HYDROLOGIC DRIVERS OF RIPARIAN TREE GERMINATION AND GROWTH ALONG THREE TEXAS RIVERS

A Thesis

By

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ABSTRACT

With increased regulation of rivers for human use, an improved understanding of the needs of the riparian ecosystem is necessary to develop management practices that sustain these ecosystems. The primary objective of this study was to develop a low expenditure method for the Texas Water Development Board to assess the riparian condition by relating germination and growth to flow histories. My study sites were located along the lower reaches of the Brazos River, Colorado River and Guadalupe River in Texas, USA. Six target riparian species were chosen for this study representing fast maturing species (*Acer negundo, Populus deltoides*, and *Salix nigra)* and slow maturing species (*Fraxinus pennsylvanica, Platanus occidentalis,* and *Taxodium distichum*). Germination years and growth indices were derived from tree cores collected from across the three rivers. The germination response to seasonal average flows and flow pulses was analyzed using binary logistic regression. Relationships between growth and precipitation and flows across various periods were analyzed using simple linear regression.

Results showed that probability of germination was positively correlated with spring and summer average flows, along with smaller flow pulses, for most species along the three rivers. For growth, precipitation had a stronger effect than flows on increasing growth as much as 0.04 per 10 mm of precipitation and 0.03 per 10 m^3s^{-1}. The period of late winter to early summer for both precipitation and flows was the most influential on growth, though in some instances these same conditions decreased germination and growth on different rivers. The results also suggest that there are detectable differences in species-specific responses across rivers with different flow regimes. The framework presented in in this study is the first of its kind to assess the effects of flows on germination and growth using tree rings and has promise for more widespread use on rivers. Further studies on these species covered here with more comprehensive sampling efforts would be beneficial in expanding our understanding of their growth and germination processes to ultimately improve management.

DEDICATION

This thesis is dedicated to my parents, Carl and Sherry Trimble, in gratitude for their unfailing moral, financial, and spiritual support throughout this project.

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I would like to thank my committee chair, Dr. Georgianne Moore, and my committee members, Dr. Charles Lafon, and Dr. Joshuah Perkin, for their guidance, tutelage and patience throughout the course of this research.

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CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Dr. Georgianne Moore (advisor) of the Department of Ecology and Conservation Biology, Dr. Charles Lafon of the Department of Geography and Dr. Joshuah Perkin of the Department of Ecology and Conservation Biology.

Tree cores were collected with the assistance of Ashley Cross, Ajinkya Desphande, Chris Adkison, Miriam Catalan, Matthew Acre, and Kristin Heath-Acre. Special thanks to Joe Trungale for access to complied hydrologic data.

All other work conducted for the thesis was completed by the student independently.

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NOMENCLATURE

TWDB	Texas Water Development Board
DBH	Diameter at breast height
HEFR	Hydrology-Based Environmental Flow Regime
RWI	Ring Width Index
HFP	High Flow Pulse

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CHAPTER I

Introduction

Riparian ecosystems are transitional ecosystems between terrestrial and aquatic systems and are key components that maintain hydrologic function, promote biodiversity, and regulate geomorphic processes in the landscape (Gregory et al. 1991, Naiman et al. 1993). As human encroachment grows, riparian ecosystems are increasingly impacted by both terrestrial environmental modification such as urban development and agriculture, and hydrologic alteration such as damming and water withdrawals (Patten 1998). As riparian forest land has declined on average 36.6% since the 1970s, Texas has experienced some of the largest growth and losses, in its High Plains ecoregion and Southern Texas Plains respectively (Jones et al. 2010). As further losses of riparian ecosystems occurs, a myriad of consequences will continue, including degradation of water quality, increased levels of erosion, loss of flood regulations, pollution filtration, disruption of nutrient cycling, and loss of wildlife habitat (Sweeney et al. 2004).

Tree Establishment

One of the most significant impacts on river systems is regulation from damming and municipal water usage and its impact on riparian tree establishment. The geomorphic processes of channel narrowing, meandering and flood deposition are key determinants in the spatial and temporal distribution of establishment of riparian trees (Scott et al. 1996, Scott et al. 1997). These processes influence turnover of riparian bank conditions vital to seedling germination. Studies have documented that new dams initially cause an increase in area able to be colonized by riparian species, though this increase is subsequently lost as vegetative succession progresses due to the lack of river meandering (Friedman et al. 1998, Dixon and Turner 2006). Areas occupied by riparian vegetation may or may not change post-dam; however, a decrease in area occupied by newly established riparian trees is likely (Benjankar et al. 2012). As human impacts continue to denaturalize flood waters through regulated flows and damming, the limiting of sediment transport and subsequent channel narrowing will lead to reduced creation of riparian zones.

Often regulations rule for seasonal pulses to maintain biota; however, timing of these events may not coordinate with crucial riparian seed dispersal and germination times. Burns and Honkala (1990) detail that “softwood” hardwoods, such as willows (*Salix spp*.) and cottonwoods (*Populus spp*.), utilize allochory and hydrochory as means for dispersal. These seeds remain viable shorter than two weeks if not in a moist area, and require open, often freshly deposited sediment for germination. Other common riparian species, such as boxelder (*Acer negundo*), possess longer dispersal times with seeds that have both longer viability as well as tolerance for variable initial conditions. Notable characteristics of these trees are their early age of maturation, often between 5 and 10 years of age, and short lifespans, averaging around 70 years. The American sycamore (*Platanus occidentalis*), like the willows and cottonwoods, relies upon allochory and hydrochory to deliver seeds to fresh alluvial sites; however, *P. occidentalis* produces seeds for 50 to 250 years after finally reaching maturity around 25 years of age. Green ash (*Fraxinus pennsylvanica*), like sycamore normally seeds at a later age, but also possess more persistent wind spread seeds that can be dormant for years in the seedbank waiting for moist, partially shaded conditions. Bald cypress (*Taxodium distichum)* is one of the longest-lived riparian species averaging a 600-year lifespan, but capable of exceeding 1200 years. Their seed strategy relies on hydrochory and a 1-to-3-month period of exposure to wetness before being able to germinate. *T. distichum* seeds can lay dormant in the seedbank for many years until conditions for germination become favorable. In summation, both *F. pennsylvanica* and *T. distichum* share utilization of hydrochory and allochory, trends towards short period of seed viability, and needs moist conditions for germination, but differentiate on lifespans, age of maturation and mature age capacity for drier environments.

While mature trees have the capacity to withstand a variety of hydrologic conditions, most riparian species have seeds with short viability periods that require specific conditions to germinate. An example of this is found in willows, which once established, have the capacity to survive in a wide range of soil types and moisture conditions. To regenerate, though, germination is heavily dependent on alluvial deposits (Mcleod and Mcpherson 1973). Some riparian trees (primarily *Salicaceae spp.*) have demonstrated a synchronization with hydrology in which they drop or disperse their seeds within a few week(s) following the peak spring flows, thus maximizing either the window of transport or the availability of fresh alluvial surfaces. The timing of seed dispersal often correlates strongly with changes in temperature and precipitation rather than streamflow as an initiating factor (Stella et al. 2006, Sedlacek et al. 2015). When these factors are desynchronized from natural hydrological regimes, the normal suite of co-occurring conditions are dissociated, thus preventing successful germination. An example of this is sensitivity to wet conditions, where willow and cottonwood seedling mortality corresponds with both the rate of drawdown as well as displaying species specific responses under experimental drawdowns (Stella et al. 2010). This illustrates the relevance of not only timing, duration, and intensity of discharge in pulses, but the stage-discharge relationship across the riverscape to ensure both germination and seedling success. Studies on bald cypress found that a long spanning seed window is linked closely to hydrologic regimes as a means of maximizing the range of areas (Schneider and Sharitz 1988). The trees relied upon the normally variable conditions, which covered some of the lowest and highest flows, to reach varying locations within the riparian area. When considering the denaturalization of river's flood events, the same process that promote germination and dispersal can become inhibitory processes preventing natural reforestation when out of sync (Doulatyari et al. 2014). A study on the Verde River found that minor changes in flood timing had no significant impact on changes in riparian tree germination. These findings support the capacity for a successful interaction between human needs in regulating waterways and the maintenance of riparian function and processes.

Tree Growth

Obligate riparian tree species are likely more vulnerable to hydrologic denaturalization than facultative or upland species that occur in riparian zones. For example, a case study comparing black cottonwood (*Populus trichopta*), an obligate riparian tree, to Jeffrey pine (*Pinus jeffreyi*), a facultative riparian tree, found cottonwood growth was more closely correlated to the stream flows on the year samples were taken, whereas pine growth was more correlated to the prior years flow (Stromberg and Patten 1990). In that same study, prior year stream flows significantly correlated with the following year's growth for more upland trees, whereas current year stream flows more strongly correlated with wetland tree growth. Lagged growth could be an indicator that residual soil moisture is important for non-obligate trees, whereas immediate effects on growth from high flows during a particular year may indicate flood tolerance adaptations. Interestingly, Stromberg and Patten (1990) concluded that distance from stream or elevation on the bank had a significant effect on current year tree growth, with higher relevance for precipitation (rather than stream flow) farther from the stream. In another case of reduced flows from damming, riparian species, such as cottonwoods, may experience a collective reduced growth or sacrifice branches and roots for periods when water needs are not met from the reduced flows recharging stream levels and/or groundwater (Schook et al. 2016a).

While the total discharge is identified as a crucial factor in effecting riparian tree growth, the depth and accessibility to the water table is also an important determinant in riparian tree growth. With the regulation of rivers from dam construction, the withholding and regulated release of water, referred to as flow pulses, can cause fluctuations in the water table as the availability of water for groundwater recharge is altered (Tockner et al. 2000, Bejarano et al. 2018). In a study on phreatophyte riparian species, or those that develop deep root systems to access its water supply, obligate species show greater sensitivity to water table depth change as opposed to absolute water table depth than do facultative species (Shafroth et al. 2000). The other noted impact of highly variable water table fluctuation is the development of shallow mean root depths as compared to low variability water table fluctuation which promotes deeper root depth on average (Tron et al. 2014). While still dependent on plant rooting behavior and soil water retention, this response likely occurs as a mechanism to avoid anaerobic conditions presented by the prolonged inundation of roots. Riparian growth and development are also influenced by the elevation of a watershed. Variability in riparian trees grown within higher elevation watersheds is explained mostly by river discharge as deep roots may not have as consistent access to the water tables, whereas in lower elevation watersheds where proximity to river flow gives more consistent connection between deep roots and the closer water table and instead precipitation through surface interactions begins to contribute to growth as much as flows (Schook et al. 2016b). When considering the cascading effects of riparian presence, it is important to note that riparian establishment is not a one-way path of hydrologic and fluvial geomorphic impacts, but the vegetation itself can impact those processes in return (Doulatyari et al. 2014). The reduction of riparian area in one location facilitates altered flows downstream that perpetuate the loss of riparian areas. Conversely, development of riparian areas modifies flows that facilitate new riparian area development downstream.

Dendrochronology

In understanding past influences on tree growth and tracking establishment, many researchers use dendrochronological approaches to assess the influences of naturalregimes and disturbances. Dendrochronology, or tree ring analysis, utilizes tree rings andthe variation in their widths to development indices for evaluating drivers of change in the environment (Stokes and Smiley 1968, Speer 2010). At the site level, tree ring chronologies measure the magnitude and frequency of reactions to environmental change. By developing chronologies for stands, a site's environmental history can be viewed, and annual patterns deduced. In a study in the Apalachicola river of Florida, hydrologic conditions often account for more of the variation found in tree growth than climatic conditions for riparian trees (Smith et al. 2013). It is important to consider that the many forms of disturbance have varying effects of the expression within the tree ring(Stoffel and Corona 2014).

Prior Flow Analyses

Texas is a critical place to evaluate the effects of flows on riparian tree germination and growth because of interest in finding minimum flow requirements to maintain riparian health on Texas Rivers with ever-increasing human demands for water. In the 2018 Texas Instream Flow Program (Texas Instream Flow Program 2018) report, flows were assessed along the middle and lower reaches of the Brazos for inundation of riparian area. The recommended flow regimes in TIFP were to provide beneficiary flood frequency and duration for seeding and germinations periods determined from prior studies along the Brazos. This prior study does not fully address the necessary site conditions for seed germination, as it bases flood pulse levels on meeting the requirements for successful germination but not the development of newly exposed area for seeds to establish. The Bonner et al. (2017) report on the Brazos River examined inundation flow rates and species composition, denoting dissimilarities between flow pulses sizes groups from riverside as well as proportion of wetland indicators in the mature trees. They found that Texas Commission on Environmental Quality (TCEQ) flow standards were inconsistent in meeting the inundation needs of the riparian zone. However, they also noted that the riparian community did display an ecological response to the pulses and overbank flows, but not base and subsistence flows under the TIFP flow categorization. They attributed this discrepancy to potential shifts in the stream channels geomorphology and biotic community as responses of life stage changes in the riparian vegetation (Bonner et al. 2017).

In a study done on the San Antonio and Brazos rivers, riparian tree responses were analyzed to assess flows that were conducive to unsuppressed growth (Duke 2011). The study used tree cores and assessed ring widths to correlate with flows that were either so high or so low that growth was suppressed. The ideal annual total flows were found to be site dependent with the lowest minimum of 0.08 km^3/y and the highest maximum of 2.0 km^3/y on the San Antonio River, whereas the Brazos River had a lowest minimum of 1.8 km^3/y and a highest maximum of 12.2 km^3/y. This study highlights not only the expected species level differences in flow requirements, but also site level differences regarding flows that promote optimal growth. Other findings in this study concluded that along these rivers the regulated flows appear to facilitate the invasion of more upland or deeper-rooted plants that can tolerate reduced flows.

The riparian framework of the Colorado-Lavaca Bay and Basin Expert Science Team (BBEST) Environmental Flow Regimes Report (Colorado River Authority 2011)noted that there was a distinct lack of site-level information for riparian response to instream flows for the river systems in question. In order to make an assessment they utilized vegetation community maps with modeled flow and stage levels under different return interval flood events to determine which size events best maintain the riparian community. Due to the lack of more in depth riparian-flow analyses on this river, this study did not address whether the flows were resulting in diminishing riparian area. Rather, the BBEST 2011 report only went as far as to assess whether the current trajectory was sustainable, be it changing or stable. Similarly, in the 2015 San Antonio River Authority (San Antonio River Authority 2015) study on the Guadalupe River, riparian area persistence and recruitment was assessed by seedling, sapling and mature tree counts of indicator species and evaluated whether the inundation needs were met or not. Their findings were that TCEQ flows were insufficient to reach 80-100% of the mature trees at their sampling sites. They also assessed the response of the trees by taking cores to develop general growth factors.

This study aims to further investigate the long-term impacts that can result from the regulation of rivers and potential future shifts in riparian community age or species composition. Currently, few studies have examined the phenomena of delayed local extirpation of riparian species caused by the desynchronization of the riparian community and river hydrology (Vesipa et al. 2017). Aforementioned studies have correlated growth to river flows and quantified recruitment by size class counts but have neglected to assess these recruitments to the same flows that they prescribed to growth. Also, these studies while showing relations of growth to flows fall short in determining the magnitudes and what changes in flows would affect riparian growth. This study will determine the influence on riparian tree communities by the hydrologic conditions occurring along three Texas rivers (Brazos, Colorado, and Guadalupe); and if so, this research can identify the crucial points of potential intervention in the process.

Objectives

The primary objective of this study is to develop a low expenditure method for the Texas Water Development Board that can be implemented by stakeholders to assess riparian conditions. Specifically, this study will relate riparian tree germination and growth to flood histories. My target species in this study represent common obligate wetland tree species that can reflect the overall condition the riparian habitat. Based on prior research, I tested the hypothesis that probability of germination would increase with floods of low size and decrease with floods of high tier, while being most beneficial in the Spring and Summer seasons. My second hypothesis was that growth will be positively correlated with increases in floods and flows in the spring and summer seasons and decreases as well.

Methods

Study Area

The study was conducted at six sites along the lower reaches of the Brazos, Colorado and Guadalupe Rivers in Texas (Fig 1). Sites were selected from active point bars within the vicinity of predetermined United States Geologic Survey (USGS) gaging stations. We selected point bars that display active deposition representative of fluvial succession, and active vegetative succession, where there is visible evidence of progressive growth and recruitment of tree growth. Permission from site landowners was granted prior to access properties from the riverside.

For the Brazos River sites, the Hearne Site (Fig. 2) is also located on private property along the Brazos River in Caldwell, TX 44.5 km downstream of the USGS gage station 08098290. From the gage station to the sampling site, it is joined by Pond Creek, Little River, Threemile Creek, and Sixmile Creek. The site had a slightly steep but sloping bank to the water's edge. Once at the vegetated edge, the topography is primarily flat with recurring troughs. Willow baccharis (*Baccharis salicina*) dominated much of the understory and clearings. The Bryan Site (Fig. 3) was also located on private property along the Brazos River in Bryan, TX 6.1 km downstream from USGS gage station 08098450 near the confluence of the Little Brazos River. The site is relatively flat with slight undulations in topography away from the river. We observed 1-2ft tall *Salix nigra* and *P. deltoides* seedling/saplings commonly occurred throughout the forest floor and many clearings.

For the Colorado River Sites, Colorado-Bastrop Site (Fig. 4) is located along the Colorado River in Bastrop, TX 1.14 km upstream of USGS gage station 08159200. The site is open for public access on Bastrop City property in Fisherman's Park. Colorado-La Grange Site (Fig. 5) is located along the Colorado River near La Grange, TX 0.7 km upstream USGS gage station 08160400. This site used was bordered by pastureland, above and at the meander apex was deemed unviable due to absence of target species, so we sampled trees from the lower portion of the meander instead.

For the two adjacent Guadalupe Sites, Seguin upstream (Fig. 6) and Seguin downstream (Fig. 7), are located off FM 1117 bridge near Seguin, TX, where upstream site is 0.47 km upstream and downstream site 0.85 km downstream from USGS gage station 08169792. Both sites represent meanders with sandy soil almost entirely dominated by *P. occidentalis.* Beyond the sample boundary, both the sites are bordered by agricultural land, with evidence that cattle do come through the upstream site. This is noted as the presence of grazing cattle may have removed or prevented establishment of some target species, prior to sampling.

