Fremont Cottonwood demographics and regeneration along an unregulated wild and scenic river

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# Abstract

Fremont cottonwoods (*Populus fremontii)* are a dominant riparian tree species in the Southwestern U.S. and are important habitat for native wildlife, highly dependent upon river hydrology. Fremont cottonwoods are included as one of the Outstandingly Remarkable Values in the 1984 amendment to the 1964 Wild Scenic River Act for a reach of the Verde Wild and Scenic River. Fremont cottonwood health and demographics along the Verde River are understudied but important for managing environmental flows. This study uses seedling plots established after a 10-to-25-year flood event that occurred during 2023 winter floods and dendrochronology to monitor regeneration and to quantify tree age and growth. Fremont cottonwoods along the Verde River are young, with the mean age being 24 years old. They continue to add biomass at a mature rate and their growth is significantly impacted by summer temperatures and river flows. Seedlings from the 2023 cohort continue to grow rapidly and their survival is governed by a diverse set of environmental conditions. Fremont cottonwoods along the Verde require a ten-year flood event to cause regeneration but stand dynamics are determined by the frequency and magnitude of flood events.

Keywords: Fremont Cottonwood (*Populus fremontii*), Verde River, Wild and Scenic Rivers, dendrochronology, riparian

# Introduction and Background

**Introduction**

Riparian forests in Arizona are disproportionately important to the landscape despite their relatively small geographic area. Riparian forests in Arizona cover only about 0.4% of land surface area yet support more biodiversity and ecosystem functions than surrounding upland habitat (Ffolliott et al., 2004). In Arizona, 80 percent of all vertebrate species complete a part of their lifecycle in riparian areas (Hubbard, 1977). Riparian forests support and enhance terrestrial and aquatic habitat, filter upland sediment and nutrients, store water and recharge aquifers and stabilize stream banks among many other functions (Schultz et al., 2009).

The Verde River in central Arizona drains over 16 thousand square km and is the longest, perennial river remaining in Arizona. Its watershed has elevations that range from over 3650 m ASL in the San Francisco Peaks to about 400 m ASL at its confluence with the Salt River. The headwaters in the upper Verde Valley originate from a series of springs draining the Big Chino and Little Chino aquifers (Wirt et al., 2005). The river then flows through the middle Verde Valley before it reaches its Wild and Scenic (W&S) designation just south of Camp Verde, AZ. Along this reach the Verde River gains volume from a string of canyons with perennial tributaries which get large portions of their base flow from springs discharging from the regional aquifers (Ecological Implications of Verde River Flows, 2008).

After the W&S reach of the river, the Verde enters its lower reach and flows through two large storage reservoirs before joining the Salt River. This allows large winter and monsoon floods to flow through the wild and scenic reach of the river and continuously change the ecology and geomorphology.

Although there are no large storage reservoirs above the Verde River Wild and Scenic corridor, the Verde River is still impacted by human use. Aquifers are pumped by municipal, irrigation, and domestic wells in the Little Chino Basin. Perennial flow of the Verde River begins about eight kilometers lower downstream than it did historically because of groundwater pumping (Ecological Implications of Verde River Flows , 2008). Surface water diversions between Clarkdale and Beasley River Access Point reduce base flow during the summer when water levels are historically at their lowest. Irrigation diversion ditches withdraw about 34,000 acre feet with about half of that being consumed (Alam, 1997; Blasch et al., 2006). The Verde Valley also is an agricultural area with land being used for: pasture, pecans, grapes, corn, and vegetables. However, most farms are small both in size and revenue (USDA, 2012; Zhao et al., 2019).

The Verde River is one of two federally designated Wild and Scenic Rivers in Arizona. The Wild and Scenic Rivers Act designated the Verde River for study in 1978 before being officially designated in 1984. To be designated, a river must possess “outstandingly remarkable scenic, recreational, geologic, fish and wildlife, historic, cultural or other similar values” (Wild and Scenic Rivers Act, 1968). Maintaining these values along the Verde are required because of this designation. Riparian forests along the Verde contribute to all the values listed in the Wild and Scenic Rivers Act. Therefore, maintaining and regenerating Fremont cottonwoods (*Populus fremontii)* along the Verde is crucial to sustaining its remarkable values.

