University of Nevada, Reno

Do Frémont cottonwoods differentially experience drought stress across a small, restored reach of the Lower Truckee River?

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in Hydrogeology

by

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We recommend that the thesis
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Do Frémont cottonwoods differentially experience drought stress across a small, restored reach of the Lower Truckee River?

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MASTER OF SCIENCE

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i. Abstract

River floodplains experience frequent flooding and deposition. Although flooding can be a disturbance to vegetation, it can also lead to nutrient-rich soils and abundant water making them hotspots for biodiversity and productivity. Consequently, floodplains provide ecosystem services by retaining the nutrients, sediment, and floodwaters brought on by flooding events. However, human activity can threaten floodplain conditions through river control structures, flow regulation, intensive use of land, and bank stabilization. Such threats have limited the establishment and vigor of Frémont cottonwoods, a pioneer tree species that often grows in riparian floodplains and are valued because they support biodiversity and stream stabilization.

This study focuses on the Frémont cottonwoods located at Mustang along the Lower Truckee River, east of Reno, NV, where restoration efforts (led by The Nature Conservancy) began in 2009, seeding in 2010, irrigation and restoration work continued through 2012 until irrigation was removed in 2014 according to Chris Sega (personal communication, 2023) . During the 2022 growing period, cottonwood stand structure, ecophysiological processes, and hydropedological conditions were studied across 25 plots in the restored floodplain in order to improve basic understanding of hydrological controls over cottonwoods, with implications for future restoration design. Our findings did not suggest that a) collocated Frémont cottonwoods of different life stage (mature trees and saplings) experienced water stress differently, and b) access to subsurface water availability was the main driver of variation among Frémont cottonwoods there; this likely reflects that all trees within the study maintained substantial connectivity to groundwater, regardless of tree age or position within the floodplain. Instead, a combination of factors

was associated with variations in tree-level and stand-level vigor such as floodplain position, and those variations were apparent across short distances of 10s-to-100s of meters. While evidence suggested that microsite differences in soil characteristics (bulk density, field capacity, gravel content, and soil moisture) may matter, especially with respect to controlling stand structure, there was no direct evidence of established trees exhibiting water stress over the study period.

This study contributes to the overall knowledge of micro-scale variation in floodplain tree physiology and provides a key step in measurements and record-keeping for this restoration site. A multi-year study would be beneficial in tracking the geomorphological changes following extreme restoration efforts and changing weather conditions.

ii. Dedication

To my parents, Martin & Hilda Leticia -- my partner, Yovvani --

and Peeta & Diamond.

iii. Acknowledgements

I would like to thank Dr. Scott Allen for the opportunity to begin this degree, and with great mentorship and encouragement over the past two years, the opportunity to complete it.

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1. Introduction

River floodplains experience frequent flooding and sediment-deposition events. These events can disturb vegetation but can also lead to nutrient-rich soils and water abundances, making floodplains hotspots for biodiversity and productivity (Junk et al., 1989; Rood, Braatne, et al., 2003; Tockner et al., 2000). Floodplains also provide ecosystem services by retaining the nutrients, sediment, and floodwaters brought on by flooding events, however, human activity (such as the straightening of rivers, flow regulation, intensive use of adjacent lands, and bank stabilization) can threaten floodplain conditions (Rood, Braatne, et al., 2003; Sankey et al., 2021). Such threats have limited the establishment and vigor of *Populus Frémontii,* commonly referred to as Frémont cottonwood. This cottonwood is a pioneer tree species, meaning they first establish in new habitats made from disturbances (Dalling, 2008), and are found in riparian zones throughout much of the arid west. They are capable of tolerating a wide range of climatic conditions and can be found in elevations as high as 2800 m (Taylor, 2000). Limitations on cottonwoods imply a limit on their value with respect to supporting biodiversity and providing stream stabilization (Rood, Braatne, et al., 2003; Schindler et al., 2016). As a result, several major restoration projects have been conducted to undo past river engineering projects and return areas to their natural floodplain conditions, such as the four tribal water projects in the Klamath Basin, OR & CA (State of California, 2022), and the Lower Truckee River restoration project in McCarran Ranch, NV (DeLong, 2014).

Frémont Cottonwood's tolerance of exceptionally arid conditions is facilitated by its deep rooting habit that allows it to tap into riparian groundwater storages; the plasticity of other traits in cottonwoods has also been observed and hypothesized to explain cottonwood's prevalence across diverse environments (e.g., between Sonora, MX and Arizona, USA; Sankey et al., 2021). Despite having favorable characteristics for resisting water stress, cottonwoods are still reported to experience water stress that manifests as reduced leaf area, mortality, and early senescence (Rood, Braatne, et al., 2003). Additionally, the dependency of cottonwoods on in-river flow patterns is well known, including how the rate of flow recession is critical in determining cottonwood establishment (Kranjcec et al., 1998; Rood et al., 1995; Rood, Gourley, et al., 2003; Segelquist et al., 1993). Of the most relevance to this thesis is Rood, Gourley, et al.'s (2003) study on Frémont cottonwoods along the Truckee River, which led them to propose a specified ideal rate of river recession that matches seedling root growth rates such they can maintain contact with the saturated zone. Specifically, they proposed that a recession rate of less than 2.5 $\frac{cm}{day}$ is ideal, a recession rate of 5 $\frac{cm}{day}$ would be stressful, and a recession rate of 10 $\frac{cm}{day}$ would be lethal (Rood, Gourley, et al., 2003); hypothetically, older trees may not be sensitive to these rates if they already have a live coarse-root system extending sufficiently deep, from which fine roots involved in water and nutrient uptake can grow.

Drought tolerance and plasticity to varying environmental conditions are crucial in places such as the Lower Truckee River in Nevada, where winters can be cold and annual precipitation is low. Because of the low annual precipitation inputs, vegetation depends on groundwater and water transported down the Truckee River as water supplies, which has a watershed that includes Lake Tahoe and high-elevation zones that receive meters of snow in typical years. Consequently, groundwater and the large watershed enable the floodplain of the Lower Truckee River to support much higher vegetation productivity and thus more habitat value than the water-limited surrounding hillsides. In past decades, however, the lower Truckee River floodplain degraded due to a variety of past management decisions (Rood, Braatne, et al., 2003; Sankey et al., 2021; Wagner & Lebo, 1996), creating a scenario where river stage was critically low relative to the floodplain, resulting in trees being unable to access groundwater throughout summer dry seasons. Consequently, until actions taken throughout the 1990s and 2000s, much of the floodplain lacked natural re-establishment and provided conditions that stressed the severely sparse relict trees (Rood, Gourley, et al., 2003); this latter observation suggests that even mature cottonwoods do not always maintain sufficient connection to groundwater to thrive. Substantial changes to Truckee River flow regimes, including increased summer-time flows, have continued since restoration efforts began about three decades ago, fostering improved floodplain vegetation health and recruitment of new Frémont cottonwoods (Rood, Gourley, et al., 2003). Growing conditions further improved along multiple reaches where large-scale restoration projects were implemented, which included lowering the floodplain and adding meanders (and locally sourced boulders) to reduce water velocities and promote flooding and deposition (DeLong, 2014).

Little research on environmental flows and floodplain restoration focuses on variations in tree physiology and hydrology within and across floodplains, so it remains unclear how microsites within these restored floodplains vary in their suitability for establishing and maintaining cottonwood forests. Considering that elevations, soil types, proximity to river, and vegetation densities can vary tremendously within a floodplain, it seems unreasonable to expect that the 2.5 $\frac{cm}{day}$ river recession rate (specified by Rood, Gourley, et al., 2003) would result in ideal growing conditions everywhere. In fact, visual observations of the Mustang restoration site (e.g., personal observations in Fall 2021) showed patchy clusters of trees, early senescence, signs of previous mortality, and atypically small leaves - possibly indicative of dry and low-productivity environments (Tozer et al., 2015); this evidence prompted questions about whether and why some zones within the restored floodplain are more suitable than others. While it is known that floodplain trees can experience drought stress despite their proximity to rivers (Allen et al., 2016), it was not visually apparent what drove the observed differences among growing conditions at the Mustang site, nor was it visually apparent what conditions led to the abundance of barren, treeless areas (covered by native grasses or invasive perennials and often showing no cottonwood seedlings or saplings).

Restoration decisions and existing fundamental knowledge on hydrological controls over cottonwoods could benefit from a study of spatial variations in ecophysiological and hydropedological conditions of cottonwood stands across a restored floodplain. Previous studies of cottonwood distributions have largely focused on stand structure data and demography without using ecophysiological measurements that can point to more specific or acute factors stressing plants. Also common of previous floodplain and environmental-flow studies has been a focus on temporal factors (e.g., river stage) without considering microsite-conditions or spatial variations within floodplains. A previous study conducted in a west-central Arizona desert riparian canyon did, however, focus on the spatial patterns of cottonwoods and concluded that they are influenced by drainage area, secondary channel presence, and aggradation and braiding (Asplund & Gooch, 1988). Although these distribution observations are relevant in natural environments, it would be challenging to implement such knowledge to inform restoration or predict vegetation dynamics in a recently restored site such as the Truckee River at Mustang Ranch, where the geomorphology was altered, and the multiple upstream dams influence river behavior. Still, the natural feedback between ecological, hydrological, and geomorphic processes are expected to proceed, even if the Mustang site history and flow regime are not natural. Thus, the areas where recruitment and establishment of cottonwoods occur are likely to become more geomorphically stable and support future habitat values, and so it is useful to understand what potential factors control the patchy and erratic patterns of recruitment and stress indicators that are present. Moreover, floodplain lowering and earthwork manipulations can create a unique experimental setting, introducing distinct heterogeneities (e.g., in elevation or sediment texture) that facilitate studies of comparative ecohydrology and ecophysiology in cottonwoods.

2. Objectives and Hypotheses

A network of monitoring plots was established to characterize fine-scale variations in (a) cottonwood tree growth, functional traits, and physiological status; (b) soil traits, moisture status, and hydraulic properties; and (c) groundwater (GW) levels and their covariation with river stage. Repeated minimally destructive measurements were used to minimize site disturbances and preserve the site's aesthetics. Additionally, as the site is a high-use public-access area, surveys using handheld equipment rather than deployed sensors were used when possible. The resulting data address the following two questions and hypotheses pertaining to spatial controls over cottonwood recruitment, stress, and persistence:

Question 1: Do collocated Frémont cottonwoods in differing life stages similarly experience water stress?

Null Hypothesis ($H1_0$): There is no difference in water stress amongst collocated Frémont cottonwoods.

Alternative Hypothesis ($H1_A$): Older cohorts of cottonwoods experience less water stress compared to younger cohorts because they have continuous access to groundwater where younger trees do not.

Alternative Hypothesis ($H1_B$): There are variable signs of water stress within plots, but they are unrelated to growth-stage.

To evaluate this hypothesis, mature cottonwood trees and saplings were compared with respect to various metrics of growth and physiological status, as well with respect to whether those metrics differently covaried with measures of hydrologic conditions for mature versus sapling trees.

Question 2: Does subsurface water availability control the functions and vigor of Frémont cottonwood trees and stands?

Null Hypothesis 2 ($H2_0$): Subsurface water availability has no control over Frémont cottonwoods.

Alternative Hypothesis ($H2_A$): A reduction in subsurface water availability will result in acute leaf-level stress responses in Frémont cottonwoods.

Alternative Hypothesis ($H2_B$): A reduction in subsurface water availability will result in tree-level stress responses in Frémont cottonwoods.

Alternative Hypothesis ($H2_C$): A reduction in subsurface water availability will result in stand-level stress responses in Frémont cottonwoods.

Alternative Hypothesis ($H2_D$): Variations in leaf-, tree-, and stand-level stress exist across the floodplain, but they are related to soil characteristics and competition rather than subsurface water availability.

To evaluate this hypothesis, multiple levels of vegetation health and water-status metrics were compared to metrics that directly reflect instantaneous and longer time-scale measures of water availability to those trees. Physiological variables were compared to groundwater levels that changed from early to late growing season and across plots differing in elevation above the river, distance from the river, soil water-holding capacity, soil moisture dynamics, and stand density. Metrics reflecting individual-tree health and stand structure were also compared across those same plots to evaluate the alternative hypotheses.

Overall, this study builds upon previous floodplain cottonwood studies, which have examined both specific ecophysiological responses (Harner & Stanford, 2003; Rood et al., 2010) and long-term temporal variations (Phelan, 2007). Understanding which specific features contribute to the recruitment and persistence of cottonwoods could be especially useful for guiding future restoration decisions. In addition to their application in testing these hypotheses, the collected data establish baseline vegetation and soil information for the site that can support future comparisons to quantify short and long time-scale changes.

3. Study Site Background

The study site is twelve miles east of Reno, along the Tahoe-Pyramid Trail by Mustang Rd, south of Interstate 80 and the Union Pacific Railroad (Figure 1). This Bureau of Land Management (BLM) property is used for diverse recreational activities including hiking, biking, fishing, and camping.

Figure 1. The study site is located along the Truckee River, 17 km East of Reno, NV (Google Earth Pro, version 7.3.6.9345).

Degradation of the Truckee River floodplain was due to a flood control project, based on the Flood Control Act of 1954, completed in the 1960s (G. A. Horton, 1997). By the 1970s, 90% of the forest canopy was lost along the river, 40% of the bird species were lost, and the Cui-ui fish (*Chasmistes cujus*) was no longer found in the river (U.S. Department of the Interior, 2011). The Pyramid Lake Paiute Tribe was able to secure environmental flows through the Truckee River Operating Agreement (2008) which enabled restoration efforts on the river (Department of the Interior & Bureau of Reclamation, 2008). At Mustang, an agreement was made in 2008 between The Nature Conservancy (TNC) and the BLM to restore this section of the Truckee River. Between 2008 and 2011, meanders were added to the river, floodplain surfaces were lowered, engineered riffles were installed to raise bed elevations, and native vegetation was planted. These changes reduced overbank flood intervals to about 2300-2500 cubic feet per second

(C. Sega, personal communication 2023). There has also been ongoing monitoring of birds, fish, and vegetation (U.S. Department of the Interior, 2011). Changes to the floodplain can be seen through a series of Google satellite images (Figure 2).

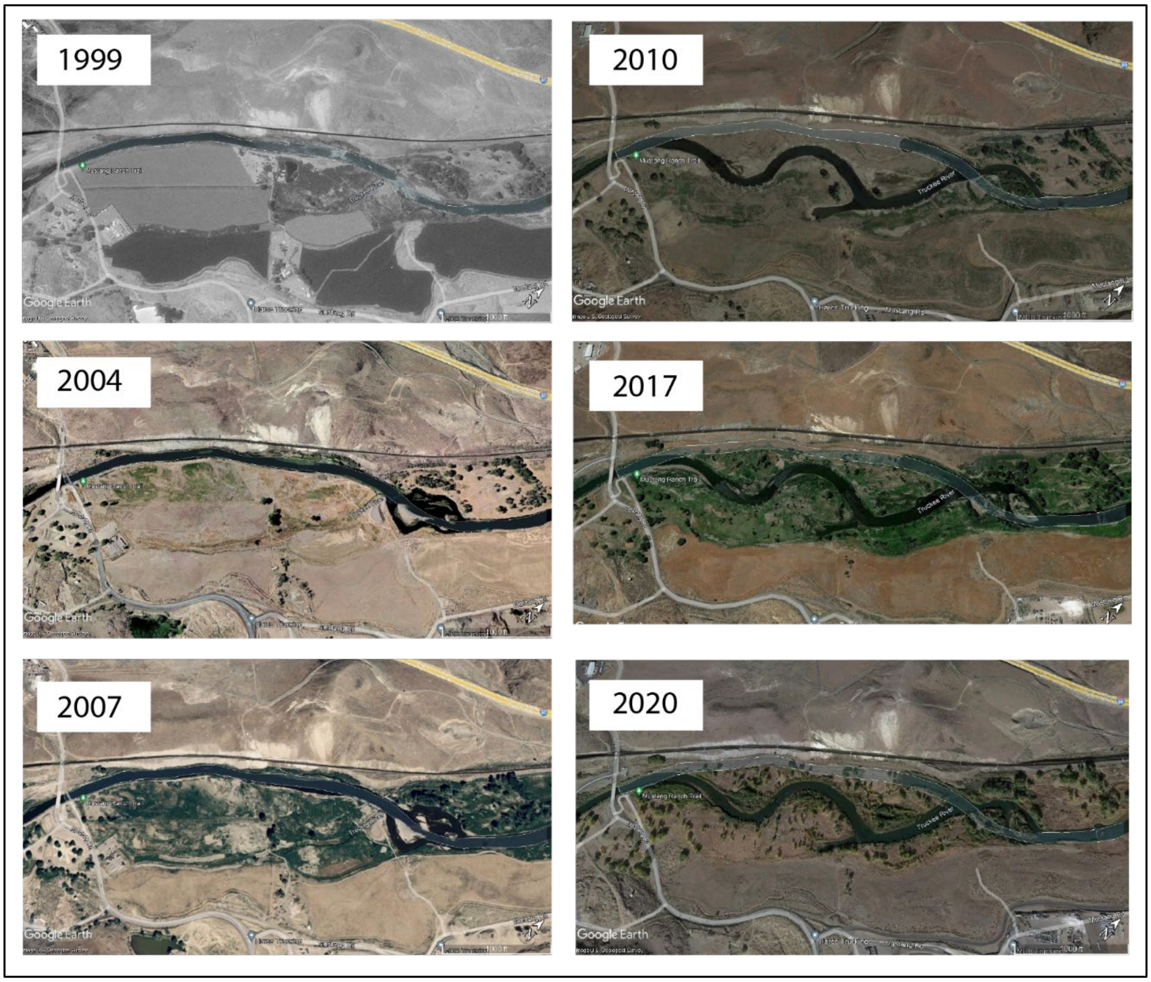

Figure 2. Satellite images of the Mustang site, for 1999, 2004, 2007, 2010, 2017, and 2020. The 1999 path of the Truckee River is highlighted throughout all the images to capture the change in river position.

The elevation within the research site varies by roughly 3m with elevations between 1317 m and 1320 m above sea level (ASL). The soils in this alluvial deposit (Stewart & Carlson, 1978) mainly consist of Carwalker Sandy Loam and Truckee Sandy Loam, with gravelly substrata (Soil Survey Staff, 2021).

