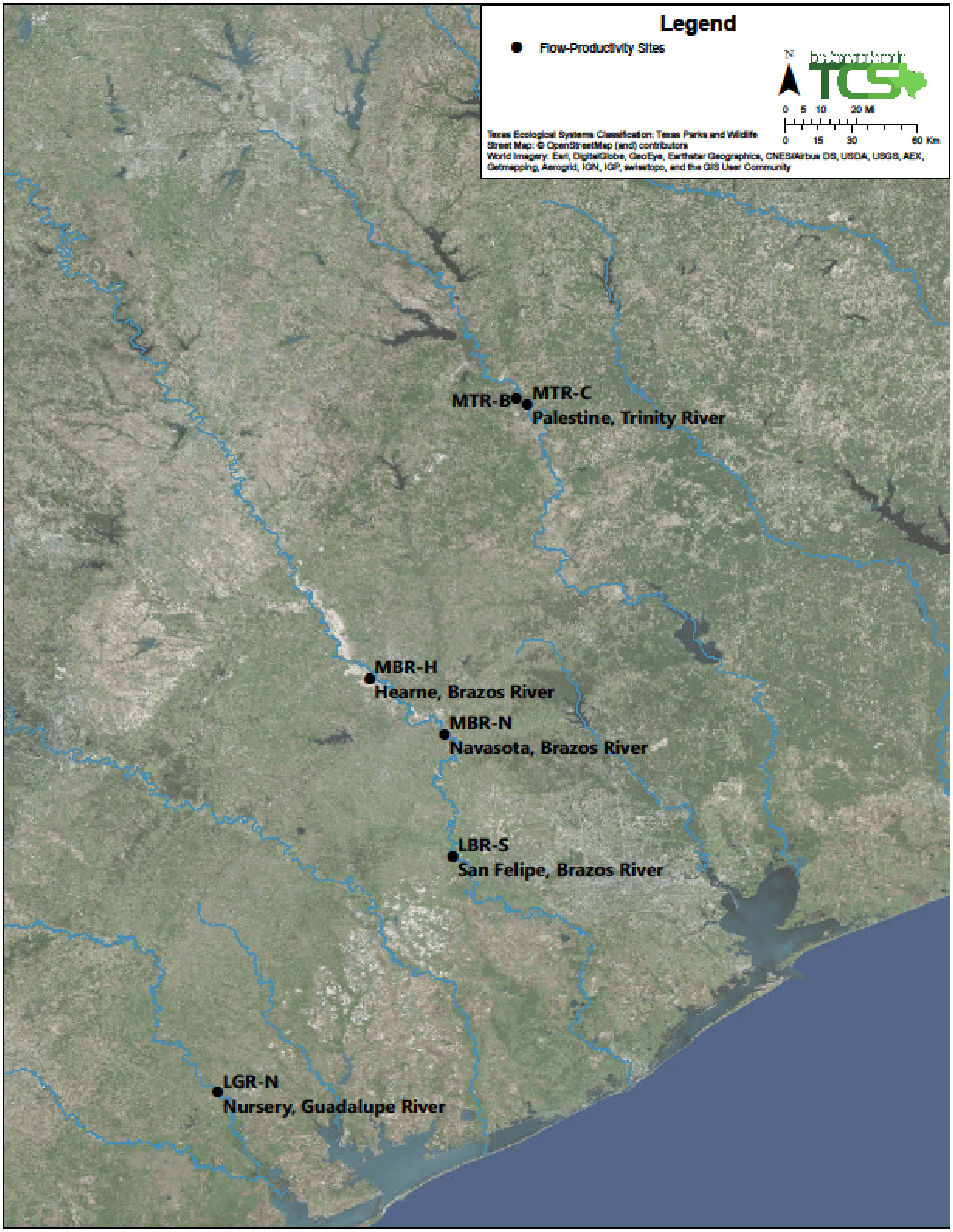
Bottomland Habitat Types [1]:	**Stream & Other Open Water**	**Forested Wetland**		**Riparian Forest**		**Transition to Uplands**
		Lower Swamp (Streamside)	**Upper Swamp** (Between 1st & 2nd Levees)	**Seasonally Flooded Forest** (Low flats & backwater areas)	**Temporarily Flooded Forest** (High flats)	
Common Tree Species (In overall order of importance):	None	Black willow Boxelder	Boxelder Green ash Black willow Slippery elm	Eastern cottonwood Boxelder Green ash Slippery Elm Sugarberry	Eastern cottonwood Slippery elm Rough-leaf dogwood Sugarberry	Rough-leaf dogwood Sugarberry Cedar elm Chinaberry Post oak Eastern red cedar
Hydrologic Regime [2]:	Permanently Flooded	Intermittently exposed	Frequently flooded	Seasonally flooded	Temporarily flooded	Intermittently flooded
Flood Frequency-percent of years [2]:	100%	~ 100%	51-100%	51-100%	11-50%	1-10%
Growing-Season Inundation + Soil Saturation, total duration [2]:	100% (~ 8 mos.)	>50% (>4 mos.)	>25% (> 2 mos.)	12.5-25% (1-2 mos.)	2-12.5% (5-30 days)	< 2% (< 5 days)

Footnotes: [1] Diamond, D. 2009. FIA Bottomland Summary: East Texas. Unpub. document, Missouri Resource Assessment Partnership, School of Natural Resources, U. Mo. - Columbia.

[2] Huffman, T., and S.W. Forsythe. 1981. Bottomland hardwood forest communities and their relation to anaerobic soil communities. <u>in</u>: Clark, J.R., and J. Benforado. Wetlands of Bottomland Hardwood Forests, Elsevier Scientific Pub. Co., New York, N.Y., pp. 187-196.

Figure created by T. Hayes, 2015

Figure 2. Site Locations, Three-Basin Riparian Productivity Study.



Texas Ecological Systems Classification: Texas Parks and Wildlife
Street Map: © OpenStreetMap (and) contributors
World Imagery: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 3. Black Willow Lower-Swamp Flow Guild, Hearne Riparian Study Site
Middle Brazos River, Three-Basin Riparian Productivity Study, 05/13/17

Figure 4. Black Willow-Box Elder Upper-Swamp Flow Guild
Hearne Riparian Study Site, Middle Brazos River, 05/17/17