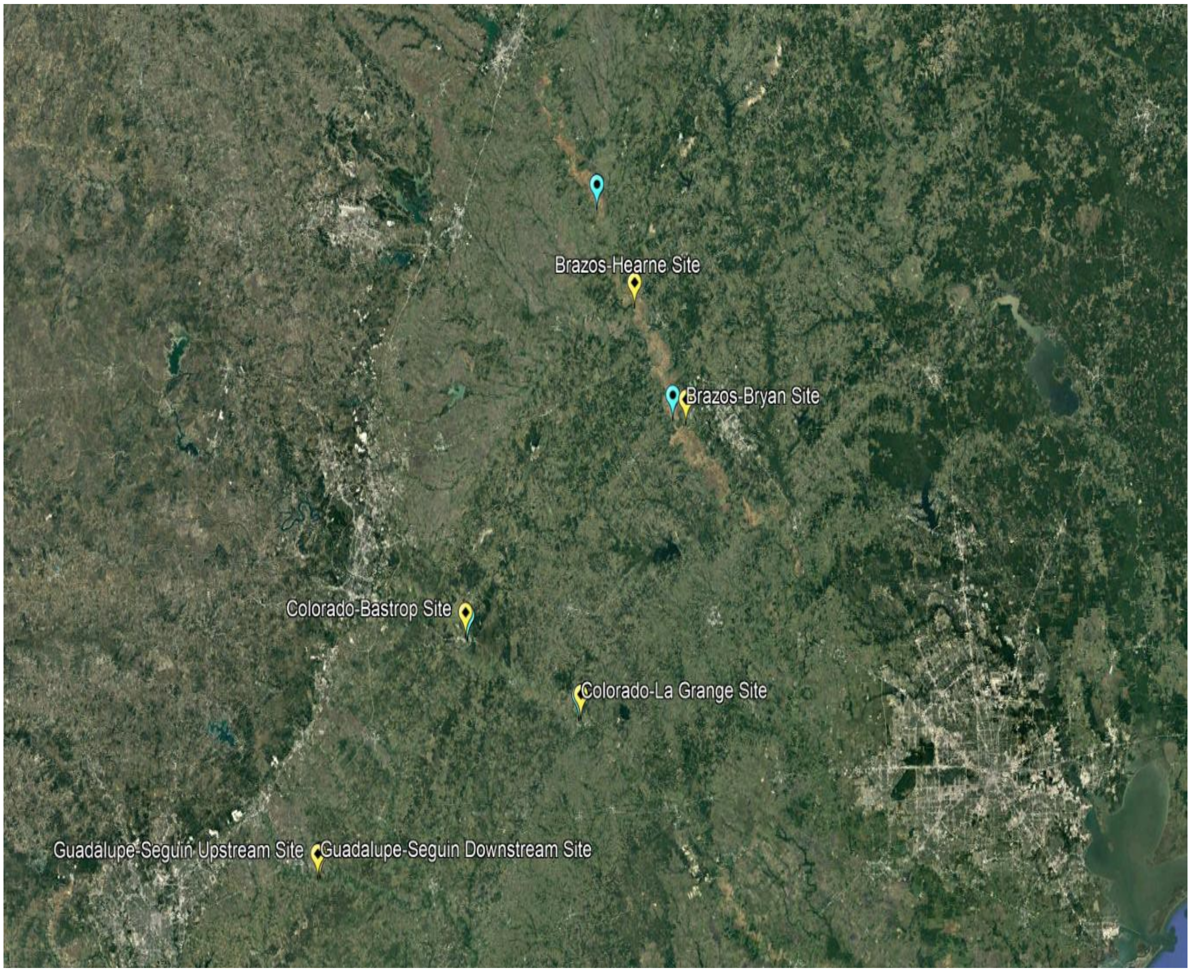

Figure 1. Site locations in yellow with name description and gage stations in blue.

Figure 2. Hearne, TX site on the Brazos River. The white outlined polygon represents the surveyed riparian area.

Figure 3. Bryan, TX site on Brazos River. The white outlined polygon represents the surveyed riparian area.

Figure 4. Bastrop, TX site on Colorado River. The white outlined polygon represents the surveyed riparian area.

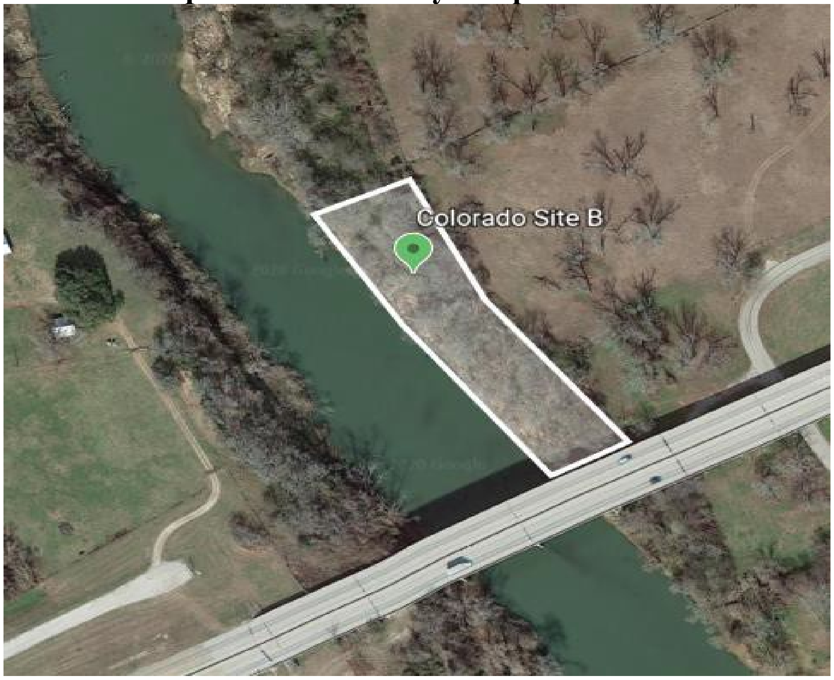

Figure 5. La Grange, TX site on Guadalupe River. The white outlined polygon represents the surveyed riparian area.

Figure 6. Upstream Seguin, TX site on the Guadalupe River. The white outlined polygon represents the surveyed riparian area.

Figure 7. Downstream Seguin, TX site on Guadalupe River. The white outlined polygon represents the surveyed riparian area.

Sample Data Collection

Tree Data

The target riparian species in this study include Black Willow (*Salix nigra*), Box Elder (*Acer negundo*), Green Ash (*Fraxinus pennsylvanica*), Eastern Cottonwood (*Populus deltoides*), American Sycamore (*Platanus occidentalis*), and Southern Bald-cypress (*Taxodium distichum*). The species were primarily selected for their representation of fast maturing species (*S. nigra, A. negundo, and P. deltoides*) and slow maturing species (*P. occidentalis, F. pennsylvanica and T. distichum*). They also represent common species and indicators of quality of riparian habitat that cover a range of seedling dispersal strategies and germination requirements. The study area falls in the Atlantic Gulf Coast plain region of Texas where the indicator status of *S. nigra* and *T. distichum* are wetland obligate species, *F. pennsylvanica* and *P. occidentalis* are facultative wetland *A. negundo* and *P. deltoides* are considered facultative.

For sites that exhibited progressive point bars, transects 50 m long with 10 m intervals were used. Transect endpoints were GPS assigned prior to site visits and then located on site with a GPS unit. At each 10-m interval, a 10-m transect was placed on alternating sides from the starting point. All viable trees within a 5-m width band were sampled. At the beginning and end of each 10-m transect, a laser range finder (mention the make and model) was used to measure elevation above the river.

Along rivers that did not form progressive point bars, sampling locations were at outer bends or meanders that exhibited staggered cohorts of trees along the bank.

Generally, these cohorts appear to have been established in a narrow band of new deposits following a previous flow event. Due to the limited reach of the stand in these conditions at these sites all viable trees were sampled within 100 m x 30 m plot that ran adjacent to the river. At every 10 m within each vegetation band, a laser range finder was used to measure the elevation from the river.

All target species with a diameter at breast height (DBH) greater than 5 cm were cored at breast height (1.3 m or lower, pending trunk suitability) on the upstream side perpendicular to the river using an increment borer (Haglöf, Sweden). Trees with a DBH less than 5 cm were cut at 50-cm height and cookies were extracted for age determination. If a target species exhibited multi-stemmed growth, the largest stem was used for sampling. A minimum of 30 trees per transect were cored.

Cores were stored in paper straws and dried at 60^0 C until constant weight was recorded. Once dried, cores were mounted to a wooden mount with glue and sanded using progressively finer sandpaper ranging from 60 to 400 grit (Speer 2010). Cores that showed low or no ring visibility were removed. The sampled cores were then measured were measured to the nearest 0.001 mm on the Texas A&M University's Department of Geography using the MeasureJ2X program linked to a sliding-stage microscope constructing core specific chronologies. Increment cores were then crossdated first using skeleton plots and verified using measured chronologies with the COFECHA software (Holmes 1983), after which problem cores were removed. The measurements of the increment cores were then combined by species for each site as well as combined into total for each river. These grouped chronologies were then standardized to master chronologies using the Regional Curve standardization using a 20-year spline in the dplyr R package (R Core Team 2021).

Hydrologic Data

Available discharge and gage height data from the USGS gage stations was collected for the nearest stations for the time periods corresponding to the oldest trees sampled until the last dated tree ring (Table 1). If a gage station had periods of missing records, the nearest gage station where the hydrology was most similar was used to supplement the missing data. The TCEQ House and Senate Bill 3 adopted flow rule and site level evaluations from Hydrology-Based Environmental Flow Regimes (HEFR) models that were used to determine threshold riverine conditions for average flow volumes and high flow pulse volumes and frequencies unique to each gage station (Table 1). These include levels that were within the 75th percentile of base flow, tier one pulses that occurred at twice per season return intervals, tier two pulses that are suggested to occur once per season return intervals, tier three pulses that are suggested to occur at once per year intervals, tier four pulses that are suggested to occur at once per two-year intervals, and tier five pulses that are suggested to occur at once per five-year intervals. From the data, seasonal average flows (m^3s^{-1}) and tier pulses (number of days) were compiled for use as explanatory variables. Using data acquired through NOAA precipitation(mm) for each river.

Table 1. List of primary USGS Gage Stations and their tiered flows from HEFR model calculations. Values reported are average discharge (cms).

<table>
<tr><td colspan="5">Brazos River USGS Gage Station 08098290</td></tr>
<tr><td></td><td>Spring</td><td>Summer</td><td>Fall</td><td>Winter</td></tr>
<tr><td>Baseflow 75th Percentile</td><td>34</td><td>35</td><td>29</td><td>35</td></tr>
<tr><td>High Flow Pulse 1</td><td>170</td><td>72</td><td>71</td><td>106</td></tr>
<tr><td>High Flow Pulse 2</td><td>362</td><td>147</td><td>139</td><td>198</td></tr>
<tr><td>High Flow Pulse 3</td><td colspan="4">725</td></tr>
<tr><td>High Flow Pulse 4</td><td colspan="4">937</td></tr>
<tr><td>High Flow Pulse 5</td><td colspan="4">1073</td></tr>
<tr><td colspan="5">Brazos River USGS Gage Station 08108700</td></tr>
<tr><td></td><td>Spring</td><td>Summer</td><td>Fall</td><td>Winter</td></tr>
<tr><td>Baseflow 75th Percentile</td><td>71</td><td>44</td><td>50</td><td>60</td></tr>
<tr><td>High Flow Pulse 1</td><td>178</td><td>NA</td><td>NA</td><td>181</td></tr>
<tr><td>High Flow Pulse 2</td><td>640</td><td>NA</td><td>351</td><td>521</td></tr>
<tr><td>High Flow Pulse 3</td><td colspan="4">1240</td></tr>
<tr><td>High Flow Pulse 4</td><td colspan="4">1616</td></tr>
<tr><td>High Flow Pulse 5</td><td colspan="4">1893</td></tr>
<tr><td colspan="5">Colorado River USGS Gage Station 08159200</td></tr>
<tr><td></td><td>Spring</td><td>Summer</td><td>Fall</td><td>Winter</td></tr>
<tr><td>Baseflow 75th Percentile</td><td>47</td><td>54</td><td>38</td><td>23</td></tr>
<tr><td>High Flow Pulse 1</td><td>97</td><td>71</td><td>65</td><td>83</td></tr>
<tr><td>High Flow Pulse 2</td><td>202</td><td>98</td><td>108</td><td>131</td></tr>
<tr><td>High Flow Pulse 3</td><td colspan="4">433</td></tr>
<tr><td>High Flow Pulse 4</td><td colspan="4">693</td></tr>
<tr><td>High Flow Pulse 5</td><td colspan="4">906</td></tr>
<tr><td colspan="5">Colorado River USGS Gage Station 08160400</td></tr>
<tr><td></td><td>Spring</td><td>Summer</td><td>Fall</td><td>Winter</td></tr>
<tr><td>Baseflow 75th Percentile</td><td>44</td><td>49</td><td>37</td><td>840</td></tr>
<tr><td>High Flow Pulse 1</td><td>151</td><td>73</td><td>75</td><td>98</td></tr>
<tr><td>High Flow Pulse 2</td><td>264</td><td>106</td><td>127</td><td>205</td></tr>
<tr><td>High Flow Pulse 3</td><td colspan="4">597</td></tr>
<tr><td>High Flow Pulse 4</td><td colspan="4">841</td></tr>
<tr><td>High Flow Pulse 5</td><td colspan="4">1265</td></tr>
<tr><td colspan="5">Guadalupe River USGS Gage Station 08169792</td></tr>
<tr><td></td><td>Spring</td><td>Summer</td><td>Fall</td><td>Winter</td></tr>
<tr><td>Baseflow 75th Percentile</td><td>15</td><td>15</td><td>16</td><td>15</td></tr>
<tr><td>High Flow Pulse 1</td><td>36</td><td>25</td><td>23</td><td>23</td></tr>
<tr><td>High Flow Pulse 2</td><td>92</td><td>128</td><td>54</td><td>39</td></tr>
<tr><td>High Flow Pulse 3</td><td colspan="4">180</td></tr>
<tr><td>High Flow Pulse 4</td><td colspan="4">211</td></tr>
<tr><td>High Flow Pulse 5</td><td colspan="4">271</td></tr>
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Data Analysis

A scatter plot and regression model of annual precipitation against annual average flow was conducted as a proxy to assess the accountancy of precipitation driving the rivers flows. This metric will also make note of rivers' flows being influenced by inputs of groundwater.

Tree germination was analyzed as the response variable in statistical models using univariate binary logistic regression with the logit function.

$$\text{Logit} = \beta_0 + \beta_1 X = \text{log odds (LO)} \tag{1}$$

where β_0, β_1, and X, are the intercept, logit defined coefficient of the independent variable, and the independent variable, respectively. The produced log odds (LO) were then converted to probabilities with the following function.

$$\frac{\exp(\text{LO})}{1 + \exp(\text{LO})} * 100 = \text{Probability } (\%) \tag{2}$$

Probability curves were made using seasonal average flows (m^3s^{-1}) and high flow pulses (count) as independent variables in the model. Given the low sample size in this study and stochastic behavior for all possible germination events that occurred on these rivers, a threshold of p-value greater than 0.2 was used to distinguish notable trends on curves. However, we retain a standard of $p < 0.05$ for reporting significant trends.

The effects of hydroclimate on tree growth were analyzed using univariate linear regression. The regressions were conducted with river wide and species-specific annual ring-width indexes against monthly precipitation and mean monthly flow. To estimate the multi-month influence of season or cross seasonal periods in the growing season, we averaged monthly climate data over progressively longer periods from January to September.

Results

A total of 230 trees was assessed to determine germination dates with notable differences in species make-up unique to each river (Table 2). The most prevalent species was *A. negundo*, making up 34% of all trees sampled with its occurrences primarily restricted to the Brazos (42%) and Colorado Rivers (63%) and with lower presence on the Guadalupe River (3%). On the Brazos, *A. negundo* and *S. nigra* were the dominant species making up 42% and 39% of the samples collected, respectively. On the Colorado River, the remaining 37% comprised roughly equal proportions of *F. pennsylvanica*, *P. occidentalis*, and *S. nigra*. While *P. occidentalis* made up 100% and 95% of the total samples collected on the Guadalupe River and Seguin Site A, respectively, their presence at other sites was minimal. *F. pennsylvanica* and *P. deltoides* were found on both the Colorado and Brazos Rivers, though their numbers were on average 3 and 5 per site on average, respectively. The least encountered species, *T. distichum,* was encountered once within sampled areas, making up only 0.004% of all samples.

Table 2. Total number of trees sampled by river, site, and species location.

River Sites	Site Location	Trees Sampled
Brazos River		
Bryan Site	7 km downstream of USGS Gage Station 08108700	Total (62) *A. negundo* (26) *F. pennsylvanica* (1) *P. deltoides* (12) *P. occidentalis* (1) *S. nigra* (22)
Hearne Site	46 km downstream of USGS Gage Station 08098290	Total (30) *A. negundo* (13) *F. pennsylvanica* (2) *P. deltoides* (1) *S. nigra* (14)
Colorado River		
Bastrop Site	1.14 km upstream from USGS Gage Station 08159200	Total: (30) *A. negundo* (17) *F. pennsylvanica* (2) *P. deltoides* (5) *S. nigra* (4)
La Grange Site	0.69 km away from USGS Gage Station 08160400	Total: (30) *A. negundo* (21) *F. pennsylvanica* (5) *P. occidentalis* (2) *S. nigra* (2)
Guadalupe River		
Seguin Site A	0.47 km upstream from USGS Gage Station 0816792	Total (37) *P. occidentalis* (37)
Seguin Site B	0.85 km downstream from USGS Gage Station 08169792	Total (41) *A. negundo* (2) *P. occidentalis* (37) *S. nigra* (1) *T. distichum* (1)

Although high correlations between annual precipitation (mm) and flows (m^3s^{-1}) were expected, the Colorado River despite having increased regulation through dams maintain a high correlation of annual precipitation to flows. Annual flow was most closely related to precipitation on the Guadalupe ($R^2 = 0.76$), whereas the Colorado and Brazos Rivers had R^2 values of 0.70 and 0.62 respectively (Figure 8).