Annual peak stage can vary tremendously, with very high flows in 2017 (3.8 m stage and 362 $\frac{m^3}{s}$) compared to that of 2021 (1.6 m stage and 22 $\frac{m^3}{s}$) (NOAA & NWS, Accessed 2021); from low to high stages across this range, the river grows in width from ~10-30 m at low-stages to >150 m in this reach at Mustang, NV. No such expansions were seen in the 2022 field season, when the site experienced severe drought conditions as categorized by the U.S. Drought Monitor throughout the 2022 growing season (NOAA & NIDIS, Accessed 2021). The site experiences a cold, semi-arid climate, with cold winters and hot summers (Weatherbase, Accessed 2021). The typical mean temperature of the coldest month is 2°C and the typical mean temperature of the warmest month is 20°C. The average precipitation is 211$\frac{mm}{yr}$, and during the four-month snow period (Nov-Mar), the average snowfall is 70mm (U.S. Climate Data, accessed 2021; Weather Spark, Accessed 2022). The climate is primarily influenced by the Sierra Nevada mountain range to the west and its rain shadow effect.

Two different age cohorts of cottonwoods can be identified in this study area, aside from the scattered large cottonwoods that long predate any restoration efforts and were preserved by the floodplain lowering. More common are the younger mature cottonwood trees that were planted as part of the restoration efforts and the saplings (< 10 years) that have naturally established since restoration; these two groups are the focus of this study. Establishment was notably observed after the 2017 water year when above average precipitation levels were experienced (California Department of Water Resources, 2017). Apart from Frémont cottonwoods, other plant species present in this area include willows (*Salix* spp.), sagebrush (*Artemisia tridentata*) and various non-native plants including

Russian thistle (*Salsola*), tall whitetop (*Lepidium latifolium*), cheatgrass (*Bromus tectorum*), and wild teasel (*Dipsacus fullonum*).

4. Methods

This research took place between 2021 and 2023, and used data collected during the 2022 growing season of Frémont cottonwoods (spring, summer, fall). Five sites, labelled as Site A-E in Figure 3 were chosen within the study location to capture the spatial variations in site properties such as elevation and distance from river.

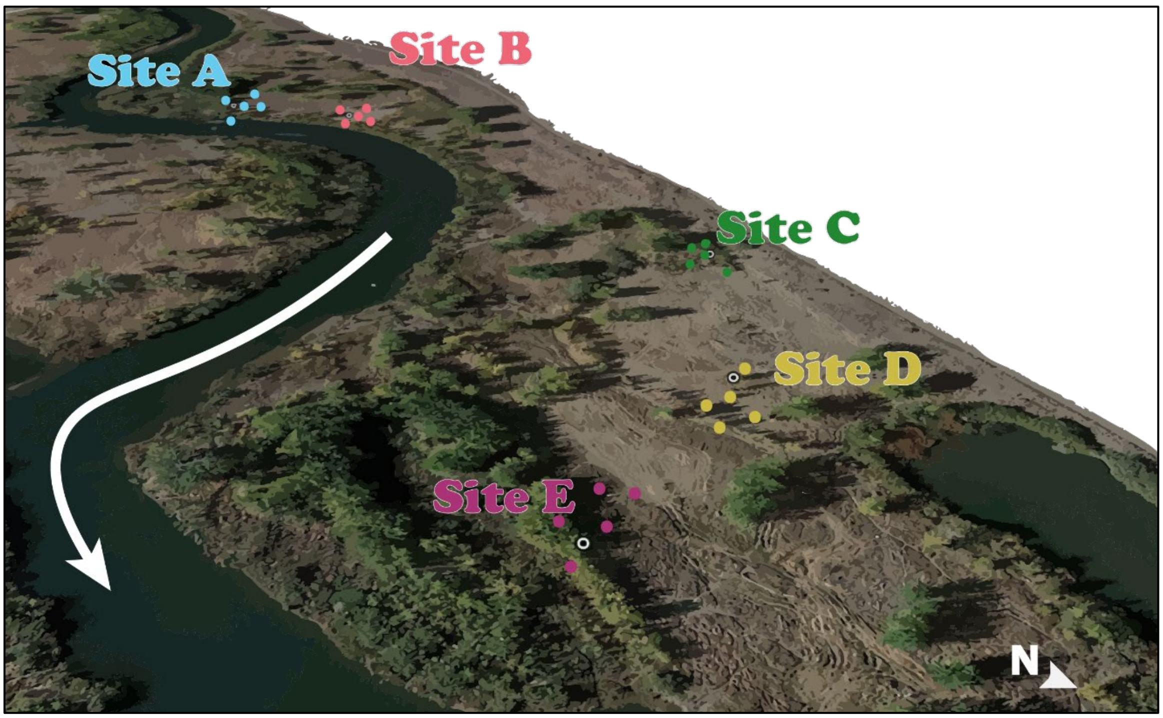

Figure 3. Distribution of sites and plot locations (dots). The position of the plots is not to scale (Google Earth Pro, version 7.3.6.9345).

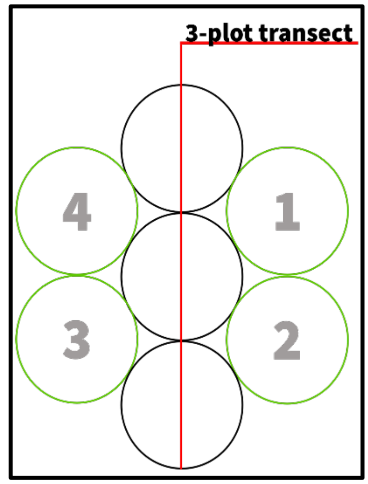

Figure 4. A 3-plot transect was decided for each site, the remaining 2 plots were randomly selected from the four labelled

Within each site, five circular plots were selected using a systematic and random approach, designed to define gradients across random variations (Figure 4). Sites A and B are perpendicular to the Truckee River, the remaining sites were selected based on the difference in visual observations in cottonwood stand appearance. For sites A and B, the three-plot transect is perpendicular to the river (Figure 3), the remaining two plots were selected randomly from four possible outcomes using a random number generator (Figure 4). At sites C and D (further distance from the river), the three-plot transects and the remaining two plots were selected randomly. This layout allowed for comparisons between sites, within sites, and in terms of distance from the Truckee River.

Within plots, specific study trees were selected, aiming for three from the older cohort (mature) and three from the younger cohort (sapling) cottonwoods per plot, where possible. This was not always possible because two plots did not have cottonwoods (in Site A and Site D), and several did not have both mature and sapling individuals. A total of 113 trees were selected and tagged to be used for repeated measurements. Table 1 shows the distribution of study trees per site. Table 2 summarizes the field visits and measurements conducted at the site. For this study, cottonwoods below two meters were considered saplings, and bark characteristics were used to label a cottonwood as either mature (coarse) or a sapling (smooth). The difference between mature and sapling cottonwoods can be seen in Figure 5.

Table 1. Distribution of study trees per site and by maturity.

Study Site	Total # of Trees	Mature	Sapling
A	21	12	9
B	22	12	10
C	30	15	15
D	18	12	6
E	22	7	15
Total	113	58	55

Table 2. Summary of field visits and measurements.

Frequency	Measurement	Amount
Continuous	Groundwater wells	5 wells
Monthly	Soil water content measurements	Up to 3 locations per plot (surface) and typically 1 per plot (at ~30 cm)
	Leaf conductance / Chlorophyll	6 trees per plot, 1 leaf per tree,
Once per growing season	Leaf Phenology: green-up timing and senescence timing	3 leaves per tree, up to 6 per plot
	Soil field characterization and sampling for in-lab characterization	1 surface and 1 ~30 cm sample per plot
	Leaf trait sampling: specific leaf area	5 leaves per tree
	Canopy Leaf Area, Basal Area, and Density survey	1 survey per plot
Twice per growing season	Stable-isotope based water-uptake-depth characterization: twig, leaf, soil, GW, surface water sampling*	1 sample per tree/GW well, 3 soil sample per plot, 1 surface water sample
	Leaf water potential (predawn)	1 leaf per tree

*Samples were collected but associated data are not included in this thesis due to unforeseen bottlenecks in sample processing.

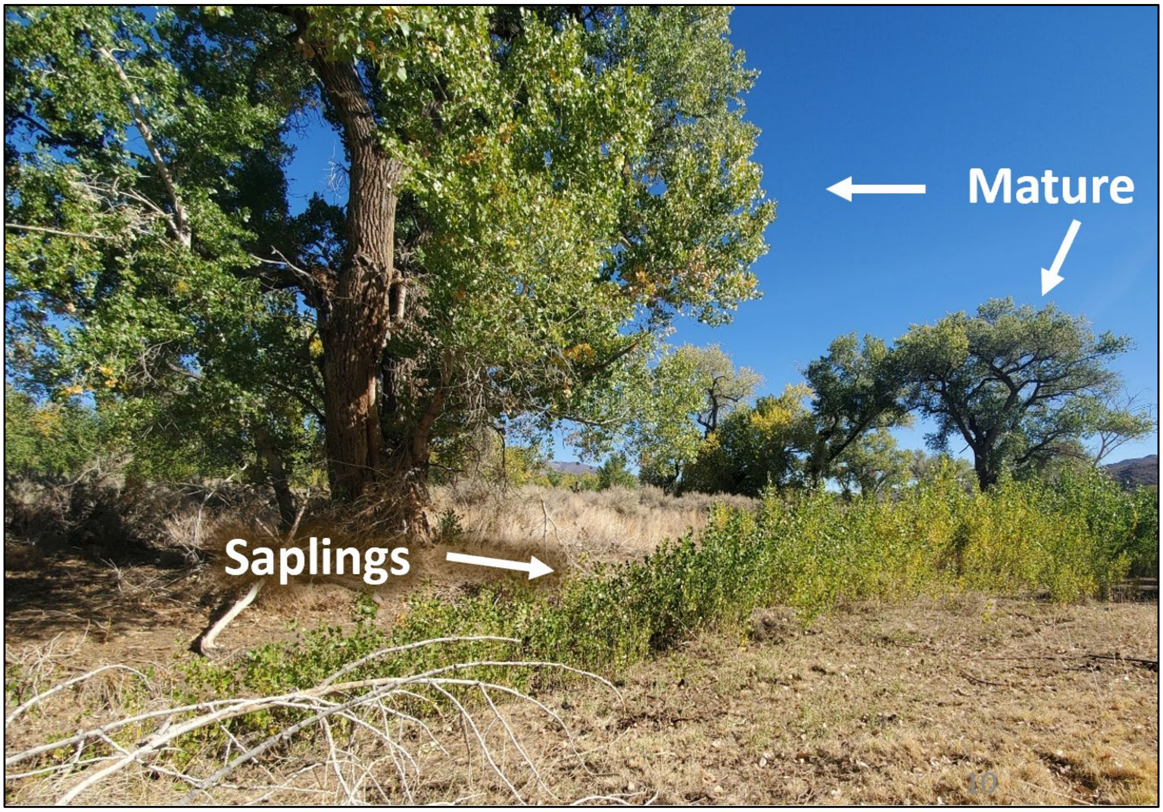

Figure 5. Example of mature and sapling cottonwoods; many of the mature trees included in the study were intermediate to those shown here (with respect to diameter).

4.1. Measurements of Dependent Data: Responses of Trees to Hydrologic Conditions and Floodplain position

4.1.1. Leaf Phenology

Tree-specific growing season lengths were quantified by repeated measures of leaf phenological variations in the plots' intensive-study trees and saplings. To characterize green-up timing, the maximum widths of three randomly selected leaves from each tree were measured bi-weekly over the month following the initial budburst. Leaf widths from the beginning of the growing period were compared to peak-growing-season leaf widths to estimate the time when 50% of maximum leaf width was reached, as a means of quantifying the green-up period timing. To quantitatively characterize the relative timing of senescence, chlorophyll concentrations were recorded weekly using an Opti-Sciences

CCM-300 after senescence began (also on three leaves per study tree); these values were interpreted as a ratio relative to the maximum values observed in mid- or early-growing seasons. Growing season length was calculated as the duration between the estimated time between 50%-leaf out and 50%-senescence. Leaf size measurements were taken for the green-up timing on April 17, April 22, May 27, and June 14. Chlorophyll measurements to measure senescence were taken on September 24, October 10, October 23, November 5, and November 20. The timing of senescence is an indicator of water stress, and the growing period length can also be used as a health metric assuming a longer growing period indicates better tree health.

4.1.2. Chlorophyll Content (monthly, more often through fall senescence)

Chlorophyll content measurements from three leaves per study tree were taken using a CCM-300 Chlorophyll Content Meter (Opti-Sciences Inc., Hudson, NH). In addition to the previously described chlorophyll measurements being used to quantify the timing of leaf senescence, they were used for intercomparison of photosynthetic potential among trees and plots (Pavlovic et al., 2015) since a reduction in photosynthesis can be a short-term response to water stress (Rood et al., 2003). In addition to the dates to quantify senescence, measurements were taken on June 1, June 25, and August 10.

4.1.3. Leaf Stomatal Conductance (Monthly)

Monthly measurements of leaf conductance using an SC-1 Leaf Porometer (METER Group, Inc., Pullman, WA) were taken from one sun-lit leaf per study tree to quantify variations in water use by trees; notes were taken if a shade leaf must be used because sun-lit leaves are inaccessible. Readings from the SC-1 Leaf Porometer include measurement time, stomatal conductance, relative humidity, and temperature. To reduce environmental influences on leaf conductance readings such as light, temperature, and relative humidity, measurements were taken at the same time each month and during similar weather conditions, so that large changes in stomatal conductance could be used to infer water stress. Stomatal conductance is also used as a leaf productivity metric and measure of photosynthetic activity.

4.1.4. Leaf Water Potentials (twice, mid-, and late- growing season)

To determine the source of water for the cottonwoods, predawn water potentials were measured using a SAPS II Plant Water Status Console (Soil Moisture Equipment, Inc.). Values close to zero indicate access to water whereas more negative water potentials indicate water stress within plants. From our study trees, one leaf from all mature cottonwoods, and only some of the saplings, were sampled at the peak of the growing season, June 22, and the end of the growing season, September 29. Predawn measurements were taken between 3 AM and 6 AM, to maximize the assumed duration since transpiration such that plant water potentials equilibrate with the water potentials of soils to which they are connected. Growing evidence that some conditions allow night-time transpiration (Donovan et al., 2001) could invalidate this assumption, but near-zero values indicating low tension within the plant to pull water from the roots would likely suggest use of groundwater regardless.

4.1.5. Leaf trait characterizations

Leaf traits were characterized from leaves sampled on July 14 (peak-growing season). They were analyzed in the lab for specific leaf area (SLA) (Equation 1), an indicator of water stress or predictors of drought-related mortality (Greenwood et al., 2017; Hoffmann et al., 2005), where a lower SLA is seen in water-conservative plants leading to smaller yet thicker leaves. Approximately five leaves from each study tree were collected and immediately placed in a Ziploc bag and into a cooler with ice to suppress metabolic activity within the leaves. Upon arrival at the lab, the leaves were placed into a freezer until processing.

$$\text{SLA} = \frac{\text{leaf area } (cm^2)}{\text{leaf mass}_{\text{dry}}(\text{g})}$$

Equation 1. Formula used to calculate SLA (Lambers et al., 2008).

The software *ImageJ* was used to calculate the leaf area using leaf images scanned on an Epson flatbed scanner (Schneider et al., 2012). In addition to being used to calculate the SLA, this leaf area was assumed to be the peak leaf area that is compared with the leaf growth rates. Similarly, smaller leaf areas are a response to water stress (Rood et al., 2003). The leaves were then dried in an oven at 50°C for approximately 48 hours then weighed to get the dry mass.

4.1.6. Stand Health Surveys (Once, peak growing season)

To characterize the density and health of the cottonwood stands, a multi-metric vegetation survey was conducted on August 24, 2022. Study trees were characterized by a) crown-condition classification (dominant, codominant, intermediate, and suppressed) to characterize tree-class diversity (Figure 6) ; b) foliage transparency (scale between 5 (least transparent) and 95 (most transparent), as another indicator of health where a lower transparency rating would suggest better health (Figure 7; Figure 8); c) a visual qualitative assessment of vigor (poor, moderate, great) (Figure 9); and d) diameter at breast height (Schomaker et al., 2007). Additionally, the number of cottonwood trees, mature and juvenile, were counted within one meter of each study tree (effectively composing 113 3.14-m^2 subplots) to characterize tree density and establishment rates. Another measure of stand density, plot-level basal area, was estimated using an angle gauge (Jim-Gem Cruz-All tool; Forestry Suppliers, Inc.) and variable-radius plots, serving as both an inventory of biomass and a measure of competition (Opie, 1968). Leaf area index (LAI), the area of leaf surfaces per area of ground (m^2 per m^2), was also measured to indicate both foliar biomass (an estimator of productivity) and competition (Binkley et al., 2003; Parker, 2020). The LAI values were collected at each plot center and above each sapling using a canopy analyzer (LAI-2200, LI-Cor Inc., Lincoln, NE). The sampling occurred on September 29 in the afternoon, using corrections for heterogeneous sky conditions.

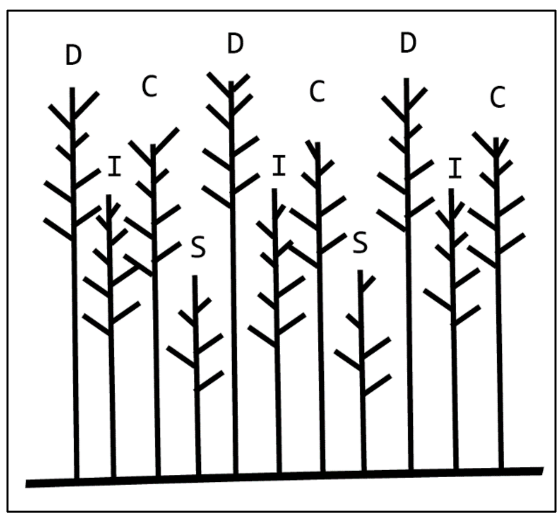

Figure 6. Illustration showing different crown classes, where D=dominant, C=codominant, I=intermediate, S=suppressed. As such, crown class should be seen as a potential limiting factor when examining individual-tree values and should be seen as an indicator of structural diversity when interpreted at the stand scale.

