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

## Abstract

Fremont cottonwood (*Populus fremontii)* is a dominant riparian tree species in the Southwestern U.S. It provides important habitat for native wildlife and is highly dependent upon river hydrologic regimes. Fremont cottonwood-dominated forests is one of the Outstandingly Remarkable Values of the Wild Scenic River Act for a reach of the Verde River designated as Wild and Scenic River in 1984. Fremont cottonwood health and demographics along the Verde River are poorly understood but an understanding of the patterns and processes that drive them are important for securing water rights and managing environmental flows. This study monitors seedling plots established in the spring 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. Verde River Fremont cottonwoods within the riparian zone are young, with the mean age being 25 years old. They continue to add biomass at a constant 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

**Riparian areas**

Riparian areas are defined as the “banks and floodplains of flowing water… influenced by processes associated with open channel flow” (Merritt 2022). 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).

* **Broad importance about PopFre** 
  + **Rarity**
  + **Importance**

**Riparian forest overview**

Fremont cottonwood *(Populus fremontii*) and Goodding’s willow (*Salix gooddingii*) are major components of riparian forests along the Verde River. Cottonwood-willow forests are rare in the Southwest but the Verde River offers one of the largest, contiguous stands.FREMONT COTTONWOOD IMPORTANCE

* One of Fremont cottonwoods most studied impacts is on bird habitat.
  + Older and mature forests are important habitat to bats as well as support more Neartic-Neotropic migrants avian than tamarisk
* Phreatophytes

Stromberg (1993) describes Fremont cottonwood and Goodding willow ecology in Arizona. Fremont cottonwoods are pioneer species, relying on disturbance and large amounts of seeds for sexual establishment. Both species produce large numbers (up to 25 million on mature, female 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. This allows the seeds to be deposited on bare, moist mineral soil scoured and deposited by high winter flows.

-Factors that impact cottonwood establishment

* Cottonwood seedlings are sensitive to groundwater level decline
* Inter and intraspecies competition can also impact. Seedlings also grow best when they are at least 15 cm apart.
* Inundation and temperature also impact seedling survivorship
* Cottonwood seedlings are also able to outcompete tamarisk species

Regeneration of Fremont cottonwood and Goodding willow occurs sporadically 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). Because most of the Verde River is unregulated and largely free-flowing, native species still dominate riparian areas. Age class structure is very diverse among riparian trees along the Verde River. 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).

Threats

Invasives

* Invasive species such as tamarisk (*Tamaris spp.*) and Arundo (*Arundo donax*) exist along the Verde River. However, invasive species are generally not dominant. For example, along the Upper Verde River, tamarisk accounts for only 8% of stems (Johnson et al. 2010). Invasive species abundance is impacted by many variables with river regulation and altered hydrologic conditions being an important factor (Horton et al., 2001; Merritt & Cooper, 2000; Shafroth et al., 2002). River regulation along the Salt River, in Arizona was found to negatively impact Fremont Cottonwoods and their regeneration (Fenner & D. R. Patton, 1985).
* Water level decline
* Grazing
  + Negative impact on seedling abundance
* Fire
  + Resprouting in some species
  + Generally negative

The winter of 2023 was the one of the wettest in Arizona in the past 30 years (Figure 2.1). 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 a four to 10 percent chance a flood of this magnitude would be equaled or exceeded 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 (Figure 2.1). 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 floodplain inundation, toppled riparian trees and in some cases, reshaped and re-routed the active channel. This flood disturbance created conditions for Fremont cottonwoods to regenerate via seed and a unique opportunity to study their establishment and survivorship.

**Verde River introduction**

The Verde River in central Arizona drains over 16,000 km2 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 the reach designated as Wild and Scenic (W&S) 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. There are no reservoirs on the upper reach, allowing large winter and monsoon floods to flow through the wild and scenic reach of the river and continuously influence 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 Big and Little Chino Basins. Perennial flow of the Verde River begins about eight km further 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 42,000,000 m3 (34,000 acre feet) with about half of that being consumed and the other half returning to the river (Alam, 1997; Blasch et al., 2006). The Verde Valley also is an agricultural area with land being used for pasture, pecans, grapes, alfalfa, barley, corn, and other vegetables. However, most farms are often small in size (USDA, 2012; Zhao et al., 2019).