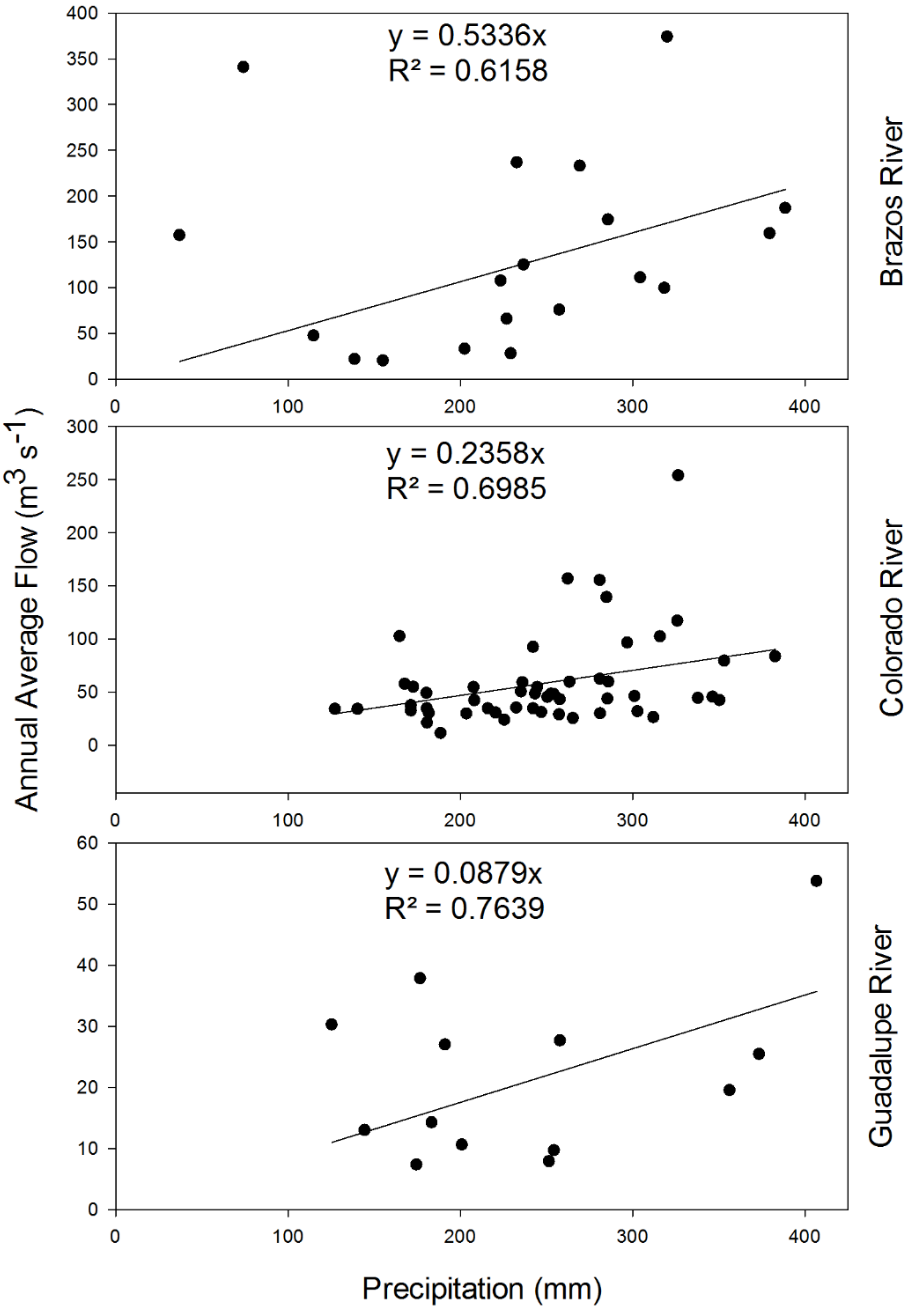

Figure 8. Figure 8. Relationship of precipitation (mm) and annual flows (m^3s^{-1}) on the Brazos River ($p < 0.0001$), Colorado River ($p < 0.0001$), and Guadalupe River ($p < 0.0001$).

On the Brazos River, spring and summer average flows were the highest during most years relative to the other seasons, with winter average flows occasionally reaching the similar levels (Fig. 9). The highest germination counts on the Brazos River occurred in 2003 and 2008 which both comprised 12 % of the germination. These periods did not overlap with high flow years, though 2008 did follow a year with the highest summer flows. *S. nigra* (SANI) experienced its highest germination in 2008, with 15% of its germination occurring in this year. *A. negundo* (ACNE), *F. pennsylvanica* (FRPE), and *P. deltoides* (PODE) germinations were distributed over a wide range of flows, though only *F. pennsylvanica* had an occurrence during ahigh flow year.

From the logistic regression, germination events on the Brazos River were generally associated with increased spring and summer flows and exhibited negative to no correlation in fall and winter flows, respectively (Fig. 10). As average spring flows increased *A. negundo* ($p = 0.08$) and *P. deltoides* ($p = 0.1$) probability of germination increased from 5% to 93% and 14% to 90%, respectively. For increasing summer average flows, the overall species ($p = 0.2$), *A. negundo* ($p = 0.04$) and *F. pennsylvanica* ($p = 0.2$) germination probabilities increased from 38% to 100%, 4% to 99% and 9% to 85%, respectively. Fall and winter flows were not associated with germination probability; however, *P. deltoides* did exhibit a positive relationship to fall flows that did not achieve significance due to low observations.

For the relationships between germination and high flow pulses (HFPs) on the Brazos River, spring and summer HFPs that commonly accumulated much longer periods of flooding also exhibited mostly positive correlations with germination probabilities (Fig. 11). *P. deltoides* displayed a significant positive response to spring 75th percentile pulses (p=0.04) with probabilities increasing from 3% to 72% as flow durations ranged up to 92 days. *A. negundo* also showed a significant positive response to summer 75th percentile pulses (p = 0.04), summer tier one pulses (p = 0.04), and summer tier two pulses (p = 0.04) with probabilities increasing from 3% to 73%. Since the tier two pulses were the same duration as the smaller HFPs, it is difficult to assess ideal flood size for *A. negundo*, i.e., its germination may have responded solely to the tier two magnitude events that occurred in a single year.

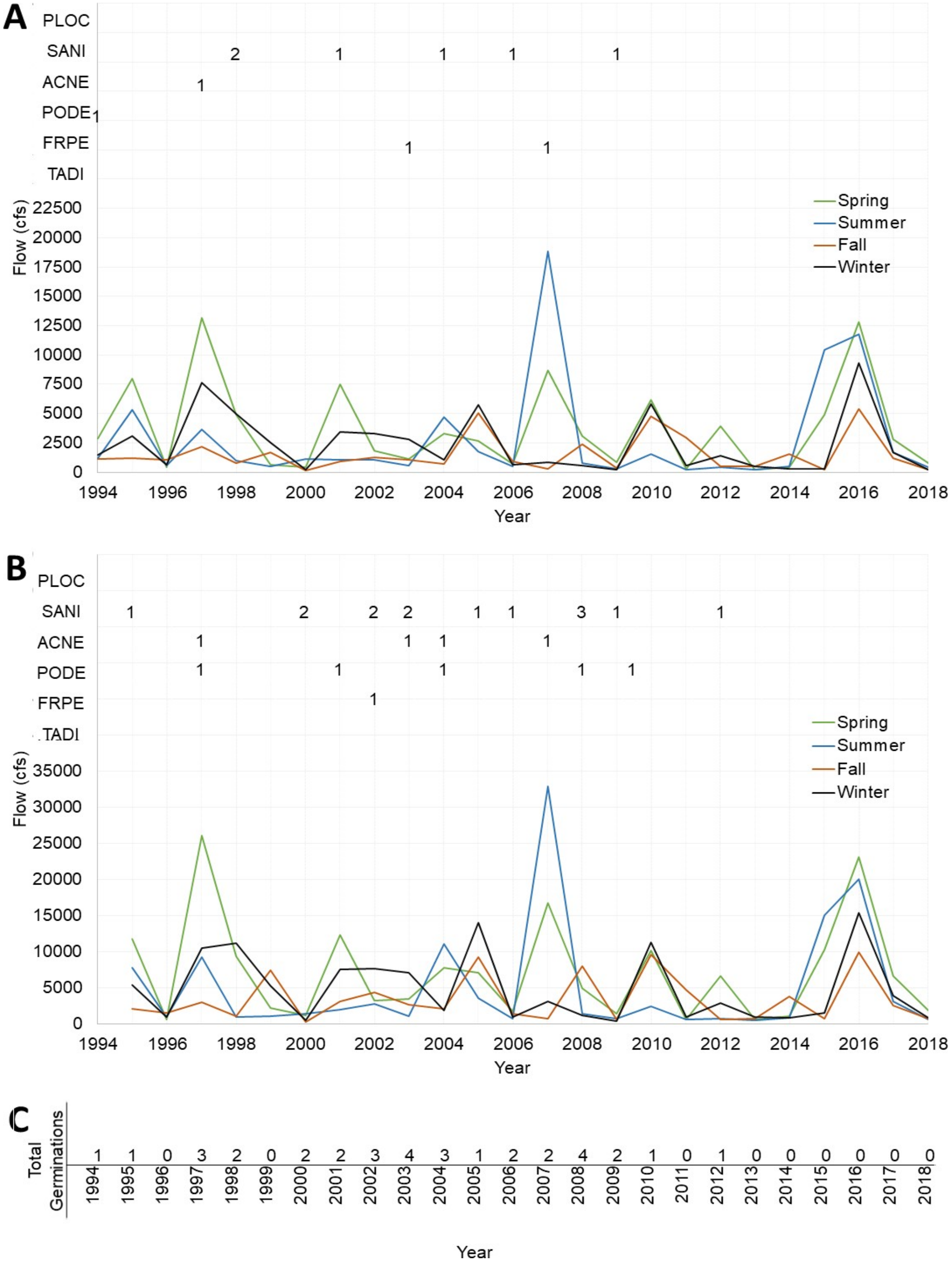

Figure 9. Seasonal flows and germination counts on the Brazos River at the Hearne, TX sites (A), Bryan, TX site (B) and total river consolidated germination counts by year (C). PLOC (*P. occidentalis*), SANI (*S. nigra*), ACNE (*A. negundo*), PODE (*P. deltoides*), FRPE (*F. pennsylvanica*), and TADI (*T. distichum).*

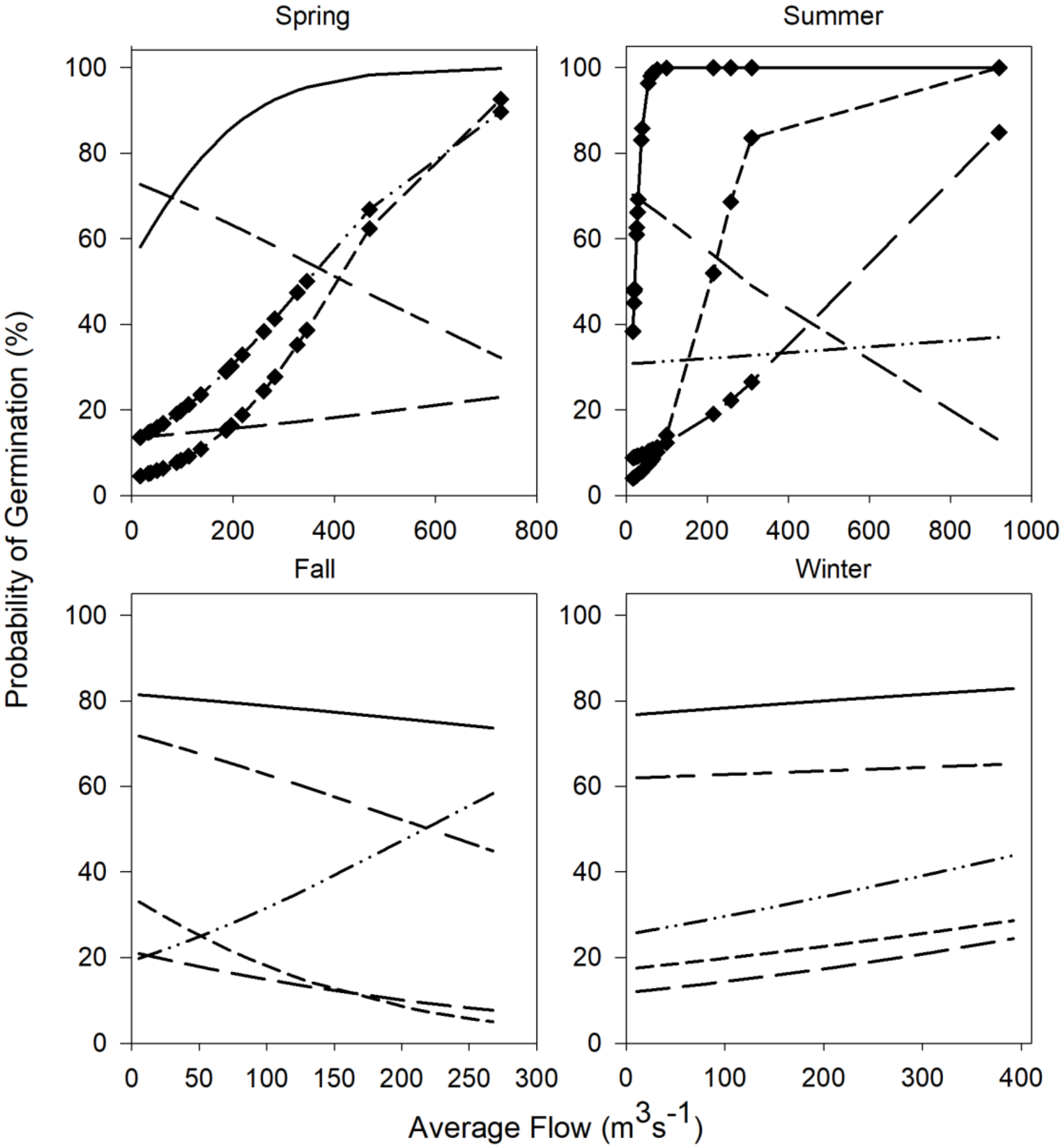

Figure 10. Brazos River Average Flow Germination Response. This figure displays the germination probabilities of the target species to the seasonal flows of the Brazos River. All species germination represented by (——), *Acer negundo* (— — — —), *Fraxinus pennsylvanica* (—— ——), *Populus deltoides* (— ·· — ·· —), and *Salix nigra* (— – — –). The ♦ denotes an interaction with a p-value < 0.2.

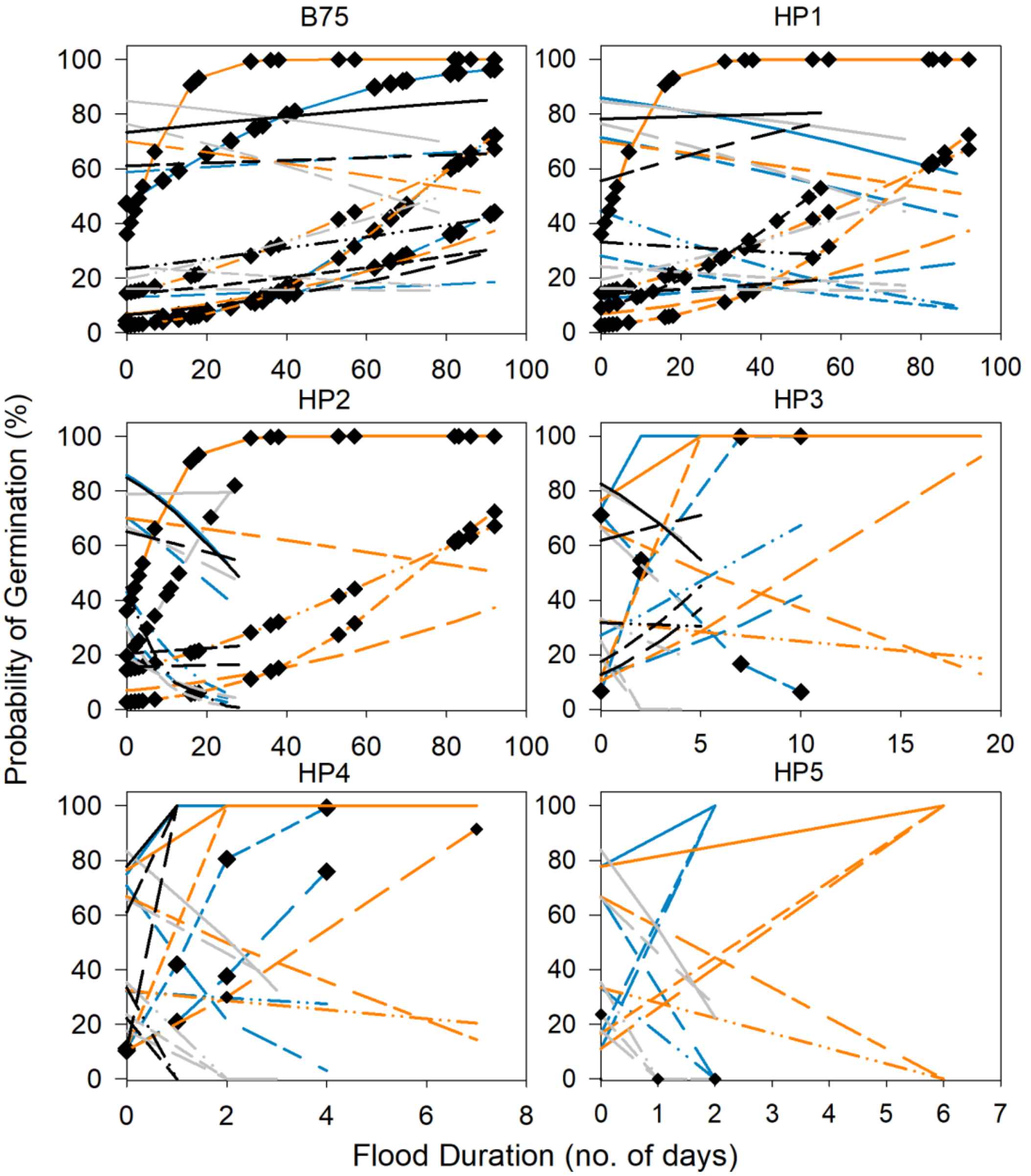

Figure 11. Brazos River High Flow Pulse Germination Response. This figure displays the germination probabilities of the target species to the HFPs of the Brazos River. All species germination represented by (——), ***Acer negundo*** **(— — — —),** ***Fraxinus pennsylvanica*** **(—— ——),** ***Populus deltoides*** **(— ·· — ·· —), and** ***Salix nigra*** **(— – – – —). The ♦ denotes an interaction with a p-value < 0.2. Seasons are in color coded as spring(blue), summer(orange), fall(gray) and winter(black).**

On the Colorado River, summer flows generally were the highest amongst the season with winter occasionally surpassing them (Fig. 12). Years with flows higher than 283 $m^3 s^{-1}$ occurred at both sites during the summers of 1987, 2002, and 2007, winter of 1992, and spring and summer 1997. While none of these years themselves had the highest germination, they were often succeeded by periods of high germination. The largest counts of germinations occurred in 1991, 1994 and 1996, each having 8% of total germination those years, the latter two of which occurred with 5 years of the largest flow recorded being the winter of 1992. *A. negundo* (ACNE), being most common, made up the largest germination events at both sites, often appearing soon after years of high spring or summer flows. The only instance of *P. occidentalis* (PLOC) germination occurred in 1979 which itself did not have nor was it preceded by any high or low flows. The remaining species were widely distributed yet tended to occur in years within a short period of high flow seasons.