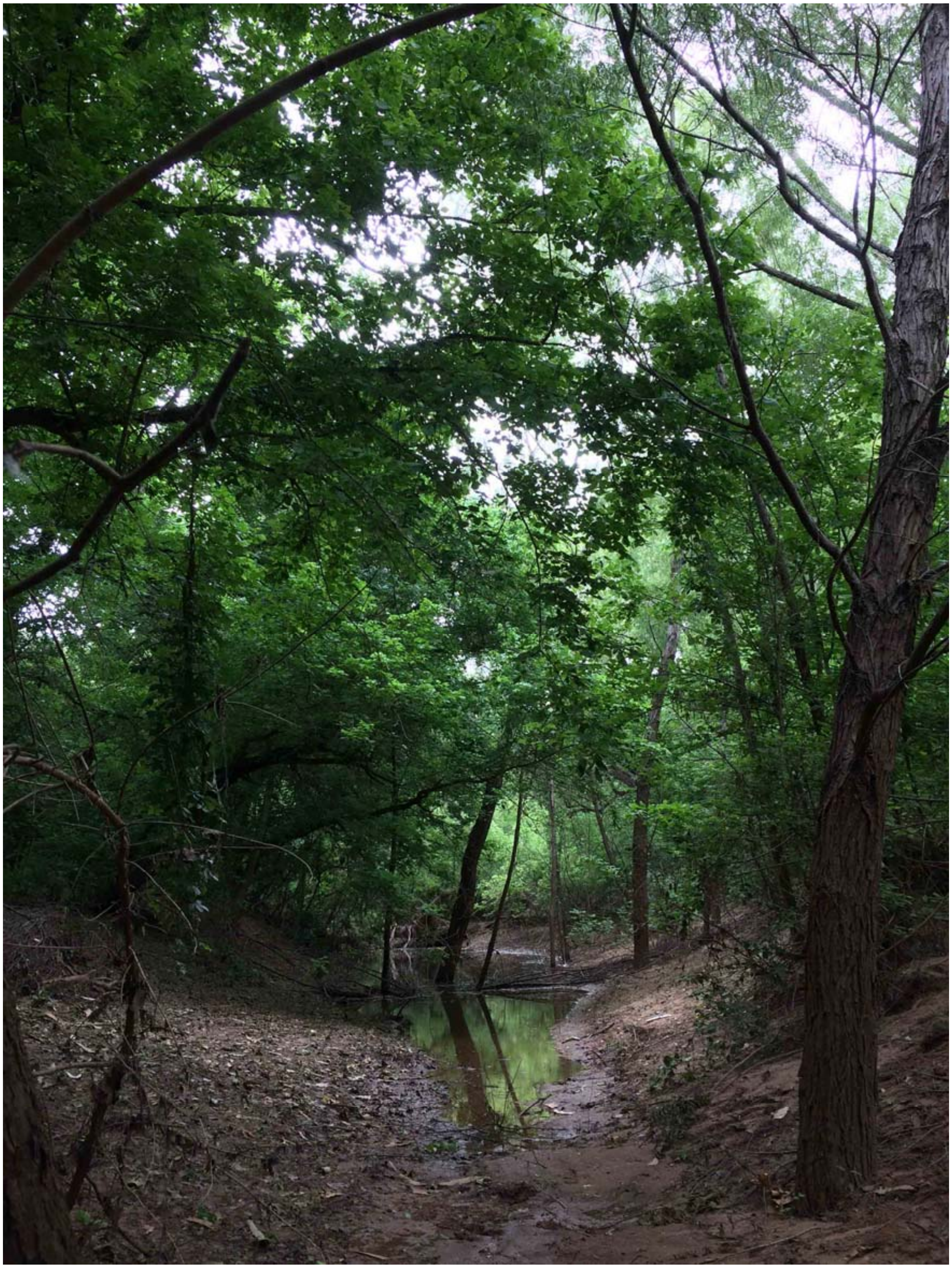
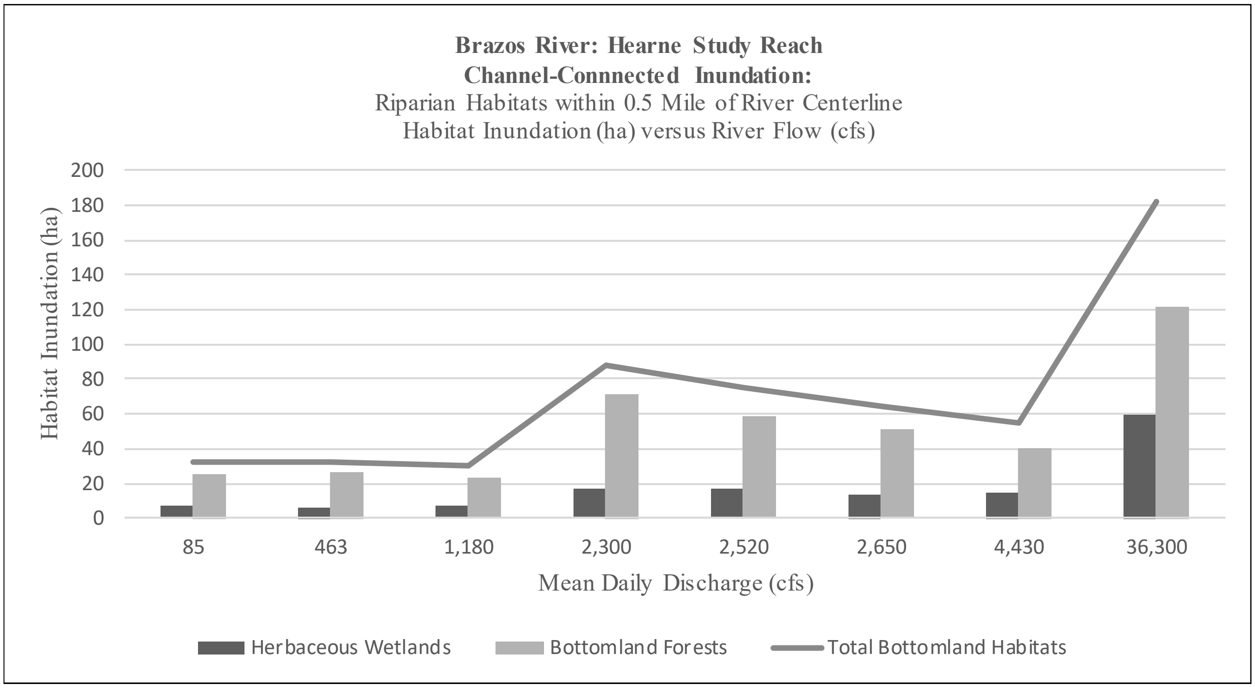


Figure 5. Backwater Slough Prior to Winter 2018-2019 Flood
San Felipe Riparian Study Site, Lower Brazos River, 04/24/18

Figure 6. Backwater Slough, Initiation of Winter 2018-2019 Flood
San Felipe Riparian Study Site, 10/18/18

Figure 7. Tree-Core Mounting, Three-Basin Riparian Productivity Study.

Figure 8. Channel-Connected and Total Habitat Inundation: Hearne Study Reach (adapted from Hayes 2016a)



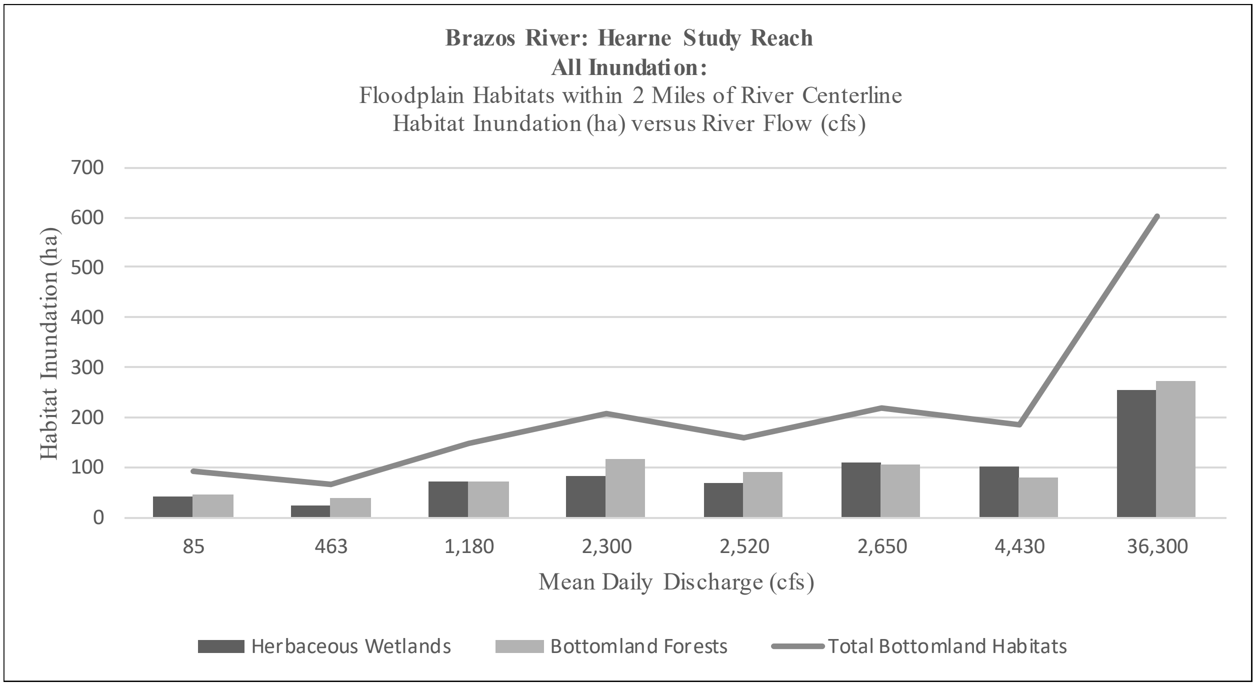
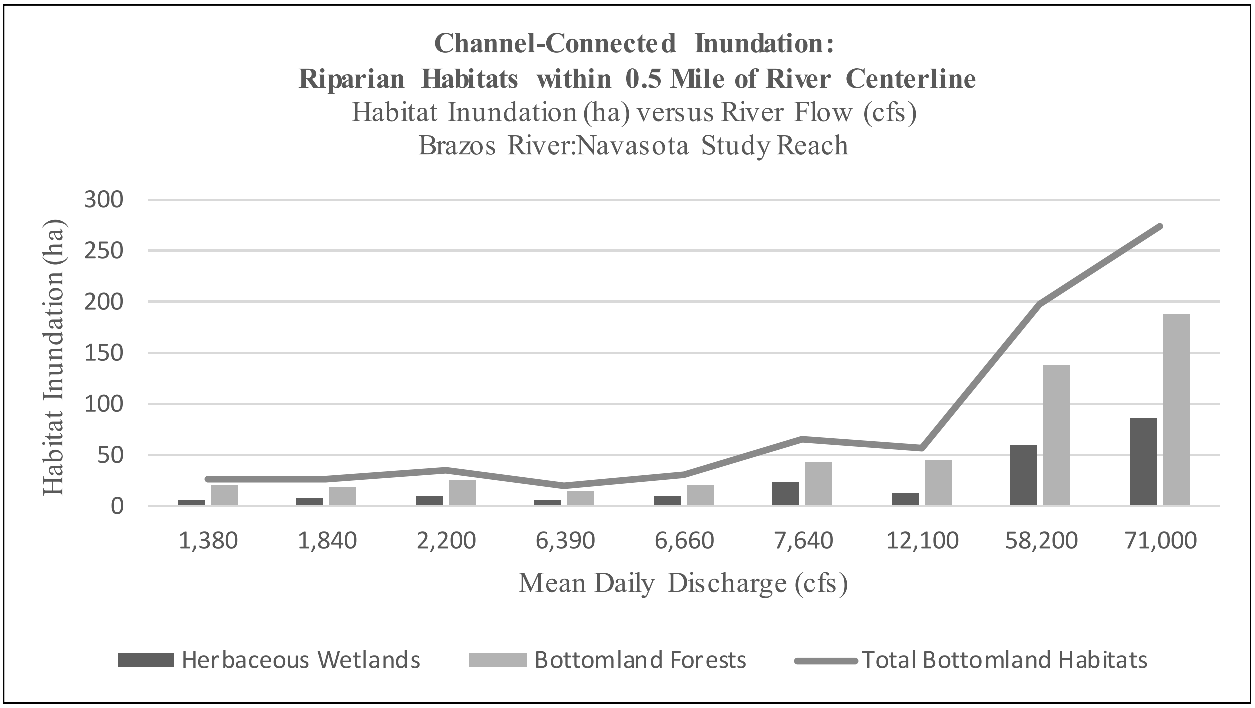