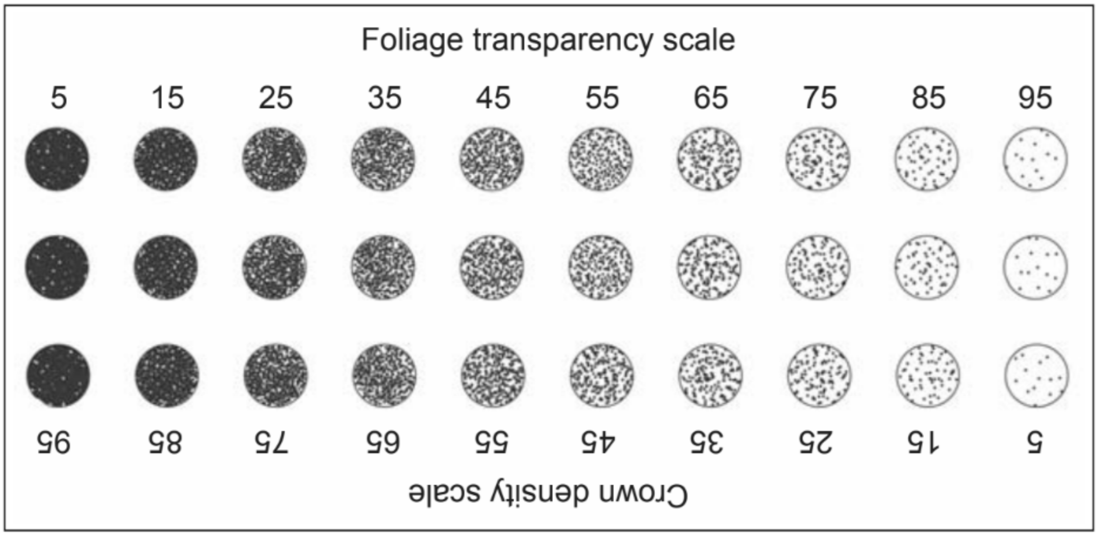

Figure 7. USDA scale to classify foliage transparency (%) (Schomaker et al., 2007).

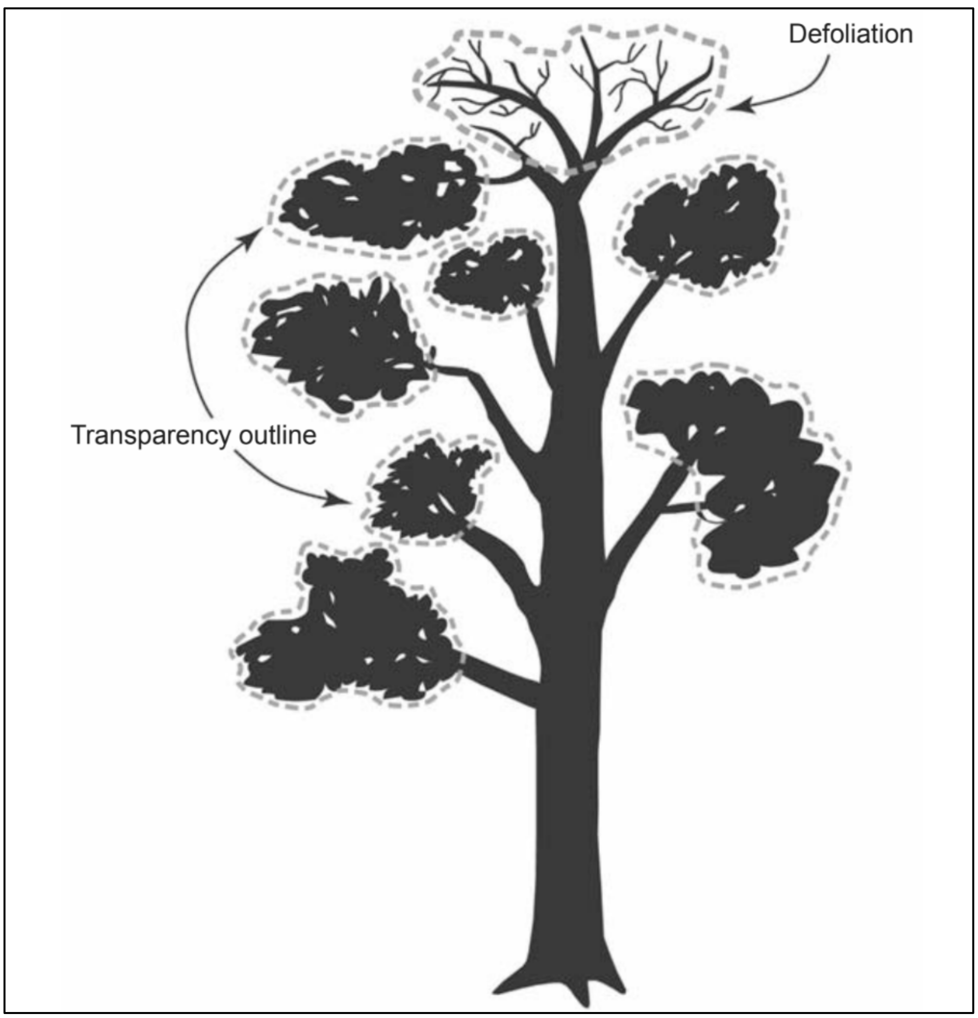

Figure 8. An illustration by the USDA on how foliage transparency is determined by averaging the transparency from each foliage clump (Schomaker et al., 2007).

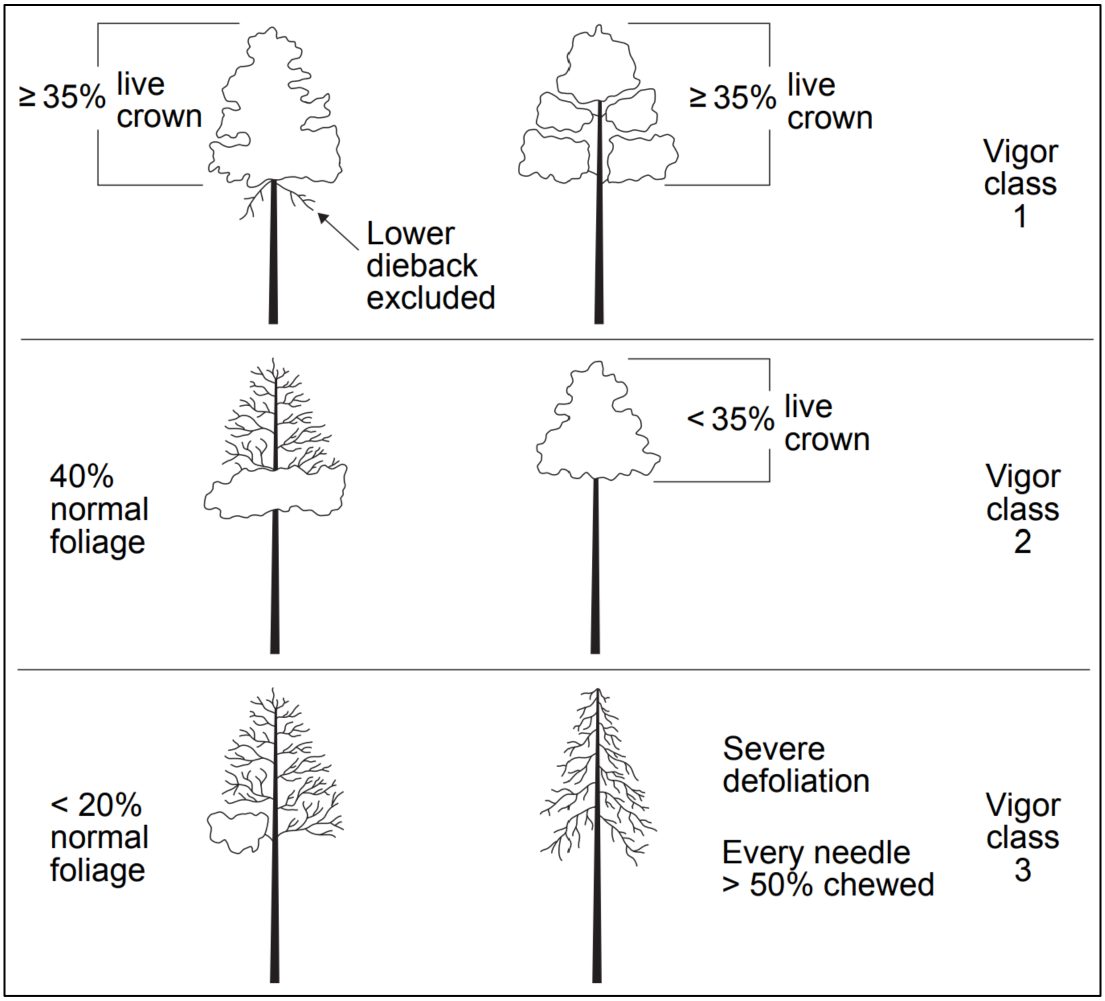

Figure 9. An illustration by the USDA to determine the vigor of saplings (Schomaker et al., 2007).

4.2. Measurements of Independent Data: Hydrologic Conditions and Floodplain Position

4.2.1. Shallow Groundwater Wells

Before the growing season, five shallow groundwater wells were installed near the centers of each site to monitor groundwater elevations across the floodplain. The wells consist of a perforated 7.6-cm-diameter PVC pipe covered by layers of nylon mesh placed at a minimum of 120 cm below the ground surface, stopping at the limits of what was practical using handheld equipment. Table 3 provides the well length, depth below the surface, and distance from the Truckee River.

Table 3. Description of wells established at each site.

	Length of PVC pipe (m)	Length below the surface (m)	Distance to the Truckee R. (m)
Well A	2.12	1.20	22.5
Well B	2.08	1.27	22.5
Well C	3.13	1.81	100
Well D	2.04	1.12	50
Well E	3.16	1.99	45

Onset HOBO Water Level Data Loggers were installed on April 22, 2023, and continue to provide continuous groundwater level data at a one-hour interval. The loggers were suspended from the top of the well using a 2 mm steel cable so that their elevation would not change if sediments accumulated in the bottom of the well.

The pressure data collected by the level loggers were adjusted for barometric pressure using data from the National Oceanic and Atmospheric Administration (NOAA) weather station, EW6551, located less than 20 km from the study site, near Rancho San Rafael Park in Reno, NV. Equation 2 was used to determine the average pressure at both the weather station and groundwater wells using their elevation above sea level (NOAA, n.d.; Google Earth Pro, version 7.3.6.9345). The difference between these pressures was then used to transform the station pressures to be relative to sea level and then projected to the elevation of the groundwater wells. This then allowed for the well data to be transformed into groundwater stage and depth to groundwater from the surface using this equation:

$p = 101325(1 - 2.25577 * 10^{-5} * h)^{5.25588}$, where p is the air pressure (Pa), h is the height above sea level (m), and 101325 is the pressure (Pa) at *normal* temperature and pressure, representing sea-level conditions.

Equation 2. Solving for pressure at a certain height above sea level (Engineering Toolbox, 2003).

4.2.2. Shallow soil water content

Shallow soil water content was sampled both at the surface and at a depth of 30 cm in three different locations per plot to get a representative sample of the site. A shovel or manual auger was used to dig to 30cm, and an ML3-ThetaProbe connected to a HH2 Moisture Meter (Dynamax Inc., Houston, TX) was used to measure the volumetric soil water content. Soil moisture measurements were taken on April 23, May 6, May 27, June 4, September 25, and October 6 of 2022. By measuring soil water content, the sensitivity of stomatal conductance to soil water content can be assessed, which may reveal whether plant-water status is dependent or independent of soil moisture conditions

4.2.3. Soil Characterizations

Soil cores from each plot were taken for in-lab measurements including bulk density (Equation 3), field capacity (FC) (Equation 4), and gravel content (Equation 5). The bags were weighed prior to sampling. On July 15 soil cores were extracted from 0-10 cm depth and from 25-35 cm depth. The volume of each soil core was 98 ± 5% mL. The soil sampled was weighed after sampling and after being dried at 50°C for 5 days until no moisture was detected, this mass was used as the dry mass.

$$\text{Bulk Density} = \frac{\text{mass}_{\text{dry}}\ (\text{g})}{\text{volume}\ (\text{cm}^3)}$$

Equation 3. Equation used to calculate bulk density (g/cm^3).

$$\text{Field Capacity}\ (\%) = \left(\frac{\text{mass}_{\text{2 days later}}(\text{g}) - \text{mass}_{\text{dry}}(\text{g})}{\text{mass}_{\text{dry}}(\text{g})} \times \frac{\text{Bulk Density}\ (\frac{\text{g}}{\text{cm}^3})}{\text{Water density}\ (\frac{\text{g}}{\text{cm}^3})} \right) * 100\%$$

Equation 4. Equation used to calculate field capacity (FC) (%) by volume of soil sample.

$$\text{Gravel Content (\%)} = \left(1 - \frac{\text{mass}_{\text{after sieving}}\ (\text{g})}{\text{mass}_{\text{dry}}\ (\text{g})}\right) * 100\%$$

Equation 5. Equation used to calculate the gravel content (%) of the soil.

To calculate the field capacity (Equation 4), each soil sample was placed in a tin container with punctures at the bottom that allowed for drainage. A 125mm Whatman filter paper was used to prevent soil loss while still allowing the water to drain freely. The soil was left to completely saturate for 24 hours, covered, then weighed. After two days of draining, the sample was weighed a final time to calculate the field capacity. The difference in mass from the dry soil and soil that had been sieved at 2mm was used to calculate the gravel content of each soil sample (Equation 5).

The overall soil texture was not assessed because we assumed that variations in gravel content would be the key factor determining variations among plots, and, moreover, characteristics affected by fractions of clays and sands would be captured in more relevant metrics through the field capacity measurements. This data will be used to determine overall soil health and water retaining properties, and will be studied in conjunction with tree health parameters and groundwater.

4.2.4. Floodplain Position

Distances to the river were estimated for each plot center using Google Earth, but field measurements were used for sites A and B since they are perpendicular to the river. Elevations of plot centers and wells above the river water table (on September 8, 2022) were measured using standard surveying techniques with a TOPCON auto level, AT-B Series. These data allowed for the height of groundwater in each well to be compared to river stage.

4.2.5. Retrieved Historical Data

Stage data for the Truckee River were retrieved from the USGS 10350000 gage at Vista, approximately 9.5km upstream from the study site, ranging from the duration of the study period and years prior to the study period (2001 to 2022) (USGS, n.d.). This data was used to study the relationship between river stage and the groundwater well data, and in conjunction with the survey data collected on September 8. Regional weather data were retrieved from NOAA databases (from a station in Reno, NV (EW6551)) (NOAA et al., n.d.).

The recession rates of the Truckee River were calculated using stage data from the USGS gage at Vista between the water years 2000 and 2022 (USGS, 2023). To perform data analysis, the dates were categorized as weeks, and the wells with weeks of missing data (due to instrument error) served as the divide between early and late growing season. For the recession rate analysis, the weeks with missing data were removed from the dataset for all wells.

Historical snow water equivalent data were collected from the California Data Exchange Center, CDEC, between 2008 and 2022 on March 1st of each year (CDEC, 2023). Data collected included the average of reporting stations, average snow water equivalent (SWE), and percent of normal for the date. Data were collected for the Central Sierra (Figure 10) to also consider the SWE fluctuation over the years (CDEC, 2023). March 1st was chosen arbitrarily as a day before or at the beginning of the growing season.

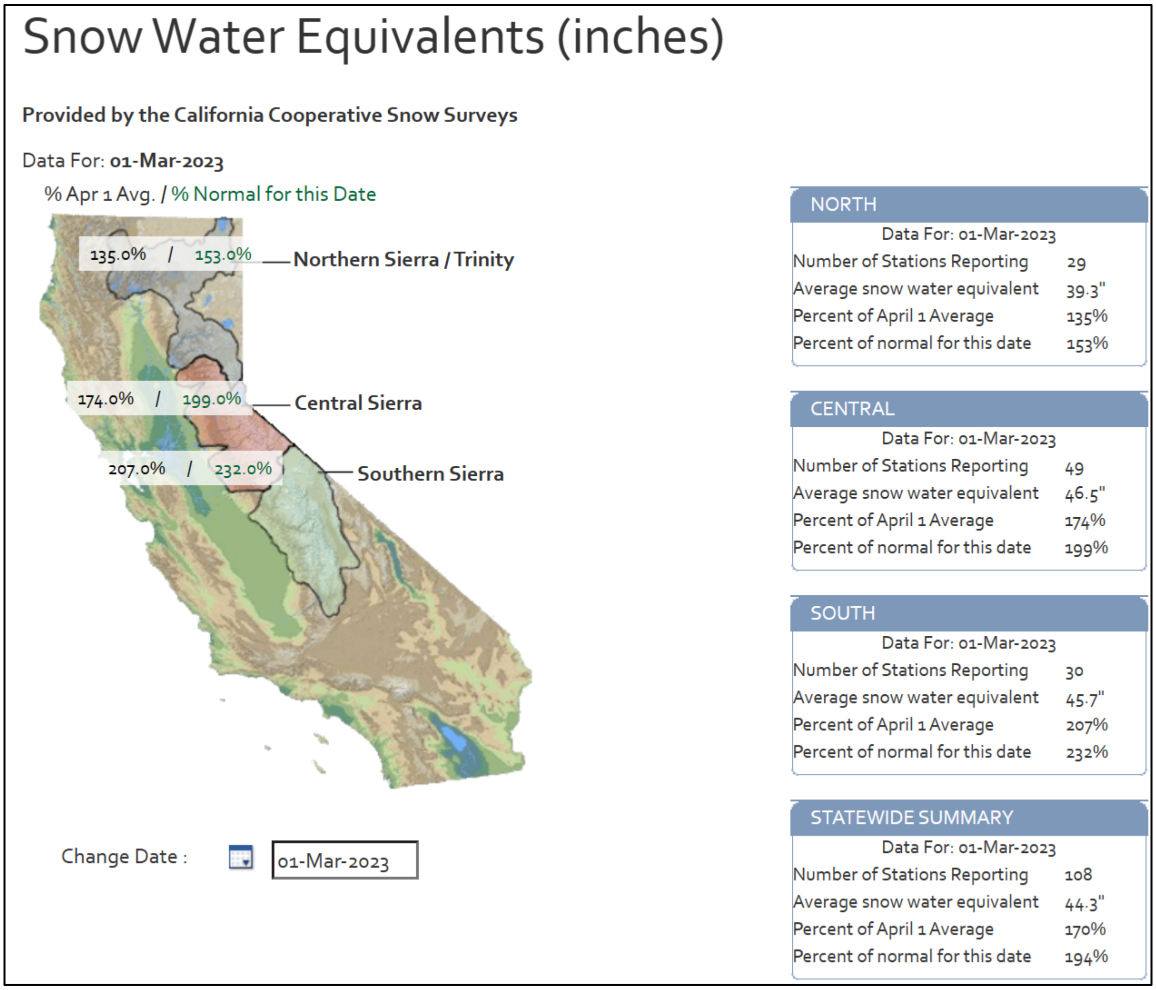

Figure 10. Data retrieving tool provided by the California Cooperative Snow Surveys. Data used in this study is from the Central Sierra. This figure shows data for March 1st, 2023 (not used in this thesis) (CDEC, 2023).