Fremont cottonwood *(Populus fremontii*) and Goodding’s willow (*Salix gooddingii*) are major components of riparian forests along the Verde River. Tree diversity is low in Verde River riparian forests with Fremont cottonwood being the dominant species. However, age class structure is usually very diverse. Stands of Fremont cottonwood and Goodding’s willow often occur in spatially separate, but same age cohorts with younger stands closer to the active channel and older stands extending up to 200 meters away (Stromberg, 1993).

The reproductive ecology of cottonwood and willow influences how and when they regenerate. These trees are pioneer species, meaning they rely on disturbance and large amounts of seeds for sexual establishment. Both species produce large amounts (up to 25 million on mature trees) of seeds each spring. The seeds are small and have “tufts'' that are designed for long distance wind and water dispersal. Seeds are released in early spring as winter floods recede (Stromberg, 1993). This allows the seeds to be deposited on bare, moist mineral soil created by high winter flows. Regeneration of Fremont cottonwood and Goodding willow are not consistent in Arizona. A study in Southern Arizona showed that regeneration occurred only about every decade and was dependent on strong winter floods to scour vegetation and deposit fine alluvial soils (Cooper et al. 1999; Stromberg, 1997).

The winter of 2023 was the one of the largest in Arizona in the past 30 years (Figure 1). On March 1st, 2023, the Verde River basin was at 318% of its normal snowpack (NRCS). As a result, during spring snowmelt the Verde River flows reached between a ten percent and a four percent annual exceedance probability (AEP) flood. This means that there is between a four and 10 percent chance a flood of this magnitude would occur in any given year. (<https://streamstats.usgs.gov/ss/?gage=09506000&tab=info>). Peak snowmelt occurred in mid-March and almost reached 1000 m3/sec. Flows then declined to the summer and fall low-flow period where base flows can drop below 1 m3/sec. This large flood caused significant flooding, toppled trees and in some cases, reshaped the active channel. This flood disturbance created conditions for Fremont cottonwoods to regenerate via seed and unique opportunity to study their regeneration and survivorship.

A graph of a graph showing the amount of snow all over the body

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Figure 1. Mean daily discharge for the Verde River near Camp Verde, AZ USGS gage (09506000) for 2023.

The Verde River’s unique and intact hydrology makes it rare in the southwest. This study used the following research questions to understand regeneration and establishment of Fremont cottonwood on this river.

1. How have seedlings from the 2023 spring cohort survived and grown in the past two growing seasons?
2. How old are Fremont cottonwoods along the Verde River?
3. What variables impact annual growth for Fremont cottonwoods along the Verde River?

## Methods

### Study Site

Access to the Verde River Wild and Scenic Corridor is restricted to a few road access points or from rafting along the river. Because of the limited access, sites were chosen that are logistically feasible and realistic to access on a frequent and continuing basis. Beasley Flat River Access Point (BRAP), downstream of Camp Verde and Childs dispersed camping area, upstream from the confluence of the Verde River with Fossil Creek (Figure 2) were chosen to visit repeatedly. A third site at Sheep Bridge River Access Point was used to collect tree cores but was not used to study seedling mortality monitoring because of its remote location. All three sites have healthy Fremont cottonwood-Goodding’s willow riparian, gallery forests and have a largely intact hydrology.

A map of a river

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Figure 2. Map of the Verde River basin showing the Wild and Scenic reach of the Verde River and study sites.

### Seedling Plots

Ten monitoring plots were established at BRAP and Childs. River reaches were walked in Fall 2023 to identify seedlings that had survived most of their first growing season. A metal pin was pounded into the ground and a radius determined to encompass all or most of the seedlings. Seedling heights were measured with a ruler or measuring tape to the nearest centimeter and the diameters near the ground were measured with calipers to the nearest millimeter within the determined radius.

If a regeneration area was too large or there were too many seedlings to feasibly measure, the area was subsampled. First the area containing the cottonwood seedling was mapped using the Arrow100 GNSS (Quebec, Canada). After the polygon was created and the area determined to the nearest square meter, a one square meter hoop was used to create subsample areas and seedlings within the hoop were then measured and recorded. 15-30% of the total area containing seedlings was sampled.