Figure 9. Channel-Connected and Total Habitat Inundation: Navasota Study Reach (adapted from Hayes 2016b)



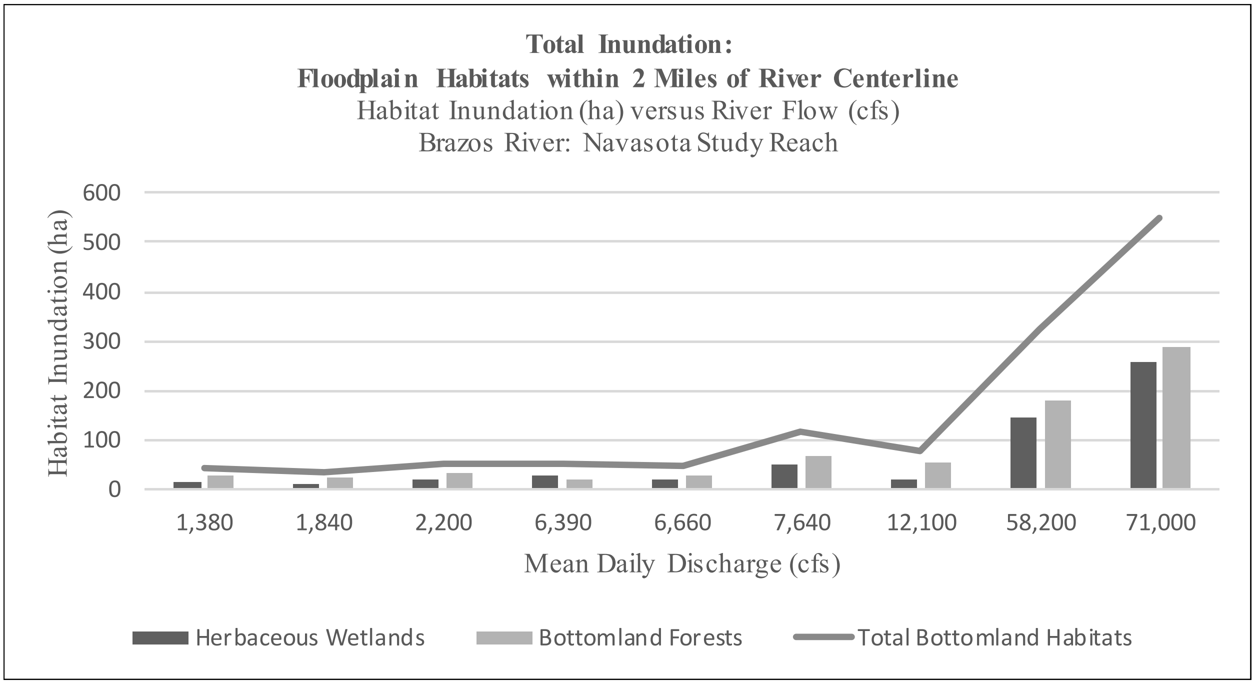


Figure 10. Current-Year Seasonal Flow Volumes: 1992-2016
Hearne Riparian Study Site

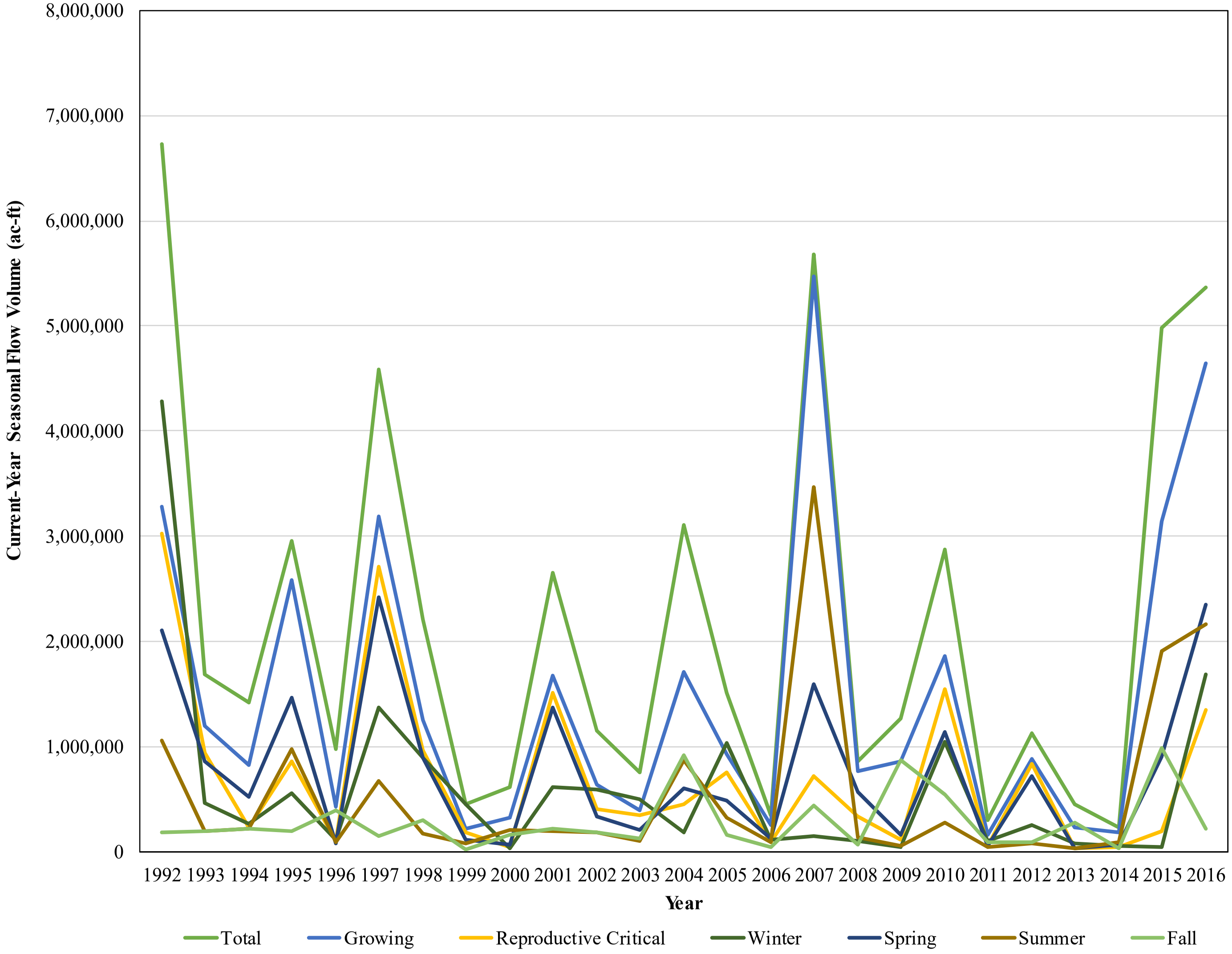


Figure 11. Current-Year Seasonal Flow Volumes (ac-ft): 2001-2016
Navasota Riparian Study Site