4.3 Analysis and Statistics

Statistical analyses and processes were conducted in Microsoft Excel (Version 2303, Microsoft Corp., Redmond, WA) and RStudio (Posit Team, 2023). Due to the hierarchical nature of the data (i.e., representing data measured and analyzed at leaf-levels, tree-levels, plot-levels, and site-levels scales), diverse inferential statistics are used throughout and reported throughout the Results and Discussion sections. Where an R^2 value is reported, it is the adjusted R^2 value, effectively penalizing for overfitting by accounting for the number of independent variables used in the model for predicting the target variable (Bhandari, 2020).

5. Results and Discussion

5.1. Observations of Dependent Variables

Select parameters were used to create Table 4, a reference for brief site descriptions.

Table 4. Brief site description.

Site	Image	Avg. Distance from the Truckee River (m)	Avg. Elevation above the Truckee River (m)	Avg. Gravel Content (%)	Avg. Basal Area (m^2/ha)	Avg. Soil Moisture (%)
A	 March ‘22	22.5	0.96	4.2	2.5	20.4
B	 March ‘22	22.5	1.25	44.3	2.3	7.8
C	 October ‘21	100	1.47	30.3	3.7	9.3

D	 May '22	50	0.71	26.6	3.4	9.6
E	 October '21	45	1.02	3.6	9.0	17.6

5.1.1. Leaf Growth Rate

Variation in leaf growth rates, calculated using leaf length measurements collected during the early growing season, were analyzed at site and plot levels (Figure 11, Figure 12). The mature cottonwoods in Site C had the highest average overall rate of 0.16 $\frac{cm}{day}$ (SE = 0.01 $\frac{cm}{day}$), and the saplings in Site D had the lowest with a rate of 0.07 $\frac{cm}{day}$ (SE = 0.01 $\frac{cm}{day}$) (Table 4).

In addition to the leaf growth rate, the peak individual leaf area (LA) was also averaged for each site using tree-level measurements and is listed in Table 5. The mature cottonwoods in Site C had the largest average leaf area (LA = 22.2 cm^2, SE = 3.02 cm^2), and Site B had the smallest average leaf area (LA = 9.6 cm^2, SE = 1.04 cm^2). The sapling cottonwoods with the largest average leaf area were also in Site C (LA = 13.5 cm^2, SE = 1.45 cm^2), and the smallest were in Site D (LA = 6.6 cm^2, SE = 1.77 cm^2). Overall, the standard deviation for the leaf out rate was minimal, ranging between 0.01 and 0.04 cm per day, showing differences among plots and sites. The standard deviation for the leaf area was slightly higher ranging between 3.0 and 11.7.

Table 5. Summary table showing average green-up rate (cm/day) and peak leaf area (cm^2) for each site by maturity, along with standard deviation (SD) and standard error (SE).

	Mature		Sapling		Mature				Sapling			
	Avg Rate $(\frac{cm}{day})$	Avg Peak LA (cm^2)	Avg Rate $(\frac{cm}{day})$	Avg Peak LA (cm^2)	SD_{Rate} $(\frac{cm}{day})$	SD_{LA} (cm^2)	SE_{Rate} $(\frac{cm}{day})$	SE_{LA} (cm^2)	SD_{Rate} $(\frac{cm}{day})$	SD_{LA} (cm^2)	SE_{Rate} $(\frac{cm}{day})$	SE_{LA} (cm^2)
Site A	0.13	11.1	0.13	10	0.02	4.8	0.01	1.60	0.02	4.73	0.01	1.37
Site B	0.13	9.6	0.10	8.9	0.03	3.6	0.01	1.04	0.02	3	0.01	1.00
Site C	0.16	22.2	0.11	13.5	0.04	11.7	0.01	3.02	0.02	5.63	0.01	1.45
Site D	0.10	11.5	0.07	6.6	0.02	4.2	0.01	1.21	0.02	4.34	0.01	1.77
Site E	0.08	14.1	0.09	10.3	0.02	4.6	0.01	1.74	0.01	4.04	0.00	1.04
Total	0.12	14.2	0.10	10.4	0.04	8.4	0.01	1.13	0.03	4.89	0.00	0.65

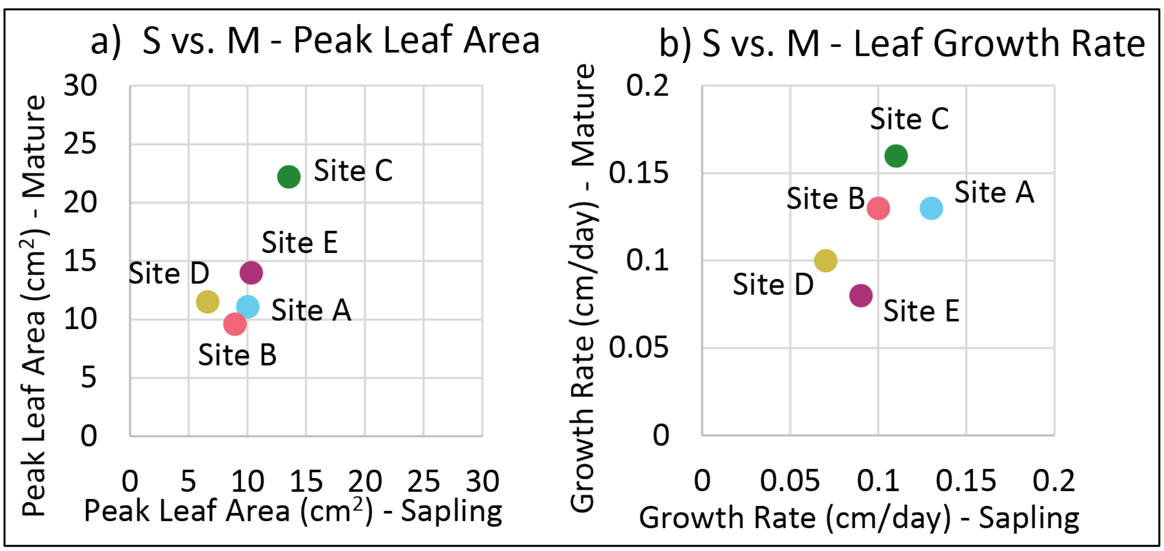

Figure 11. Site-level Mature (M) vs. Sapling (S) graphs of a) Peak Leaf Area and b) Leaf Growth Rate averages were calculated for each site.

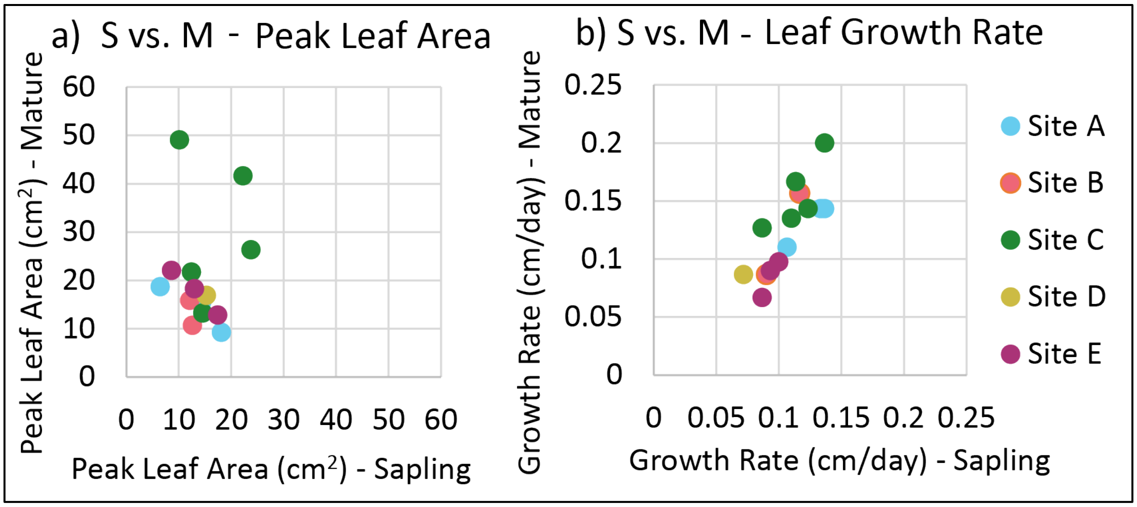

Figure 12. Plot-level Mature (M) vs. Sapling (S) graphs of a) Peak Leaf Area and b) Leaf Growth Rate. Averages were calculated for each plot.

Scatter plots of peak leaf area and leaf growth rate compare mature and sapling cottonwood site averages (Figure 11), and plot averages (Figure 12). There was no significant correlation found between mature and saplings regarding the peak individual leaf area or the leaf growth rate (Appendix Table 1). These relationships were studied by calculating Pearson and Spearman coefficients at the site-level using plot level data. There was a stronger correlation between mature and saplings when comparing the leaf growth rate, and some within-site among-plot correlations were significant (with p-value less than 0.05) (Appendix Table 1).

5.1.2. 50% Leaf Out

Along with the leaf growth rate, the timing of 50% leaf out was also calculated using the leaf length measurements. To create a fixed scale for the graphs, by-tree values were divided by the maximum leaf measurement recorded to attain units that were a fraction of a maximum. Figure 13 shows the visualization of leaf growth per site and identifies when 50% leaf out occurs. The median date of 50% leaf out for mature trees was similar in range between May 5 and May 17 across all sites (Table 5). The sapling-median dates were very similar to those of the mature trees, with dates between May 5 and May 18. Overall, the median date for leaf out was May 12 (Table 5), with the median date for mature cottonwoods and saplings being May 11 and May 14, respectively, implying that leaf out was synchronous.

Although saplings did not leaf out earlier, a potential source of bias in this inference was introduced because many smaller saplings were excluded from selection as study trees because they appeared dead at the start of the growing season. Many of those were observed to produce shoots and leaves from the base of the stem later in the summer, demonstrating that the aboveground biomass was dead, but the roots were still alive. Indeed, vegetative reproduction of aboveground biomass is common of cottonwoods and can be beneficial to stressed cottonwoods because above-ground biomass can be lost enabling the root system, and thus groundwater access, to persist until the next season (Taylor, 2000). Nonetheless, those that were likely the most stressed trees (inferred from their above-ground mortality, although it is unclear whether that resulted from winter-time low temperatures, previous-summer drought, or other factors) surely had a substantially later leaf-out date than the study trees.

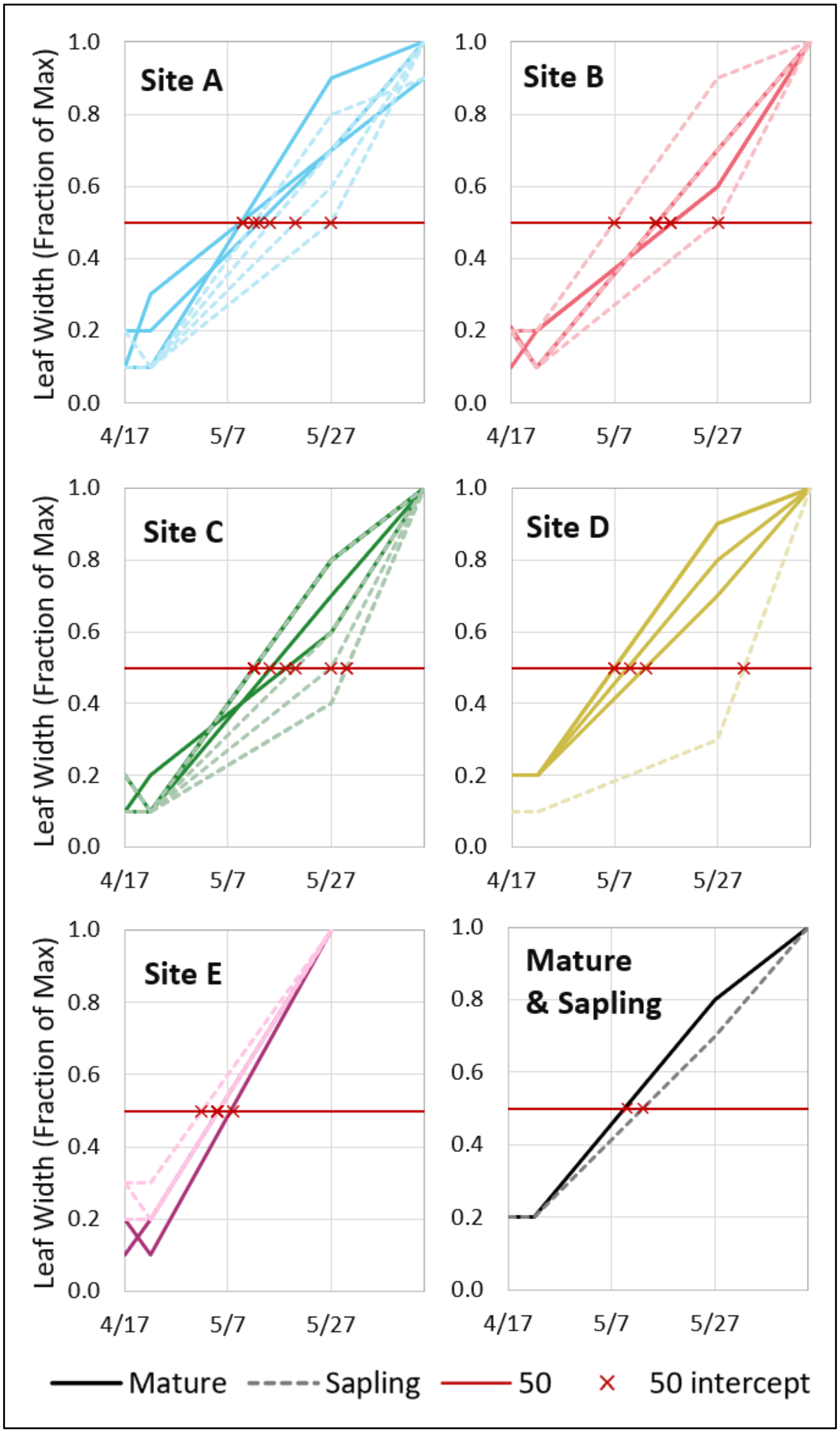

Figure 13. Visualization of Frémont cottonwood leaf growth highlighting the timing of 50% leaf out. Mature data points are represented with a solid line and saplings with a dashed line. It should be noted that the earlier peak date for the Site E data reflects missing data from the last data collection on June 14.

Table 6. Median timing of 50% leaf out for each site and in total, categorized by maturity levels.

	Mature	Sapling
Site A	5/10	5/17
Site B	5/15	5/12
Site C	5/12	5/18
Site D	5/10	5/16
Site E	5/5	5/5
Total	5/11	5/14
Combined	5/12	

5.1.3. 50% Senescence

Similar to using the leaf dimensions of their expansion period to quantify leaf-out dates, the date of 50% senescence was calculated using chlorophyll measurements taken at the end of the growing season. Figure 14 shows the visualization of leaf senescence per site and identifies when 50% senescence occurred. The median date of 50% senescence for mature trees ranged between October 7 and October 25 (Table 6). For saplings, the range of 50% senescence dates were between September 18 and October 27. The median date of senescence for mature cottonwoods was October 15th, and for saplings it was October 13th. Overall, the median date of senescence was October 13.

Although a reader might examine these senescence curves for one site and conclude that saplings senesce later (e.g., Site C), examining all shows no consistent differences. While there may be systematic reasons for difference at some sites but not others, they cannot be inferred from this study.

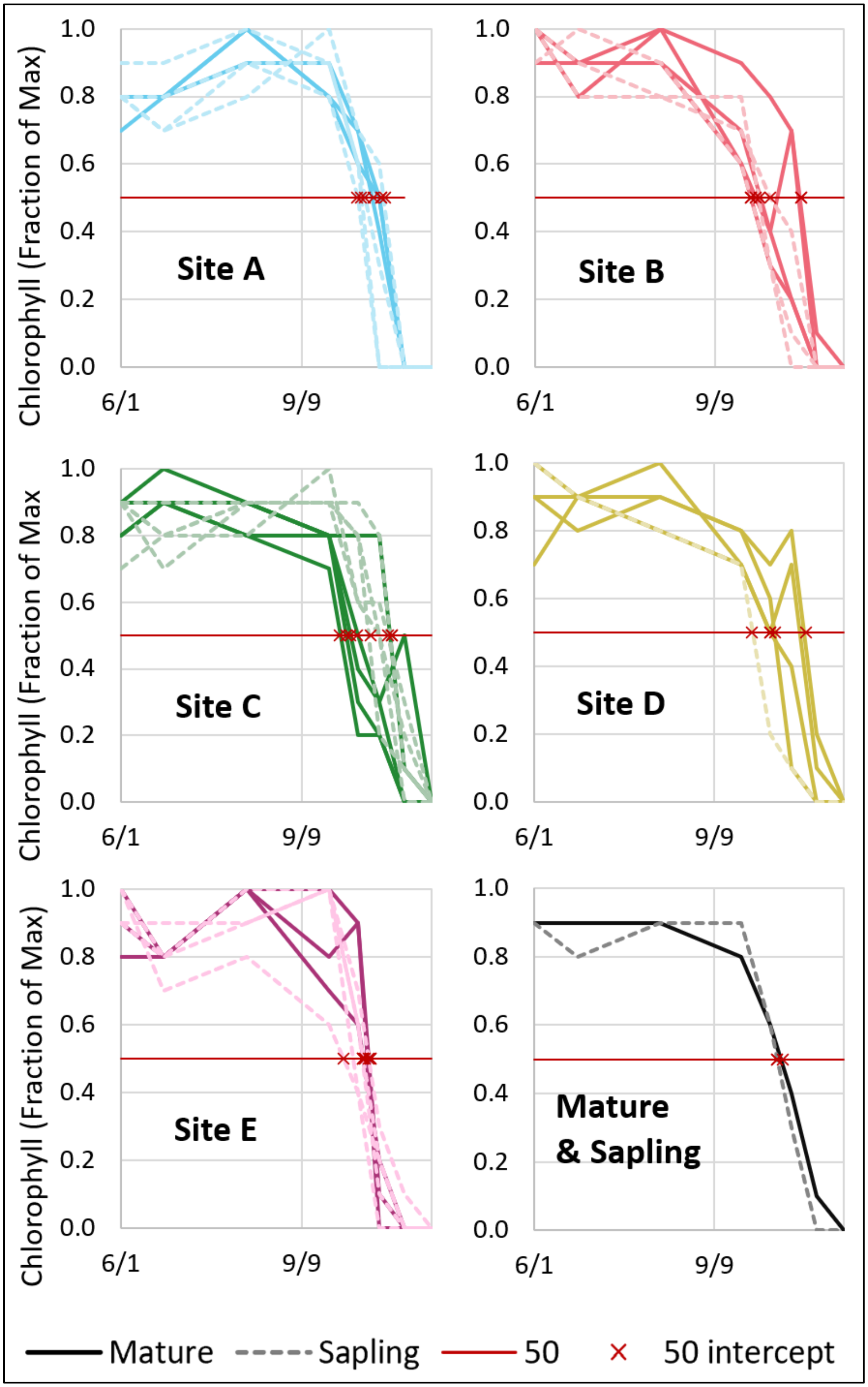

Figure 14. Visualization of leaf die-off highlighting the timing of 50% senescence. Mature data points are represented with a solid line and saplings with a dashed line.