**Light**

Light intensity was measured with a Li-COR LI-1500 Light Sensor Logger (Lincoln, NE). The pyranometer sensor was placed in the or near the plot and allowed to acclimate. A reading was taken every minute for 5 minutes. These readings were then averaged to get an average W/m2 value at each plot at an accuracy of ± 0.3%.

**Herbaceous**

Herbaceous competition was estimated using the Braun-Blanquet 6 step scale (Braun-Blanquet, 1964). Only plants within the plots and rooted at the same elevation as the cottonwood seedlings were considered as herbaceous competition.

**Soil**

Soil samples were collected inside the seedling plots using a trowel. Soil samples are from the first few inches of the soil horizon where the cottonwoods originally germinated. Samples were dried in an oven for 6 hours at 70o C. The samples were placed in a shaker and sieved for 15 minutes and the percent fines (0.075mm or smaller) was calculated for each site. Grain size distributions were based on dry weight percentage.

**Analysis Methods**

R studio scripts were used to calculate summary statistics (R version 4.4.2). Height and diameter values were converted into a single Height-Diameter ratio (HDR) so that each seedling had a single value describing its size. A higher HDR means that a seedling is becoming thinner and taller.

Equation 1.

Changes in density and seedling size were determined by subtracting the Fall 2024 values from the Fall 2023 values. To measure between significant changes between visit (Fall 2023, Spring 2024 and Fall 2024) and growth (mean height, diameter and HDR) an Analysis of Variance (ANOVA) was used to test for significant changes. Tukey’s HSD test was used to test for significant changes between variables. A critical P-value of less than or equal to 0.05 was used to test for significance.

A logistic regression model was used to see how the three measured variables impacted seedling survivorship. The three site variables were compared to Fall 2024 survivorship. A stepwise selection model was run to determine which variables, and which combinations were significant.

### Dendrochronology

To determine the age and growth of Fremont cottonwood trees, cores were collected in October 2023 at all three study sites. A variety of size classes of live Fremont cottonwoods across the floodplain were selected for coring. A core was taken as low on the tree trunk as possible, at an angle perpendicular to the tree’s lean and aimed to be as close to the pith as possible. The borer was then drilled into the tree far enough to ensure that the pith had been passed.

Cores were prepared and sanded using standard methods according to Stokes and Smiley (1968). The cores were placed under a dissecting microscope and rings were counted. For cores without a pith, a concentric circle ruler was used to estimate position and determine the number of the few missing rings. Ages of the innermost ring as well as the estimated pith date were recorded. For cores where a pith date could not be estimated, a minimum age was recorded.

To measure the ring widths of each core, the cores were scanned, placed on an electronic scanner and uploaded into Cybis CooRecorder software (<https://www.cybis.se/forfun/dendro/index.htm>). Each ring was marked in the software so that the date could be verified and ring widths measured.

**Crossdating**

Dated and scanned cores are saved as a .RWL file and uploaded into Cdendro (<https://www.cybis.se/forfun/dendro/index.htm>). Files were separated into four different sites: Upper Beasley, Lower Beasley, Childs and Sheep. All the cores (n=133) were analyzed with COFECHA and cores with a correlation coefficient of +0.30 were separated. This separated series (n=39) was then ran through COFECHA to check for any dating issues. The dplR package created by Dr. Andy Bunn was used (Bunn, 2010) to calculate Ring Width Indices (RWI) and Basal Area Increment (BAI) for the crossdated series to then be compared to climate variables.

**Correlation to climate**

Four climate variables were used to run a response function analysis on the chronologies. Mean monthly values for: average temperature, precipitation, and Palmer Drought Severity Index (PDSI) were downloaded from the NOAA climate monitoring website (<https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/county/time-series/AZ-025/tmin/1/0/1993-2023?base_prd=true&begbaseyear=1901&endbaseyear=2000>) from 1993 to 2023 for Yavapai County, Arizona. Mean monthly stream flow was gathered from the Verde River near Camp Verde (09506000) USGS gauge from 1988-2023. This gage was selected as it is located near the Wild and Scenic portion of the river and had the longest continuous discharge record (1988 to current).