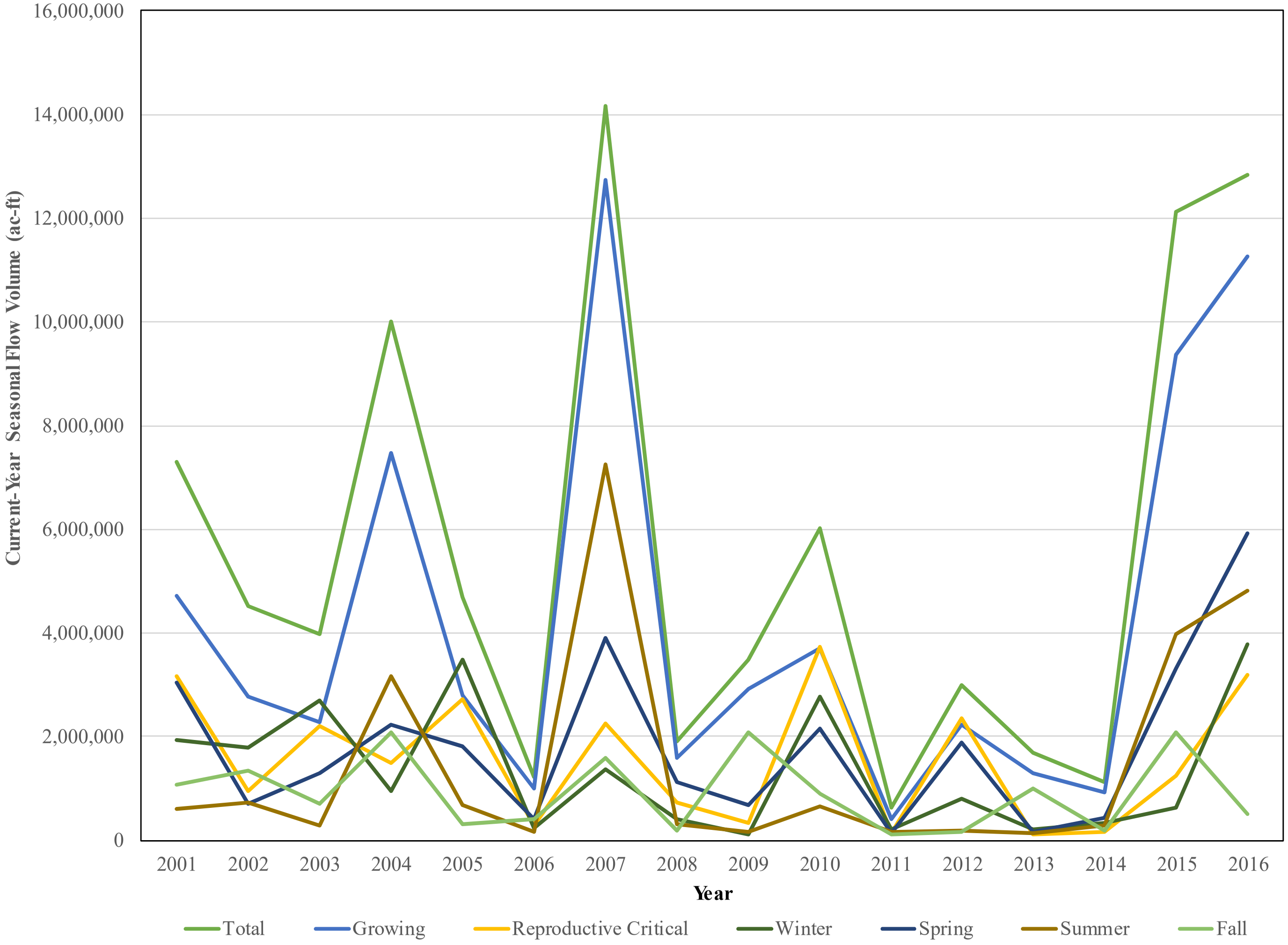


Figure 12. Current+Prior-Year Seasonal Flow Volumes (ac-ft): 1992-2016
Hearne Riparian Study Site

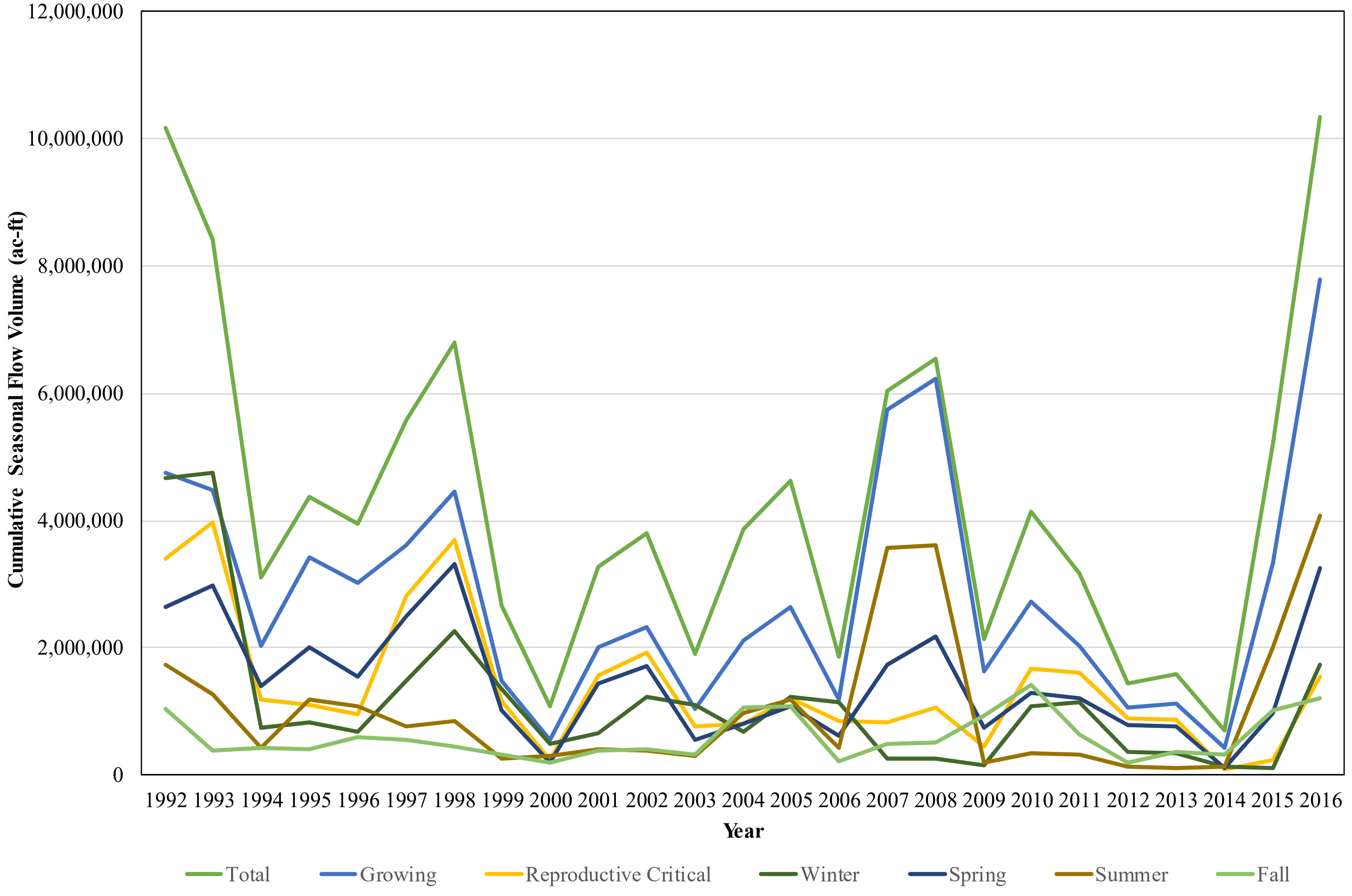


Figure 13. Current+Prior-Year Seasonal Flow Volume (ac-ft): 2002-2016
Navasota Riparian Study Site

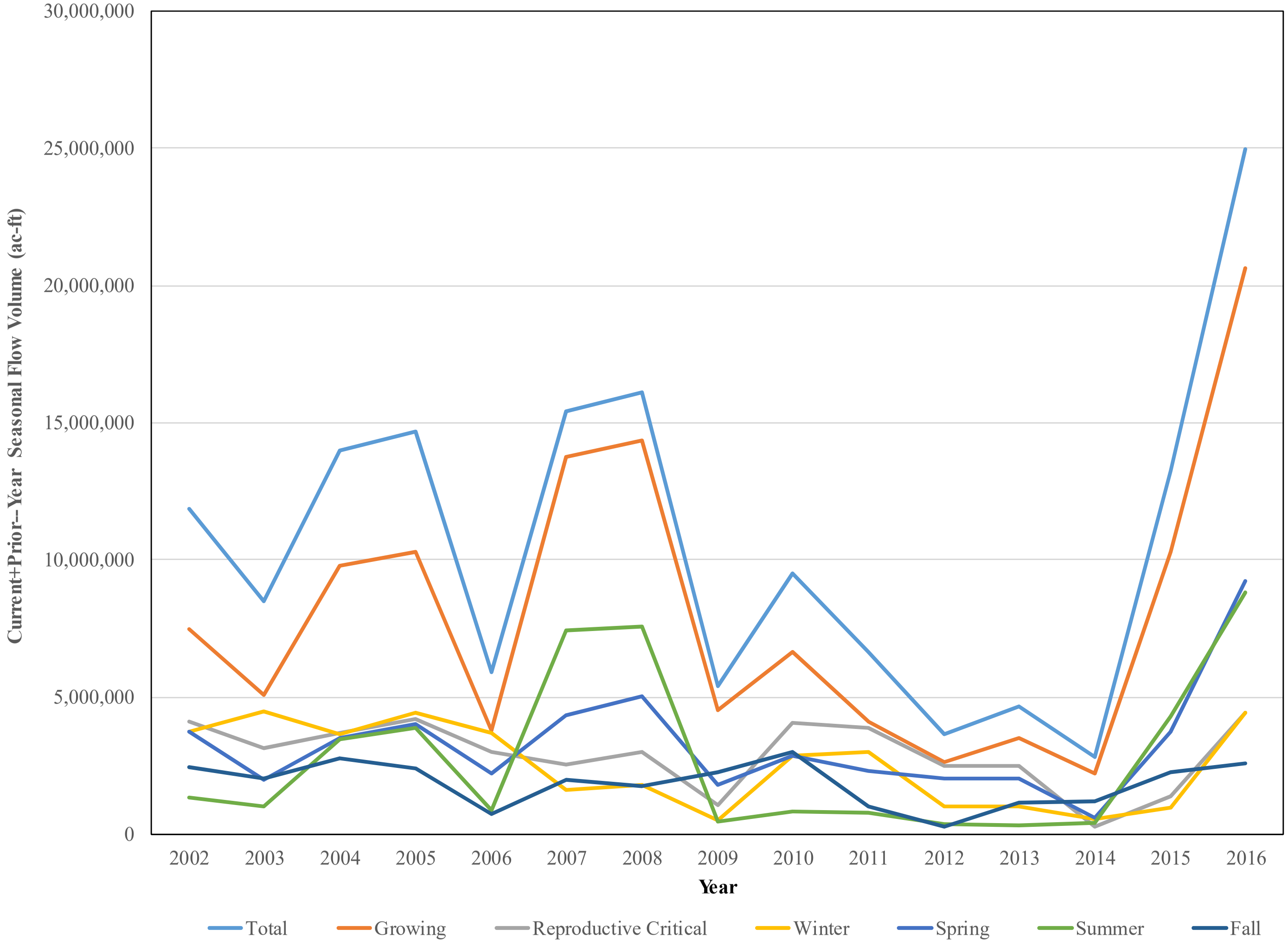


Figure 14. Box Elder Chronologies: RWI Productivity Index (1994-2016)
Hearne and Navasota Riparian Study Sites