The Verde River is also important economically for the State of Arizona. The Nature Conservancy (2011) estimated in 2010 that the economic value of the Middle Verde River was $150-161 million and created 737 jobs. About $88 million was related to tourism. About $35 million was estimated for agriculture (including the wine industry) and they estimated the ecological value of the Middle Verde River at $15-22 million. In addition, about 60% of water delivered to the Phoenix metropolitan area is supplied by the Salt and Verde Rivers (https://www.phoenix.gov/administration/departments/waterservices/supply-conservation/drought/drought-shortage-operations.html#:~:text=The%20City%20uses%20nearly%2060,Central%20Arizona%20Project%20(CAP)). Most Arizonans live within the Phoenix metro area, making the Verde River a critical water supply in the region.

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” (ORVs; Wild and Scenic Rivers Act, 1968). Maintaining these values along the Verde River are required because of this designation. Riparian forests along the Verde River contribute to many of the ORVs identified 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.

A graph of a graph showing the amount of snow melts

AI-generated content may be incorrect.

Figure 2.1 Mean daily discharge for the Verde River near Camp Verde, AZ USGS gage (09506000) for 2023.

The Verde River’s unique and intact flow regime makes it rare in the Southwest. We used the following research questions to understand regeneration and establishment of Fremont cottonwood on this river. We also investigated the impact of certain climate variables on the growth (fitness) of Fremont cottonwoods.

1) How have seedlings from the 2023 spring cohort survived and grown in the past two growing seasons?

2) What are the demographics of Fremont cottonwood along the Verde River?

3) What climate variables impact annual growth (fitness) of Fremont cottonwood 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 continuous 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 2.2) 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 unaltered flood hydrology.

A map of a river

AI-generated content may be incorrect.

Figure 2.2 Map of the Verde River basin showing the Wild and Scenic reach of the Verde River and study sites.

**Seedling Plots**

River reaches were walked in fall 2023 to identify seedlings that had survived their first growing season. We established ten monitoring plots at BRAP and Childs using purposive (subjective) sampling. Plots were selected in areas where live seedlings occurred, not randomly across the floodplain. Seedlings were concentrated forming dense patches and a random or systematic approach likely would not have located the regeneration. By choosing sites where regeneration had survived their first growing season, it allowed us to better study and understand which variables impact their survivorship.

We pounded metal pin into the ground and a radius was determined to encompass the seedlings. We then measured seedling heights with a ruler or measuring tape to the nearest centimeter and the diameters near the ground with calipers to the nearest millimeter within the determined radius.

If a regeneration area was too dense to feasibly measure every seedling, we subsampled the area. First, we mapped the area containing the cottonwood seedling using an 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. We sampled 15-30% of the total area containing seedlings.

**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 Coverage**

We measured herbaceous coverage to observe competition of other herbaceous plants with cottonwood seedlings. Herbaceous coverage was estimated using the Braun-Blanquet 6 step scale (Braun-Blanquet, 1964). Only herbaceous plants within the plots and rooted at the same elevation as the cottonwood seedlings were considered as herbaceous competition. Plants rooted at the same elevation as cottonwood seedlings would be competing for light, water, space and nutrients.

**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 by subtracting the weight of fine sediment from the total sediment weight. Grain size distributions were based on dry weight percentage.

**Survey data/distance to water level**

We surveyed seedling plots to incorporate them into larger hydraulic models. The goal of the surveying is to determine what river discharge is required to inundate seedling sites. Sites at BRAP and Childs were surveyed with a Trimble R10 GNSS base and rover (Westminster, CO) with an accuracy of 8mm horizontally and 15 mm vertically. Transects were surveyed starting at the upper mesquite (*Propsis spp.*) terrace, down through the seedling plot and to the edge of the water. Points were taken at different geomorphic features (top and bottom of swales etc.) to create a detailed cross-section of the floodplain where the seedlings regenerated.

TO BE INCORPORATED FULLY LATER

**Analysis Methods**

R was used to calculate summary statistics (R version 4.4.2). Height and diameter values were converted into a single Height-Diameter ratio (HDR),(Rose et al., 1999) so each seedling had a single value describing its size. A higher HDR means that a seedling is thinner and taller.

Equation 2‑1

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

A logistic regression model was used to model the three measured variables impacted seedling survivorship (APPENDIX X). 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 predictors of survival.

**Dendrochronology**

To determine the age and diameter growth of Fremont cottonwood trees, cores were measured and collected in October 2023 at all three study sites. Fremont cottonwoods (n=175) and a few Goodding willows (n=15) from the riparian area where cored. The riparian area is defined as the part of the floodplain dominated that is subjected to inundation and fluvial disturbance (Merritt, 2022). On the Verde River, we sampled the riparian area immediately adjacent to the active channel of the river. Other terraces or locations that are infrequently influenced by fluvial processes were not considered riparian. Within this area, we cored most Fremont cottonwoods within a few hundred meters of the access point. We did not core trees smaller than 5 cm at their base.