For the germination responses to seasonal average flows on the Colorado River, there were few correlations (Fig. 13). The probability of *A. negundo* germination increased with flows for all seasons, but this trend was only marginally significant for summer flows (p=0.1). Due to *A. negundo* making up most of the sampled species, the overall germination reflects a similar relationship despite not having a notable correlation. No relations were found for other species likely due to low numbers of germination observations.

On the Colorado River, we found a general trend that flood pulses of varying sizes had a positive effect on germination (Fig 14). In contrast to the Brazos River where spring and summer events were important predictors of germination, we found that fall events appear to be critical for germination on the Colorado River. Germination of *P. deltoides* responded positively to fall events above the 75% percentile (p=0.009) as well as fall tier one pulses (p=0.08), increasing probability from 2% to 40% and 4% to 57%, respectively for flow durations up to 90 days. Despite the rarity of tier three and tier four events, *A. negundo* appears to germinate in response to those larger events lasting as much as 18 days in the summer (p=0.07 and 0.08, respectively) with probabilities increasing from 28% to 79% and 28% to 86%, respectively, compared with smaller high flow pulses.

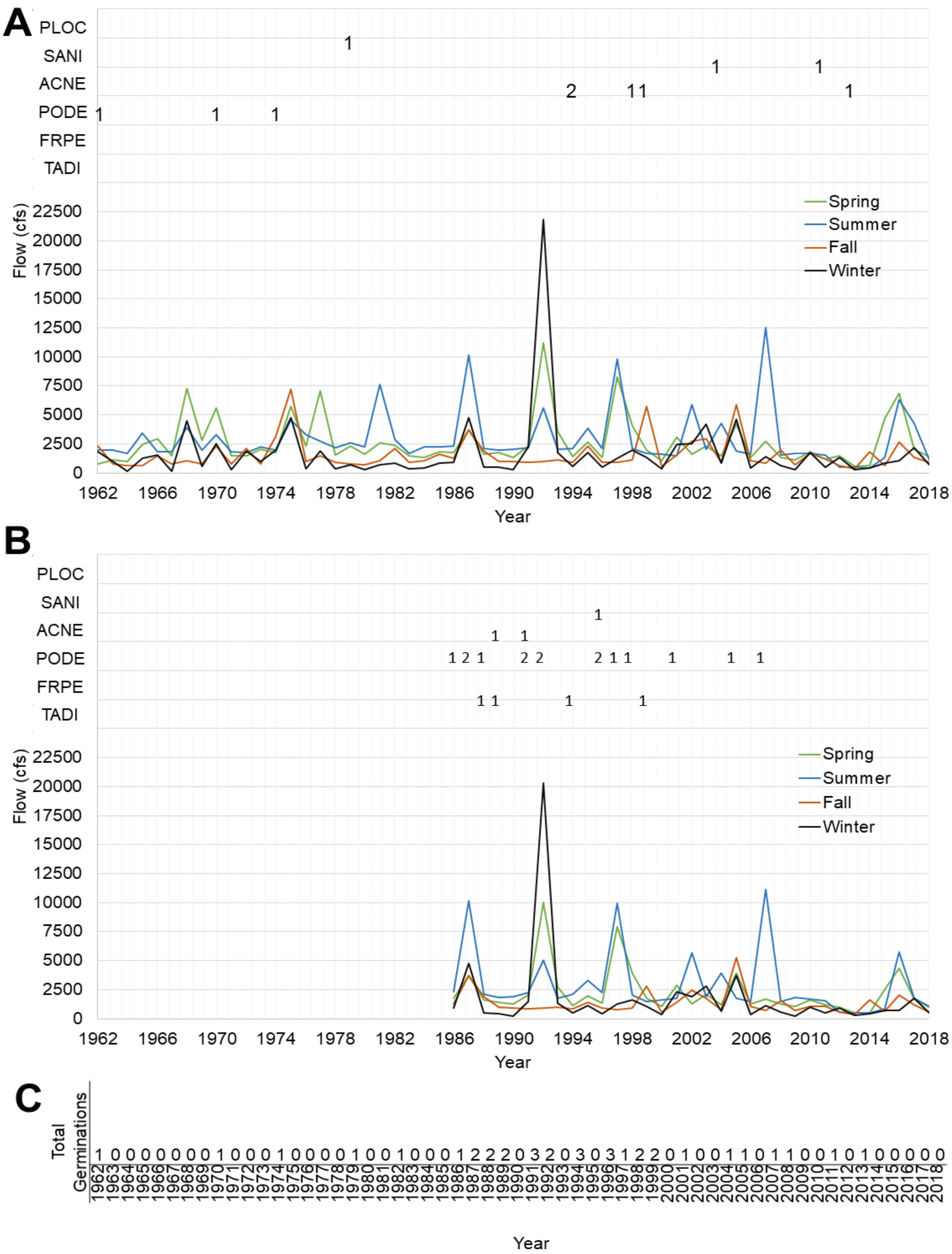

Figure 12. Seasonal flows and germination counts on the Brazos River at the Bastrop, TX sites (A), La Grange, TX site (B) and total river consolidated germination counts by year (C). PLOC (*P. occidentalis*), SANI (*S. nigra*), ACNE (*A. negundo*), PODE (*P. deltoides*), FRPE (*F. pennsylvanica*), and TADI (*T. distichum*).

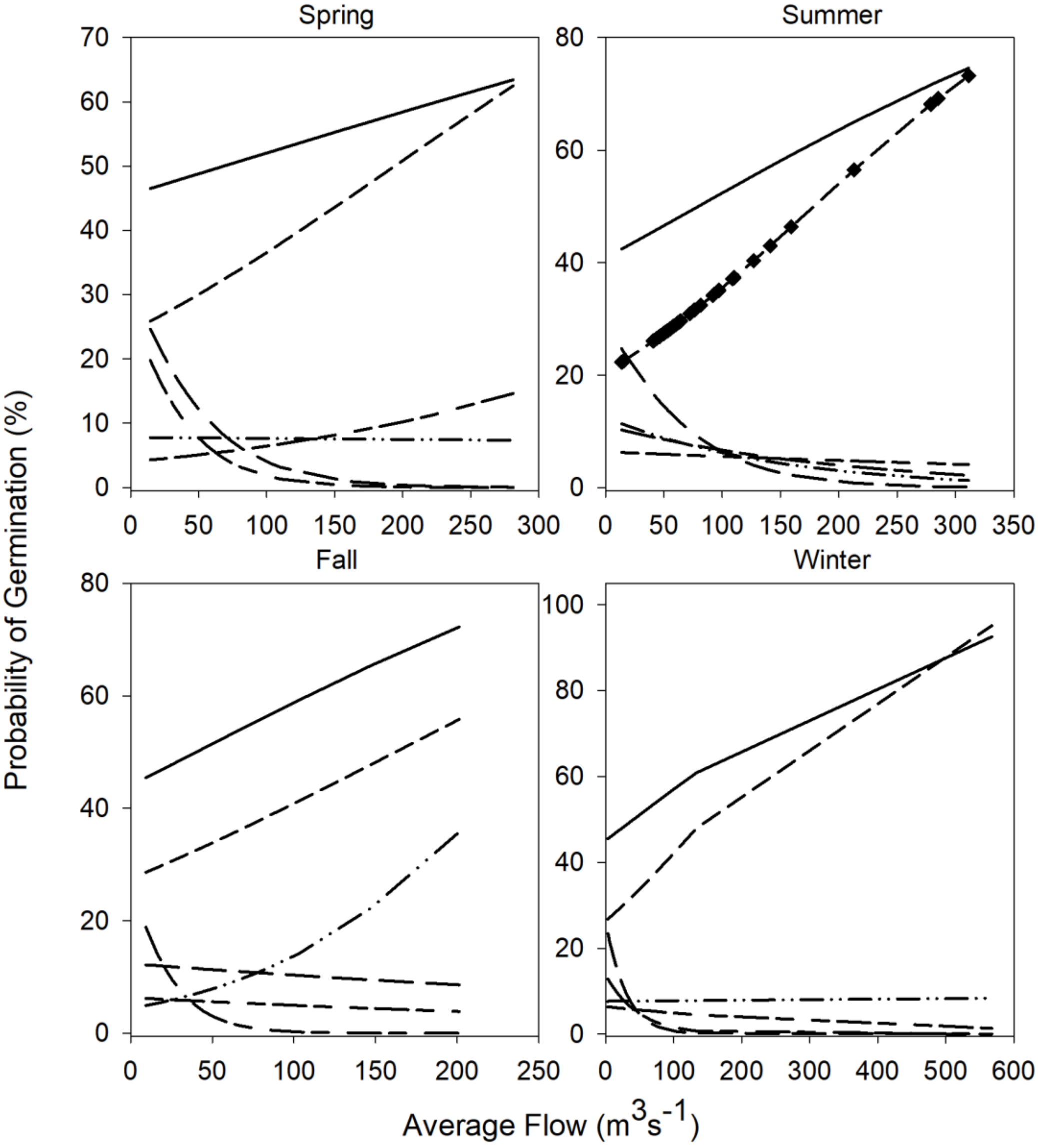

Figure 13. Colorado River Average Flow Germination Response. This figure displays the germination probabilities of the target species to the seasonal average flows of the Colorado River. All species germination represented by (——), *Acer negundo* (— — — —), *Fraxinus pennsylvanica* (—— ——), *Platanus occidentalis* (– — – – — –), *Populus deltoides* (— ·· — ·· —), and *Salix nigra* (— – — –). ♦ denotes an interaction with a p-value < 0.2.

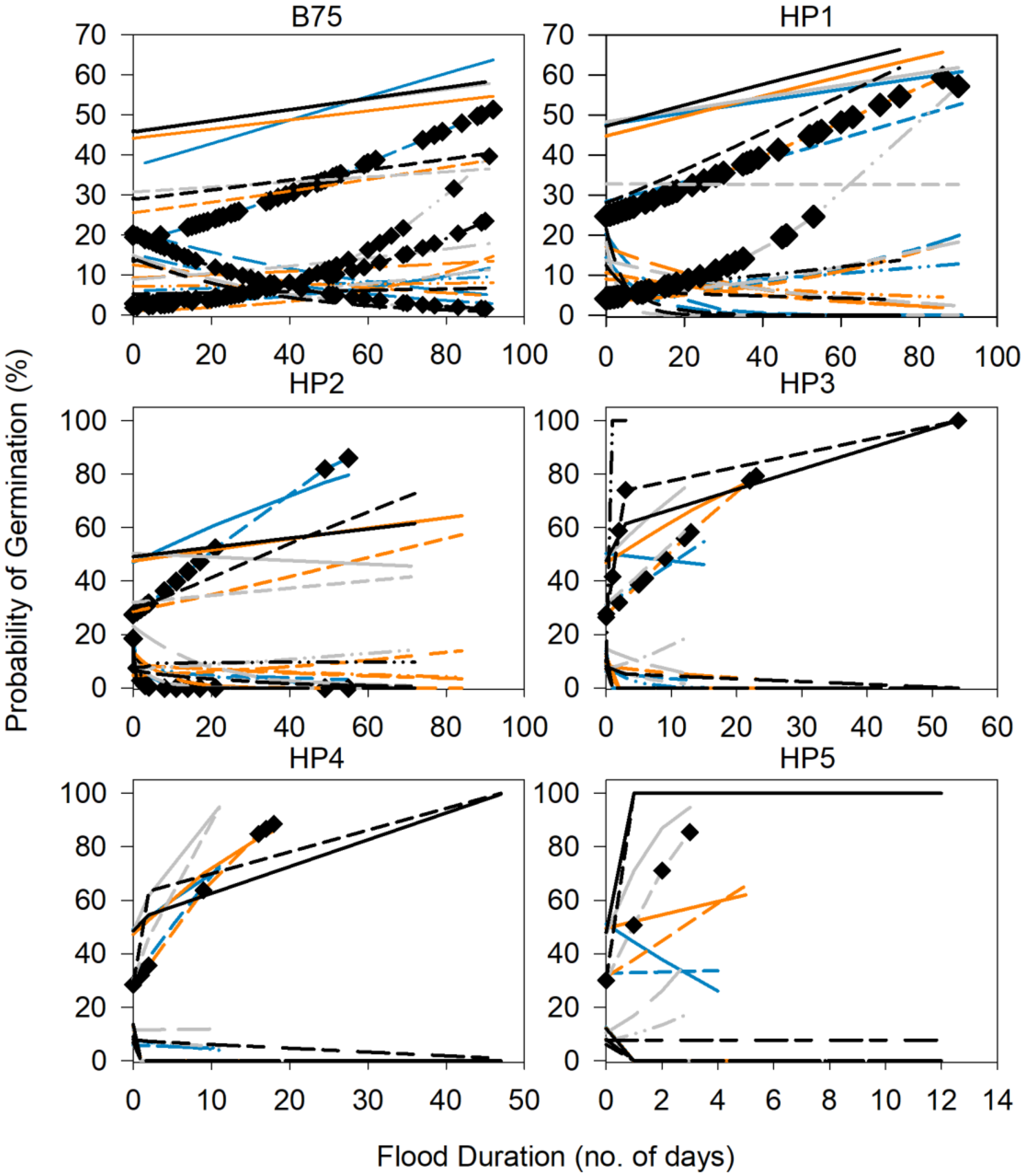

Figure 14. Colorado River High Flow Pulse Germination Response. This figure displays the germination probabilities of the target species to the seasonal HFPs of the Colorado River. All species germination represented by (——), *Acer negundo* (— — — —), *Fraxinus pennsylvanica* (—— ——), *Platanus occidentalis* (– – – – – –), *Populus deltoides* (— ·· — ·· —), and *Salix nigra* (— – – –). ♦ denotes an interaction with a p-value < 0.2. Seasons are in color coded as spring(blue), summer(orange), fall(gray) and winter(black).

On the Guadalupe River summer flows were regularly the highest among seasons (Fig. 15). The year 2007 had the highest flows in the record with summer flows reaching 142 $m^3 s^{-1}$. During this year 10% of germination occurred with 3 counts of *P. occidentalis* and 1 of *S. nigra*. However, 2011 to 2014 was a drier than average period, yet contained 42% of the germination with 2013 containing 21% of total germination occurred, all of which was comprised by *P. occidentalis*. The only instance of *S. nigra* germination was in 2007 and the only instance of *A. negundo* was in 2011.

For the logistic regressions of flows to germination, most models suggest a declining probability of germination with increasing flows, but none of those trends were statistically significant (Fig 16). Note that the germination record on the Guadalupe only extends back to 2004, so limited data were available to test germination trends on this river. *P. occidentalis* was dominant species along this river and displayed no notable relationship to the seasonal flows. Relationships of *A. negundo* and *S. nigra* are of limited use due to their minimal number of observations.

HFPs on the Guadalupe River, often showed minimal influence on germination probabilities (Fig. 17). However, two instances of winter tier one (p=0.2) and tier two (p=0.2) pulses lasting 71 and 29 days, respectively, had a weak negative effect on *P. occidentalis* germination, decreasing probabilities from 88% to 21% and 90% to 4%, respectively. Overall, target species did demonstrate changes as HFPS either increased in size or increased in duration but did not pass the threshold.