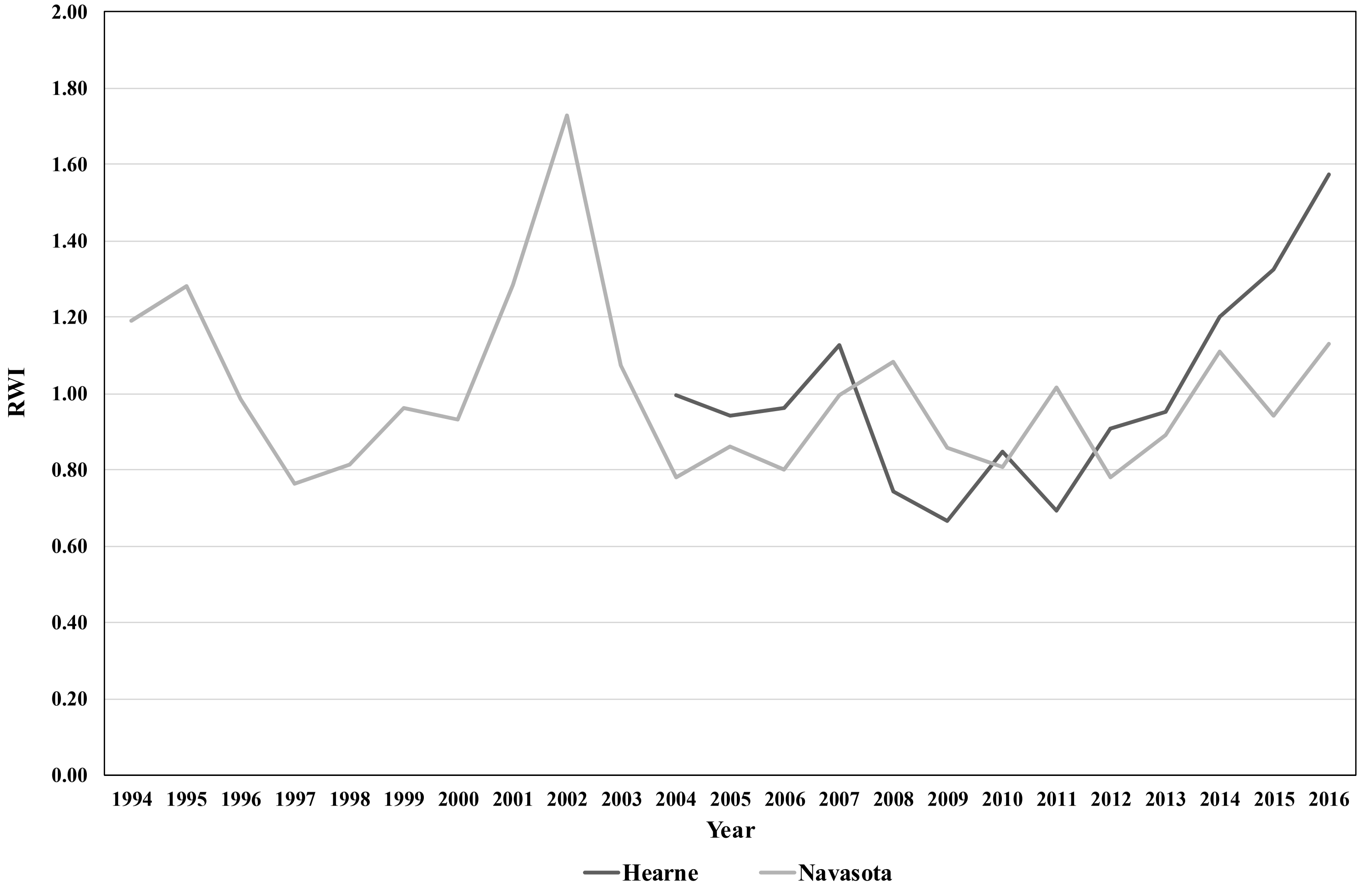


Figure 15. Black Willow Chronologies: RWI Productivity Index (1999-2016)
Hearne and Navasota Riparian Study Sites

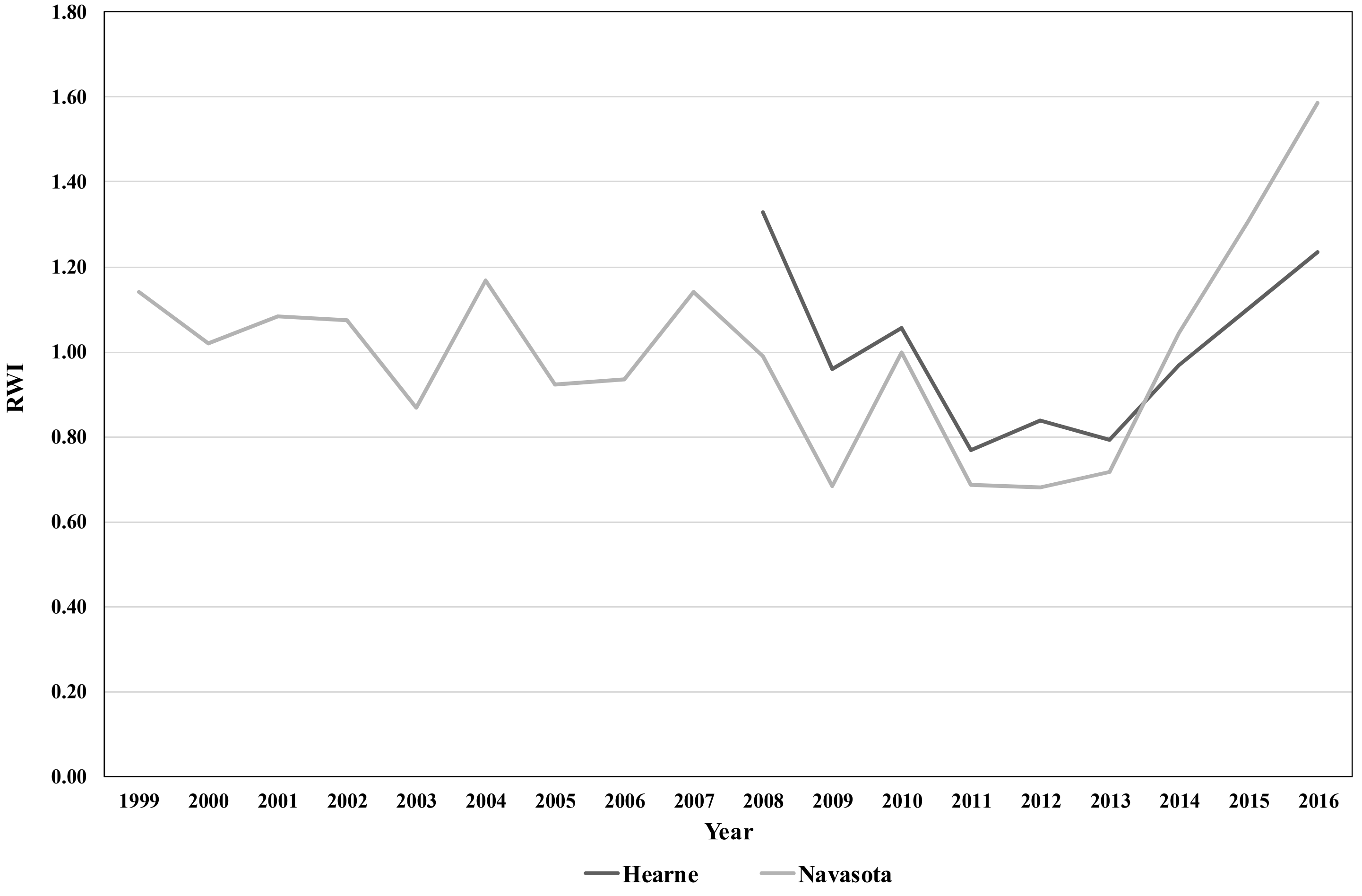
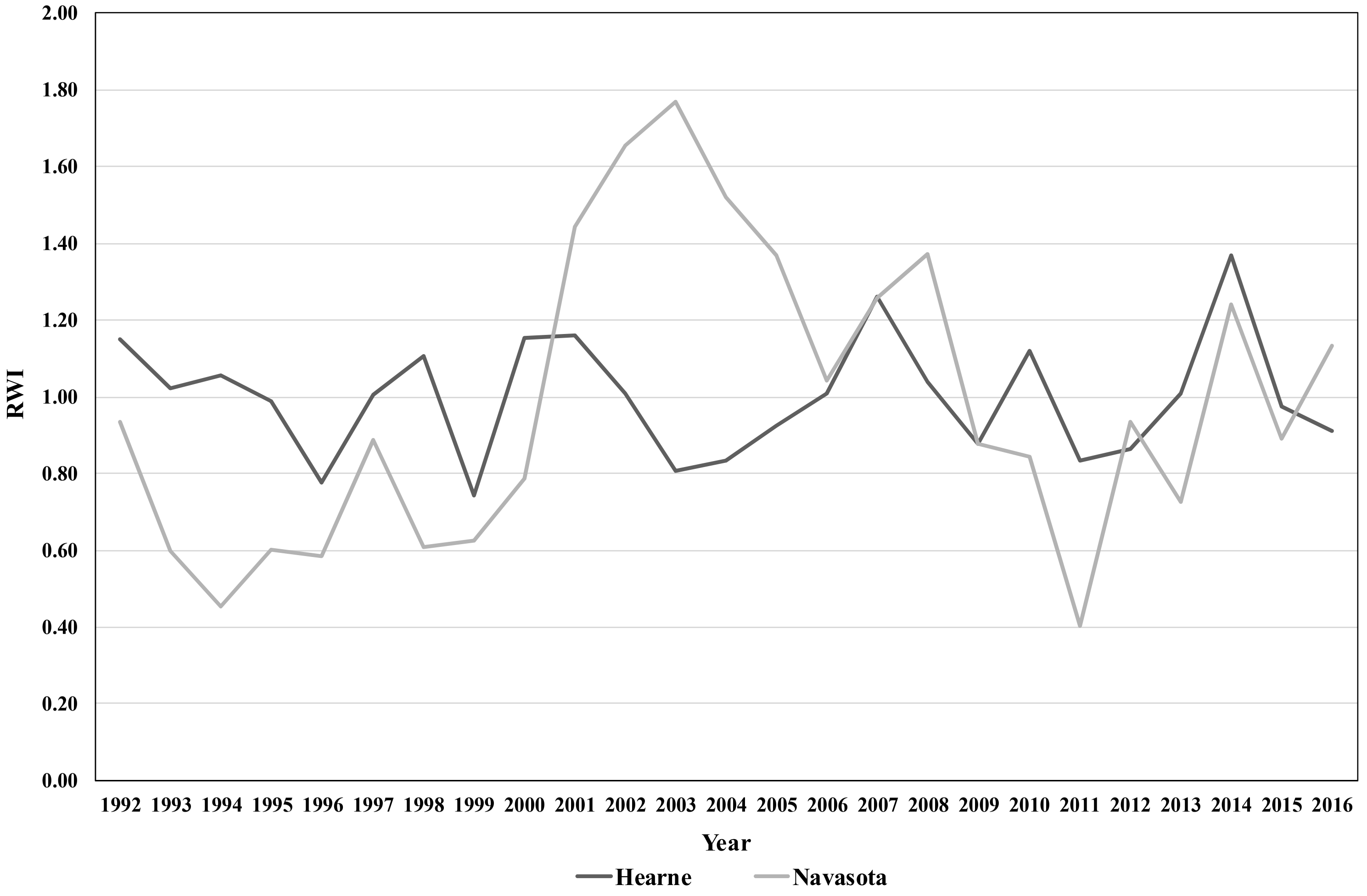