Table 7. Median timing of 50% senescence for each site and in total, categorized by maturity levels.

	Mature	Sapling
Site A	10/20	10/11
Site B	10/11	10/2
Site C	10/7	10/27
Site D	10/25	9/18
Site E	10/15	10/11
Total	10/15	10/13
Combined	10/13	

5.1.4. Growing Period

The days between the dates at 50% leaf out and 50% senescence allowed for the estimated growing period to be calculated for each individual study tree. Figure 15 shows a distribution of the different growing period lengths with the data organized by sites and maturity (Figure 15). There are subtle differences between maturity levels in each site regarding the length of the growing period or the range in lengths. For example, Site A saplings experience a shorter growing season than the mature cottonwoods. Also, Sites B, C, and E mature cottonwoods have a larger range of growing period length than their corresponding saplings. The mature cottonwoods in Site D have a higher average length of growing period than the rest of the sites, while also having the saplings with the shortest growing season. It is worthy to note that the six saplings in Site D were all found in one plot.

Overall, the average range in growing periods for both mature and saplings was between 128 and 156 days. Site A was the highest at 156 days followed by Site E at 154, Site B at 150, Site C at 134 and finally Site D at 128 days. Site D saplings had the shortest length of 99 days, and Site E mature cottonwoods had the longest at 168 days.

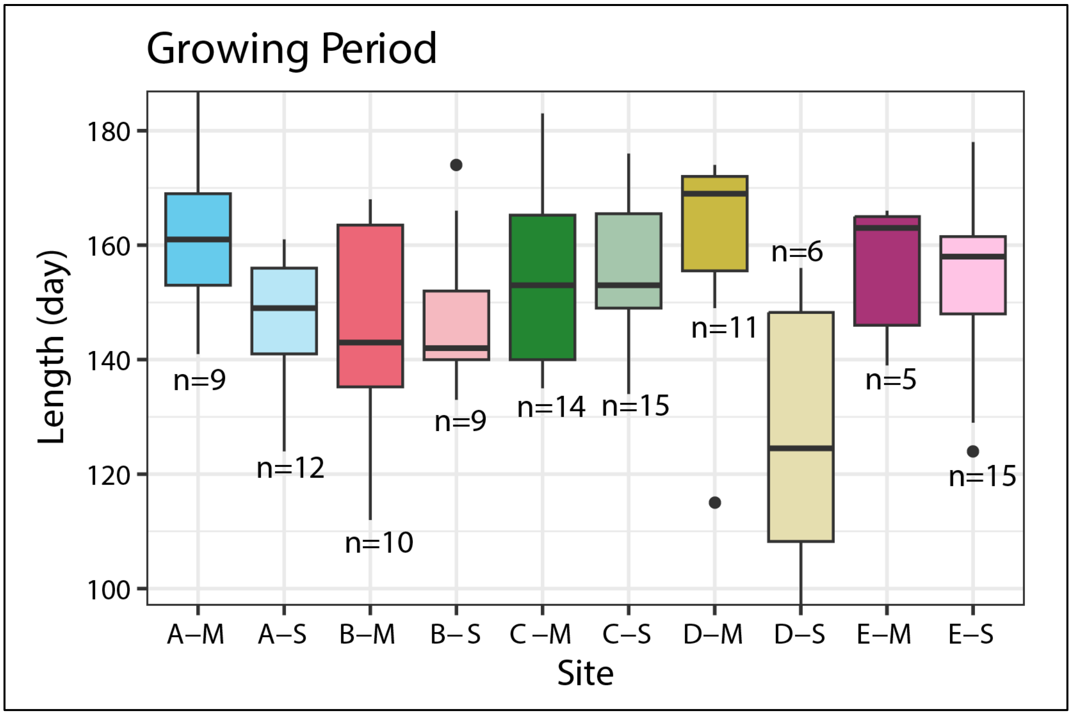

Figure 15. Visual length of growing period, days between 50% leaf out and 50% senescence .

A one-way ANOVA test indicated that there was a significant difference in the length of the growing period depending on the site and maturity stage of the cottonwoods ($F(9,95) = 3.051$, $p < 0.001$) (Table 7). A post hoc analysis Tukey test indicated a significant difference between saplings in Site D and mature cottonwoods in Site A ($p = 0.003$), C ($p = 0.02$), and D ($p = 0.001$), along with saplings in Site C ($p < 0.001$) and E ($p = 0.013$).

Table 8. One-way ANOVA results for growing period data of cottonwoods, ($F(9,95)=3.051$, $p<0.001$).

		Df	Sum sq	Mean Sq	F	Pr(>F)
Length of Season	Site-Maturity	9	6707	745.2	3.051	**2.99E-03**
	Residuals	95	23204	244.3		

Shortened growing seasons imply a reduced duration over which trees can photosynthesize and gain carbon, however, it can also represent a means of drought avoidance (Parolin et al., 2010). The large contrast in growing-season length between saplings and mature trees in site D, apparently driven mostly by differences in senescence timing (Table 6), is unsurprising given the microtopography of that site; specifically, the mature trees were largely sitting in a low drainage spot whereas the saplings were up on the bank from that drainage, likely implying differences in access to water.

5.1.5. Chlorophyll

Chlorophyll (chl) measurements were used to quantify the photosynthesis process of the study trees. Figure 16 shows how chl fluctuates throughout the growing period at a sitewide level, with the data organized by sampling date and maturity. No pattern in chlorophyll was evident, except for the October 10^{th} chl measurement showing an overall decrease in the chl median, and a greater distribution of measurements (Figure 16).

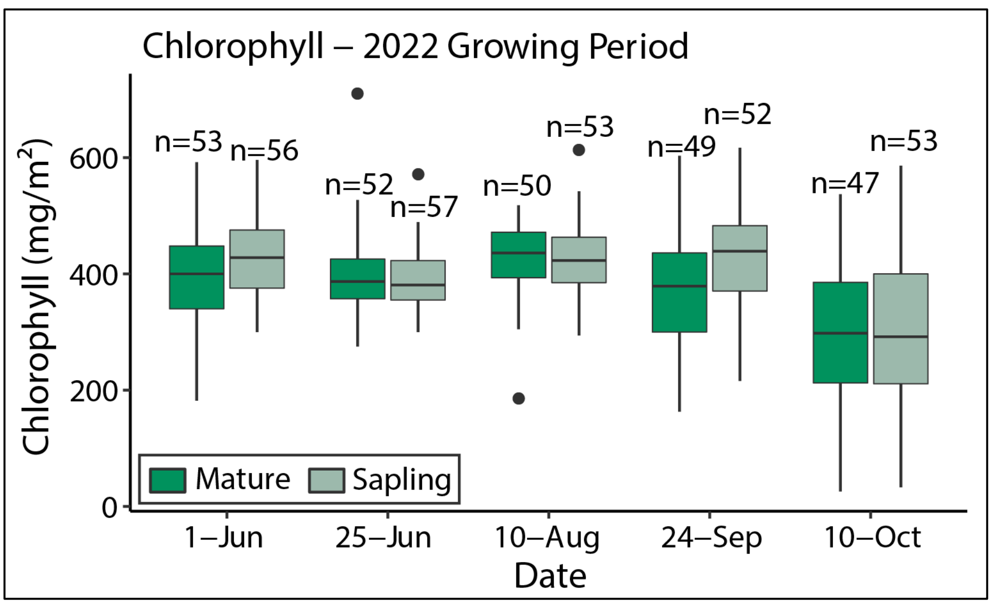

Figure 16. Distribution of chlorophyll throughout the 2023 growing period.

To lump the data for subsequent analyses, the chlorophyll measurements were categorized as one of Early Season (June 1 & June 25), Peak Season (August 10), or Late Season (September 24 & October 10) to study seasonal change. Figure 17 shows those changes in chl using boxplots. There was no consistent positive or negative change between the seasons. There was less variation in chl values observed between the early and peak season (Figure 17). Site B saplings generally had greater decreases in chl content than mature cottonwoods in Site B. In contrast, the mature cottonwoods in Site C experienced a greater decrease in chl content than their saplings. Site E saplings experienced a greater decrease in chl content than Site E mature cottonwoods.

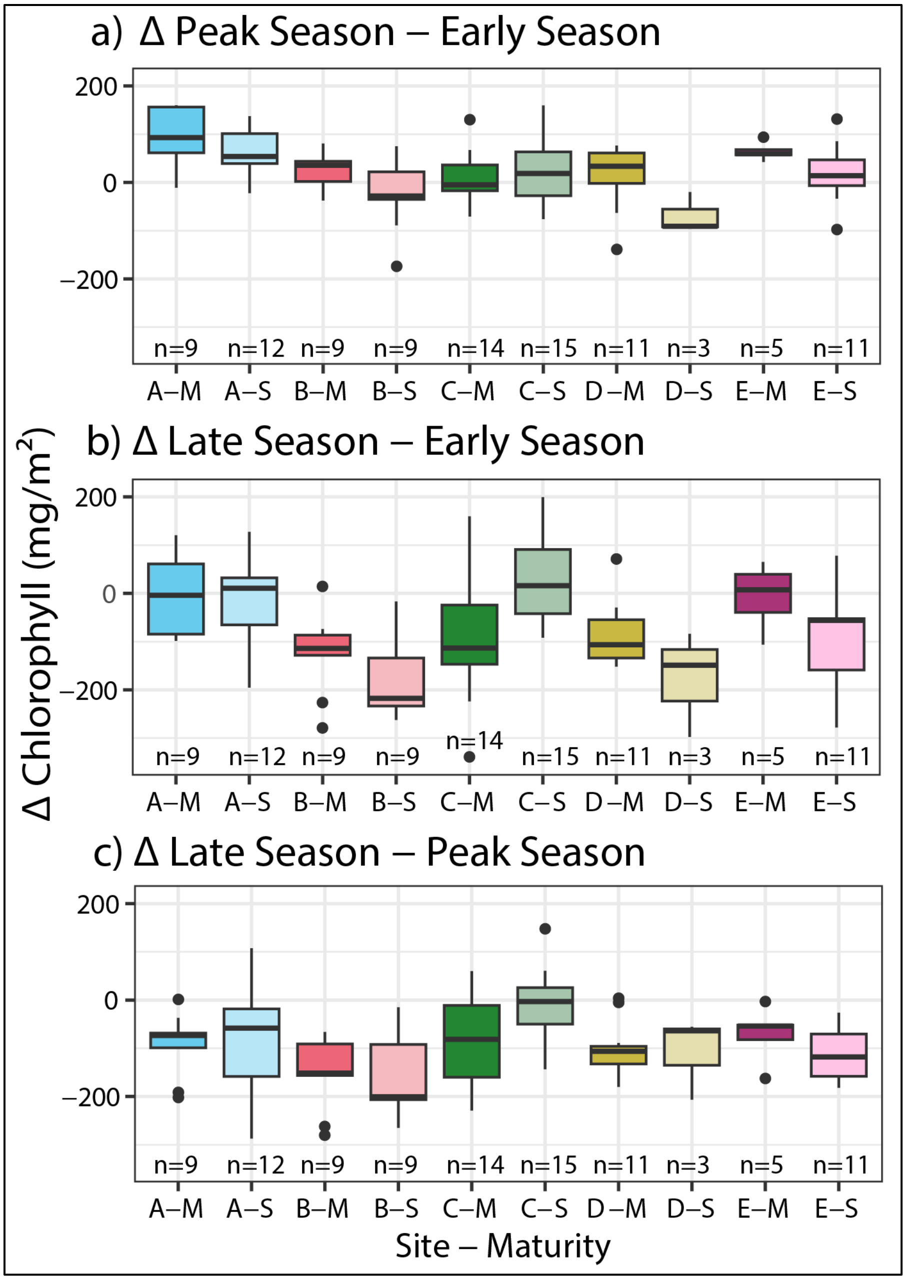

Figure 17. The seasonal changes in chl plotted by site and maturity where, Early Season = June 1 & June 25, Peak Season = August 10, and Late Season = September 24 & October 10.

Appendix Table 2 provides an overview of the chl data used in the boxplots of Figure 17. Overall, Site D had greater standard variations throughout all seasons than the rest. The standard deviation was greatest for the saplings in the Late Season (SD = 110 $\frac{mg}{m^2}$, SE = 16 $\frac{mg}{m^2}$) and lowest for the saplings in the Early Season (SD = 57 $\frac{mg}{m^2}$, SE = 8 $\frac{mg}{m^2}$).

5.1.6. Stomatal Conductance

Stomatal conductance (g_s) measurements were also used to quantify the photosynthesis process of the study trees. Figure 18 shows how g_s fluctuates throughout the growing period at a sitewide level, with the data organized by sampling date and maturity. This range in stomatal conductance (<600 mmol/(m^2s)) is similar to the Frémont cottonwood range seen in a Spring 2009 study in Sacramento, CA which focused on seedlings (Tozzi et al., 2013), and a two-year study in Maricopa County, Arizona that calculated the mean stomatal conductance of 0.261 ± 0.010 (Horton et al., 2001).

The pattern in g_s differed from that of chl, showing low values at both the beginning and end of the growing season and high values in the middle; that pattern was more evident for the saplings, which showed higher stomatal conductance values overall between June and August (Figure 18).

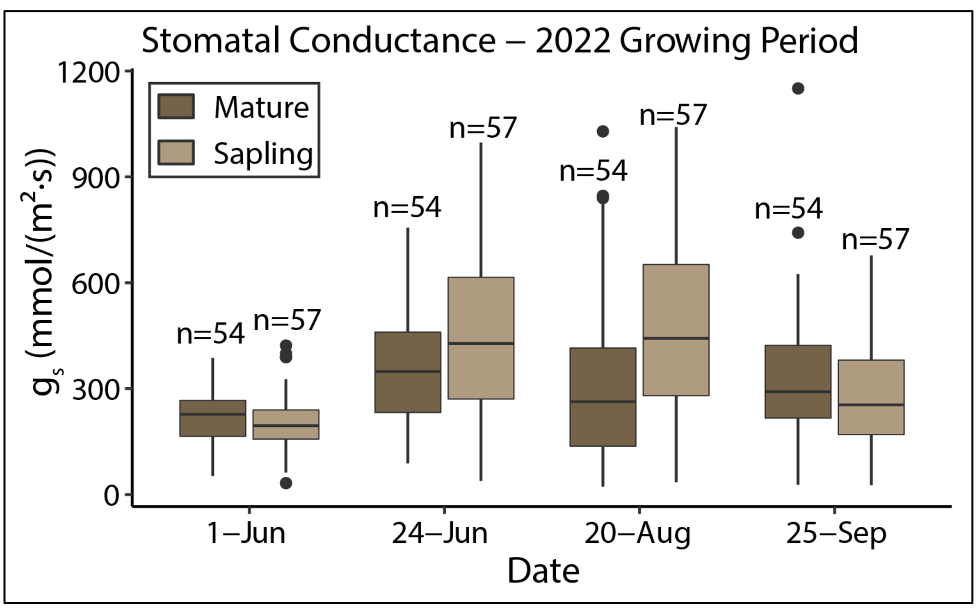

Figure 18. Stomatal conductance fluctuation throughout the 2023 growing period.

The stomatal conductance measurements were also categorized as either Early Season (June 1 & June 24), Peak Season (August 20), and Late Season (September 25) to study seasonal change. Figure 19 visualizes the g_s seasonal change using boxplots. The seasonal changes in g_s were inconsistent among sites and between mature and sapling trees, showing a mixture of positive change and negative change in g_s values, even within a specific site and maturity. However, one notable pattern can be observed in Figure 19C: across sites, the stomatal conductance values of the mature trees showed less reductions from peak-season to late-season than they did for the saplings, suggesting that the saplings were more likely to down-regulate their water use in response to late-season conditions. This observation of down-regulation in saplings could be responsible for the later senescence date for saplings than mature cottonwoods (Figure 14).

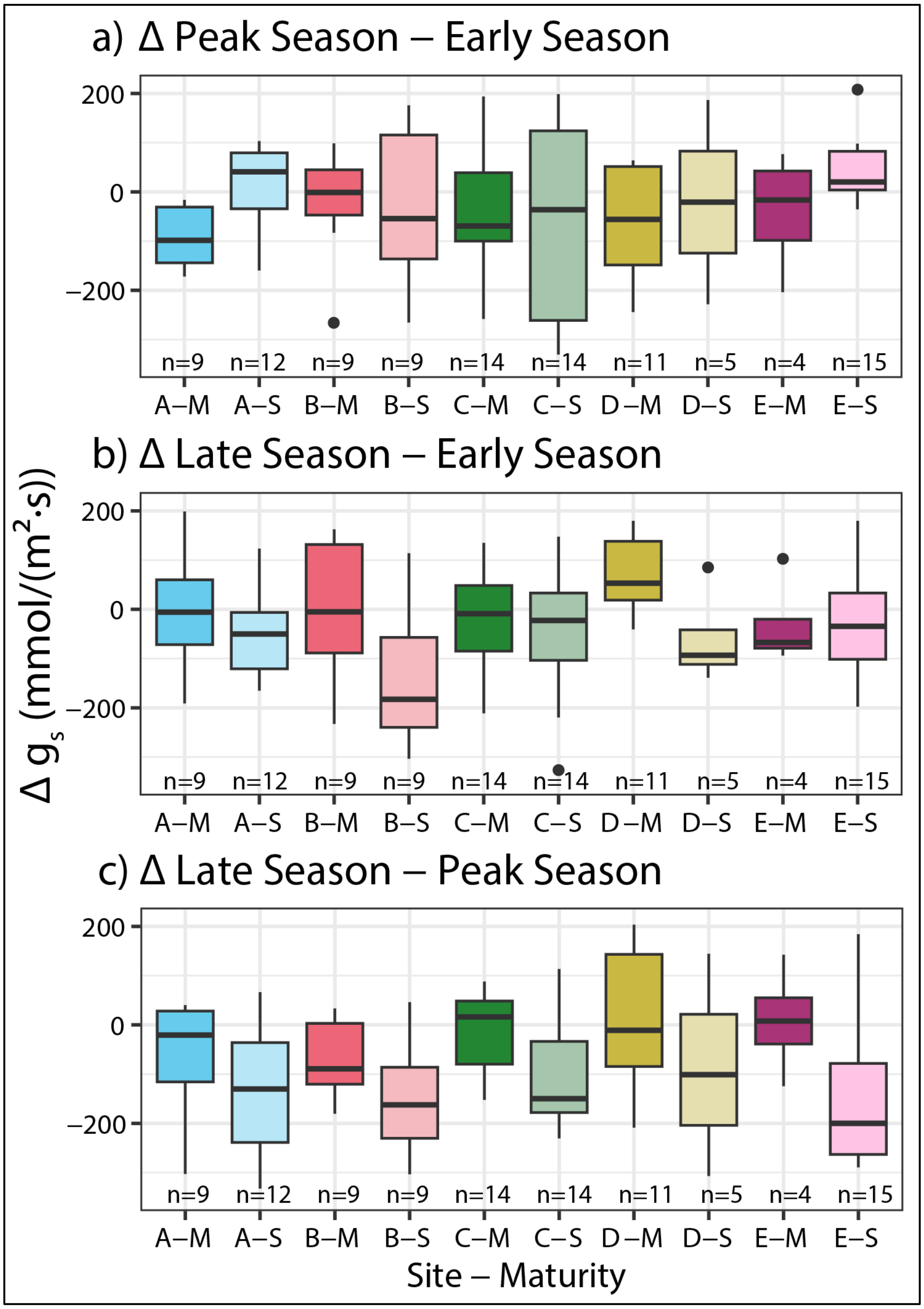

Figure 19. The seasonal changes in gs plotted by site and maturity where, Early Season = June 1 & June 24, Peak Season = August 20, and Late Season = September 25.