**Response Function Analysis**

Response function analysis is used to help determine relationships between climate variables and tree growth. These analyses differ from simple correlations in that they address the autocorrelation that is usually prevalent in both climate and tree growth data. Response functions and their results are more robust than correlations. Using the Treeclim package in R (Zang & Biondi, 2015) chronologies were tested for the four climate variables. A critical P-value of less than or equal to 0.05 was used to determine if a trend was significant and an exact bootstrap method was used (Meko et al., 2011). An exact bootstrapping method tests for significance but does not produce specific p-values, just whether the relationship is significant. A response function analysis was used for water year (September-October) was used to test against the annual growth.

# Results

Seedling Survivorship

A graph of a number of children

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Figure 3. Mean site seedling densities across the three visits.

At both BRAP and Childs, densities only slightly decreased between Fall 2023 and Spring 2024 visits (Figure 3). Both sites saw larger decreases from the 2024 growing season with Childs densities decreasing by over half. Both sites had nearly identical mean densities following Fall 2024 surveys.

**Seedling sizes**

At the plot level, mean height and diameters of seedlings increased between all three visits. At BRAP, mean HDR values increased between all three visits as well. At Childs, HDR decreases between Fall 2023 and Spring 2024 visits before increasing in Fall 2024.

At BRAP, seven out of nine variables changed significantly between the different visits. All the BRAP heights changed significantly between visits. Diameters between Spring 2024 and Fall 2024 did not change significantly and HDRs between Fall 2023 and Spring 2024 did not change significantly. At Childs, all variables changed significantly with eight out of nine being highly significant (p-value ≤ 0.001).

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**Logistic regression model**

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A logistic regression model indicated that light, herbaceous competition, and fine sediment were highly significant for seedling survival at BRAP. Because all three variables were originally significant, the stepwise model did not have to remove any insignificant variables and see if this made other variables significant.

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The Childs logistic regression model run indicated that light and fines sediment as significant variables in seedling survivorship but not herbaceous competition. Once the stepwise model was run and the herbaceous variable removed, the p-value for fines decreased slightly.

**Age at Coring Height**

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Figure 4. Age at coring height. The bar graph is the number of trees dating back to each year while the line graph is the cumulative count of all cores over time.

Tree core analyses (n=133) were used to determine the number of trees dating back to year of regeneration. The age at coring height distribution is not normal (Shapiro-Wilk test of p<0.05) (Figure 4). The mean age at coring height was 24 years old. The most recent core was from 2016.

**Annual Growth**

The final crossdated series (n=39) produced an interseries correlation of +0.395 and a mean sensitivity of 0.533. This was the series used to determine growth and ring widths as well as to test against climate variables. Basal Area Index (BAI) is generally increasing from 1995 to 2010 before stabilizing until 2023 (Figure 6). Ring Width Index (RWI) has been generally decreasing since about 2000 until 2023 (Figure 5). Both BAI and RWI saw large increases in the year 2023.

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Figure 5. Ring Width Index (RWI) by year for the crossdated series.

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Figure 6. Basal area increment (BAI) by year for the cross-dated chronology.

**Response function analysis**

Five variables were found to be significant in determining annual tree growth through a response function analysis. Three of these variables were streamflows of certain months while the other two were variables related to climate. Four out of the five significant variables were positive. In addition, all the significant variable months were between June and October.

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## Discussion Seedling survivorship and demographics

Densities decreased or stayed constant in 80% of plots surveyed across the two sites. The remaining 20% of plots increased, possibly indicating that there was recruitment following the seed release in Spring of 2024 that survived into Fall 2024.

Seedling size was used a proxy for seedling health and potential survivorship. Both sites had all three-size metrics increase between the beginning and end of the study. Seedlings grew larger at Childs and densities also decreased at a higher rate than those at BRAP. It is possible that quicker growing seedlings decrease in density quicker as well. Both sites ended with similar mean seedling densities. HDR values increased in both sites meaning seedlings became taller and thinner as they grow over their first two years.

Causes of mortality were difficult to determine. No significant floods scoured away seedlings during the study. At some sites, the seedlings were showing signs of desiccation during the spring 2024 visits, while sites LB 3 and LB 4 had encroachment of Common Cocklebur (*Xanthium strumarium*). The Common Cocklebur seemed to be most highly concentrated in the sandy center of the depressions while Fremont cottonwood seedlings ring the outside of the depression. Fremont cottonwoods within the center were taller as they were forced to grow quickly to compete with the cocklebur. Browsing was infrequently observed and at no plots did browsing seem to be a significant impact.