Figure 16. Sugarberry Chronologies: RWI Productivity Index (1992-2016)
Hearne and Navasota Riparian Study Sites



Appendix C: Riparian Productivity Assessment
Dendrochronological Software Applications

MeasureJ2X

Many programs have been developed to measure tree rings and date tree rings. One such program is MeasureJ2X (VoorhTech Consulting Inc. 2017), which is recommended when buying the Velmex "TA" system. The J2X takes tree-ring width data that are fed to the computer through a data recording box such as QuikCheck. At the same time, the user initiates a date for the first ring to be measured. This program also has some data editing features that enable the user to correct measuring mistakes while still at the measuring system. Its graphical user interface functions like most Microsoft programs. All of the measurements will be displayed on the screen along with the year of each ring. Once all measurements are completed, it is important to save data permanently to the hard drive. At this point another series can be initialized and new measurements will be appended to the bottom of the last file measured. The data can be saved either in decadal (tucson) (*.raw) or in csv (excel) (*.csv) format – both formats can be readily used by the programs COFECHA and ARSTAN.

Stepwise Protocol: MeasureJ2X

1. Place the core on the measuring stage of the Velmex system. MeasureJ2X has menu options of File, Series, Options, or Setup. To start a new series, go to the Series menu and choose New. The next window will then appear on the screen, requesting the series ID and start year for that core. To enter series identification code (ID), it is standard to have a three character site designation and a two digit tree number. Once these data are entered, click OK and go to the initialization of measurements.

2. The measuring window appears next. The sample ID is at the top of that internal window, with the first year to be measured also displayed on the screen. The program needs to be initialized at this time, which entails sending a beginning measurement from which all other measurements will be calculated. This enables the user to reset the stage at any time without needing to zero out the measurements. Click on the Measure button. A new window will pop up asking for an initial measurement. Click Start on the left corner of the screen. It is customary to reset the measurement to zero at this stage and click send on the remote. A new box will pop up saying what the initial measurement was, then click OK.

3. Now the program is initialized and waiting for measurements. Turn the measuring dial, which moves the stage and the sample, until the crosshair is at the next ring boundary. Push the Send button on the remote, which sends the measurement to the computer screen. The computer screen will show the Display Value, which shows both the cumulative measurement for that core plus the width of the individual ring in millimeters. This procedure is repeated for each ring on the core. All of the measurements will be displayed on the screen along with the year of each ring. Care should be taken when there are cracks or gaps on the core. The core measurements should be adjusted manually to strictly avoid the cracks being included in the measurement. The computer will beep each time a measurement is entered, and a second beep should be heard for each decade year that is measured. It is important to pay attention to this second beep and to use the decade years as landmarks, so that a measurement mistake can be identified within the measured decade.

4. Once all measurements are finished, it is important to note that the data are only in the computer memory, and have not been saved permanently to the hard drive. The user should click the Stop button on the screen, then close out the measuring window by clicking the small x in the top right hand corner of the screen. Be very careful that only the measuring window is being closed and not the entire program window. If the program is closed, the measurements are lost. Once the measuring window is closed, the user can save the file by going to the drop-down menu in File and clicking Save. At this point another series can be initialized by clicking Series and New (as above) and when this file is saved, it will append these new measurements to the bottom of the last file measured. It is possible to Delete or Shift the series in the Measuring Window, if a mistake occurs. To delete one or more rings, highlight the ring width measurements in the Measurement column. Click Delete and choose to leave the first year or the last year fixed in time.

COFECHA

COFECHA is a quality-control software program for tree-core dating, which statistically creates a master chronology for the cores that the operator enters into the program. Therefore, if undated series are entered into the program, then the master chronology will be useless. Two attempts at dating are necessary to provide the quality control that has been the hallmark of good dendrochronological research. The first attempt should include a visual dating method during which the researcher learns the wood (explained earlier). The second check on the dating can be done by a statistical check such as with COFECHA.

COFECHA is a simple DOS program (Grissino-Mayer 2001). The input file names can be eight characters in length. It is best if the program COFECHA is placed in the same directory as the files to be analyzed so that you do not have to type in the directory chain each time the program is run. COFECHA leads the operator through default options with most of the command steps. On the command line, COFECHA will often provide answer options such as "<Yes>/No". The option that is in brackets is the default option and pressing enter will choose that answer. Proper use of these default responses can facilitate efficient use of this program.

COFECHA takes the ring width measurements that were obtained from a measuring stage and, by default, fits a 32-year cubic smoothing spline to the cores for standardization. Next, it averages all of the index series for all of the cores together to create the master chronology. It then removes the core that is about to be analyzed, cuts it into 50-year segments with 25 years of overlap, and statistically correlates each segment against the master chronology. If the correlation is below the specified confidence level, which is set at 99% by default, then COFECHA checks from -10 to +10 lag years for a better match. If it finds a better match it reports a B flag in the output; if it does not find a better match it reports an A flag for that segment, simply meaning that it has a low correlation. The operator strives to address the B flags by reexamining the cross-dating in the raw data and correcting for any wrong dates. After this, the program is re-run to check if the correlation is improved.

Stepwise Protocol: COFECHA

1. To start the program, double-click on COFECHA.EXE in the directory. A command box for the program will open. The first entry that the program asks for is a five-digit identifier for your program run. This identifier will be tacked on as a prefix on any subsequent file created by this program, to identify file content. TCS usually uses a two letter site designation, along with two letters for species when multiple species are sampled on a site, and then a number at the end that can progress each time a new run is started (such as BNBW1 for Brazos Navasota Black Willow first run). COFECHA is typically run many times per site before you are done with the chronology.