However, Fremont cottonwoods exist outside of the riparian zone along the Verde River. To include older trees that may not be in the riparian zone, we cored a stand of larger trees outside of the active floodplain. This stand was located just upstream from the confluence of the Verde River and one of its tributaries, West Clear Creek. These large trees (more than one meter diameter at breast height) were around 100 m from the active channel at the Verde River.

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. No cores were taken from trees smaller than 5cm at the elevation where cores were taken.

Cores were air dried, glued to wooden mounts and then progressively sanded until cells were visible under magnification (Stokes and Smiley, 1968). We placed the cores 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 using the software so that the date could be verified and ring widths measured. We saved dated and scanned cores 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 Bridge.

**Crossdating/dating**

Crossdating involves matching ring-width patterns among individuals or to a pre-existing chronology. No pre-existing chronology exists for any cottonwood species in Arizona and New Mexico. In addition, cored trees were generally short (20-30 years old) and exhibited high variation in interannual growth. This makes traditional crossdating impossible. Cottonwoods along the Verde River have access to perennial ground water which means that missing rings are unlikely. To maximize the in common signal across sites, we identified cores with a correlation coefficient of +0.30 to the mean of all cores measured. We then separated and saved these cores into a different “correlated” series. These cores showed in common signals with each other driven by larger factors instead of cores impacted by individual growth, competition, disease, etc. We ran this separated series (n=39) through COFECHA to check for any dating issues. We analyzed the COFECHA output for each core and checked it for potential dating issues. If we found a potential dating issue the core was reexamined under the microscope. 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. To determine RWI, raw ring widths were detrended using an age dependent spline method.

**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 data were acquired 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 (October-September) to test against the annual growth.

## Results

Seedling Survivorship

A graph of a number of children

AI-generated content may be incorrect.

Figure 2.3 Mean site seedling densities across the three visits.

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. At both BRAP and Childs, densities only slightly decreased between Fall 2023 and Spring 2024 visits (Figure 2.3). Both sites saw larger decreases from the 2024 growing season with Childs densities decreasing by over half. Both sites had similar mean densities following Fall 2024 surveys.

**Seedling sizes**

At the plot level, mean height and diameters of seedlings increased between all three visits (Table 2.1). At BRAP, mean HDR values increased between all three visits as well. At Childs, HDR decreased 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 (Table 2.2). 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, Table 2.3).

Table 2‑1 Summary of mean height, diameter, and height-to-diameter ratio (HDR) for seedlings across three visits at both sites.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Site | Visit | Height (cm) | Diameter (mm) | HDR | Density (no/m2) |
| BRAP | Fall 2023 | 22 | 2.5 | 84.3 | 3.36 |
| BRAP | Spring 2024 | 28.4 | 3.1 | 88.9 | 2.99 |
| BRAP | Fall 2024 | 36.4 | 3.3 | 106.2 | 2.08 |
| Childs | Fall 2023 | 32.1 | 2.9 | 108.1 | 7.39 |
| Childs | Spring 2024 | 41.8 | 4.5 | 91 | 6.82 |
| Childs | Fall 2024 | 64.7 | 6.3 | 116.2 | 1.96 |

Table 2‑2. ANOVA results for BRAP size metrics across all three visits. \* Indicates P ≤ 0.05, \*\* indicates P ≤ 0.01, \*\*\*indicates P ≤ 0.001

|  |  |  |
| --- | --- | --- |
| Variable | Comparison | P-Value |
| Diameter | Fall 2023-Spring 2024 | ≤0.001 \*\*\* |
| Diameter | Spring 2024-Fall 2024 | 0.53 |
| Diameter | Fall 2023-Fall 2024 | ≤0.001 \*\*\* |
| Height | Fall 2023-Spring 2024 | 0.003 \*\* |
| Height | Spring 2024-Fall 2024 | ≤0.001 \*\*\* |
| Height | Fall 2023-Fall 2024 | ≤0.001 \*\*\* |
| HDR | Fall 2023-Spring 2024 | 0.165 |
| HDR | Spring 2024-Fall 2024 | ≤0.001 \*\*\* |
| HDR | Fall 2023-Fall 2024 | ≤0.001 \*\*\* |