In two growing seasons, seedling heights reached an average height of 36 cm and 64 cm at BRAP and Childs respectively. These heights are about half of what Fremont cottonwood seedlings were found to have grown in a similar study in Central Arizona (Stromberg, 1997). However, final seedling densities at both BRAP and Childs were similar to one of the studied rivers in Central Arizona. The smaller sizes found on the Verde River could also be because all cottonwoods regardless of size or cohort were incorporated. For example, large numbers of seedlings from 2024 floods were measured in both the Spring 2024 and Fall 2024 visits. In addition, the rivers selected in Central Arizona were at lower elevations and at a more southern latitude. Seedlings here likely had a longer growing season to grow larger than along the Verde River. Finally, both rivers in Central Arizona are in large open reaches, where sunlight is largely unlimited. In contrast, sites along the Verde River are in canyons, limiting their sunlight and growing season and potentially explaining the differences in growth. Light was found to be a significant variable for seedling survivorship in this study so it being limited compared to other Arizona rivers could explain the slower seedling growth.

### Variables impacting survivorship

**Light**

Riparian cottonwoods are generally considered to be shade intolerant species. Light is often considered a secondary variable to water available (Cooper et al., 1999). Light was found to be highly significant (p-value ≤ 0.001) for both sites.

**Herbaceous**

Herbaceous competition was found to be a highly significant variable at BRAP. However, it was found to be not significant in predicting seedling survival at Childs. At BRAP herbaceous competition was positively related to seedling survival. This contradicts the idea that seedling competition with other species would be expected to decrease survival. One explanation for this is that sites that had favorable conditions for cottonwood seedlings (adequate water and light) were also suitable for competitors. However, because this was still a positive, significant relationship, cottonwood seedlings could be able to outcompete their competitors.

**Soil**

Soil is often cited as one of the most important factors in determining cottonwood seedling survival (Bhattacharjee et al., 2008; Cooper et al., 1999). Soil trenches are often used when determining soil characteristics for cottonwood survival in floodplain settings (Cooper et al., 1999; Varani et al., 2024). However, because this method was not used in this study it is difficult to make wide reaching assumptions about soil texture and seedling survival on the Verde River. Soil samples were taken from the first few inches of soil where seedlings initially germinated, so this variable only addresses the soil in which cottonwood seedlings germinated. Percent fines were found to be a significant variable at both sites. However, the relationship seems to be more complicated, because sites had very different amounts of fines in their soils. The average percent fines at BRAP were about 16.5% while the average at Childs was 6.3%. There was a negative relationship for percent fines at BRAP indicating that as fines increase, survivorship decreases. It is likely that sites with high percentages of fines (>50%) are in more isolated depositional sites that are further removed from the river and therefore not as frequently replenished by groundwater. Childs had a more traditional relationship in that as fines increased, so did survival. This is more consistent with existing literature that an increase in fines increases water holding potential.

### Dendrochronology

**Minimum ages**

Most of the cottonwoods along the Verde River are young. The mean age at coring height is the year 2000.4. Previous research on riparian forests found that cottonwood-willow forests in the Verde Valley have spent the most of the 1900s recovering from various Euro-American settlement disturbances. Cottonwood-Willow forests covered only 270 acres of the Verde Valley in 1940. This then peaked in 1977 with 551 acres before stabilizing following large floods in 1983 and 1993 ( Lopez &Springer, 2002). This recovery could help explain why there are few cottonwoods dating back to this time. It is possible that cottonwood-willow forests were limited from heavy human influences such as: agriculture, land clearing and a copper smelter before being allowed to recover by the 1970s. Then, large floods in 1983, 1993, 2005 and 2023 have kept riparian forests young and replenished.

There is also a very weak correlation but significant (r2 = 0.06, p-value ≤ 0.05) between the age and diameter of cottonwoods cored. With no strong trend between age and diameter, it means that other factors may be influencing size. For example, competition between trees for sunlight may be suppressing smaller trees. Cottonwoods are shade intolerant species and because they tend to regenerate in short, distinct timeframes suppressed trees may be much smaller than dominant trees of the same age.