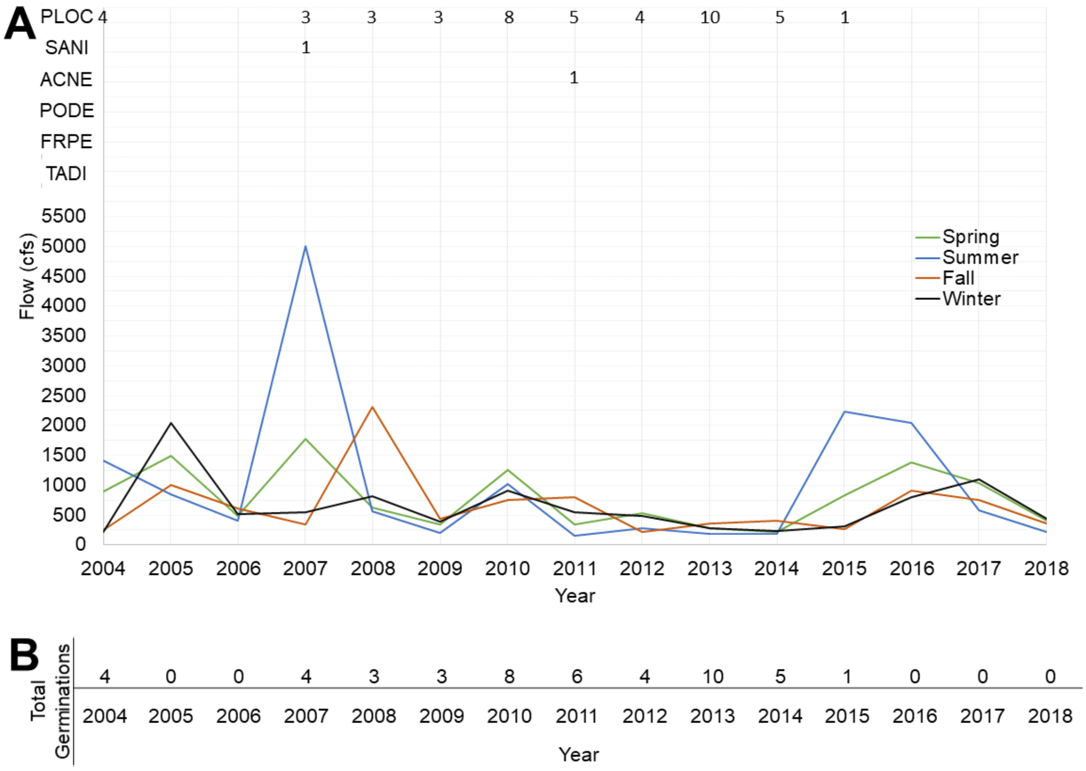

Figure 15. Seasonal flows and germination counts on the Brazos River at the Seguin, TX sites (A) and total river consolidated germination counts by year (B). PLOC (*P. occidentalis*), SANI (*S. nigra*), ACNE (*A. negundo*), PODE (*P. deltoides*), FRPE (*F. pennsylvanica*), and TADI (*T. distichum).*

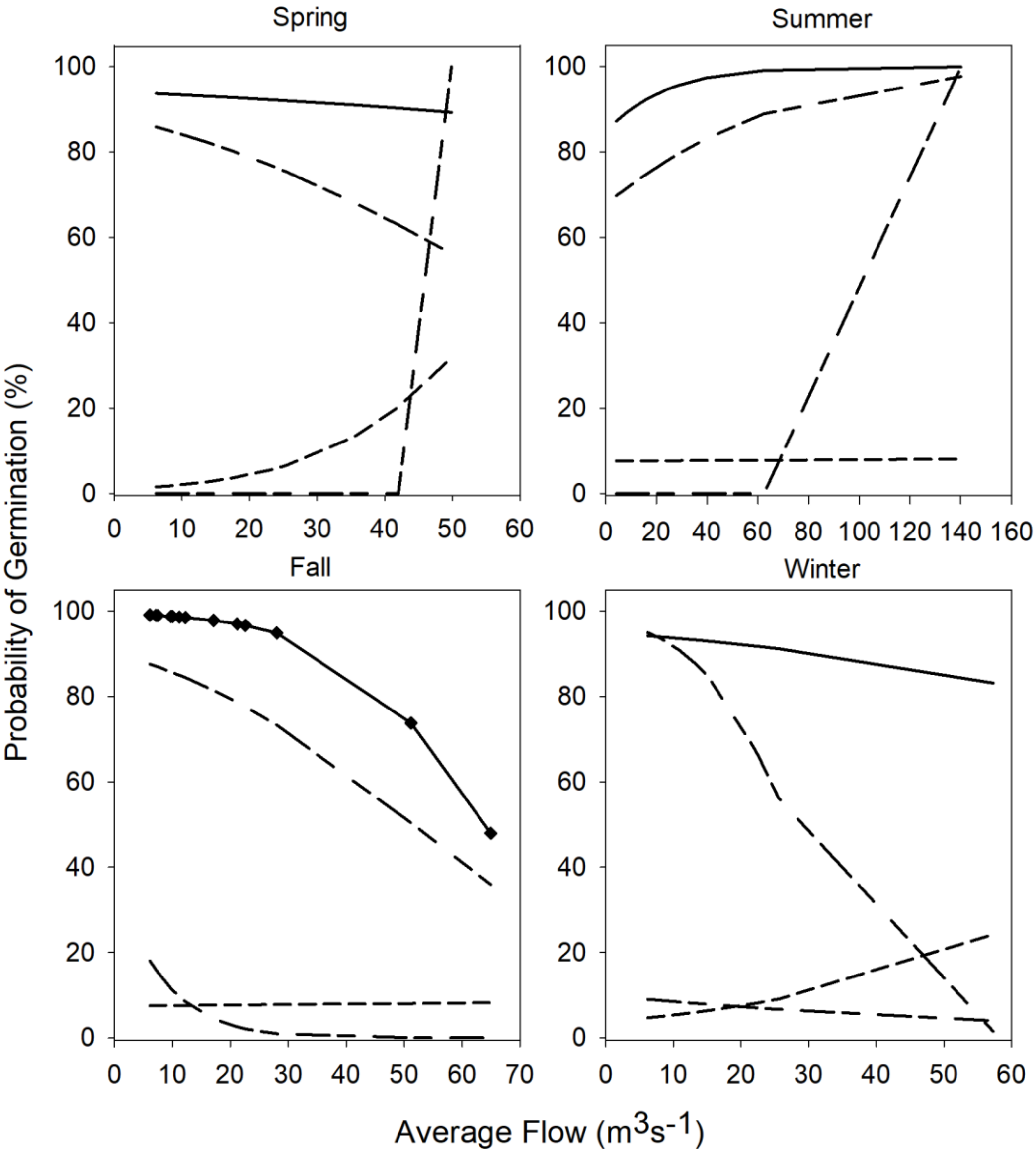

Figure 16. Guadalupe River Average Flow Germination Response. This figure displays the germination probabilities of the target species to the seasonal average flows of the Guadalupe River. All species germination represented by (——), *Acer negundo* (— — — —), *Platanus occidentalis* (− — − — − —),and *Salix nigra* (− − − −). ♦ denotes an interaction with a p-value < 0.2.

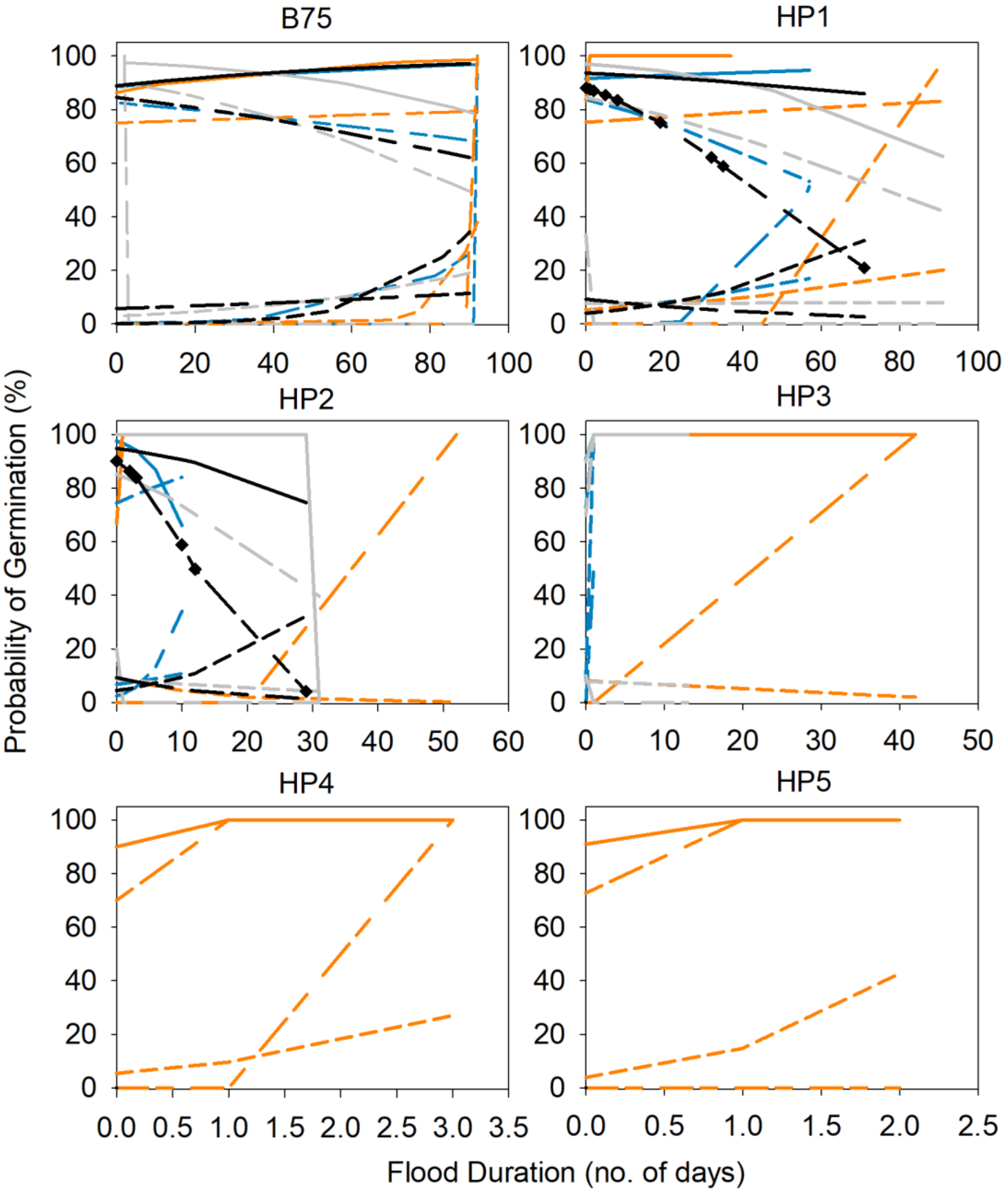

Figure 17. Guadalupe River High Flow Pulse Germination Response. This figure displays the germination probabilities of the target species to the seasonal HFPs of the Guadalupe River. All species germination represented by (——), *Acer negundo* (— — — —), *Platanus occidentalis* (− — − — − —),and *Salix nigra* (— − — −). ♦ denotes an interaction with a p-value < 0.2. Seasons are in color coded as spring(blue), summer(orange), fall(gray) and winter(black).

In the ring width development, annual growth was correlated with hydroclimate, but those effects differed from site-to-site, even within the same river. (Fig. 18). Trees at both the Brazos River sites reached peak growth in 1996 and exhibited a similar upward trend of growth from 2006 to 2009; however, the upstream Hearne site experienced a spike in growth from 2000 to 2003 unlike the Bryan site. As for the Colorado River, trees at both sites were similar in the minimal variation in ring width, despite earlier peaks in their chronologies. On the Guadalupe River, ring widths increased sharply in 2006 before dropping in 2007, which was an extreme wet year, and returned to a slow increase from 2008 to 2012, which encompasses several low flow years.

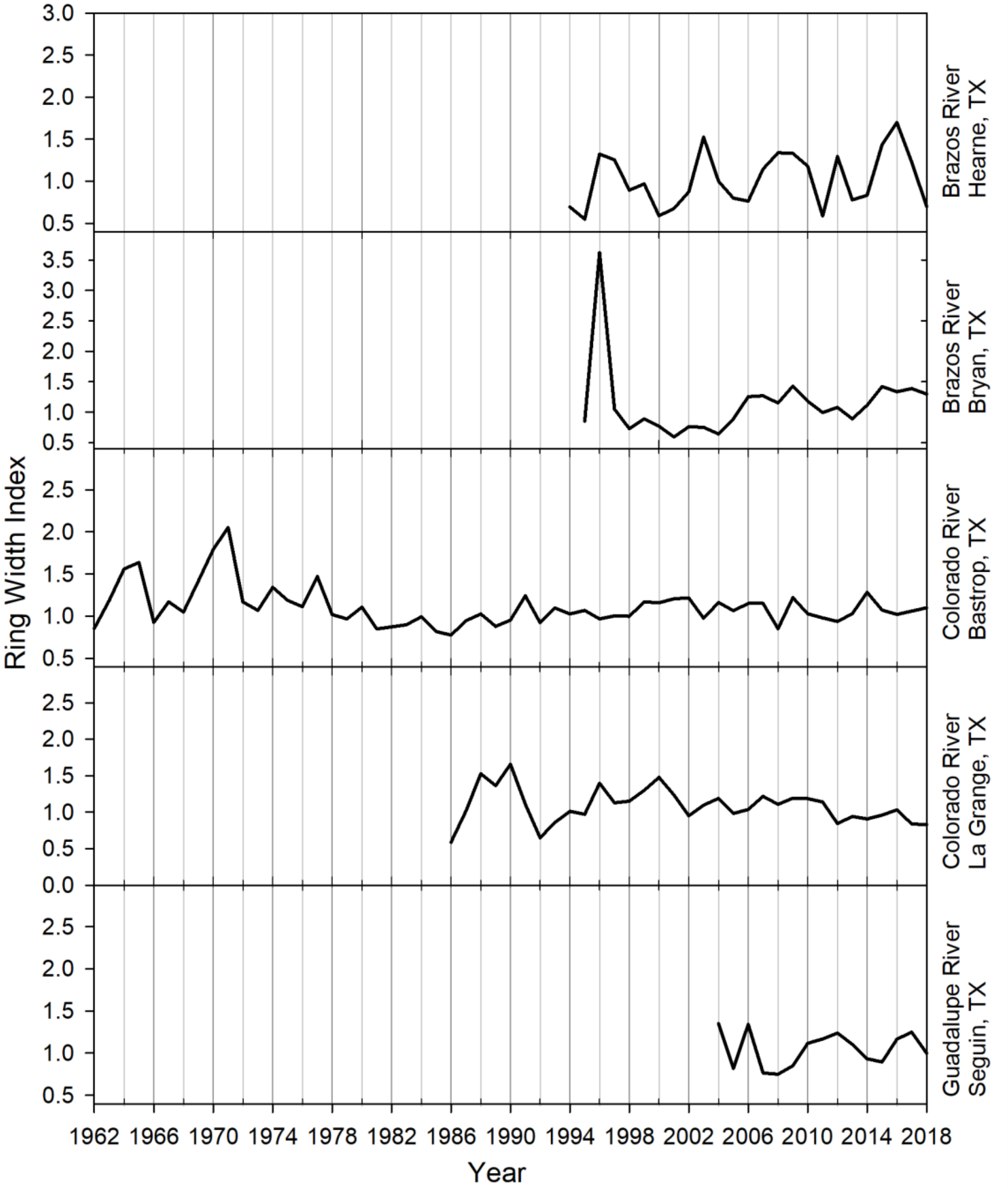

Figure 18. Standardized ring width indexes (RWIs) of all species for all sites across the three rivers.

On the Brazos River, trees grew significantly more during years when spring to early summer precipitation was greater (Table 3). The multiple species growth was strongly correlated to April precipitation ($R^2 = 0.19$, p = 0.03) where a 10 mm increase in precipitation resulted in a 0.035 increase in growth. For *A. negundo*, growth was most strongly and highly correlated to July precipitation ($R^2 = 0.3$, p = 0.008) where a 10 mm increase resulted in a 0.04 increase in growth. May precipitation ($R^2 = 0.28$, p = 0.03) was highly correlated to *F. pennsylvanica* growth, increasing growth by 0.05 per 10 mm increase in precipitation. The March to June period ($R^2 = 0.28$, p = 0.03) and May-June period precipitation ($R^2 = 0.28$, p = 0.03) were also highly correlated growth, but did not produce as strong of an increase in growth, only increasing growth by 0.03 and 0.04 per 10 mm increase in precipitation, respectively. Growth for *P. deltoides* was strongly correlated with April precipitation ($R^2 = 0.3$, p = 0.008) with a 10 mm increase in precipitation increase growth by 0.04. *S. nigra* did not produce any significant regressions.

The flow results for the Brazos River resulted in significant regressions ranging from late winter to early summer (Table 4). There were no significant regressions for the multiple species assessment, *A. negundo*, *P. deltoides*, and *S. nigra*. While many combinations of months during the early growing season until mid-summer were related to growth of *F. pennsylvanica*, the months of February to May were most highly correlated with growth ($R^2 = 0.37$, p = 0.01). During this period, growth is predicted to increase 0.03 per 10 m^3s^{-1} increase in flows. Over the average flows for this period, growth was predicted to be 1.43, 32% higher than the average growth overall.

Table 3. Simple linear regression results of precipitation (mm) from the corresponding months (predictor variables) and annual ring-width index (mm) of the same year (response variable) on the Brazos River. Only statistically significant regressions are reported.

Species	Month Period	Intercept	Slope	R^2	p-value
All Species					
	April	0.88	0.0035	0.19	0.03
	August	0.97	0.0014	0.16	0.04
ACNE					
	July	0.88	0.0041	0.30	0.008
FRPE					
	May	0.84	0.0046	0.28	0.03
	March–May	0.63	0.0028	0.24	0.05
	March–June	0.43	0.0026	0.28	0.03
	April–May	0.79	0.0033	0.25	0.04
	April–June	0.63	0.0028	0.27	0.03
	May–June	0.65	0.0035	0.28	0.03
PODE					
	February	1.27	-0.0028	0.20	0.02
	April	0.86	0.0042	0.27	0.008
	January–February	1.37	-0.0021	0.17	0.04
SANI					
	None				

Table 4. Simple linear regression results between average flows (m^3s^{-1}) from the corresponding months (predictor variables) and annual ring-width index (mm) of the same year (response variable) on the Brazos River. Only statistically significant regressions are reported.