Table 2‑3 ANOVA Childs results for size metrics across all three visits. \* Indicates P ≤ 0.05, \*\* indicates P ≤0.01, \*\*\*indicates P≤ 0.001

|  |  |  |
| --- | --- | --- |
| Variable | Comparison | P-Value |
| Diameter | Fall 2023-Spring 2024 | ≤0.001 \*\*\* |
| Diameter | Spring 2024-Fall 2024 | ≤0.001 \*\*\* |
| Diameter | Fall 2023-Fall 2024 | ≤0.001 \*\*\* |
| Height | Fall 2023-Spring 2024 | ≤0.001 \*\*\* |
| Height | Spring 2024-Fall 2024 | ≤0.001 \*\*\* |
| Height | Fall 2023-Fall 2024 | ≤0.001 \*\*\* |
| HDR | Fall 2023-Spring 2024 | ≤0.001 \*\*\* |
| HDR | Spring 2024-Fall 2024 | ≤0.001 \*\*\* |
| HDR | Fall 2023-Fall 2024 | 0.008 \*\* |

**Logistic regression model**

Table 2‑4 BRAP logistic regression model. \*\*\*indicates P ≤ 0.001

|  |  |
| --- | --- |
| Variable | P-Value |
| Light | ≤0.001 \*\*\* |
| Herbaceous | ≤0.001 \*\*\* |
| Fines | ≤0.001 \*\*\* |

\*\*Placeholder for model coefficients and other data\*\*

A logistic regression model indicated that light, herbaceous competition, and fine sediment were highly significant for seedling survival at BRAP (Table 2.4). Because all three variables were originally significant, the stepwise model did not have to remove any insignificant variables.

Table 2‑5 Childs logistic regression model. \* Indicates P ≤0.05, \*\* indicates P ≤ 0.01, \*\*\*indicates P ≤ 0.001

|  |  |
| --- | --- |
| Variable | P-Value |
| Herbaceous | 0.7778 |
| Light | ≤.001 \*\*\* |
| Fines | .0036 \*\* |

The Childs logistic regression model run indicated that light and fines sediment were significant variables in seedling survivorship but not herbaceous competition (Table 2.5). Once the stepwise model was run and the herbaceous variable removed, the p-value for fines decreased slightly.

**Age at Coring Height**

A graph with a line going up

AI-generated content may be incorrect.

Figure 2.4 Age at coring height. The bar graph is the number of trees dating back to each year while the line graph is the total cumulative number of cores over time. Curious which of these to include

A diagram of a graph

AI-generated content may be incorrect.

Figure 2.5 All riparian trees diameter vs age relationship. R2 value of 0.06 and a p-value of 0.003

Tree core analyses (n=133) were used to determine when trees regenerated. The age at coring height distribution is not normal (Shapiro-Wilk test of p<0.05) (Figure 2.5). The mean age of riparian trees at coring height was 25 years old. The most recent core was from 2016. In addition, when diameter at coring height and calculated pith year are compared there is a weak (r2=0.06) but significant (p-value= 0.003) relationship (Figure 2.5).

A graph with black dots

AI-generated content may be incorrect.

Figure 2.6. Age vs. size distribution of old-growth series.

Large legacy trees found outside of the active riparian corridor were cored to get a more complete understanding of Fremont cottonwood ages along the Verde River. The trees radii were much larger than our increment borer so the pith and curvature on the other side were not able to be reached. As a result, only the minimum ages for these trees could be calculated (Figure 2.6). The oldest of these trees dated back to 1910, making it a minimum of 115 years old. Other legacy trees are a minimum of 110 and 95 years old.

**Annual Growth**

The final correlated series (n=39) containing trees from all three sites 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) generally increased from 1995 to 2010 before stabilizing around 2010 (Figure 2.8). Ring Width Index (RWI) had a large spike in 2023 (Figure 2.7). Both BAI and RWI saw large increases in the year 2023.

A graph of a graph showing the growth of the year

AI-generated content may be incorrect.

Figure 2.7 Ring Width Index (RWI) by year for the crossdated series

A graph with lines and numbers

AI-generated content may be incorrect.

Figure 2.8 Basal area increment (BAI) by year for the correlated chronology.

**Response function analysis**

Five variables were found to be significant in determining annual tree growth through a response function analysis (Table 2.6). 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.