2. Next, the program requests that the existing input file name is entered. Remember that the file name must be eight digits or less, and not include any spaces or odd characters. COFECHA can read files in many different formats: compact, measurement, indices, Accurate measurements, meteorological, spreadsheet, single column of values, two columns of values, or a user-defined protocol. The program automatically recognizes most of these formats, then asks if it has identified the correct format. Next it will ask for the file name containing samples to run as undated tree-ring series. COFECHA can attempt to date undated series by breaking the series into 50-year segments and statistically testing each segment against the master chronology, but not include it in the master chronology. The output from this option will show up in the program output near the bottom of the .OUT file. Assuming that you do not want to enter undated series into COFECHA, simply click Enter.

3. The next option is to enter a title for this run, which can be up to 36 characters including spaces and odd characters. The title should be an informative description for each run. In order to identify the specific run maybe years into the future, the title should be long enough to include the site name, species, date, and any other notes for this run. When you are done entering the title for this run, hit enter to get to the next stage of the program.

4. The main user interface of COFECHA is the table that allows you to change the spline length for creation of the master chronology, change the segment length and overlap, run an autoregressive model, change the critical level of correlation that is based on your segment

length or N, decide whether to save the master dating series, list the ring-width measurements in the output, list the parts of the output to include, and decide whether to calculate absent rings in the master series. The default options in this program are listed on the right side of the screen and are applicable to most purposes. Holmes (1983) tested a series of spline lengths for creating the master chronology and found that the 32-year cubic smoothing spline is the most appropriate spline length for enhancing the interannual variability that leads to accurate dating. This segment length is optimal for providing a high N for statistical tests and providing the flexibility to pin-point where missing or false rings may occur in the chronology. These segments are lagged, by default, at 25 years, again making it possible to pinpoint dating problems.

5. The default options in this table work well for most analyses. To run the program, hit Enter once you have made any changes that you want in the table. The program will then execute and very quickly display on the screen the progress of the program and finally the correlation of each core with the master, as shown by a series of brackets where each bracket represents a 0.05 overall correlation. This will flash by on the screen and the program will exit itself. An output file with the result of the run is placed in the directory where you ran the program. The file will begin with the prefix that you entered at the beginning of this run and the three letters COF to designate this as a COFECHA file.

Reading the Output of COFECHA:

The output file contains all of the summary statistics about the master chronology, the correlation of each core with that master, and some descriptive statistics for each core. The first page of the output provides the program name and version, the date of the run, the title that was entered, as well as the file name used in the analysis, the parts included in the output, and the control options that were selected during the run. The bottom half of the page contains the summary statistics for the chronology, starting with the time span of the master chronology, the entire continuous time span for the chronology, and the portion of the chronology with a sample depth of two or more series. Next, COFECHA provides a warning of any rings that are inserted as absent on only one series. There are several parts in the COFECHA output file, but I am going to discuss a couple of them (Parts 1 and 6) that are important for our analysis.

The table bracketed by stars in Part 1 is the most important summary of the COFECHA run. The table presents the number of dated series, the master chronology length, the total number of rings in all series, and the total number of dated rings (as in those that overlap with at least one other chronology), the series intercorrelation, the mean sensitivity, and the segments with possible problems. The series intercorrelation is a measure of the stand-level signal, and mean sensitivity is a measure of the year-to-year variability in the master chronology. Finally, a complete list of any absent rings is listed by core.

Part 6 presents each core, one at a time, with a closer look at how well it correlates to the master and reports any measurements that are outliers. The core name is given in the top left corner and a series number is assigned to each core based on its order in the file. These series numbers can be used to find the cores more easily in COFECHA. Section A in Part 6 is printed only when segments have a low correlation (as shown by an “A” flag) or a better date somewhere else in the 20 year window around the present date for the segment (as shown by a “B” flag). Section B is always presented showing the five years that added the most weight to the correlation, labeled “higher”, and the five years that lowered the correlation the most, labeled “lower”. This section also provides the correlation of each series to the master. Section C presents any year-to-year differences (such as an acute increase or decrease in growth from one year to the next) that were unexpected based on the master chronology. Any absent rings in a core will be presented in section D, along with a comparison to what the master shows. Section E presents any ring width measurements that are more than three standard deviations from the mean. Because environmental effects on the trees are likely to cause rings that are larger or smaller than the mean, the measurements should be rechecked for human error rings if they are five or more standard deviations off of the mean.

ARSTAN

ARSTAN is a much more powerful program that is used for chronology building. The tree-ring series that are screened in COFECHA will be input into ARSTAN for final chronology development. ARSTAN is one of the main programs in dendrochronology that is used to build the final stand-level chronologies. ARSTAN differs from COFECHA in that it has a broader range of standardization techniques that can be used on individual series before a master chronology is compiled. This should not be confused with the master chronology that is developed in COFECHA. COFECHA also uses standardization (usually a 32-year cubic smoothing spline) to create a master chronology for the dating of other cores. This master chronology is created specifically for dating purposes and is not the master chronology that should be used for the final analysis. In ARSTAN, different standardization techniques can be used to maximize the signal of interest and remove noise from the final chronology. The program fits a curve to the measurements from each core, divides the ring width by the modeled curve value, averages the resultant index for each core to create a tree-level index, then averages together the tree indices to develop a stand-level chronology.

Historically, a negative exponential curve has been considered a conservative standardization technique because it removes a known age-related trend from the ring-width series. A negative exponential curve works best where the trees are open grown and do not experience many disturbance events. Dendrochronologists have contended the need for more complex standardization techniques in closed canopy forests that have more stand dynamic signal than open grown forests. Cubic smoothing splines take into consideration autocorrelation (the effect of previous growth or climate on the current year's growth). Currently these spline fits are commonly used, particularly for climate change research.

Stepwise Protocol: ARSTAN

To begin, the ring-width file from a measuring program, which has been checked with COFECHA, should be placed in the ARSTAN directory and the ARS37win_5f.exe file should be executed. Enlarge the windows so that they fill the whole screen. Next, hit "enter" twice to get past the introduction to the program. At this point the user is prompted for the name of the data file. Following that, the user can identify a second file to include in this run or hit enter to use only the first file. The user should then enter a descriptive title for the run that will allow the run to be identified at a later date. The next option allows the user to run ARSTAN in batch mode, enabling the user to run ARSTAN on many file sets. The default response is no.

The main menu in ARSTAN, which controls the entire program, appears next. There are more than 20 options that one can access at this point in the program. The options that may be most useful are [4] first de-trending and [19] summary plots. ARSTAN provides the most powerful standardization options among dendrochronological programs. With option [4], the user can choose to fit a negative exponential, linear trend, or various cubic smoothing splines. A 20-year cubic smoothing splines option is often preferred to keep most of the flow-event related variance in the chronology, because most of the chronologies in our research date back less than 40 years. Many of the standard de-trending methods, for example most cubic smoothing splines, will remove noise such as a negative exponential curve, so that two runs at de-trending the series are not necessary. Also, two separate de-trending curves will move the data farther from the actual raw ring widths initially measured on the core. Option [19] provides summary plots so that you can visualize your final chronologies.

Reading the Output of ARSTAN:

When ARSTAN is run in interactive mode it plots the ring-width measurements, the curve fits, and the resultant indices so that the user can see how well each curve fits the data. These curves are not saved, so it is useful to do a screen capture (Ctrl + Prnt Scrn) of the plots and then paste them into another document such as Word or PowerPoint.

The output from ARSTAN summarizes all of the descriptive statistics for the raw ring widths, then goes through the same descriptive statistics for the standard, residual, and Arstan chronologies (explained below). These statistics include the start and end dates of each core, the mean, standard deviation, skewness, kurtosis, mean sensitivity, and first order autocorrelation for each core. The ARSTAN output also lists the de-trending curve for each core, so that any changes that have been made in the interactive de-trending part of the analysis are recorded for later reference. Four chronologies are produced by ARSTAN. The raw chronology is a simple average of the raw ring widths, in other words, no standardization was done on these series. The standard chronology is an average of the index values from the standardization process chosen by the dendrochronologist. This chronology still has all autocorrelation included in the final chronology, which may be an issue when conducting regression analyses later as one of the assumptions of regression analyses is that the series are not autocorrelated. The residual chronology has had all autocorrelation stripped from the series making it a more suitable chronology for regression analysis, but not necessarily the most sensitive to the signal of interest. The Arstan chronology has been calculated by removing the autocorrelation, modeling it, and reintroducing a stand-level autocorrelation back into the chronology. All three chronologies are output in the .crns file, meaning chronologies file. A benefit of interactive mode is that these chronologies are also plotted on the screen along with a sample depth curve for all of the chronologies.