Species	Month Period	Intercept	Slope	R^2	p-value
All Species					
	None				
ACNE (5)					
	None				
FRPE (3)					
	March	0.97	0.0023	0.24	0.04
	January–March	0.97	0.0031	0.24	0.05
	January–April	0.92	0.0033	0.26	0.04
	January–May	0.85	0.0035	0.34	0.01
	January–June	0.91	0.0028	0.32	0.02
	January–July	1.01	0.0022	0.23	0.05
	February–March	0.99	0.0026	0.25	0.04
	February–April	0.91	0.0031	0.29	0.03
	February–May	0.83	0.0033	0.37	0.01
	February–June	0.91	0.0026	0.34	0.01
	February–July	1.02	0.0020	0.24	0.05
	March–April	0.94	0.0027	0.25	0.04
	March–May	0.94	0.0025	0.29	0.02
	March–June	1.01	0.0019	0.26	0.03
	April–May	1.04	0.0019	0.24	0.05
PODE (5)					
	None				
SANI (9)					
	None				

For the Colorado River, the precipitation regressions resulted in notable species differences and significant periods extending throughout the year (Table 5). For the multiple species regressions, the growth had a low negative correlation with the May to June period precipitation (R^2 = 0.073, p = 0.04) decreasing growth by 0.011 per 10 mm increase in precipitation. For *A. negundo*, *P. occidentalis, P. deltoides*, and *S. nigra* no significant correlations were found. For *F. pennsylvanica*, growth was found to have a very significant but low correlation to May precipitation (R^2 = 0.13 p = 0.005), where a 10 mm increase in precipitation decreases growth by 0.03.

For the flow regression on the Colorado River, tree growth was most negatively impacted by increasing flows in the late winter and early-spring months with periods that span the entire year (Table 6). For the multiple species analyses, *A. negundo*, *F. pennsylvanica*, *P. occidentalis*, and *P. deltoides* no significant regression was found. For *S. nigra*, growth was very significantly and strongly correlate with the March to April period (R^2 = 0.25, p = 0.005) with a 10 m^3s^{-1} in average flows reducing growth by 0.036. Additional periods with significant correlations all started in late-winter to early-spring and spanned to progressive periods throughout the year.

Table 5. Colorado River results obtained from univariate linear regressions between precipitation from the corresponding months (predictor variables) and annual ring-width index of the same year (response variable). Only statistically significant regressions are reported.

Species	Month Period	Intercept	Slope	R2	p-value
All Species					
	May	1.31	-0.0012	0.073	0.04
	May–June	1.38	-0.0011	0.11	0.01
ACNE					
	None				
FRPE					
	May	1.40	-0.0033	0.13	0.005
	May–June	1.43	-0.0018	0.082	0.03
PLOC					
	None				
PODE					
	None				
SANI					
	None				

Table 6. Colorado River results obtained from univariate linear regressions between average flow from the corresponding months (predictor variables) and annual ring-width index of the same year (response variable). Only statistically significant regressions are reported.

Species	Month Period	Intercept	Slope	R^2	p-value
All Species					
	None				
ACNE					
	None				
FRPE					
	None				
PLOC					
	None				
PODE					
	None				
SANI					
	February	1.16	-0.0012	0.14	0.04
	March	1.27	-0.0025	0.23	0.007
	April	1.36	-0.0046	0.20	0.01
	January–February	1.17	-0.0015	0.13	0.05
	January–March	1.21	-0.0019	0.17	0.02
	January–April	1.24	-0.0024	0.19	0.02
	January–May	1.26	-0.0027	0.18	0.02
	January–June	1.29	-0.0027	0.18	0.02
	January–July	1.30	-0.0029	0.17	0.02
	January–August	1.32	-0.0032	0.17	0.02
	January–September	1.33	-0.0036	0.17	0.02
	February–March	1.21	-0.0018	0.18	0.02
	February–April	1.25	-0.0025	0.21	0.01
	February–May	1.28	-0.0027	0.18	0.02
	February–June	1.30	-0.0027	0.18	0.02
	February–July	1.31	-0.0028	0.17	0.02
	February–August	1.33	-0.0032	0.17	0.02
	February–September	1.34	-0.0036	0.17	0.02
	March–April	1.33	-0.0036	0.25	0.005
	March–May	1.33	-0.0033	0.17	0.02
	March–June	1.32	-0.0028	0.16	0.03
	March–July	1.30	-0.0026	0.13	0.05
	March–August	1.32	-0.0031	0.13	0.05
	March–September	1.34	-0.0035	0.13	0.05

For the Guadalupe River, growth responses varied even amongst tree species, but were most often affected by late-springs to early-winter (Table 7). There were no significant regressions from the all species analyses. For *A. negundo*, growth was most highly correlated with March precipitation (R^2 = 0.50, p = 0.03) which decreases growth by 0.01 per 10 mm increase in precipitation. For *P. occidentalis*, growth was highly correlated to July precipitation (R^2 = 0.39, p = 0.01) with a 10 mm increase in precipitation increasing growth by 0.022. For *S. nigra*, was highly correlated to the March to May period (R^2 = 0.39 p = 0.03) with growth increasing by 0.013 per 10 mm increase in precipitation.

For the flow interaction, there were primarily no significant correlations found within the examined time period for any species on the Guadalupe River (Table 8).

Table 7. Guadalupe River results obtained from univariate linear regressions between precipitation from the corresponding months (predictor variables) and annual ring-width index of the same year (response variable). Only statistically significant regressions are reported.

Species	Month Period	Intercept	Slope	R^2	p-value
All Species					
	None				
ACNE					
	March	1.07	-0.0011	0.50	0.03
	January–April	1.23	-0.00083	0.46	0.04
PLOC					
	July	0.96	0.0022	0.39	0.01
	June–September	0.85	0.00088	0.27	0.04
	July–August	0.90	0.0020	0.33	0.02
	July–September	0.86	0.0015	0.31	0.03
SANI					
	January–May	0.62	0.00071	0.35	0.04
	March–May	0.58	0.0013	0.38	0.03

Table 8. Guadalupe River results obtained from univariate linear regressions between average flow from the corresponding months (predictor variables) and annual ring-width index of the same year (response variable). Only statistically significant regressions are reported.

Species	Month Period	Intercept	Slope	R^2	p-value
All Species					
	None				
ACNE					
	None				
PLOC					
	None				
SANI					
	None				

Discussion

Tree Germination

This study has demonstrated that across three Texas rivers, increased flows overall benefitted riparian tree germination. I found that higher flows during the spring and summer months, which correspond with most (if not all) of the germination and growing season, was the most critical time of year for riparian trees to successfully germinate on these rivers. Although our results support the hypotheses that riparian-adapted tree species are more likely to germinate under higher flow conditions, it is possible that many germination events occurred under sub-optimal flow conditions, but those trees did not survive to maturity. Given each river has their own unique flow regimes and bank characteristics, we found it difficult to generalize across the three rivers, though the high flow pulses for tiers 1 and 2 were generally the strongest correlations for recruitment. Although further study is needed to decipher more species-specific interactions, our study found substantial evidence that higher flows in a given year and season were associated with higher probabilities of germination.

For germination on the Brazos River, germination responded well with increases in flows and flow pulses. In particular, the average flows and lower-level high flow pulses were the most common conditions found to increase germination. The fast-maturing species, *A. negundo* and *P. deltoides,* and slow maturing *F. pennsylvanica* were the most responsive, all of which would naturally rely on high flows to wet areas of the riverbank. These species' germination responded well to conditions that represented flows just above average. In a study by Auble et al. (1997) that also included *Fraxinus* *spp*., *Populus spp.* and *Salix spp.* , looked at germination in a more urban setting and found that optimal germination at discharge rates around 15m^3/s^{-1} with these rates being more in the mid-ranges of experienced flows.. Interestingly, despite large sample sizes in our study, we found little effect of flows on *S. nigra* germination, even though its life history is remarkably similar to *P. deltoides* in terms of reproductive strategy and physiology (Burns and Honkala 1990). This may allude to more intricate factors influencing germination, such as light availability or interspecific competition. A noteworthy consideration comes from field observations as both sites near to where *S. nigra* was collected exhibited extensive steep and eroded banks giving the river a very channelized appearance. It is possible the tiered topography of the Brazos River restricts flows from reaching the vegetated bank. Additionally, this bank topography common to the Brazos River likely prevents crucial sediment from being deposited in areas accessible for long term colonization by riparian tree species.

Along the Colorado River, flows and pulses of spring and summer were again found to positively impact probability of germination; however, responses were weaker compared to the Brazos River. Of the fast-maturing species, the germination habits of *A. negundo* likely contributed to higher probability of germination at higher spring and summer seasonal average flows and low flood pulses since they readily germinate in shaded or sunny areas with higher moisture levels. Relatively higher spring and summer flow levels are likely associated with ideal growing conditions, whereas prior winter precipitation and high winter flows may either move seeds into more favorable growing areas or prepare alluvial soils for spring germination. Surprisingly, *P. deltoides* germination was also associated with the lowest fall flood pulse tiers, which is contrary to its known germination process. This may have been an artifact of the trees sampled. When looking at slower maturing species on the Colorado River, *F. pennsylvanica* germination years showed only weak negative associations with most increased flows, likely pointing to a lower level of flood dependency or even a negative impact of high flows. Greater sampling of this species may be needed to detect more significant trends.

For the Guadalupe River sites, very few relationships between flows and germination were detected in our study. It is important to note that of the sites sampled, the Guadalupe site had overall lower flows and smaller and less frequent high flow pulses. Literature on the most common species sampled on the Guadalupe River, *P. occidentalis*, notes that while moist conditions on alluvial soil are necessary for *P. occidentalis* germination, high light availability is also crucial to seedling survival. There is potential that the rarely observed winter high flow pulse events on the Guadalupe River near the study site do indeed scour the riverbank producing alluvial surfaces, but timing and magnitude of the flood disturbance may have been insufficient. From field observations, sites further down river, while not suitable for sampling, did show greater diversity of target species showing the effects of the flows may have been more beneficial under a different bank topography.

This study's finding is similar to the findings of Shafroth et al. (1998) where flows to high likely removed seedlings, but flows that were too low or dropped to quickly desiccated seedlings. The flows found in their study, where rates approaching 200 $m^3/s^{-1,}$ produced the wetted alluvial area for germination, where similar to the high flow pulse 3 rates in this study. These findings allude to fast shifts in the riparian habitat creating and removing suitable habitat for each species. Some studies suggest that while not only do these rivers, especially in degraded or disturbed stages, undergo frequent topographical shifts, but as the systems recover the linkages and feedbacks that control for recruitment become poorly understood in part because of their transient nature (Hupp 1992, Bendix and Hupp 2000). If this is the case for these river systems, assessing them amidst shifts for fast maturing species would only provide short term inferences on germination directions; whereas, for slow maturing species may present opportunity to characterize early periods of establishment.

Tree Growth

Surprisingly, we did not find any generalizable trends for growth responses to precipitation or flows across all three rivers. In most cases late winter to early summer precipitation, and to a lesser extent winter to late spring flows, positively impacted growth. We found precipitation was a stronger predictor for growth than flow. However, we were surprised to see such weak relationships between precipitation and growth. It is possible that riparian tree growth is highly influenced by regulated flow conditions on these rivers in ways that we could not capture in our study. Despite, the regressions showing the most regulated river having a high correlation of precipitation to flows its likely there is an interaction not captured by simple regression and it is this interaction that causes irregularities in growth. Other possibilities could be the presence of lagged effects of previous conditions, such as wet prior years, or that some response might be non-linear. A study by Keeland et al. (1997) looking at riparian trees in similar environments in different regions found that even amongst species site characteristics can shift the species response to flow regimes. This disparity is likely mirrored in this study as even amongst the species studied, the responses across rivers for growth varied significantly.

For the fast-maturing species, late winter precipitation through spring and even to early summer were the best predictors of growth. *Acer negundo* displayed mixed results in its response to precipitation. On the Brazos River, *A. negundo* responded positively to July precipitation, but responded negatively to March precipitation on the Guadalupe River. This difference may be explained by the single odd years driving trends in the negative direction, given the low sample size for the Guadalupe River. Interestingly, *A. negundo*, showed no response to precipitation or flows on the Colorado River, to any period of precipitation. This suggest that along the Colorado River that *A. negundo*, and other species, this may be rooting to the water table buffering themselves from variations in precipitation or instances where channelization restricts flows. Notably, *A. negundo* has shown rapid mortality from long term inundation of periods over 85 days and likely would shows signs of stress for inundation periods that would approach this threshold (Friedman and Auble 1999). This may also be an explanatory cause for the lack of correlation as high flows may negatively impact growth as well as low flows. *Populus deltoides* only showed a single response to April precipitation on the Brazos River which suggest that it is most reliant upon mid spring precipitation to facilitate growth. *Salix nigra* also displayed mixed results, where on the Colorado the March to April precipitation period negatively affected growth, on the Guadalupe River, the March to

May precipitation had a stronger positive effect on growth. The discrepancy between the two likely stems from sample size, of which several samples were removed due to rot in cores and would require increased sampling to confirm any trends. Additional analysis with greater replication of sampling for the Colorado River would be needed to truly determine if these conditions are really inhibiting growth.

For the slow maturing species, the timing of precipitation in the early to mid-growing season (February to May) appeared to influence that year's annual growth. *Fraxinus pennsylvanica*, had a positive response to May precipitation where on the Brazos River where its growth also responded well to flows from February to May. However, it had a weaker negative positive effect on the Colorado River, which may be caused by the irregularities from a more regulated river. *Platanus occidentalis* responded well only to increased precipitation that occurred in July, the drier and hotter period of the year, and only showed a response on the Guadalupe River. The singular response is likely due to the large sample size on the Guadalupe River, highlighting the species' dependence on the July period of precipitation. The lack of flow response may come from the Guadalupe River sites used experienced lower volumes of flows. Additionally, the sites used had a flatter topography that likely facilitated a relatively high-water table for the riparian trees to access. We lacked sufficient sample sizes of *Platanus occidentalis* on other rivers to evaluate that species responses beyond the Guadalupe River.

Study Implications

From this study we propose a rates-based approach framework to detect impacts of flow variation on tree germination and growth. We found that the use of binary logistic regression allowed us to detect how the probability of germination changes across a range of flow conditions and floods of different sizes. Our approach also shows promise for relating growth trends to flow conditions. However, some of the target species used did not consistently produce ideal rings for dendrochronological analysis. Several species used in our study are rarely used for dendrochronology. Thus, more work on methods for better identifying tree rings or knowledge of the wood anatomy for these species would be needed to get more precise results for germination dates, but especially growth trends. From this study we have learned that the low total number of trees sampled is a limiting factor in realizing the full utility of binary logistic regression. In future research, we recommend requiring at least 30 viable samples of a target species per river to develop better species-specific chronologies and germination data.

Considering the species response and the lab work on identifying the rings, the easiest and most reliable species for this type of study were *F. pennsylvanica*, *P. deltoides*, and *P. occidentalis*. Additionally, though only one sample was collected and could not be used, there is notable literature to support the use of *T. distichum* for dendrochronological analyses because of its excellent ring production and known tendency to show strong correlations to hydroclimate. In studies by Smith et al. (2013) and Young et al. (1995) that were looking at riparian growth responses in river modification, both found *T. distichum* yearly growth correlates primarily to the flows and precipitation experienced that year as well as still being able to capture long term trends. However, there few studies that explicitly focus on correlating hydrologic condition to germination, a study by Schneider and Sharitz (1988) looking at hydrochory and regeneration in *T. distichum* found trends of both dispersal and success to be tied to the hydrologic conditions present. In general, the species is known for showing high correlation to the hydroclimate of the area and has germination that is correlated to hydrologic regime. For *A. negundo* and *S. nigra*, we found these species to be somewhat more challenging to work with. Although *A. negundo* had clear associations between germination and flows, it produces barely visible rings, whereas S. nigra germination was relatively unresponsive to flows and often suffers from rot rendering the cores illegible and incomplete. Additionally, field observations of *A. negundo* and *S. nigra* revealed them to be in high numbers, which suggest that their flow needs for growth and germination are being met enough for them to visibly appear as the dominant riparian trees. Ultimately, for a representative of the fast-maturing species, *P. deltoides*, despite its uncommon occurrence, is the best candidate as its cores are the most suitable for legibility. Further, *P. deltoides'* life history and indicator status is a combination of characteristics found in both *S. nigra* and *A. negundo*. For a slow maturing species *F. pennsylvanica* or *P. occidentalis* are suitable as candidates for this type of approach, where the former is found in more appreciable numbers on the Brazos River and Colorado River, the latter was found more frequently on the Guadalupe River. Both *F. pennsylvanica* and *P. occidentalis* showed good responses when they were present and able to be sampled. However, if given the opportunity, *T. distichum* would make the better candidate if substantial individuals can be found and cored.

Given the results of this study, river managers seeking to increase germination of riparian-dependent trees can increases the probability of successful events by increasing spring and summer average flows and high flow pulses from the 75th percentile to tier two. Additionally, a study with increased sampling could utilize ordinal logistic regression to better determine magnitudes of germination. For increasing growth, more research is needed on species with clearer rings. With this a more sophisticated study using multiple regressions that consider legacy effects of prior year flows on growth and other factors such as hydropower pulsing. However, increasing spring average flows in general would benefit growth of a few species and in doing so overlaps with practices that are beneficial for germination.

CHAPTER II

CONCLUSIONS

From this study the conventional knowledge that riparian trees benefit from increased precipitation and flows is partially supported. We found that ultimately, increased flows and low flood pulses in the spring and summer season best benefit germination, and that precipitation is a bigger driver than flows for growth. However, this study also shows that trees commonly labeled riparian may need increased study to better assess their reliance on hydrologic drivers as a means of germination and growth. This study's use of binary logistic regression for germination analysis shows promise as means to acquire detailed information on past hydrologic conditions and their effects. However, it is important to note that this method relies upon a large sample size of target species as well as having a complete record of environmental conditions in order to generalize results to most Texas rivers and better predict germination following future events.