Table 2‑6 Significant results from the response function analysis. Shown results are significant at P ≤ 0.05.

|  |  |  |  |
| --- | --- | --- | --- |
| Chronology | Climate Variable | Significant Month | Correlation Values |
| Crossdated | Mean Monthly Flow | June | 0.435 |
| Crossdated | Mean Monthly Flow | July | 0.419 |
| Crossdated | Mean Monthly Flow | September | -0.251 |
| Crossdated | Mean Monthly Temp | October | 0.305 |
| Crossdated | Mean Monthly PDSI | June | 0.105 |

## **Discussion**

**Seedling survivorship and demographics**

Seedling plots were established in places where cottonwood seedlings survived their first growing season (spring-fall 2023) meaning that the results are specific to the characteristics of the plots selected, not the entire river. During the first growing season, seedlings at Childs were originally over twice as dense as seedlings at BRAP (Figure x.x). By the end of the second growing season, both sites had similar mean density. At Childs, seedlings were about twice as large as their counterparts at BRAP. As seedlings at Childs grew quicker, they also thinned themselves out and decreased their densities at a higher rate than those at BRAP.

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 and Fall 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 for sunlight. 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) studied Fremont cottonwood, Goodding willow and tamarisk regeneration on the Hassayampa and Santa Maria rivers following floods in 1993 and 1995. Final seedling densities at both BRAP and Childs were similar to densities on the Santa Maria River after two growing seasons. The smaller sizes found on the Verde River could 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 Hassayampa and Santa Maria 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.

**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. Light availability is impacted by both the geographic setting as well as the biological community. Plots located in constrained canyon reaches or under large canopy cover will have less light availability. Higher light availability led to higher seedling survival. Light availability was highly significant at both sites meaning that some combination of the geographic setting and/or the canopy cover can help predict seedling survivorship.

**Herbaceous Coverage**

Herbaceous competition was found to be a highly significant variable, enhancing survivorship 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 texture 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 conclusions 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 soil at our sites had very different amounts of fines. 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 increased, survivorship decreased. 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. Fine soil has a higher ability to hold water, allowing seedlings at Child to better survive the summer drought period.

**Dendrochronology**

**Minimum ages**

Most of the cottonwoods within the riparian zone are young. The mean age at coring height is about 25 years. Previous research on riparian forests found that cottonwood-willow forests in the Verde Valley recovered for most of the 1900s 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 between 412 and 439 acres following large floods in 1983 and 1993 (Lopez &Springer, 2002). This recovery in most of the 21st century could help explain why there are few cottonwoods in the riparian corridor 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 are cottonwood trees more than 25 years old, but they are mostly outside of the riparian area.

There is also a very weak but significant correlation (r2 = 0.06, p-value =.003. Figure 2.5) between the age and diameter of cottonwoods cored. A study on the Yampa River in Colorado also found a weak but significant trend between Fremont cottonwood age and growth (Andersen, 2015). With no strong trend between age and diameter, it means that other factors are influencing size. For example, competition for sunlight may be suppressing smaller trees. Cottonwoods are shade intolerant and because they tend to regenerate in short, distinct timeframes suppressed trees may be much smaller than dominant trees of the same age.

Even though Fremont cottonwoods cored within the riparian zone are young, that does not mean that older trees do not exist. Large, legacy cottonwoods exist along the Verde River (Figure 2.9). Older trees tend to be further from the active channel (Stromberg, 1993) and could be interspersed with young trees along other reaches of the Verde W&S River not sampled. Fremont cottonwoods are shorter lived species compared to other North American cottonwoods. Rood and Polzin (2003) states that the oldest Fremont cottonwoods in Arizona live to be around 110 years along the San Pedro River in southern Arizona. In contrast, Narrowleaf cottonwood (*P. angustafolia*) and Black cottonwood (*P. trichocarpa*) can reach ages of between 300-400 years in Alberta, Canada.

The old-growth Fremont cottonwoods cored for this study had minimum ages going back to 115-95 years. No curvature was found on the other side of the core and diameters were over 1.5m at coring height. In addition, we took cores higher on these older trees (over 1 meter above ground level), where gaps between the bark could be used to get the corer further into the tree. It is likely that some of these individuals’ approach or exceed the 110-year limit generally accepted for the Fremont cottonwoods in Arizona (Rood and Polzin, 2003). However, dating these trees proved difficult. The inability to reach the pith or curvature means that there is no way of knowing how exactly many rings are missing. In addition, large areas of rotten, undatable sections mean that even among older cores, the minimum age in some cases is significantly younger than the actual tree core.

A satellite view of a land

AI-generated content may be incorrect.