**Tree growth**

(R. Willms et al., 2006) describes cottonwoods in Canada as following a general growth pattern, reaching their peak growth at about 20 years after their germination before entering the mature stage of their growth. Cottonwoods along the Verde River seem to follow this trend (Figure 7). Basal area increased slowly during the establishment phase (for about 10 years). This was then followed by another decade of rapid growth before leveling off and entering the mature growth stage. A key difference between the Canadian study and this study being the amount of growth. R. Willms et alt. described growth between 1-9 cm2 while the cottonwoods along the Verde are within the 10-30 cm2 range. So, while Verde Cottonwoods growth follows a similar trend, they grow much more rapidly.

A comparison of a graph

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Figure 7. Showing R. Willms et al. generalized trend of cottonwood growth (left) compared to the 5-year BAI moving average for cottonwoods along the Verde (right).

Although cottonwoods are pioneer species, they are still relatively young at 25-30 years old. Fremont cottonwoods are shorter lived species compared to other North American cottonwoods. It is generally accepted that few Fremont cottonwoods live to be over 150 years. A few old growth Fremont cottonwoods cored for this study had minimum ages going back to the 1920s. No curvature was found on the other side of the core and diameters were over 1.5m at coring height. It is likely that some of these individuals approach or exceed the 150-year limit generally accepted for the species. In colder climates, Plains (*P. deltoides)* and Narrowleaf (*P. angustafolia*) cottonwoods have been documented over 200 and 300 years (Rood & Polzin, 2003).

**Response to climate**

Different cottonwood species in different geographic areas respond differently to seasonal streamflows. For example, plains cottonwoods (*P. deltoides)* in the Northern Rockies had growth most correlated to March to June or April to July streamflows (Schook et al., 2016). This is reflective of a snowmelt driven system. Rio Grande cottonwoods (*P. deltoides spp. wislizeni*) along a regulated reach of the Rio Grande in New Mexico were most correlated to July-September streamflow which indicates a monsoon driven system (Varani et al., 2024). The Verde River is unique because it is a snowmelt driven system in the Southwest that also is relatively unregulated. It is an interesting blend of aspects of both the Northern Rockies reach as well as the regulated reach of the Rio Grande.

June and July streamflows had the highest correlation to tree growth. In the Verde River, June streamflows are typically the lowest of the year. Although the monsoon season officially begins June 15th, meaningful precipitation usually arrives in mid-July. Therefore, June and July before the arrival of the North American Monsoon often have the lowest flows and highest temperatures. In addition, June and July is peak irrigation season for agriculture within the Verde Valley (Garner & Bills, 2012). Groundwater and surface water are highly related in the Southwest . Higher flows, and therefore higher groundwater levels, could also saturate more of the rhizosphere allowing for more roots to be able to access water. This water could then contribute to tree growth or cooling. Fremont cottonwoods can cool themselves remarkably well from high summer temperatures as long as they have adequate water (Moran et al., 2023). Higher flows could increase water availability and allow them to cool themselves more efficiently.

October temperatures (positive) is significantly correlated to annual growth. Higher October temperatures may help prolong the growing season for riparian trees which would allow them to increase their growth. June PDSI could positively impact tree growth because if temperatures are higher in June and trees have adequate water, they may be able to grow quicker. September streamflow was negatively correlated to annual tree growth, but this seems inconsistent with cottonwood ecology.

## Establishment

The Verde River and its floodplain are largely depositional. Riparian tree root collars are submerged by sediment, and the amount of deposition is impossible to know without direct excavation. Therefore, ages collected from this study are the minimum ages a tree could be at the height the core was taken. However, Fremont cottonwoods grow rapidly. Stromberg (1997) documented them averaging heights of over 1m in just two growing seasons. Seedlings from this study averaged over 0.5 m in two growing seasons. It is unlikely that ages at coring height are many years off from their original germination date.

Riparian forests along the Verde spent most of the 20th century recovering from anthropogenic impacts (Lopez & Springer, 2002). However, Fremont cottonwoods establishment within the past 40 years seems to be tied to large winter floods. The average age at coring height was the year 2000 which means trees most likely date back to floods in 1993 (less than a 2% AEP), and 1995 (4% AEP) and the following years.