Appendix Table 3 provides an overview of the g_s data used in the boxplots of Figure 19. Overall, Site D had greater standard variations throughout all seasons than the rest. The standard variation across all sites was greatest for the saplings in the Peak Season

(SD = 269 $\frac{mmol}{m^2 s^1}$, SE = 36 $\frac{mmol}{m^2 s^1}$) and lowest for the mature cottonwoods in the Early Season (SD = 92 $\frac{mmol}{m^2 s^1}$, SE = 13 $\frac{mmol}{m^2 s^1}$).

5.1.7. Leaf Water Potential

Predawn water potential values ($\Psi_{predawn}$) from June were very similar across the floodplain, ranging between -0.1 Mpa and -0.3 Mpa for mature cottonwoods and 0 Mpa to -0.3 Mpa for saplings (Table 8). The September $\Psi_{predawn}$ measurements were very similar to the June values. The range for mature cottonwoods was between -0.4 Mpa and -0.2 Mpa; for saplings it was between -0.4 Mpa and -0.1 Mpa (Table 9).

Two noteworthy observations are apparent in the predawn data. First, across all sites, the water potential was low, implying roots were connected to substantial water supplies, whether they were in the saturated zone, capillary fringe, or in moist deeper soils. Secondly, the late-season (when river stage has receded further and been low for longer periods of time) predawn water potentials are not substantially lower than the early season (~0-to-0.1 Mpa), suggesting that a similar level of access to subsurface waters exists in late season as it does in the early season; the effect of this season change is not larger for saplings, as might be expected if their roots were to lose connectivity to subsurface waters.

Table 9. Summary table of water potential (Ψ) averages and standard deviations (SD) for June measurements.

	June Ψ (Mpa)			
	Mature		Sapling	
	$\Psi_{Predawn}$	SD	$\Psi_{Predawn}$	SD
Site A	-0.2	0.1	-0.2	0.1
Site B	-0.3	0.1	0.0	0.0
Site C	-0.2	0.1	-0.3	0.1
Site D	-0.2	0.0	-0.3	0.0
Site E	-0.1	0.1	-0.2	0.2
Total	-0.2	0.1	-0.2	0.2

Table 10. Summary table of water potential (Ψ) averages and standard deviations (SD) for September measurements.

	September Ψ (Mpa)			
	Mature		Sapling	
	$\Psi_{Predawn}$	SD	$\Psi_{Predawn}$	SD
Site A	-0.2	0.0	-0.2	0.1
Site B	-0.3	0.1	-0.1	0.1
Site C	-0.3	0.1	-0.3	0.1
Site D	-0.4	0.0	-0.4	0.0
Site E	-0.3	0.1	-0.2	0.1
Total	-0.3	0.1	-0.2	0.1

These water potential values are slightly lower than the mean predawn water potentials measured by Horton et. al. 2001 in Arizona, –0.66 ± 0.01 Mpa (Horton et al., 2001), suggesting better water access at the Mustang site.

5.1.8. Specific Leaf Area

The specific leaf area (SLA) appears higher in saplings located in Site C (Figure 20). Generally, however, saplings had a lower median than the mature cottonwoods in the same sites (Figure 20). There were greater variations in values in Site C saplings, and Site E cottonwoods (Figure 20). Once again, comparing these values with the mean specific leaf area from Horton et. al. 2001 study, these values are rather close to their mean of 124 ± 0.1 cm^2/g.

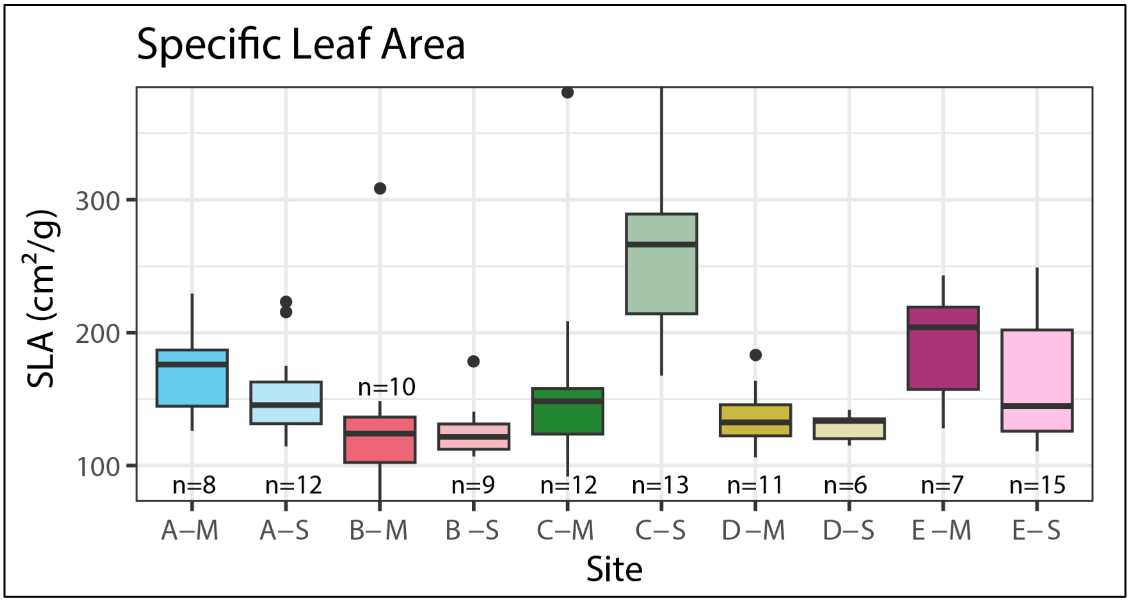

Figure 20. A comparison of the SLA by site and maturity across the floodplain. This data are from leaf samples collected on July 14 .

5.1.9. Stand Health Surveys

5.1.9.1.Crown-Condition Classification

In all the sites, mature cottonwoods were mainly classified as being dominant trees in their canopy followed by codominant, with some in Site A and Site C classified as an intermediate tree and one in Site B as suppressed (Figure 21). For saplings, Sites A and Site B had evenly distributed classification, and Site C and Site D lacked trees in the dominant category (Figure 21). Site C also had the most trees in the suppressed category, followed by Site E (Figure 21). These results are useful in that they justify the interpretability of inter-site comparisons of mature trees because they contained samples of trees with roughly similar crown classes (i.e., mostly dominant for mature trees).

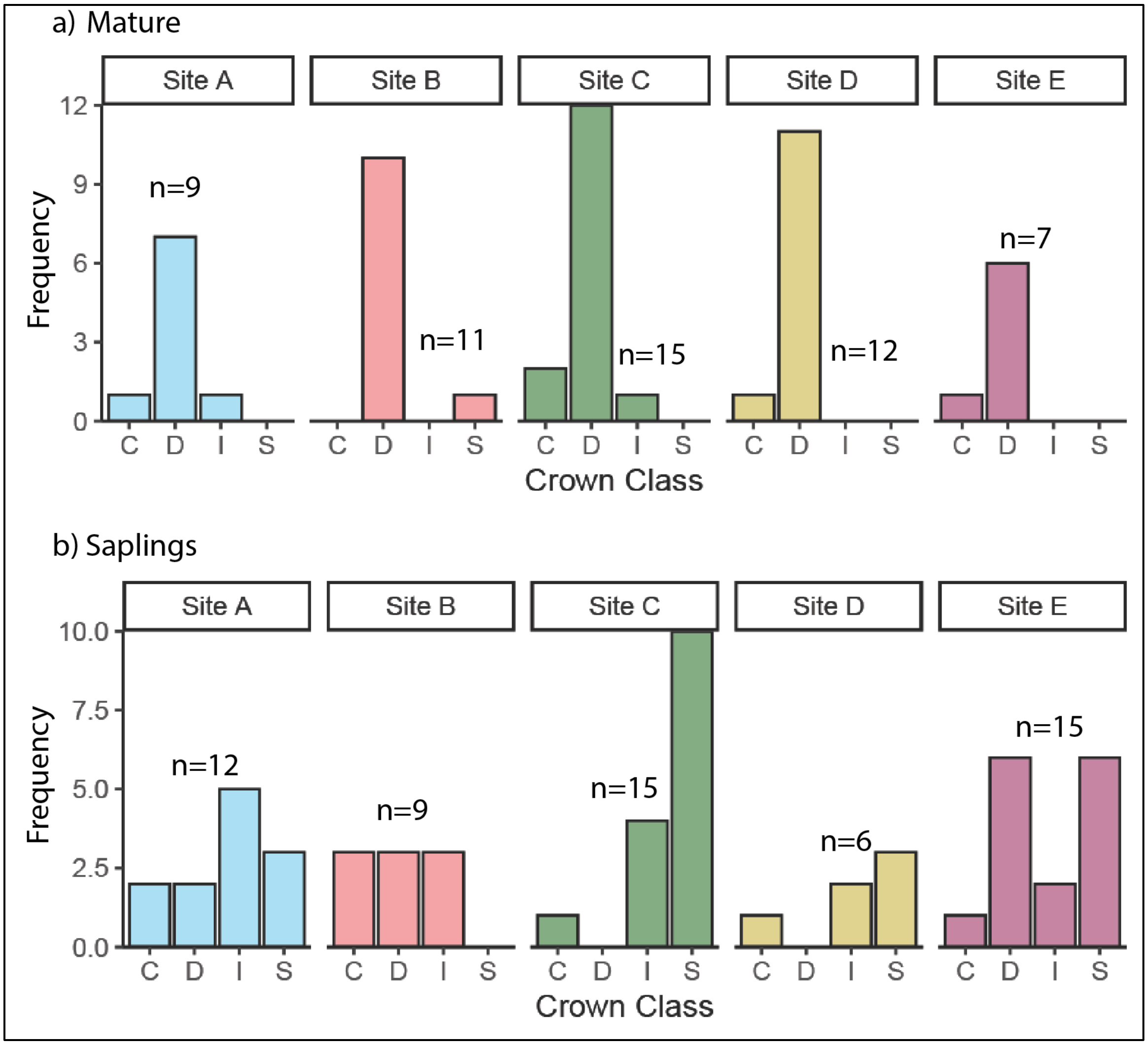

Figure 21. Histograms of crown class survey results, with frequency on the vertical axis , for a) Mature and b) Saplings, where D=Dominant, C=Codominant, I=Intermediate, S=Suppressed (DeYoung, 2016).

5.1.9.2. Foliage Transparency

Sites A, B, C, and D all appeared to have the greatest number of cottonwoods with crown transparencies between 50 and 70 percent (Table 10; Figure 22). Site E had most of its mature cottonwoods with a crown transparency of 30, where a 5 is least transparent, and 95 is most transparent (Figure 22). All sites had cottonwoods with a wide range of crown transparency classifications.

Table 11. Summary of foliage transparency values across the sites, with standard deviations (SD).

	Foliage Transparency	SD
A	56.10	12.70
B	59.10	17.40
C	64.30	14.40
D	56.70	14.00
E	45.00	16.30

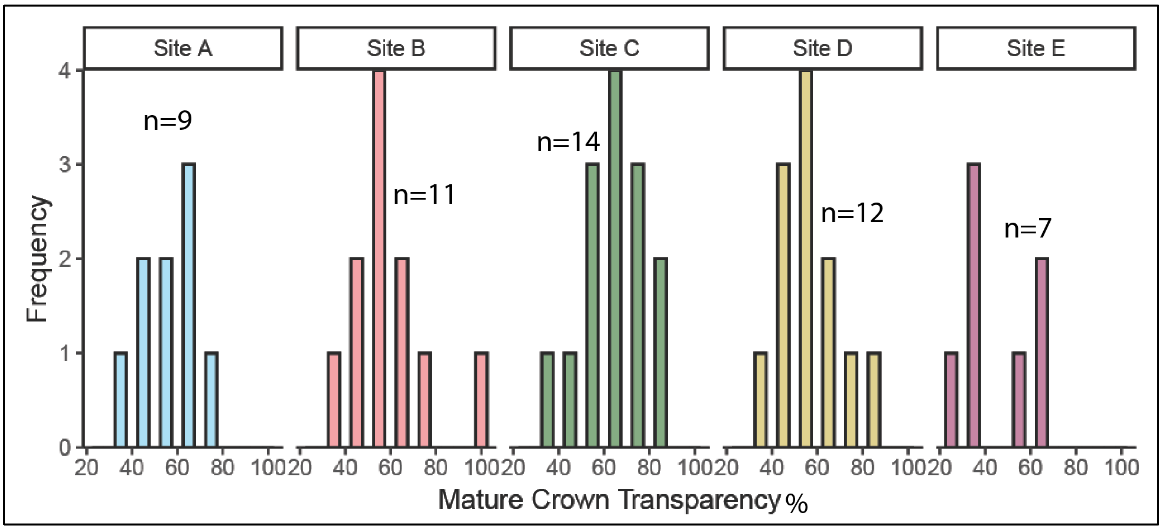

Figure 22. Histogram of foliage transparency (%) results for mature cottonwoods (bin width = 5) (Schomaker et al., 2007).

5.1.9.3. Vigor

All the saplings in Site E were in moderate condition (Figure 23). Most of the saplings in Site B were in good condition, with few in moderate condition. Site A had a roughly equal amount of good and moderate condition saplings, with few saplings in poor conditions. Site D had an even amount of moderate and poor saplings. Overall, sites with saplings in good condition included Site A, B, and C. Sites with saplings in poor conditions include Sites A, C, and D (Figure 23).

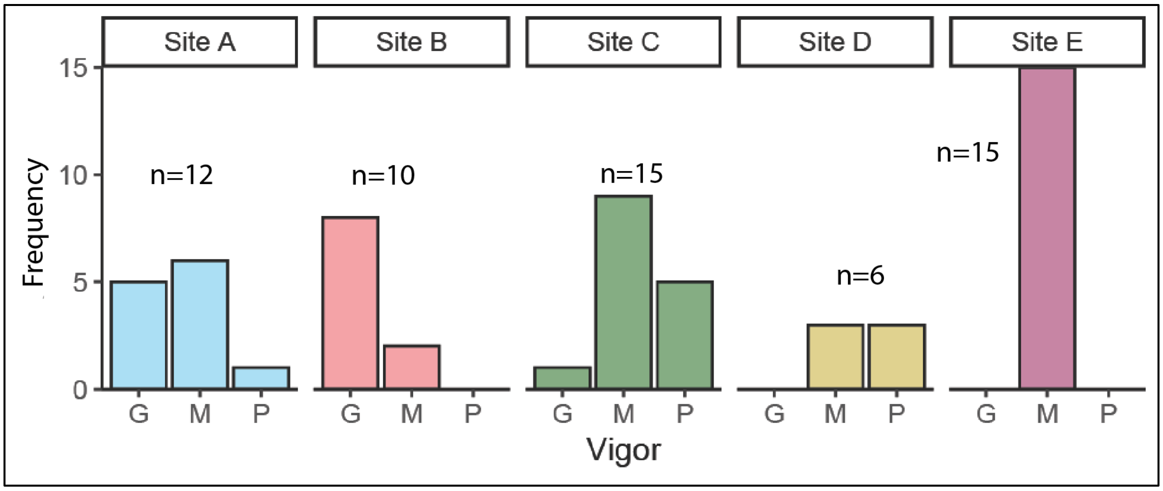

Figure 23. Histograms of vigor conditions of saplings, with frequency on the vertical axis, where G=Good, M=Moderate, and P=Poor (Schomaker et al., 2007).

5.1.9.4.Tree Diameter

The maximum diameter for the saplings was 4 cm, largely attributed to the larger-diameter saplings in Site E (Figure 24), whereas Site A and Site B sapling diameters were below 3 cm, and Sites C and D saplings diameters were below 2 cm. The mature cottonwoods were as large as 30 cm, with a range of sizes in all sites, albeit with somewhat smaller trees in Sites A and B (Figure 24). Size is challenging to interpret as a metric of stress or vigor unless ages are precisely known, although the finding of relatively larger saplings in Site E is consistent with expectations given that shallow soil water was most abundant at this site (see later sections), and thus recruitment may occur more frequently there than in the other sites, allowing trees there to have possibly more success in most years, including prior to the 2017 floods. For comparison, the diameter of Frémont cottonwoods can range between 50 to 390 centimeters (Taylor, 2000).