Figure 2.9 Location of old-growth grove near the confluence of the Verde River and West Clear Creek.

These large legacy trees are located far (>100m) from the active river channel. They also are growing multiple meters in elevation above the river channel. Finally, these trees were growing in a large grassland with no other woody plant competition. These trees are likely connected to the groundwater and can grow without competition or impact from floods, allowing them to reach their old age.

The lack of young trees was also influenced by the sampling design. Saplings must have an adequate size to not be severely damaged by the increment borer. The minimum diameter at coring height was about 5 cm. The study did not cut or age trees smaller than this diameter. Regeneration between seedlings and saplings was infrequent and destroying these intermediate trees was not done. This means that there are younger trees between those cored and the 2023 cohort measured in this study.

**Tree growth**

In a study in 2006 along the Oldman River in Canada, R. Willms et al. (2006) describes cottonwoods as following a general growth pattern, reaching their peak growth rate at about 20 years after their germination before entering the mature stage. This is the stage where cottonwoods are growing and adding biomass (BAI) at a constant rate. Cottonwoods along the Verde River seem to follow this trend (Figure 2.10). Basal area increased slowly during the establishment phase (for about 10 years), followed by a decade of rapid growth before leveling off and entering the mature growth stage (Figure 2.10). A key difference between the Canadian study and this study being the amount of growth. R. Willms et al. (2006) described basal area increment growth between 1-9 cm2 during the first 20 years of growth while the cottonwoods along the Verde are growing in the 10-30 cm2 within that same period. So, while Verde Cottonwoods growth follows a similar trend, they grow much more rapidly.

A comparison of a graph

Description automatically generated with medium confidenceA graph with numbers and lines

AI-generated content may be incorrect.

Figure 2.10 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).

This rapid growth is likely do to the more favorable climate found along the Verde River. Fremont cottonwoods along the Verde River have a much longer growing season with higher temperatures. In addition, winters are much milder than those in Alberta. These more favorable climate conditions allow Fremont cottonwoods on the Verde River to grow much quicker than other cottonwoods at higher latitudes.

**Response to climate**

Five variables were found to be significantly correlated with annual growth of Fremont cottonwoods. Mean June and July streamflow (positive), mean October temperature (positive), mean June PDSI (positive) and mean September streamflow (negative).

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 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.

The previous October’s temperatures (positive) are significantly correlated to annual growth. Higher October temperatures before senescence may help prolong the growing season for riparian trees which would allow them to increase their growth the following year. More positive PDSI values indicate overall wetter conditions. A positive response to June PDSI indicates that wetter June conditions positively impact tree growth. September streamflow was negatively correlated to annual tree growth, but this seems inconsistent with cottonwood ecology.

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 growth response is reflective of a snowmelt driven system. Rio Grande cottonwoods (*P. deltoides* subsp*. wislizeni*) along a regulated reach of the Rio Grande in New Mexico were most correlated to July-September streamflow which indicates a monsoon driven growth 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. The response function analysis indicates that the low flow period between the end of the snowmelt season and the beginning of the monsoon season is when riparian cottonwoods need water the most.

A graph of a number of years

AI-generated content may be incorrect.

**Establishment**

The Verde River and its floodplain are constantly transitioning between erosional and depositional patterns. Riparian tree root collars are often 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 coring height.

Riparian forests along the Verde recovered for most of the 20th century 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 a series of floods between 1993 and 2005.

A single, large flood can “set the stage” for cottonwoods to regenerate for many years. Stromberg (1997) found cottonwood regeneration occurred in successive years following the 1993 and 1995 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 suggests 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 2.4). 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. Regeneration following the 1993 flood is lower than regeneration following the 1995-2005 period, despite 1993 being a larger flood. Because only two growing seasons occurred between the 1993 and 1995 floods, most seedlings would have been too small to withstand another large flood. Stromberg (1997) also reported high mortality among the 1993 cohort from the 1995 flood along rivers in Central Arizona. Therefore, a limited number of seedlings from the 1993 cohort would have survived the 1995 flood.

However, the largest peak in ages between 1997 and 2003 is 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 spring floods as is the case with cottonwoods elsewhere. It appears that a flood magnitude with an AEP of ten percent or less is required to initiate meaningful Fremont cottonwood regeneration. Previous studies on a free-flowing river in Arizona found similar results (Stromberg et al., 1993). Following a 10-year flood on the Hassayampa River, Fremont cottonwood and Goodding willows regenerated into a new cohort while tamarisk had a much higher mortality and less regeneration than native species. 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 limited in number of years. This age limitation makes it difficult to produce high resolution 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, rings were wide, and ring series were variable. These factors make crossdating challenging but 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.