Stromberg (1997) found cottonwood regeneration occurred in successive years following these two large floods. This study observed seedling survival through the first growing season for cohorts from both 2023 and 2024. While 2023 was a large winter flood, 2024 floods had an AEP of more than 50% (<https://streamstats.usgs.gov/ss/?gage=09506000&tab=info>). This shows that cottonwood regeneration is not tied directly to a single year but rather multiple years following floods, even if following years don’t have large floods.

Peaks in regeneration were observed following 1993, 1997 and 2005 (Figure 4.). Peaks in regeneration after 1993 and 2005, which had an AEP between a 10% and 4%, are likely directly related to large floods of that year. Although 1993 had the largest flood the peak in tree ages associated with that year is much lower than the following 1997 to 2003 period. Because only two growing seasons occurred between the 1993 and 1995 floods, most seedlings would have been too small to withstand another large flood. Therefore, a limited amount of them would have survived the 1995 flood and explains why the 1993 peak is small compared to the flood magnitude.

However, the largest peak in ages between 1997 and 2003 is likely just regeneration occurring in successive years following floods. Large floods in 1993 and again in 1995 would have created large areas of suitable habitat for regeneration. The absence of large floods between 1995 and 2005 could have allowed seedlings to grow without being scoured away. As seedlings continued to recruit and grow during this time, observed ages decline as available habitat is occupied. When the winter 2005 floods occurred, seedlings were already large and flexible enough to withstand the large floods. Less saplings and trees were destroyed by this winter flood, leading to less available habitat and regeneration. This could explain why the regeneration peak in 2005 was lower than the 1997 to 2003 period.

Establishment of Fremont cottonwoods on the Verde River is driven by large winter floods as is the case with cottonwoods elsewhere. It appears that a flood magnitude of with an AEP of ten percent or less is required to initiate meaningful Fremont cottonwood regeneration. On the Verde River, this means a flood of just over 1200 m3/s (42500 cfs) is required to cause Fremont cottonwood regeneration. However, the exact cohort and ages of trees seems to be driven by a complex combination or the frequency and size of floods. Because of the largely free-flowing nature of the Verde, this creates a diverse range of ages and cohorts that respond to flood regimes.

On a site level, local topography is important in establishing seedling regeneration. Scoured out depressions formed on the floodplains had the highest concentration and size of seedlings. These depressions also had perennially wet soil at the bottom, indicating that they were close to the water table. Over time, these depressions will likely fill in with sediment from future floods, but the seedlings will already have reached the water table. These sites created very productive and local spots for regeneration that may not be identifiable in the future. These depressions would create linear, same-aged cohorts described in Stromberg 1993.

**Limitations/Assumptions**

The series and cores collected are short in nature. This makes it difficult to produce high correlations for crossdating. COFECHA was used to select cores that were correlated to each other and the overall collection of tree cores to use for further analysis. Because Fremont cottonwoods grow in riparian areas with access to year around water, it is unlikely that rings are missing which means that the trees are likely dated correctly even though this may be difficult to statistically prove. Another challenge with this project is that most trees are young. This makes it more difficult to crossdate the series as well as could make reaching a critical P-value of 0.05 more difficult for statistical tests.

**Conclusions and Implications**

Fremont cottonwoods that established after the 2023 winter floods continue to grow and reduce in density. Seedling plots seem to be impacted by light and percent fines being significant across both sites and herbaceous competition at BRAP. The differing significant variables impacting seedling survival shows that a combination of factors is important in maintaining seedlings. Most Fremont cottonwoods on the Verde are relatively young and date to the year 2000. Despite their young age, Fremont cottonwood growth appears to have achieved a mature growth rate. Their growth also is driven by early-summer streamflow. This season is when streamflows are the lowest and temperatures are the highest and irrigation diversion season is at a peak in the region. As base flows continue to decline, cottonwood growth and resilience could be at risk. Maintaining higher flows during the summer irrigation season would positively benefit riparian forests. However, Fremont cottonwoods still require large, winter floods to create habitat required for their regeneration. A flood magnitude of ten percent AEP or lower seems to be able to recruit cottonwoods on a large, river scale. Keeping the natural systems and environmental flows along the Verde River will maintain and protect its riparian forests.

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