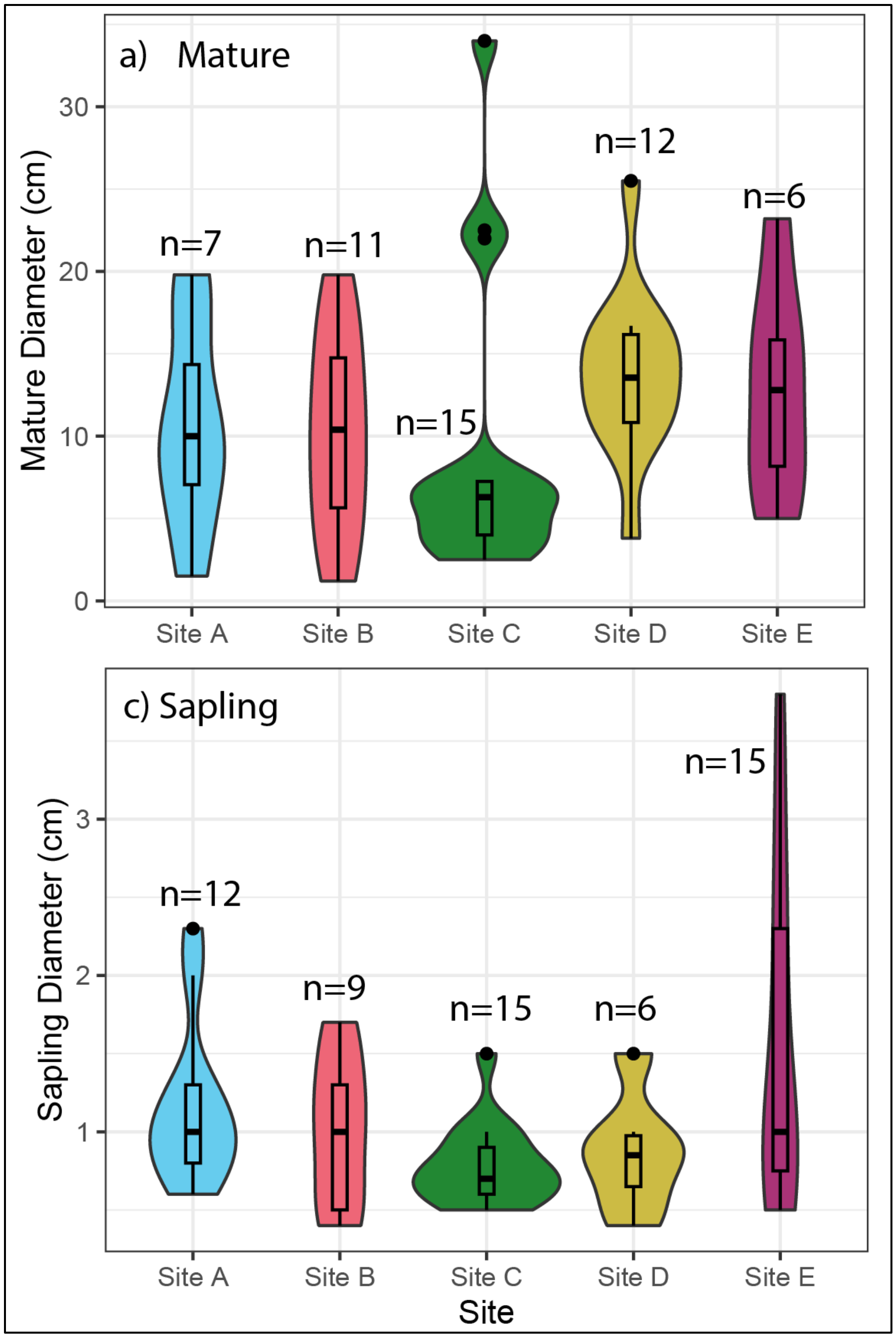

Figure 24. Violin plot of diameter survey results for a) mature cottonwoods and b) saplings.

5.1.9.5. Cottonwoods within 1m from the Study Trees

The study trees had less mature cottonwoods within one meter of them than saplings (Figure 25). Site C had the greatest number of cottonwoods within one meter than any other site. There was also a greater frequency of saplings within one meter in Site E (Figure 25).

These higher densities of saplings indicate greater recruitment of trees occurring in Sites C and E. It is also important for readers to note that all sites included at least one of the twenty-five plots with zero cottonwood trees.

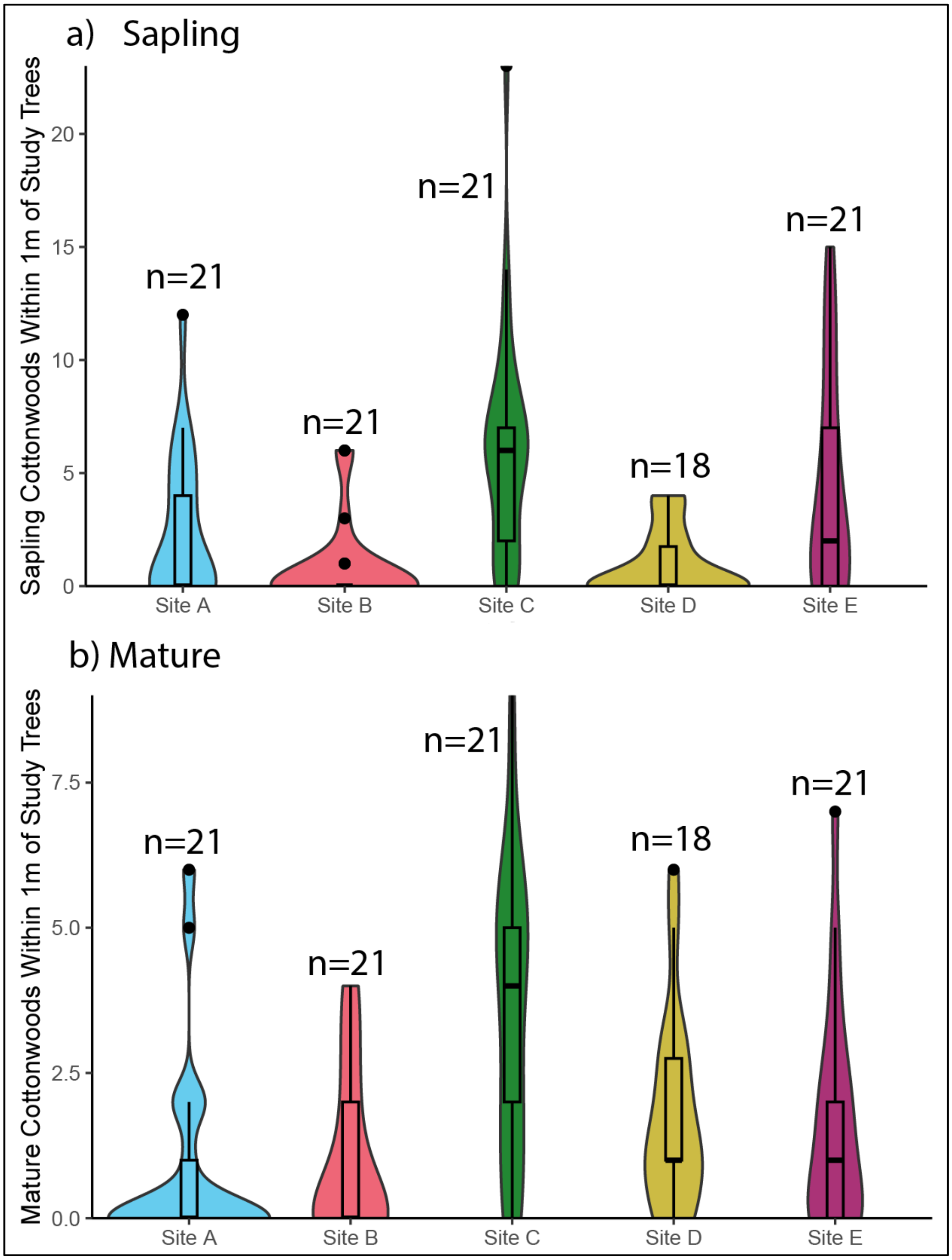

Figure 25. Violin plot of the counting survey of a) mature cottonwoods and b) saplings within one meter of the study trees.

5.1.9.6. Basal Area

Site B had the lowest basal area (BA) throughout the site with four out of five plots having an effective BA of 0 m^2/ha (Figure 26). Site E had two plots with a BA at or above 20 m^2/ha (Figure 26). All the sites had at least two plots where the BA was zero and at least one plot with a BA of 5 m^2/ha (Figure 26). Site E had the highest BA, suggesting it likely has the greatest biomass, and that its conditions facilitate recruitment, density, and growth.

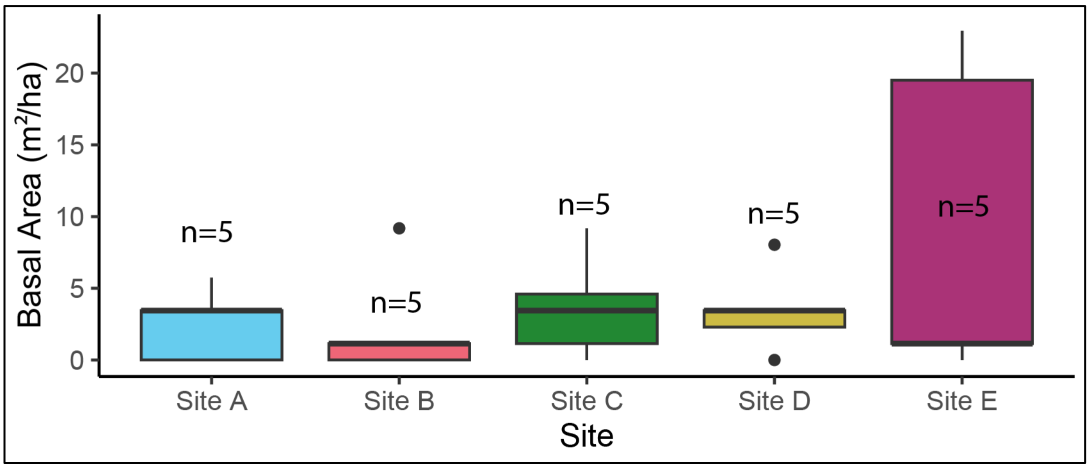

Figure 26. Boxplot of basal area survey.

5.1.9.7. Leaf Area Index

The saplings in Site C experienced the greatest Leaf Area index (LAI) above them, followed by Site E (Figure 27, Table 12). The variations in the LAI over each sapling generally corresponded with plot-level differences (Table 10), indicating that the densest plots also had to the greatest shading of the saplings. Site B had the lowest LAI (Figure 27, Table 12), high foliage transparency (Figure 22), and least population of cottonwoods present (Figure 26, Figure 27). Thus, in regard to metrics reflecting long-term stressors on tree and stand production, site B is severely limited (despite being adjacent to the river).

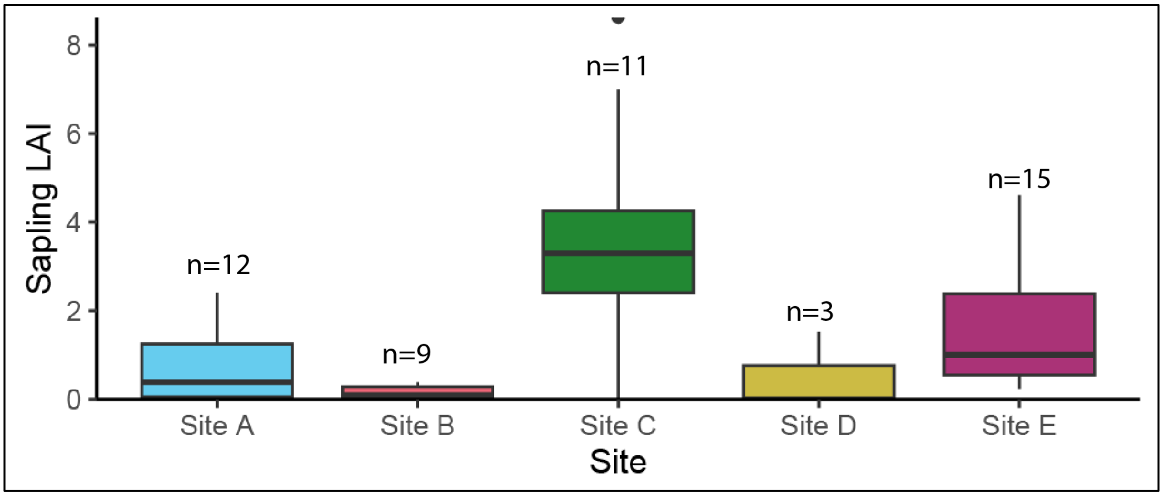

Figure 27. LAI results for saplings.

Table 12. Site average LAI values with standard deviation (SD) using plot level data (as opposed to tree level data).

	LAI	SD
Site A	1.12	1.18
Site B	0.66	0.92
Site C	3.76	3.78
Site D	1.50	1.59
Site E	2.66	2.48

5.2. Observations of Independent Variables

5.2.1. Shallow Groundwater Wells

Groundwater declined from May through mid-July in all wells, reaching low levels that remained largely stable through the following months. The depth to groundwater is graphed in Figure 28. The depth to groundwater in Site A is the shallowest, Sites B, C, and D are similar in depth, and Site C has groundwater at the greatest depth. Overall, all sites follow a similar trend in groundwater levels, though there is a slight delay and decrease in peak sizes visible in Site C (Figure 28). The Site C groundwater data best reflects the storm event in September, as seen with the larger spike in the data, but the reason for that is unclear (Figure 28).

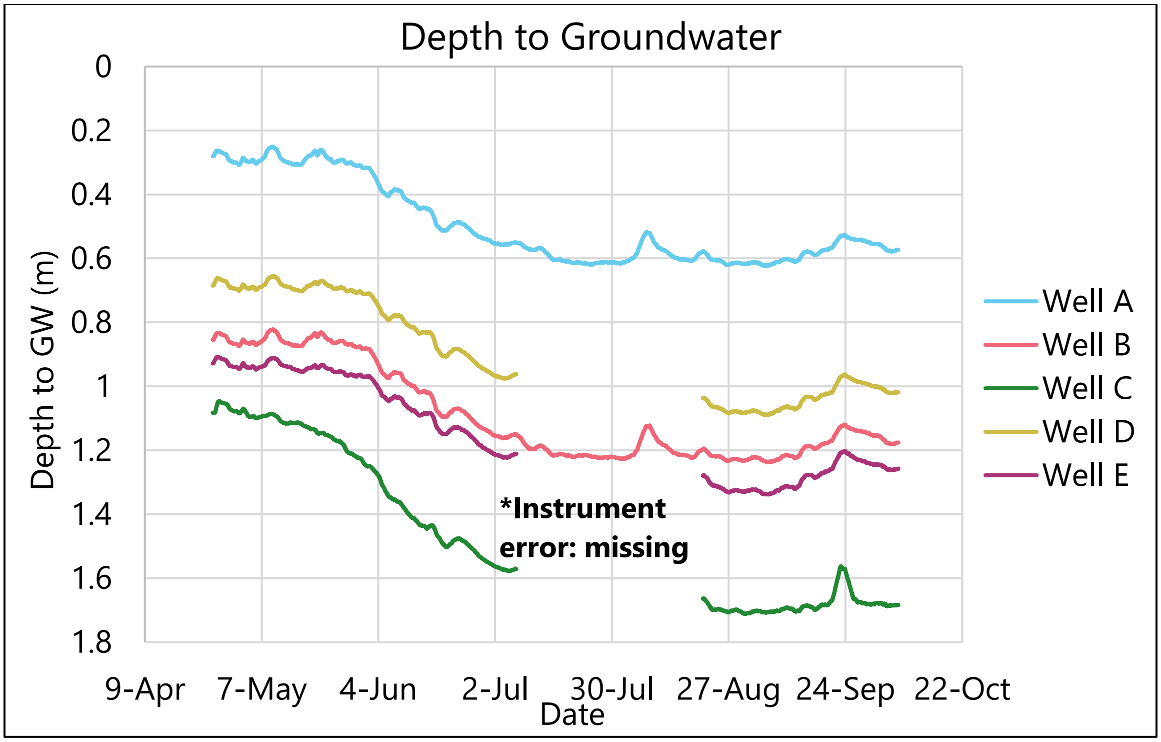

Figure 28. Groundwater levels across the five study sites. Gaps in data are due to instrument malfunction.

To address the gap in the data, the data were split into Early Season (April 22 to July 9) and Late Season (August 14 to October 6) where weeks 13-17 of data were removed and indicated the break between seasons. The average change in depth to groundwater for each well for each season was then calculated and reported in Table 13. Recession of the groundwater only occurred during the Early Season (April 22 to July 9). There was little change in groundwater rates in the Late Season (August 14 to October 6), and three out of the five wells experienced an increase in the water table. The site with the greatest recession rate during the Early Season is Site C at an average 0.7 $\frac{cm}{day}$ and the site with the smallest recession rate was Site D at 0.4 $\frac{cm}{day}$. Site A and Site B effectively showed no changes in groundwater levels throughout the Late Season, whereas Sites C and E had an average increase in groundwater levels at a rate of 0.2 $\frac{cm}{day}$, and Site D had an average increase of 0.1 $\frac{cm}{day}$.

Table 13. Summary table for each well including the elevation above the Truckee River calculated through the elevation survey done on September 8, distance from the Truckee River estimated using Google Earth, and the change in depth of groundwater for the early and late season (Google Earth Pro, version 7.3.6.9345). The depth to groundwater data is separated into two seasons, early season (April 22 to July 9) and late season (August 14 to October 6).

Well	Elevation above the Truckee R. (m)	Distance from the Truckee R. (m)	Early Season (Δdepth to GW/day) (cm)	Late Season (Δdepth to GW/day) (cm)
A	0.96	22.5	-0.6	0.0
B	1.25	22.5	-0.5	0.0
C	1.47	100	-0.7	0.2
D	0.71	50	-0.4	0.1
E	1.02	45	-0.5	0.2

Four graphs were made to show the change in groundwater levels at each site. The four graphs include (a) early season average daily groundwater level change plotted against the distance to the Truckee River, (b) late season average daily groundwater level change plotted against the distance to the Truckee River, (c) early season average daily groundwater level change plotted against the elevation of the well above the Truckee River, (d) late season average daily level change plotted against the elevation of the well above the Truckee River (Figure 29). Included in the graphs are the equation of the slope line, the coefficient of determination, R^2, and the Pearson correlation coefficient, r. The strongest relationships were found in graphs (b) ($R^2 = 0.64$, $r = 0.8$, $p=0.014$) and graph (c) ($R^2 = 0.46$, $r = -0.68$, $p=0.001$).