## **Conclusions and Implications**

Fremont cottonwood seedlings that established after the 2023 winter floods continue to grow and reduce in density. Light and percent fines are significant growth factors across both seedling plots as is 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 within the Verde River immediate riparian zone are relatively young and are about 25 years old. Despite their young age, Fremont cottonwood growth appears to have achieved a constant growth rate (what is that per year?). Their growth is driven by early-summer streamflow, in between the snowmelt and monsoon period. 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 set the stage for their regeneration. A flood magnitude of ten percent AEP or lower seems to be sufficient 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.

Works Cited

Alam, J. (1997). Irrigation in the Verde Valley. *A Report of the Irrigation Diversion Improvement Project. Verde Natural Resource Conservation District*.

Andersen, D. C. (2015). Tree Mortality in Mature Riparian Forest: Implications for Fremont Cottonwood Conservation in the American Southwest. *Western North American Naturalist*, *75*(2), 157–169. https://doi.org/10.3398/064.075.0204

Bhattacharjee, J., Taylor, J. P., Smith, L. M., & Spence, L. E. (2008). The Importance of Soil Characteristics in Determining Survival of First‐Year Cottonwood Seedlings in Altered Riparian Habitats. *Restoration Ecology*, *16*(4), 563–571. https://doi.org/10.1111/j.1526-100X.2007.00328.x

Blasch, K. W., Hoffmann, J. P., Graser, L. F., Bryson, J. R., & Flint, A. L. (2006). *Hydrogeology of the upper and middle Verde River watersheds, central Arizona*. U. S. Geological Survey.

Bradley D. Garner & Donald J. Bills. (2012). *Spatial and seasonal variability of base flow in the Verde Valley, central Arizona, 2007 and 2011* (Scientific Investigations Report) [Scientific Investigations Report].

Braun-Blanquet, J. (1964). *Pflanzensoziologie*. Springer Vienna. https://doi.org/10.1007/978-3-7091-8110-2

Bunn, A. G. (2010). Statistical and visual crossdating in R using the dplR library. *Dendrochronologia*, *28*(4), 251–258. https://doi.org/10.1016/j.dendro.2009.12.001

Cooper, D. J., Merritt, D. M., Andersen, D. C., & Chimner, R. A. (1999). Factors controlling the establishment of Fremont cottonwood seedlings on the upper Green River, USA. *Regulated Rivers: Research & Management: An International Journal Devoted to River Research and Management*, *15*(5), 419–440.

Dyson, M., Bergkamp, G., & Scanlon, J. (2003). Flow: The essentials of environmental flows. *IUCN, Gland, Switzerland and Cambridge, UK*, 20–87.

*Ecological Implications of Verde River Flows* (Hydrology of the Upper and Middle Verde, pp. 5–14). (2008). Arizona Water Institute, The Nature Conservancy, and Verde River Basin Partnership.

Fenner, B. P., & D. R. Patton. (1985). Effects of regulated water flows on regeneration of Fremont cottonwood. *Rangeland Ecology and Management*.

Ffolliott, P. F., DeBano, L. F., Baker Jr, M. B., Neary, D. G., & Brooks, K. N. (2004). Hydrology and impacts of disturbances on hydrologic function. *Riparian Areas of the Southwestern United States: Hydrology, Ecology, and Management; Baker, MB, Ffolliott, PF, DeBano, LF, Neary, DG, Eds*, 51.

Horton, J. L., Kolb, T. E., & Hart, S. C. (2001). PHYSIOLOGICAL RESPONSE TO GROUNDWATER DEPTH VARIES AMONG SPECIES AND WITH RIVER FLOW REGULATION. *Ecological Applications*, *11*(4), 1046–1059. https://doi.org/10.1890/1051-0761(2001)011[1046:PRTGDV]2.0.CO;2

Johnson, T. D., Kolb, T. E., & Medina, A. L. (2010). Do riparian plant community characteristics differ between Tamarix (L.) invaded and non-invaded sites on the upper Verde River, Arizona? *Biological Invasions*, *12*(8), 2487–2497. https://doi.org/10.1007/s10530-009-9658-2

Meko, D. M., Touchan, R., & Anchukaitis, K. J. (2011). Seascorr: A MATLAB program for identifying the seasonal climate signal in an annual tree-ring time series. *Computers & Geosciences*, *37*(9), 1234–1241. https://doi.org/10.1016/j.cageo.2011.01.013