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Appendix D: TWDB Comments on Draft Report

Texas Water Development Board

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Phone (512) 463-7847, Fax (512) 475-2053

485816

Ms. Tammy Dunham
Texas Parks and Wildlife Department
4200 Smith School Road
Austin, Texas 78744

RE: Interagency Cooperation Contract amendment with the Texas Parks and Wildlife Department, Contract No. 1600011933, Comments on Draft Report Entitled "Riparian Productivity in the Brazos, Guadalupe, and Trinity River Basins, Texas"

Dear Ms. Dunham:

Staff members of the Texas Water Development Board (TWDB) have completed a review of the draft report prepared under the above-referenced contract. ATTACHMENT 1 provides the comments resulting from this review. As stated in the TWDB contract, Texas Parks and Wildlife Department will consider revising the final report in response to comments from the Executive Administrator and other reviewers. In addition, Texas Parks and Wildlife Department will include a copy of the Executive Administrator's draft report comments in the Final Report.

Please note: The TWDB logo should not be used in the Final Report.

The TWDB's Contract Administration staff looks forward to receiving one (1) electronic copy of the entire Final Report in Portable Document Format (PDF) and five (5) bound double-sided copies. **Please further note, that in compliance with Texas Administrative Code Chapters 206 and 213 (related to Accessibility and Usability of State Web Sites), the digital copy of the final report must comply with the requirements and standards specified in statute. For more information, visit http://www.sos.state.tx.us/tac/index.shtml**. If you have any questions on accessibility, please contact David Carter with the Contract Administration Division at (512) 936-6079 or david.carter@twdb.texas.gov.

Texas Parks and Wildlife Department shall also submit one (1) electronic copy of any computer programs or models, and, if applicable, an operations manual developed under the terms of this Contract.

If you have any questions concerning this contract, please contact Dr. Mark Wentzel with TWDB's Surface Water staff at (512) 936-0823 or email at mark.wentzel@twdb.texas.gov.

Sincerely,

John T. Dupnik., P.G.
Deputy Executive Administrator
Water Science & Conservation

Date: 6-11-19

Enclosures

c w/o enc.: Mark Wentzel, Ph.D., Surface Water

Attachment 1
Texas Parks and Wildlife Department
Riparian productivity in the Brazos, Guadalupe, and Trinity River Basins, Texas
Contract No. 1600011933
TWDB Comments on Draft Report

General Draft Final Report Comments:

This study involved the analysis of cores from dominant riparian tree species to establish relationships between flow conditions and riparian productivity. Tree cores were collected from six sites along three rivers (Brazos, Guadalupe, and Trinity). Sampling was limited to three dominant riparian tree species at each site. Because a minimum of 20 cores are desired to increase the statistical significance of relationships and some cores are found to be unsuitable during processing, 30 to 40 cores were collected for each of the three dominant riparian species at each site. Standard methods for core collection and processing were followed and are documented in the report. The report also provides a good description of analysis methods as described in the literature. This project represents a refinement of previous riparian productivity work completed for the Texas Instream Flow Program, which has identified annual flow volume criteria that promote riparian productivity. In addition to annual flow requirements, this analysis evaluated seasonal and monthly flow criteria for their correlation to riparian productivity. Overall, the report is well written and data collection and analysis methods are described adequately. Analysis in the draft report, however, was limited to cores from two study sites in the Brazos River Basin. Complete results for all three basins are expected in the final report.

Significant findings include:

- Higher mean discharge in the summer promotes overall riparian productivity.
- Black willow responds positively to increased summer and spring mean discharges and increased overbank events in May.
- Box elder responds positively to higher mid-summer mean flows and negatively to higher February mean flow. Increased overbank events in the fall and reduced overbank events in the spring accelerate box elder growth.
- Sugarberry productivity is increased by higher mean flows in winter and summer. Overbank events in winter and spring are most beneficial for this species.

REQUIRED CHANGES TO REPORT

1. Please check the report for typos such as the following and correct as necessary:
    a. Page 3, 3rd paragraph, last sentence, "tree cores are sampled" should be "tree cores were sampled."
    b. Page 6, 2nd paragraph, 4th sentence, "Figure 1 is a map" should be "Figure 2 is a map."
    c. Page 6, 2nd paragraph, last sentence, "used in Figure 1" should be "used in Figure 2."

  d. Page 7, 3rd paragraph, last sentence, "due the death" should be "due to the death."
  e. Page 8, 4th paragraph, 1st sentence, "Coring a trees" should be "Coring a tree."
  f. Page 9, 2nd paragraph, 4th sentence, "Sometime the wood-core" should be "Sometimes the wood-core."
  g. Page 11, 2nd paragraph, 2nd sentence, "allowed to dip off" should be "allowed to drip off."
  h. Page 11, 2nd paragraph, 3rd sentence, "HCL acid" should be "HCl acid."
  i. Page 14, 3rd paragraph, 2nd sentence, "increased twelve" should be "increased to twelve."
  j. Page 15, 1st paragraph, last sentence, "daily man discharge" should be "daily mean discharge."
  k. Page 15, 2nd paragraph, 1st sentence, "Basic unit" should be "The basic unit."
  l. Page 16, 1st paragraph, 2nd sentence, "Stromberg and Patten (1996)" should be "Stromberg and Patten (1990)."
  m. Page 32, 3rd paragraph, 1st sentence, ",To guide" should be "To guide."

2. In Figure 1, riparian species guilds (and their location relative to the stream) are provided. Two of the three focal species for this study are included (black willow and box elder). Please provide the guild and relative location of sugarberry, the third focal species for this study, in Figure 1.
3. In the third paragraph on page 18, it is stated that both sites (Hearne and Navasota) "had the highest cumulative two-year mean discharge volumes during 2015-2016 and 2007-2008." However, in Figure 12, it appears that the largest two-year mean discharge volumes for the Hearne site were (in decreasing size): 2015-2016, 1991-1992, 1997-1998, and then 2007-2008. Please revise the text in the report or the data in Figure 12 as necessary.
4. In the second paragraph in Section 4.2 Species Productivity, the statement is made that "the black willow response appears strongest in the graphs." However, in the graphs (Figures 14-16), it appears that black willow RWI varies from about 0.7 to 1.6, while box elder RWI varies from about 0.7 to 1.7 and sugarberry RWI varies from 0.4 to 1.7. Please provide further explanation of how the graphs show black willow has the strongest response.

SUGGESTED CHANGES TO REPORT

5. To improve the ease of reading the report, please consider embedding tables and figures within the body of the report rather than appended to the end of the report.
6. To make results understandable to the widest audience, please consider using both imperial and metric units throughout the document. In the report, data is provided in a mix of imperial or metric units (not both). For example, on page 3, 2nd paragraph, valley width is provided in kilometers (but not miles) while in Figures 10 and 11, flow volume is provided in units of ac-ft (but not cubic meters).
7. In the 3rd paragraph on page 5, two citations are provided for the observation that wet conditions may contribute to lower growth for some tree species. This was

also a conclusion of Duke (2011), a previous study funded by the Texas Instream Flow Program. Please consider adding Duke (2011) to the citations in this paragraph.

8. Please consider providing a citation for the following statement (last sentence of the first paragraph on page 15): "This is why researchers standardize and average productivity data."

Appendix E: TCS Response to TWDB Comments on Draft Report

Appendix E
Texas Parks and Wildlife Department
Riparian productivity in the Brazos, Guadalupe, and Trinity River Basins, Texas
TWDB Contract No. 1600011933
TCS Response to TWDB Comments on Draft Report

TCS completed all required changes and most of the suggested changes. The only suggested edits that were not fully addressed were numbers 6-7, for reasons described below.

REQUIRED CHANGES TO REPORT

1. The thirteen listed typos (1.a-1.m) were corrected, with the entire report reviewed for additional typos.

2. Figure 1 was corrected as suggested, so that “sugarberry” was substituted for “hackberry,” so that the common name for this species was consistent throughout the report.

3. On page 18, the text was corrected to read as follows:

   As discussed, two-year (current + prior) seasonal flow volumes often correlate better with tree productivity, compared to current-year volumes. These two-year flow data are graphed in Figures 12 (Hearne) and 13 (Navasota). At the Hearne and Navasota sites, the highest and lowest cumulative two-year mean discharge volume were in 2015-2016 and 2013-2014, respectively.

4. The subject paragraph was rewritten as follows:

   Though no data outliers were removed, the synchrony within intervals of one to two years between the two sites in each species’ annual productivity response to environmental variables is visually apparent. All tree species appear to react to annual environmental change, such as drought and high-flow years. The range of RWI values are similar for the three study species. However, black willow RWI values indicate this species most frequently exhibits a strong response to seasonal and monthly measures of mean discharge volume (see Tables 4, 6, and 7), possibly due to black willow distribution being nearest the main river channel.

SUGGESTED CHANGES TO REPORT

5. TCS decided not to insert tables and figures throughout the text, and to keep them together at the end of the report, since their large number may impede readability if dispersed throughout the report. A separate PDF file of only Appendices A and B (tables and figures) was instead provided, in case that is helpful for cross-referencing while reading the report.

6. Instead of using dual sets of values, TCS suggests that all measurements be only metric in the final report, like is standard in scientific papers. However, the need to reach out to stakeholders and the general public is well understood. Please advise if we should add an appendix in the final report, which lists factors for converting metric measures to imperial measures.

7. Many researchers, including Duke (2011), have shown that wet conditions may reduce tree growth. However, Duke (2011) was not cited, since the paragraph is more concerned with the parabolic nature of the relationship between tree growth and wet-dry conditions.

8. The requested citation (Phipps 1982) was added.