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APPENDIX A

BRAZOS LOGIT EQUATIONS

Independent Variable	Dependent Variable	Intercept	Intercept p-value	Slope	Slope p-value	AIC
FaAvgFlow	S_Germination	1.488	0.085	-0.002	0.793	23.489
FaAvgFlow	ACNE_Germination	-0.662	0.427	-0.009	0.369	22.487
FaAvgFlow	FRPE_Germination	-1.305	0.015	-0.004	0.620	20.295
FaAvgFlow	PODE_Germination	-1.435	0.075	0.007	0.263	26.408
FaAvgFlow	SANI_Germination	0.958	0.196	-0.004	0.445	28.419
FaB75	S_Germination	1.716	0.085	-0.011	0.610	23.295
FaB75	ACNE_Germination	-1.143	0.067	-0.006	0.803	23.494
FaB75	FRPE_Germination	-1.652	0.107	-0.001	0.978	20.573
FaB75	PODE_Germination	-1.399	0.116	0.018	0.368	26.862
FaB75	SANI_Germination	1.170	0.166	-0.018	0.341	28.069
FaHP1	S_Germination	1.697	0.086	-0.011	0.624	23.316
FaHP1	ACNE_Germination	-1.145	0.024	-0.006	0.803	23.494
FaHP1	FRPE_Germination	-1.648	0.106	-0.001	0.974	20.573
FaHP1	PODE_Germination	-1.419	0.112	0.018	0.353	26.804
FaHP1	SANI_Germination	1.177	0.162	-0.018	0.334	28.037
FaHP2	S_Germination	1.314	0.055	0.001	0.985	23.556
FaHP2	ACNE_Germination	-0.850	0.046	-0.139	0.349	22.036
FaHP2	FRPE_Germination	-1.412	0.054	-0.063	0.581	20.186
FaHP2	PODE_Germination	-1.413	0.039	0.108	0.132	24.978
FaHP2	SANI_Germination	0.700	0.235	-0.029	0.632	28.779
FaHP3	S_Germination	1.453	0.022	-0.234	0.593	23.288
FaHP3	ACNE_Germination	-1.099	0.007	-7.859	0.995	21.995
FaHP3	FRPE_Germination	-1.466	0.022	-8.179	0.997	19.442
FaHP3	PODE_Germination	-0.699	0.186	-0.174	0.719	27.558
FaHP3	SANI_Germination	0.680	0.196	-0.281	0.494	28.533
FaHP4	S_Germination	1.608	0.013	-0.779	0.218	21.979
FaHP4	ACNE_Germination	-1.179	0.039	-8.168	0.997	22.550
FaHP4	FRPE_Germination	-1.540	0.016	-7.989	0.997	19.844
FaHP4	PODE_Germination	-0.606	0.151	-8.449	0.996	26.074
FaHP4	SANI_Germination	0.653	0.200	-0.409	0.499	28.535
FaHP5	S_Germination	1.634	0.012	-1.435	0.195	21.572
FaHP5	ACNE_Germination	-1.179	0.039	-16.025	0.996	22.550
FaHP5	FRPE_Germination	-1.540	0.016	-15.673	0.996	19.844
FaHP5	PODE_Germination	-0.606	0.232	-16.574	0.996	26.074
FaHP5	SANI_Germination	0.676	0.185	-0.836	0.418	28.275

SpAvgFlow	S_Germination	0.188	0.835	0.008	0.214	20.991
SpAvgFlow	ACNE_Germination	-3.165	0.014	0.008	0.075	18.413
SpAvgFlow	FRPE_Germination	-1.855	0.050	0.001	0.788	20.505
SpAvgFlow	PODE_Germination	-1.941	0.034	0.006	0.112	24.260
SpAvgFlow	SANI_Germination	1.022	0.167	-0.002	0.380	28.194
SpB75	S_Germination	-0.107	0.910	0.037	0.119	20.333
SpB75	ACNE_Germination	-3.071	0.050	0.031	0.171	21.224
SpB75	FRPE_Germination	-1.906	0.118	0.005	0.819	20.521
SpB75	PODE_Germination	-3.564	0.032	0.049	0.042	21.420
SpB75	SANI_Germination	0.354	0.683	0.004	0.800	28.944
SpHP1	S_Germination	1.807	0.055	-0.017	0.484	23.073
SpHP1	ACNE_Germination	-0.939	0.018	-0.016	0.581	23.223
SpHP1	FRPE_Germination	-1.955	0.055	0.010	0.709	20.439
SpHP1	PODE_Germination	-0.218	0.777	-0.023	0.381	26.824
SpHP1	SANI_Germination	0.916	0.232	-0.014	0.519	28.584
SpHP2	S_Germination	1.794	0.026	-0.066	0.338	22.647
SpHP2	ACNE_Germination	-0.837	0.018	-0.111	0.329	22.194
SpHP2	FRPE_Germination	-1.335	0.075	-0.071	0.513	20.041
SpHP2	PODE_Germination	-0.289	0.636	-0.098	0.262	26.060
SpHP2	SANI_Germination	0.856	0.176	-0.050	0.422	28.351
SpHP3	S_Germination	1.012	0.083	8.616	0.997	21.397
SpHP3	ACNE_Germination	-2.643	0.007	1.326	0.123	14.123
SpHP3	FRPE_Germination	-1.908	0.009	0.157	0.409	19.953
SpHP3	PODE_Germination	-0.984	0.077	0.171	0.349	26.775
SpHP3	SANI_Germination	0.904	0.099	-0.358	0.195	26.154
SpHP4	S_Germination	1.099	0.057	15.959	0.996	21.995
SpHP4	ACNE_Germination	-2.076	0.019	1.748	0.115	17.618
SpHP4	FRPE_Germination	-2.160	0.006	0.827	0.144	18.095
SpHP4	PODE_Germination	-0.754	0.151	-0.055	0.916	27.688
SpHP4	SANI_Germination	0.879	0.105	-1.086	0.222	26.053
SpHP5	S_Germination	1.253	0.027	8.157	0.997	23.069
SpHP5	ACNE_Germination	-1.609	0.011	9.588	0.996	20.220
SpHP5	FRPE_Germination	-2.079	0.006	9.823	0.996	16.558
SpHP5	PODE_Germination	-0.693	0.166	-7.937	0.995	26.915
SpHP5	SANI_Germination	0.693	0.166	-8.630	0.994	26.915
SuAvgFlow	S_Germination	-2.089	0.313	0.098	0.190	17.084
SuAvgFlow	ACNE_Germination	-3.436	0.010	0.016	0.039	14.478
SuAvgFlow	FRPE_Germination	-2.409	0.006	0.004	0.156	17.656
SuAvgFlow	PODE_Germination	-0.811	0.158	0.000	0.896	27.682
SuAvgFlow	SANI_Germination	0.909	0.124	-0.003	0.313	27.563

SuB75	S_Germination	-0.571	0.530	0.177	0.166	15.230
SuB75	ACNE_Germination	-3.616	0.018	0.050	0.036	17.102
SuB75	FRPE_Germination	-2.602	0.025	0.023	0.247	16.166
SuB75	PODE_Germination	-1.780	0.038	0.027	0.103	24.734
SuB75	SANI_Germination	0.845	0.231	-0.009	0.542	28.636
SuHP1	S_Germination	-0.571	0.530	0.177	0.166	15.230
SuHP1	ACNE_Germination	-3.616	0.020	0.050	0.036	17.102
SuHP1	FRPE_Germination	-2.602	0.025	0.023	0.247	19.166
SuHP1	PODE_Germination	-1.780	0.038	0.027	0.103	24.734
SuHP1	SANI_Germination	0.845	0.231	-0.009	0.542	28.636
SuHP2	S_Germination	-0.571	0.530	0.177	0.166	15.230
SuHP2	ACNE_Germination	-3.616	0.196	0.050	0.036	17.102
SuHP2	FRPE_Germination	-2.602	0.025	0.023	0.247	19.166
SuHP2	PODE_Germination	-1.780	0.038	0.027	0.103	24.978
SuHP2	SANI_Germination	0.845	0.231	-0.009	0.542	28.636
SuHP3	S_Germination	1.179	0.039	3.248	0.997	22.550
SuHP3	ACNE_Germination	-2.015	0.057	3.845	0.995	16.315
SuHP3	FRPE_Germination	-2.140	0.005	0.245	0.201	17.171
SuHP3	PODE_Germination	-0.730	0.153	-0.038	0.772	27.605
SuHP3	SANI_Germination	0.702	0.167	-0.137	0.362	27.758
SuHP4	S_Germination	1.179	0.039	8.173	0.997	22.550
SuHP4	ACNE_Germination	-2.015	0.007	9.650	0.996	16.315
SuHP4	FRPE_Germination	-2.142	0.005	0.645	0.188	17.232
SuHP4	PODE_Germination	-0.735	0.916	-0.090	0.798	27.627
SuHP4	SANI_Germination	0.700	0.168	-0.355	0.362	27.815
SuHP5	S_Germination	1.253	0.027	2.719	0.997	23.069
SuHP5	ACNE_Germination	-1.609	0.011	3.196	0.996	20.220
SuHP5	FRPE_Germination	-2.079	0.006	3.274	0.996	16.558
SuHP5	PODE_Germination	-0.693	0.166	-2.646	0.995	26.915
SuHP5	SANI_Germination	0.693	0.166	-2.877	0.994	26.915
WiAvgFlow	S_Germination	1.188	0.162	0.001	0.839	23.515
WiAvgFlow	ACNE_Germination	-1.563	0.084	0.002	0.720	23.430
WiAvgFlow	FRPE_Germination	-2.010	0.053	0.002	0.661	20.385
WiAvgFlow	PODE_Germination	-1.078	0.172	0.002	0.607	27.435
WiAvgFlow	SANI_Germination	0.488	0.504	0.000	0.928	29.000
WiB75	S_Germination	1.008	0.217	0.008	0.621	23.306
WiB75	ACNE_Germination	-1.816	0.270	0.011	0.508	23.105
WiB75	FRPE_Germination	-2.651	0.045	0.020	0.327	19.487
WiB75	PODE_Germination	-1.189	0.149	0.010	0.505	27.246
WiB75	SANI_Germination	0.451	0.537	0.002	0.874	28.983

WiHP1	S_Germination	1.277	0.110	0.002	0.938	23.551
WiHP1	ACNE_Germination	-2.299	0.211	0.044	0.170	21.530
WiHP1	FRPE_Germination	-1.809	0.051	0.007	0.837	20.532
WiHP1	PODE_Germination	-0.701	0.317	-0.004	0.886	27.678
WiHP1	SANI_Germination	0.223	0.740	0.018	0.520	28.573
WiHP2	S_Germination	1.717	0.019	-0.063	0.310	22.557
WiHP2	ACNE_Germination	-1.352	0.011	0.006	0.935	23.550
WiHP2	FRPE_Germination	-1.686	0.025	0.002	0.977	20.573
WiHP2	PODE_Germination	-0.211	0.738	-0.167	0.304	25.391
WiHP2	SANI_Germination	0.623	0.276	-0.016	0.787	28.936
WiHP3	S_Germination	1.553	0.019	-0.273	0.410	22.912
WiHP3	ACNE_Germination	-1.553	0.057	0.273	0.410	22.912
WiHP3	FRPE_Germination	-1.926	0.011	0.279	0.429	19.999
WiHP3	PODE_Germination	-0.765	0.158	-0.012	0.972	27.698
WiHP3	SANI_Germination	0.484	0.352	0.084	0.802	28.943
WiHP4	S_Germination	1.253	0.027	16.313	0.997	23.069
WiHP4	ACNE_Germination	-1.253	0.027	-16.313	0.997	23.069
WiHP4	FRPE_Germination	-2.079	0.006	19.645	0.996	16.558
WiHP4	PODE_Germination	-0.693	0.232	-15.873	0.995	26.915
WiHP4	SANI_Germination	0.452	0.350	16.114	0.995	28.057
WiHP5	S_Germination	1.322	0.019	N/A	N/A	21.557
WiHP5	ACNE_Germination	-1.322	0.019	N/A	N/A	21.557
WiHP5	FRPE_Germination	-1.674	0.008	N/A	N/A	18.574
WiHP5	PODE_Germination	-0.773	0.117	N/A	N/A	25.699
WiHP5	SANI_Germination	0.539	0.257	N/A	N/A	27.008

APPENDIX B

COLORADO LOGIT EQUATIONS

Independent Variable	Dependent Variable	Intercept	Intercept p-value	Slope	Slope p-value	AIC
FaAvgFlow	S_Germination	-0.238	0.593	0.006	0.499	75.602
FaAvgFlow	ACNE_Germination	-0.969	0.036	0.006	0.480	69.229
FaAvgFlow	FRPE_Germination	-1.957	0.005	-0.002	0.885	41.171
FaAvgFlow	PLOC_Germination	-2.692	0.005	-0.003	0.897	26.919
FaAvgFlow	PODE_Germination	-3.071	0.000	0.012	0.246	31.077
FaAvgFlow	SANI_Germination	-1.005	0.475	-0.049	0.334	30.409
FaB75	S_Germination	-0.160	0.746	0.005	0.696	75.934
FaB75	ACNE_Germination	-0.809	0.125	0.003	0.841	69.685
FaB75	FRPE_Germination	-2.317	0.004	0.009	0.661	41.006
FaB75	PLOC_Germination	-3.217	0.004	0.013	0.628	25.754
FaB75	PODE_Germination	-3.991	0.001	0.039	0.089	29.244
FaB75	SANI_Germination	-1.738	0.044	-0.029	0.357	31.205
FaHP1	S_Germination	-0.070	0.833	0.006	0.707	75.944
FaHP1	ACNE_Germination	-0.722	0.042	0.000	0.998	69.726
FaHP1	FRPE_Germination	-1.839	0.000	-0.021	0.554	40.750
FaHP1	PLOC_Germination	-3.034	0.000	0.017	0.512	26.119
FaHP1	PODE_Germination	-3.142	0.000	0.038	0.078	29.284
FaHP1	SANI_Germination	-1.511	0.013	-0.370	0.258	27.001
FaHP2	S_Germination	0.013	0.966	-0.003	0.913	76.075
FaHP2	ACNE_Germination	-0.750	0.019	0.006	0.818	69.674
FaHP2	FRPE_Germination	-1.204	0.000	-0.064	0.524	40.446
FaHP2	PLOC_Germination	-2.692	0.000	-0.029	0.755	26.667
FaHP2	PODE_Germination	-2.541	0.000	0.010	0.780	32.135
FaHP2	SANI_Germination	-2.138	0.000	-0.204	0.455	30.730
FaHP3	S_Germination	-0.051	0.861	0.095	0.541	75.675
FaHP3	ACNE_Germination	-0.778	0.012	0.093	0.513	69.297
FaHP3	FRPE_Germination	-1.764	0.000	-0.088	0.772	41.088
FaHP3	PLOC_Germination	-2.639	0.000	-15.351	0.996	25.761
FaHP3	PODE_Germination	-2.550	0.000	0.089	0.651	32.032
FaHP3	SANI_Germination	-2.431	0.000	-0.140	0.757	32.062
FaHP4	S_Germination	-0.067	0.815	0.271	0.444	74.925
FaHP4	ACNE_Germination	-0.820	0.008	0.333	0.335	67.718
FaHP4	FRPE_Germination	-2.038	0.000	0.003	0.991	41.193
FaHP4	PLOC_Germination	-2.686	0.000	-14.869	0.996	26.314
FaHP4	PODE_Germination	-2.473	0.000	-0.041	0.918	32.192

FaHP4	SANI_Germination	-2.375	0.000	-15.168	0.996	31.180
FaHP5	S_Germination	-0.103	0.720	0.998	0.261	74.012
FaHP5	ACNE_Germination	-0.845	0.007	0.873	0.187	67.481
FaHP5	FRPE_Germination	-2.147	0.000	0.553	0.354	40.462
FaHP5	PLOC_Germination	-2.708	0.000	-15.263	0.996	26.444
FaHP5	PODE_Germination	-2.546	0.000	0.339	0.653	32.033
FaHP5	SANI_Germination	-2.398	0.000	-15.567	0.996	31.708
SpAvgFlow	S_Germination	-0.177	0.692	0.003	0.615	75.830
SpAvgFlow	ACNE_Germination	-1.136	0.018	0.006	0.262	68.455
SpAvgFlow	FRPE_Germination	-0.772	0.472	-0.024	0.275	38.817
SpAvgFlow	PLOC_Germination	-3.176	0.001	0.005	0.559	32.204
SpAvgFlow	PODE_Germination	-2.470	0.003	0.000	0.982	32.203
SpAvgFlow	SANI_Germination	-0.965	0.489	-0.030	0.324	30.204
SpB75	S_Germination	-0.525	0.358	0.012	0.293	74.955
SpB75	ACNE_Germination	-1.505	0.019	0.017	0.153	67.631
SpB75	FRPE_Germination	-1.325	0.115	-0.018	0.370	40.299
SpB75	PLOC_Germination	-3.742	0.007	0.019	0.402	26.866
SpB75	PODE_Germination	-2.731	0.012	0.005	0.790	32.134
SpB75	SANI_Germination	-1.710	0.087	-0.020	0.418	31.461
SpHP1	S_Germination	-0.098	0.771	0.006	0.608	75.820
SpHP1	ACNE_Germination	-0.924	0.012	0.011	0.326	68.771
SpHP1	FRPE_Germination	-1.366	0.010	-0.097	0.246	37.200
SpHP1	PLOC_Germination	-3.286	0.000	0.021	0.253	26.919
SpHP1	PODE_Germination	-2.635	0.000	0.008	0.668	32.034
SpHP1	SANI_Germination	-1.787	0.005	-0.113	0.334	29.284
SpHP2	S_Germination	-0.122	0.691	0.027	0.372	75.164
SpHP2	ACNE_Germination	-0.970	0.004	0.051	0.127	66.655
SpHP2	FRPE_Germination	-1.485	0.007	-1.029	0.182	35.013
SpHP2	PLOC_Germination	-2.742	0.000	-0.012	0.859	26.906
SpHP2	PODE_Germination	-2.359	0.000	-0.036	0.678	31.942
SpHP2	SANI_Germination	-2.082	0.000	-0.248	0.452	30.565
SpHP3	S_Germination	0.011	0.972	-0.011	0.917	76.076
SpHP3	ACNE_Germination	-0.789	0.013	0.065	0.538	69.350
SpHP3	FRPE_Germination	-1.819	0.000	-16.754	0.995	37.487
SpHP3	PLOC_Germination	-2.747	0.000	-0.057	0.845	26.700
SpHP3	PODE_Germination	-2.339	0.000	-0.297	0.619	31.663
SpHP3	SANI_Germination	-2.169	0.000	-16.323	0.995	29.793
SpHP4	S_Germination	-0.033	0.909	0.088	0.627	75.831
SpHP4	ACNE_Germination	-0.789	0.010	0.161	0.378	68.854
SpHP4	FRPE_Germination	-1.922	0.000	-15.415	0.995	39.900