Merritt, D. M., & Cooper, D. J. (2000). Riparian vegetation and channel change in response to river regulation: A comparative study of regulated and unregulated streams in the Green River Basin, USA. *Regulated Rivers: Research & Management*, *16*(6), 543–564. https://doi.org/10.1002/1099-1646(200011/12)16:6<543::AID-RRR590>3.0.CO;2-N

Moran, M. E., Aparecido, L. M. T., Koepke, D. F., Cooper, H. F., Doughty, C. E., Gehring, C. A., Throop, H. L., Whitham, T. G., Allan, G. J., & Hultine, K. R. (2023). Limits of thermal and hydrological tolerance in a foundation tree species ( *Populus fremontii* ) in the desert southwestern United States. *New Phytologist*, *240*(6), 2298–2311. https://doi.org/10.1111/nph.19247

R. Willms, C., W. Pearce, D., & B. Rood, S. (2006). Growth of riparian cottonwoods: A developmental pattern and the influence of geomorphic context. *Trees*, *20*(2), 210–218. https://doi.org/10.1007/s00468-005-0027-1

Rose, R., Ketchum, J. S., & Hanson, D. E. (1999). Three-Year Survival and Growth of Douglas-Fir Seedlings Under Various Vegetation-Free Regimes. *Forest Science*, *45*(1), 117–126. https://doi.org/10.1093/forestscience/45.1.117

Schook, D. M., Friedman, J. M., & Rathburn, S. L. (2016). Flow reconstructions in the Upper Missouri River Basin using riparian tree rings: Upper Missouri River Basin flow reconstructions. *Water Resources Research*, *52*(10), 8159–8173. https://doi.org/10.1002/2016WR018845

Schultz, R., Isenhart, T., Colletti, J., Simpkins, W., Udawatta, R., & Schultz, P. (2009). Riparian and upland buffer practices. *North American Agroforestry: An Integrated Science and Practice*, 163–218.

Shafroth, P. B., Stromberg, J. C., & Patten, D. T. (2002). RIPARIAN VEGETATION RESPONSE TO ALTERED DISTURBANCE AND STRESS REGIMES. *Ecological Applications*, *12*(1), 107–123. https://doi.org/10.1890/1051-0761(2002)012[0107:RVRTAD]2.0.CO;2

Sharon Masek Lopez & Abraham E. Springer. (2002). *Assessment of Human Influence on Riparian Change in the Verde Valley, Arizona*.

Stromberg, J. C. (1993). Fremont cottonwood-Goodding willow riparian forests: A review of their ecology, threats, and recovery potential. *Journal of the Arizona-Nevada Academy of Science*, 97–110.

Stromberg, J. C. (1997). Growth and survivorship of Fremont cottonwood, Goodding willow, and salt cedar seedlings after large floods in central Arizona. *The Great Basin Naturalist*, 198–208.

Stromberg, J. C., Ritcher, B. D., Patten, D. T., & Wolden, L. G. (1993). *Response of a Sonoran riparian forest to a 10-year return flood*.

USDA. (2012). *Yavapai County Profile* (Census of Agriculture). https://agcensus.library.cornell.edu/wp-content/uploads/2012-Arizona-cp04025.pdf

USFWS. (2012). *Designation of Critical Habitat for Southwestern Willow Flycatcher* (Endangered and Threatened Wildlife and Plants).

Varani, H., Margolis, E. Q., Muldavin, E. H., & Pockman, W. T. (2024). Patterns and drivers of cottonwood mortality in the middle Rio Grande, New Mexico, USA. *Ecohydrology*, *17*(8), e2692. https://doi.org/10.1002/eco.2692

Wirt, L., DeWitt, E., & Langenheim, V. E. (2005). *Geologic framework of aquifer units and ground-water flowpaths, Verde River headwaters, north-central Arizona*. US Geological Survey.

Zang, C., & Biondi, F. (2015). treeclim: An R package for the numerical calibration of proxy‐climate relationships. *Ecography*, *38*(4), 431–436. https://doi.org/10.1111/ecog.01335

Zhao, X., Du, D., Xiong, J., Springer, A., Masek Lopez, S. R., Winkler, B., & Hubler, K. (2019). The impact of forest restoration on agriculture in the Verde River watershed, Arizona, USA. *Forest Policy and Economics*, *109*, 101999. https://doi.org/10.1016/j.forpol.2019.101999