SpHP4	PLOC_Germination	-2.786	0.000	-0.021	0.956	26.936
SpHP4	PODE_Germination	-2.464	0.000	-0.068	0.868	32.171
SpHP4	SANI_Germination	-2.375	0.000	-14.984	0.995	32.004
SpHP5	S_Germination	0.045	0.875	-0.271	0.547	75.692
SpHP5	ACNE_Germination	-0.724	0.018	0.011	0.980	69.725
SpHP5	FRPE_Germination	-1.946	0.000	-14.937	0.996	40.170
SpHP5	PLOC_Germination	-2.708	0.000	-14.193	0.996	26.444
SpHP5	PODE_Germination	-2.398	0.000	-14.497	0.996	31.536
SpHP5	SANI_Germination	-2.398	0.000	-14.497	0.996	32.097
SuAvgFlow	S_Germination	-0.369	0.431	0.005	0.337	75.086
SuAvgFlow	ACNE_Germination	-1.350	0.007	0.008	0.119	67.066
SuAvgFlow	FRPE_Germination	-0.862	0.451	-0.018	0.330	39.372
SuAvgFlow	PLOC_Germination	-2.679	0.007	-0.001	0.890	26.641
SuAvgFlow	PODE_Germination	-1.947	0.059	-0.008	0.585	31.773
SuAvgFlow	SANI_Germination	-2.089	0.030	-0.005	0.653	31.941
SuB75	S_Germination	-0.234	0.729	0.005	0.705	75.943
SuB75	ACNE_Germination	-1.067	0.150	0.007	0.608	69.460
SuB75	FRPE_Germination	-2.273	0.038	0.005	0.812	41.136
SuB75	PLOC_Germination	-4.546	0.021	0.030	0.302	26.239
SuB75	PODE_Germination	-2.558	0.046	0.001	0.950	32.200
SuB75	SANI_Germination	-1.941	0.093	-0.011	0.617	31.954
SuHP1	S_Germination	-0.211	0.579	0.010	0.420	75.423
SuHP1	ACNE_Germination	-1.114	0.009	0.017	0.174	67.854
SuHP1	FRPE_Germination	-1.582	0.004	-0.028	0.303	39.810
SuHP1	PLOC_Germination	-3.354	0.000	0.021	0.350	25.792
SuHP1	PODE_Germination	-2.318	0.001	-0.009	0.733	32.079
SuHP1	SANI_Germination	-2.133	0.001	-0.020	0.490	31.626
SuHP2	S_Germination	-0.101	0.759	0.008	0.572	75.762
SuHP2	ACNE_Germination	-0.909	0.012	0.014	0.334	68.796
SuHP2	FRPE_Germination	-1.852	0.002	-0.138	0.317	36.882
SuHP2	PLOC_Germination	-3.004	0.000	0.014	0.582	26.903
SuHP2	PODE_Germination	-2.383	0.000	-0.009	0.765	32.105
SuHP2	SANI_Germination	-2.365	0.000	-0.011	0.724	32.064
SuHP3	S_Germination	-0.126	0.672	0.062	0.267	74.677
SuHP3	ACNE_Germination	-0.959	0.004	0.100	0.075	65.969
SuHP3	FRPE_Germination	-1.998	0.000	-7.340	0.995	38.754
SuHP3	PLOC_Germination	-2.590	0.000	-7.465	0.997	26.893
SuHP3	PODE_Germination	-2.277	0.000	-7.118	0.995	30.615
SuHP3	SANI_Germination	-2.415	0.000	-0.041	0.737	32.065
SuHP4	S_Germination	-0.110	0.705	0.107	0.235	74.202

SuHP4	ACNE_Germination	-0.922	0.004	0.165	0.081	65.155
SuHP4	FRPE_Germination	-1.897	0.000	-14.284	0.994	36.624
SuHP4	PLOC_Germination	-2.663	0.000	-14.532	0.996	26.180
SuHP4	PODE_Germination	-2.351	0.000	-14.839	0.996	31.180
SuHP4	SANI_Germination	-2.351	0.000	-14.839	0.996	31.360
SuHP5	S_Germination	-0.019	0.946	0.101	0.754	75.987
SuHP5	ACNE_Germination	-0.782	0.011	0.284	0.387	68.944
SuHP5	FRPE_Germination	-1.969	0.000	-14.625	0.995	40.434
SuHP5	PLOC_Germination	-2.730	0.000	-13.875	0.995	26.572
SuHP5	PODE_Germination	-2.420	0.000	-14.181	0.995	31.708
SuHP5	SANI_Germination	-2.420	0.000	-14.181	0.995	31.536
WiAvgFlow	S_Germination	-0.197	0.570	0.005	0.390	74.920
WiAvgFlow	ACNE_Germination	-1.029	0.008	0.007	0.263	67.309
WiAvgFlow	FRPE_Germination	-1.053	0.150	-0.039	0.206	38.154
WiAvgFlow	PLOC_Germination	-2.683	0.000	-0.003	0.822	26.921
WiAvgFlow	PODE_Germination	-2.492	0.000	0.000	0.979	32.203
WiAvgFlow	SANI_Germination	-1.835	0.025	-0.023	0.416	31.057
WiB75	S_Germination	-0.171	0.673	0.006	0.562	75.750
WiB75	ACNE_Germination	-0.899	0.041	0.006	0.578	69.417
WiB75	FRPE_Germination	-1.357	0.016	-0.031	0.171	38.591
WiB75	PLOC_Germination	-2.885	0.001	0.003	0.886	26.715
WiB75	PODE_Germination	-3.554	0.001	0.026	0.137	29.862
WiB75	SANI_Germination	-1.802	0.007	-0.032	0.254	30.329
WiHP1	S_Germination	-0.112	0.727	0.011	0.500	75.615
WiHP1	ACNE_Germination	-0.941	0.008	0.019	0.224	68.217
WiHP1	FRPE_Germination	-1.291	0.013	-0.242	0.213	36.138
WiHP1	PLOC_Germination	-2.729	0.000	-0.006	0.560	26.574
WiHP1	PODE_Germination	-2.614	0.000	0.010	0.662	32.023
WiHP1	SANI_Germination	-1.955	0.001	-0.123	0.377	30.068
WiHP2	S_Germination	-0.037	0.903	0.007	0.749	75.983
WiHP2	ACNE_Germination	-0.867	0.008	0.026	0.263	68.382
WiHP2	FRPE_Germination	-1.705	0.010	-17.608	0.996	32.091
WiHP2	PLOC_Germination	-2.669	0.000	-0.035	0.705	26.796
WiHP2	PODE_Germination	-2.335	0.000	-0.046	0.634	31.772
WiHP2	SANI_Germination	-2.248	0.000	-0.101	0.593	31.366
WiHP3	S_Germination	-0.098	0.750	0.187	0.641	74.466
WiHP3	ACNE_Germination	-1.025	0.003	0.689	0.107	64.701
WiHP3	FRPE_Germination	-1.922	0.000	-16.634	0.995	38.137
WiHP3	PLOC_Germination	-2.539	0.000	-15.996	0.996	25.465
WiHP3	PODE_Germination	-2.225	0.000	16.199	0.995	30.215

WiHP3	SANI_Germination	-2.419	0.000	-0.157	0.847	32.062
WiHP4	S_Germination	-0.058	0.840	0.119	0.697	74.702
WiHP4	ACNE_Germination	-0.909	0.006	0.730	0.295	66.345
WiHP4	FRPE_Germination	-1.846	0.000	-16.153	0.994	39.051
WiHP4	PLOC_Germination	-2.615	0.000	-16.270	0.996	25.904
WiHP4	PODE_Germination	-2.303	0.000	-16.662	0.996	30.808
WiHP4	SANI_Germination	-2.459	0.000	-0.049	0.831	31.360
WiHP5	S_Germination	-0.080	0.777	16.072	0.993	73.235
WiHP5	ACNE_Germination	-0.847	0.006	16.995	0.993	65.086
WiHP5	FRPE_Germination	-1.992	0.000	-14.974	0.996	40.462
WiHP5	PLOC_Germination	-2.752	0.000	-14.219	0.996	26.697
WiHP5	PODE_Germination	-2.442	0.000	-14.561	0.996	31.877
WiHP5	SANI_Germination	-2.485	0.000	0.000	1.000	31.536

APPENDIX C

GUADALUPE LOGIT EQUATIONS

Independent Variable	Dependent Variable	Intercept	Intercept p-value	Slope	Slope p-value	AIC
FaAvgFlowz	S_Germination	5.20	0.09	-0.08	0.18	8.59
FaAvgFlow	ACNE_Germination	-2.52	0.12	0.00	0.98	11.05
FaAvgFlow	PLOC_Germination	2.22	0.06	-0.04	0.23	16.55
FaAvgFlow	SANI_Germination	-0.64	0.81	-0.14	0.56	10.22
FaB75	S_Germination	3.69	0.10	-0.03	0.45	10.42
FaB75	ACNE_Germination	-3.50	0.10	0.02	0.50	10.57
FaB75	PLOC_Germination	2.22	0.07	-0.02	0.26	16.68
FaB75	SANI_Germination	90.79	1.00	-36.24	1.00	4.00
FaHP1	S_Germination	3.44	0.04	-0.03	0.30	10.03
FaHP1	ACNE_Germination	-2.50	0.05	0.00	0.99	11.05
FaHP1	PLOC_Germination	1.69	0.04	-0.02	0.35	17.16
FaHP1	SANI_Germination	-0.69	0.57	-9.15	1.00	1.82
FaHP2	S_Germination	609.80	1.00	-20.33	1.00	4.00
FaHP2	ACNE_Germination	-2.36	0.04	-0.03	0.84	11.00
FaHP2	PLOC_Germination	1.74	0.05	-0.07	0.23	16.56
FaHP2	SANI_Germination	-1.39	0.22	-17.22	1.00	9.00
FaHP3	S_Germination	2.20	0.04	16.31	1.00	10.50
FaHP3	ACNE_Germination	-2.47	0.02	-0.02	0.96	11.05
FaHP3	PLOC_Germination	0.85	0.22	17.63	1.00	16.22
FaHP3	SANI_Germination	-2.20	0.04	-16.31	1.00	10.50
FaHP4	S_Germination	2.49	0.02	N/A	N/A	9.05
FaHP4	ACNE_Germination	-2.49	0.02	N/A	N/A	9.05
FaHP4	PLOC_Germination	1.20	0.07	N/A	N/A	16.05
FaHP4	SANI_Germination	-2.49	0.02	N/A	N/A	9.05
FaHP5	S_Germination	2.49	0.02	N/A	N/A	9.05
FaHP5	ACNE_Germination	-2.49	0.02	N/A	N/A	9.05
FaHP5	PLOC_Germination	1.20	0.07	N/A	N/A	16.05
FaHP5	SANI_Germination	-2.49	0.02	N/A	N/A	9.05
SpAvgFlow	S_Germination	2.78	0.17	-0.01	0.86	11.02
SpAvgFlow	ACNE_Germination	-4.62	0.11	0.08	0.33	9.97
SpAvgFlow	PLOC_Germination	2.02	0.14	-0.04	0.46	17.50
SpAvgFlow	SANI_Germination	-255.57	1.00	5.57	1.00	4.00
SpB75	S_Germination	2.02	0.15	0.01	0.69	10.86
SpB75	ACNE_Germination	-3272.56	1.00	35.70	1.00	4.00
SpB75	PLOC_Germination	1.55	0.14	-0.01	0.65	17.84

SpB75	SANI_Germination	-5.85	0.23	0.05	0.36	9.10
SpHP1	S_Germination	2.38	0.05	0.01	0.88	11.03
SpHP1	ACNE_Germination	-2.90	0.05	0.02	0.60	10.80
SpHP1	PLOC_Germination	1.63	0.06	-0.03	0.39	17.32
SpHP1	SANI_Germination	-8.50	0.49	0.15	0.50	6.95
SpHP2	S_Germination	3.69	0.07	-0.30	0.32	9.97
SpHP2	ACNE_Germination	-2.62	0.05	0.05	0.86	11.02
SpHP2	PLOC_Germination	1.07	0.18	0.06	0.78	17.70
SpHP2	SANI_Germination	-3.69	0.07	0.30	0.32	9.97
SpHP3	S_Germination	2.30	0.03	16.26	1.00	10.70
SpHP3	ACNE_Germination	-2.30	0.03	16.26	1.00	10.70
SpHP3	PLOC_Germination	0.98	0.15	17.59	1.00	16.89
SpHP3	SANI_Germination	-21.57	1.00	21.57	1.00	6.77
SpHP4	S_Germination	2.49	0.02	N/A	N/A	9.05
SpHP4	ACNE_Germination	-2.49	0.02	N/A	N/A	9.05
SpHP4	PLOC_Germination	1.20	0.07	N/A	N/A	16.05
SpHP4	SANI_Germination	-2.49	0.02	N/A	N/A	9.05
SpHP5	S_Germination	2.49	0.02	N/A	N/A	9.05
SpHP5	ACNE_Germination	-2.49	0.02	N/A	N/A	9.05
SpHP5	PLOC_Germination	1.20	0.07	N/A	N/A	16.05
SpHP5	SANI_Germination	-2.49	0.02	46.44	1.00	9.05
SuAvgFlow	S_Germination	1.72	0.28	0.05	0.66	10.60
SuAvgFlow	ACNE_Germination	-2.50	0.06	0.00	0.99	11.05
SuAvgFlow	PLOC_Germination	0.74	0.41	0.02	0.55	17.43
SuAvgFlow	SANI_Germination	-61.28	1.00	0.61	1.00	4.00
SuB75	S_Germination	1.84	0.12	0.03	0.53	10.44
SuB75	ACNE_Germination	-15.92	0.43	0.17	0.46	8.36
SuB75	PLOC_Germination	1.10	0.23	0.00	0.88	18.02
SuB75	SANI_Germination	-1187.79	1.00	13.12	1.00	4.00
SuHP1	S_Germination	1.61	0.14	17.62	1.00	9.41
SuHP1	ACNE_Germination	-2.87	0.04	0.02	0.60	10.81
SuHP1	PLOC_Germination	1.11	0.06	0.01	0.84	18.00
SuHP1	SANI_Germination	-67.86	1.00	1.00	1.00	4.00
SuHP2	S_Germination	2.08	0.05	16.42	1.00	10.28
SuHP2	ACNE_Germination	-2.27	0.04	-0.08	0.76	10.80
SuHP2	PLOC_Germination	0.69	0.33	16.74	1.00	15.46
SuHP2	SANI_Germination	-52.87	1.00	1.48	1.00	4.00
SuHP3	S_Germination	2.20	0.04	16.80	1.00	10.50
SuHP3	ACNE_Germination	-2.41	0.02	-0.04	0.84	10.98
SuHP3	PLOC_Germination	0.85	0.22	17.18	1.00	16.22

SuHP3	SANI_Germination	-24.87	1.00	1.18	1.00	4.00
SuHP4	S_Germination	2.20	0.04	17.09	1.00	10.50
SuHP4	ACNE_Germination	-2.87	0.03	0.62	0.48	0.62
SuHP4	PLOC_Germination	0.85	0.22	17.37	1.00	16.22
SuHP4	SANI_Germination	-46.34	1.00	23.27	1.00	4.00
SuHP5	S_Germination	2.30	0.03	15.92	1.00	10.70
SuHP5	ACNE_Germination	-3.21	0.03	1.46	0.25	9.81
SuHP5	PLOC_Germination	0.98	0.15	16.22	1.00	16.89
SuHP5	SANI_Germination	-69.33	1.00	N/A	N/A	4.00
WiAvgFlow	S_Germination	2.94	0.09	-0.02	0.72	10.93
WiAvgFlow	ACNE_Germination	-3.24	0.07	0.04	0.54	10.72
WiAvgFlow	PLOC_Germination	3.81	0.08	-0.14	0.21	13.79
WiAvgFlow	SANI_Germination	-2.21	0.23	-0.02	0.86	11.02
WiB75	S_Germination	2.07	0.11	0.02	0.68	10.85
WiB75	ACNE_Germination	-6.55	0.26	0.07	0.35	8.57
WiB75	PLOC_Germination	1.70	0.10	-0.01	0.48	17.55
WiB75	SANI_Germination	-2.79	0.09	0.01	0.78	10.97
WiHP1	S_Germination	2.68	0.04	-0.01	0.78	10.98
WiHP1	ACNE_Germination	-3.17	0.04	0.03	0.39	10.37
WiHP1	PLOC_Germination	2.00	0.18	-0.05	0.17	15.76
WiHP1	SANI_Germination	-2.29	0.06	-0.02	0.79	10.96
WiHP2	S_Germination	2.90	0.03	-0.06	0.51	10.67
WiHP2	ACNE_Germination	-3.06	0.03	0.08	0.38	10381.00
WiHP2	PLOC_Germination	2.21	0.03	-0.19	0.15	14.08
WiHP2	SANI_Germination	-2.28	0.05	-0.07	0.76	10.92
WiHP3	S_Germination	2.49	0.02	N/A	N/A	9.05
WiHP3	ACNE_Germination	-2.49	0.02	N/A	N/A	9.05
WiHP3	PLOC_Germination	1.20	0.07	N/A	N/A	16.05
WiHP3	SANI_Germination	-2.49	0.02	N/A	N/A	9.05
WiHP4	S_Germination	2.49	0.02	N/A	N/A	9.05
WiHP4	ACNE_Germination	-2.49	0.02	N/A	N/A	9.05
WiHP4	PLOC_Germination	1.20	0.07	N/A	N/A	16.05
WiHP4	SANI_Germination	-2.49	0.02	N/A	N/A	9.05
WiHP5	S_Germination	2.49	0.02	N/A	N/A	9.05
WiHP5	ACNE_Germination	-2.49	0.02	N/A	N/A	9.05
WiHP5	PLOC_Germination	1.20	0.07	N/A	N/A	16.05
WiHP5	SANI_Germination	-2.49	0.02	N/A	N/A	9.05