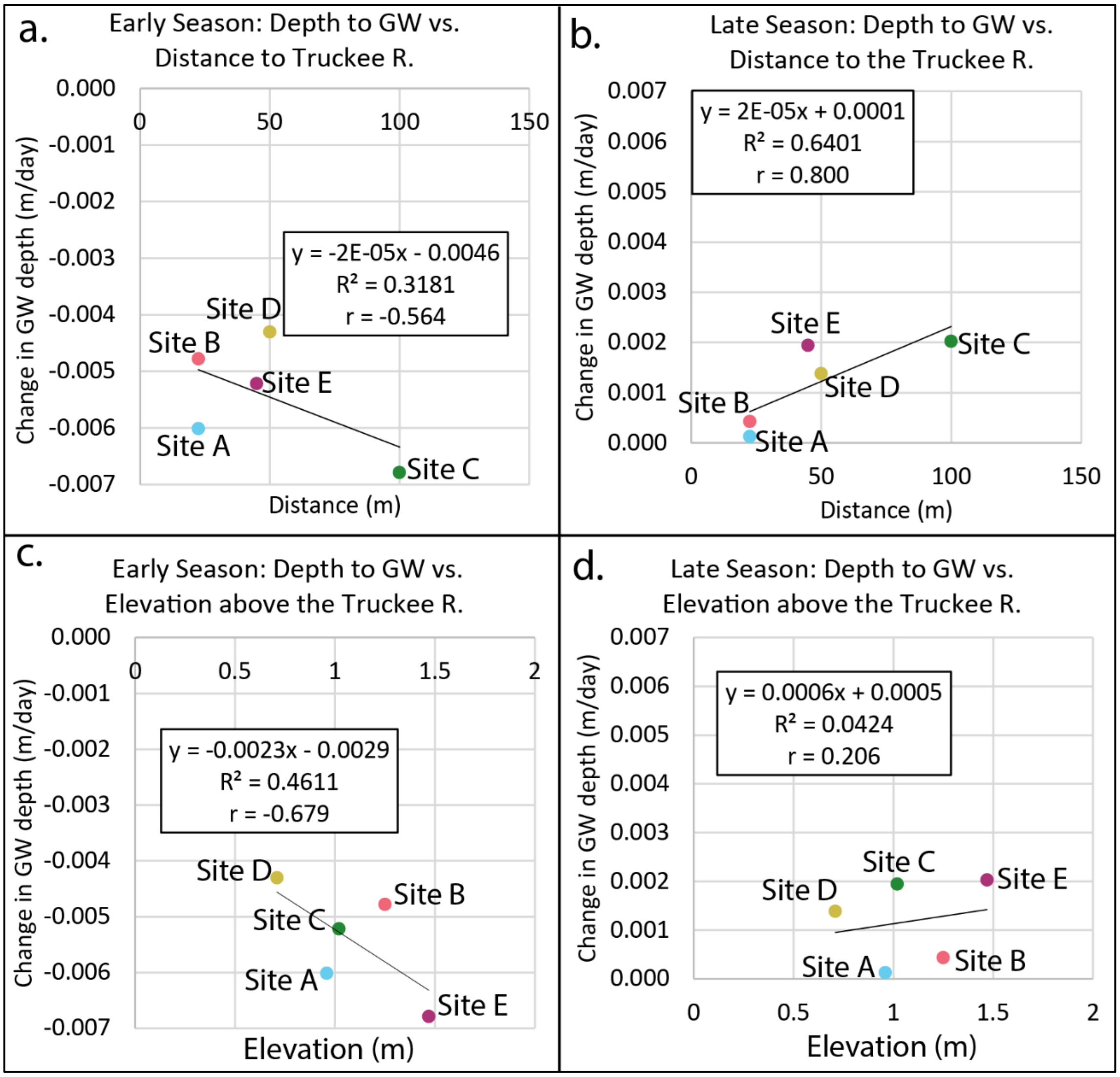

Figure 29. The change in depth to groundwater for each well is graphed in each of the four graphs. The depth to groundwater data is separated into two seasons: early season (April 22-July 9) and late season (August 14-October 6). In graphs (a) and (b), the change in depth to groundwater is graphed against the distance of the well to the Truckee River which was estimated using Google Earth (Google Earth Pro, version 7.3.6.9345). In graphs (c) and (d), the depth to groundwater is graphed against the elevation of the wells above the Truckee River using surveying data collected on September 8.

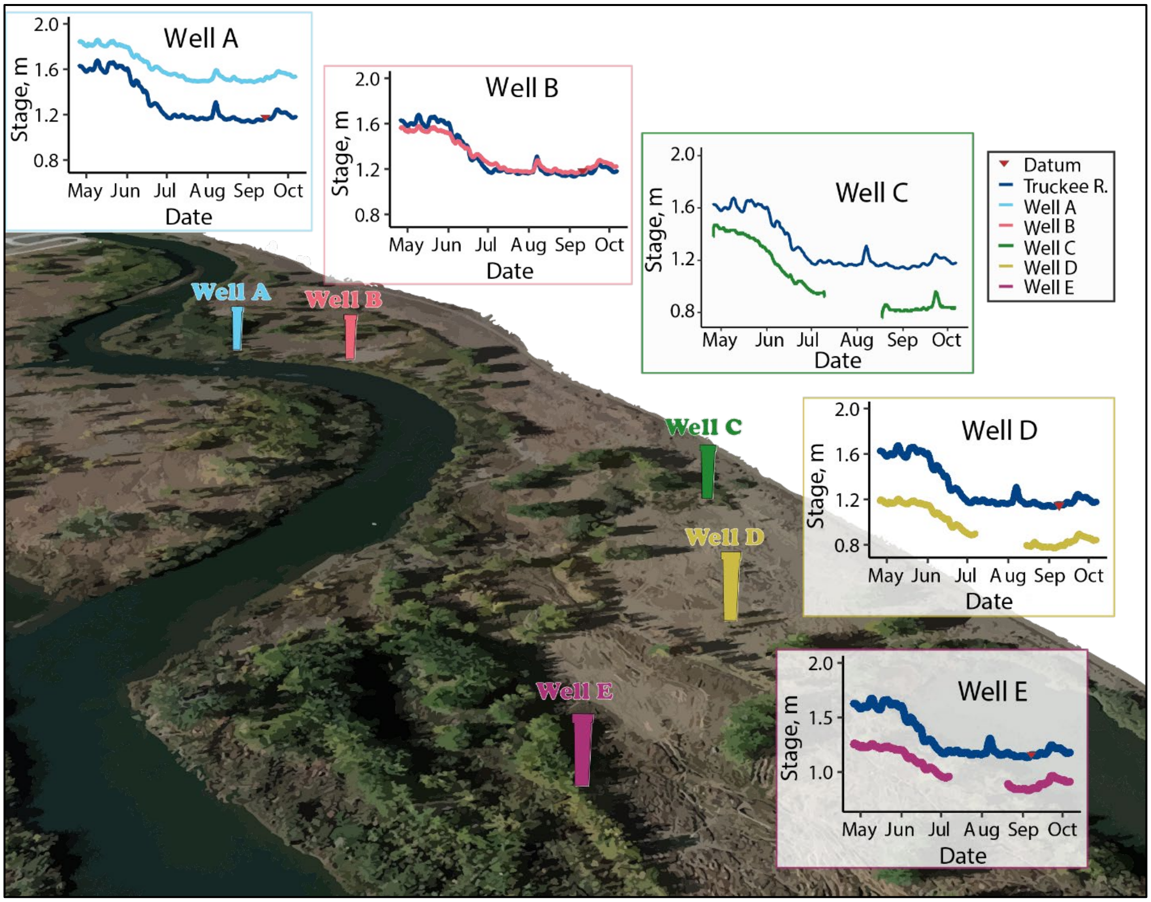

Figure 30. Satellite image of the study area with groundwater graphs corresponding to the five wells. The groundwater levels are graphed relative to the Truckee R iver stage. using elevation data collected from the survey done in September (Google Earth Pro, version 7.3.6.9345).

Using the surveying data collected on September 8th, the groundwater levels were graphed relative to the Truckee River stage (Figure 30) using stage data from the USGS gauge at Vista, approximately 9.5 km upstream. The water at Site B overlaps with the Truckee River at multiple locations. Site A is the only site where the water table remains above the Truckee River; the water table at Sites C, D, E is consistently below the Truckee River. The panel for Well B best demonstrates groundwater response to changes in river stage, in that the patterns are roughly matched but somewhat dampened for groundwater, showing slower changes and a smaller decline. Figure 30 also demonstrates that the groundwater begins to recede rather quickly in Well C, the well that is furthest from the river. Interestingly, Well C reflects groundwater that is likely the most disconnected from the river yet has a rate of recession that is similar to what is seen in the river, demonstrating the potential uniqueness of localized groundwater recession rates (Figure 30).

5.2.2. Soil Characterization (Bulk Density, Field Capacity, Gravel Content)

Soil measurements were collected at the site and plot levels. A one-way ANOVA test, which analyzes the difference in means between two groups, was conducted to test whether bulk density, field capacity, and gravel content values differed between sites (Bevans, 2022). Table 14 summarizes the average values between sites and overall data, distinguished by samples taken at 0-10 cm and 25-35 cm in depth. It also includes the difference in values between the two depths, and the standard deviation of the corresponding data.

For bulk density, the standard deviations were low overall ranging between 0.06 $\frac{g}{cm^3}$ and 0.25 $\frac{g}{cm^3}$, and the standard deviations for the entire data set were 0.30 $\frac{g}{cm^3}$ for 0-10 cm measurements and 0.28 $\frac{g}{cm^3}$ for 25-35 cm measurements. The greatest difference for bulk density between deep and shallow measurements was in site D, with a difference of 0.46 $\frac{g}{cm^3}$. Site B had the highest bulk density at 1.52 $\frac{g}{cm^3}$ and 1.55 $\frac{g}{cm^3}$, and Site E and the lowest bulk density at 0.84 $\frac{g}{cm^3}$ and 0.92 $\frac{g}{cm^3}$. A one-way ANOVA test showed that site location significantly influenced the bulk density at 0-10 cm ($F(4,20)=11.43$, $p<0.0001$) and at 25-35 cm ($F(4,19) = 9.189$, $p = 0.0002$) (Table 14). Post hoc analysis using a Tukey test (Appendix Table 5) indicated there was a significant difference ($p < 0.05$) between Site A and Site B, and between Site B and Site E. There was significant difference at 0-10 cm between Site E and C, and Site E and Site D; and a significant difference at 25-35 cm between Site D and Site B.

Field capacity varied substantially among sites, albeit with relatively small standard deviations among samples implying systematic differences in soil hydraulic traits across sites. The standard deviation for the total data was 0.08 for the 0-10 cm measurements, and 0.09 for the 25-35 cm measurements. Field capacity generally decreased with depth (Table 14). A one-way ANOVA test showed that site location did not influence the field capacity at 0-10 cm ($F(4,20) = 1.682$, $p = 0.194$), but did at 25-35 cm ($F(4,19) = 13.48$, $p < 0.0001$) (Table 14). Post hoc analysis using a Tukey test (Appendix Table 5) indicated significant differences at 25-35 cm ($p < 0.05$) between Site A and Site B; Site A and Site C; Site B and Site D; Site B and Site E; and Site C and Site E.

Soil gravel content values were found to range among sites from 2% to 44%. Site B had the highest gravel content at 44.3 % and 35.8 %, and Site E had the lowest gravel content at 4.2% and 2.3%. A one-way ANOVA test showed that site location significantly influenced the gravel content at 0-10 cm ($F(4,20) = 8.331$, $p = 0.0004$) and at 25-35 cm ($F(4,19) = 6.986$, $p = 0.001$) (Table 14). Post hoc analysis using a Tukey test (Appendix Table 5) indicated there were significant differences ($p < 0.05$) between Site A and Site B; Site A and Site C, Site B and Site E; and Site C and Site E.

Lastly, the soil moisture data was categorized as the mean soil moisture and the minimum soil moisture by plot. The minimum soil moisture was used to capture the driest soil moisture conditions at each location. Table 14 has the mean soil moisture per site at both the surface and at a depth of 30 cm. The mean soil moisture among the sites at the surface ranged between 5.8% and 12.6%, at 30 cm the range was between 2.9% to

26.4% (Table 13). The greatest difference in soil moisture between the surface and 30 cm was in Site A (13.8%) and Site E (8.7%). Site C had the smallest difference between measurement at 30 cm and at the surface (2.9%). The minimum soil moisture among the sites at the surface ranged between 1.8% and 5.0%, and at 30 cm the range was between 3.9% and 9.5%. The greatest difference in minimum soil moisture between the surface and 30 cm was in Site E at 5.7%, and the least difference was in Site C at 1.8% (Table 14).

The low gravel content, high field capacity, and low bulk density in the river-adjacent sites A and B are likely interrelated, and also likely associated with higher organic matter in soils (Curtis & Post, 1964; U.S. Department of Agriculture, 2008). Alternatively, the high gravel content and high bulk density at Site B are unsurprisingly associated with water retention, as reflected by field capacity, because there is less soil to retain water. The consistency in field capacity values across sites suggests that soil properties are relatively consistent across sites, and also lend support to using this metric as a characterization of the soils' hydraulic conditions. The soil moisture values likely have an inverse relationship to the gravel content in soil, where the less gravel a soil has, the higher the soil moisture (Table 13).

Table 14. Summary table of soil characteristics (bulk density (ρ_b), field capacity ($\theta_{v\text{-}fc}$), gravel content (%), mean soil moisture (%), and minimum soil moisture (%), averaged by site and total across the study site. The change in values (Δ) from shallow to deeper depth is also listed, along with the standard deviation (SD) of samples is also listed. The soil samples used for these calculations were collected on July 15.

	Bulk Density (ρ_b), g/cm^3						Mean Soil Moisture				
Site	0-10cm	25-35cm	$\Delta_{\rho b}$	$SD_{0\text{-}10cm}$	$SD_{25\text{-}35cm}$	Site	Surface	30cm	$\Delta_{\%}$	$SD_{0\text{-}10cm}$	$SD_{25\text{-}35cm}$
Site A	1.09	1.00	-0.09	0.06	0.15	Site A	12.6%	26.4%	13.8%	0.06	0.07
Site B	1.52	1.55	0.03	0.25	0.16	Site B	5.8%	9.3%	3.5%	0.02	0.03
Site C	1.35	1.25	-0.10	0.16	0.24	Site C	7.7%	10.7%	2.9%	0.01	0.01
Site D	1.39	0.93	0.46	0.13	0.54	Site D	6.1%	12.5%	6.5%	0.03	0.03
Site E	0.84	0.92	0.08	0.23	0.21	Site E	11.6%	20.4%	8.7%	0.10	0.06
Total	1.27	1.22	-0.05	0.30	0.36	Total	8.3%	14.6%	6.3%	0.06	0.08

	Field Capacity by Volume ($\theta_{v\text{-}fc}$), %						Minimum Soil Moisture				
Site	0-10cm	25-35cm	$\Delta_{\theta v\text{-}fc}$	$SD_{0\text{-}10cm}$	$SD_{25\text{-}35cm}$	Site	Surface	30cm	Δ%	$SD_{0\text{-}10cm}$	$SD_{25\text{-}35cm}$
Site A	38.1%	36.7%	-1.4%	0.04	0.04	Site A	5.0%	9.5%	4.5%	0.02	0.10
Site B	27.6%	18.2%	-9.4%	0.07	0.03	Site B	1.8%	3.9%	2.1%	0.01	0.01
Site C	32.4%	26.7%	-5.8%	0.05	0.07	Site C	2.7%	4.4%	1.8%	0.00	0.02
Site D	31.9%	32.5%	0.6%	0.12	0.06	Site D	2.2%	5.7%	3.5%	0.00	0.02
Site E	34.9%	37.4%	2.5%	0.05	0.05	Site E	3.5%	9.1%	5.7%	0.01	0.04
Total	33.0%	30.20%	-2.8%	0.08	0.09	Total	2.8%	6.1%	3.3%	0.02	0.05

	Gravel, %				
Site	0-10cm	25-35cm	$\Delta_{\%}$	$SD_{0\text{-}10cm}$	$SD_{25\text{-}35cm}$
Site A	4.2%	2.3%	-1.9%	0.04	0.02
Site B	44.3%	35.8%	-8.4%	0.17	0.20
Site C	30.3%	28.4%	-1.9%	0.09	0.18
Site D	26.6%	13.3%	-13.2%	0.23	0.10
Site E	3.4%	2.4%	-1.0%	0.05	0.02
Total	21.7%	16.4%	-5.3%	0.20	0.18

Table 15. One-Way ANOVA analysis on soil bulk density, field capacity, and gravel content.

		Df	Sum sq	Mean Sq	F	Pr(>F)
Bulk Density 0-10cm	Site-Soil	4	1.473	0.3683	11.43	**5.42E-05**
	Residuals	20	0.6444	0.0322		
Bulk Density 25-35cm	Site-Soil	4	1.187	0.29674	9.189	**2.63E-04**
	Residuals	19	0.6136	0.03229		
Field Capacity 0-10cm	Site-Soil	4	0.035	0.008749	1.682	**1.94E-01**
	Residuals	20	0.1041	0.005202		
Field Capacity 25-35cm	Site-Soil	4	0.1205	0.030125	13.48	**2.27E-05**
	Residuals	19	0.04247	0.002235		
Gravel Content 0-10cm	Site-Soil	4	0.6242	0.15604	8.331	**3.99E-04**
	Residuals	20	0.3746	0.01873		
Gravel Content 25-35cm	Site-Soil	4	0.463	0.11576	6.986	**1.09E-03**
	Residuals	20	0.3314	0.01657		

5.2.3. Floodplain Position

The elevation of each plot and well above the Truckee River, along with the distance to the Truckee River is summarized in Table 16. The site furthest from the Truckee River is Site C with distances over 80 m and the sites closest to the Truckee River are Sites A and B which are adjacent to the riverbank. Some sites had considerable microtopography within them across plots, as demonstrated by the greatest variation in elevation ranging from a standard deviation of 0.32 m at Site D to one of 0.10 m at Site C.

Table 16. Summary table for the plot and well distance from the Truckee River, and the elevation above the Truckee River calculated from the surveying done on September 8.

	Elevation above the Truckee R. (m)	Distance from the Truckee R. (m)		Elevation above the Truckee R. (m)	Distance from the Truckee R. (m)
Well A	0.96	22.50	Well D	0.71	50.00
Plot 1	0.91	7.50	Plot 1	0.66	48.00
Plot 2	1.06	22.50	Plot 2	1.29	50.00
Plot 3	1.53	37.50	Plot 3	1.36	55.00
Plot 4	0.96	15.00	Plot 4	1.36	58.00
Plot 5	1.00	30.00	Plot 5	1.06	38.00
SD	0.23	10.61	SD	0.32	6.88
Well B	1.25	22.50	Well E	1.02	45.00
Plot 1	1.04	7.50	Plot 1	0.77	36.00
Plot 2	1.25	22.50	Plot 2	1.07	46.00
Plot 3	1.77	37.50	Plot 3	0.89	56.00
Plot 4	1.33	30.00	Plot 4	1.12	54.00
Plot 5	1.02	30.00	Plot 5	0.80	44.00
SD	0.27	10.25	SD	0.15	7.28
Well C	1.47	100.00			
Plot 1	1.52	104.00			
Plot 2	1.47	97.00			
Plot 3	1.62	87.50			
Plot 4	1.60	86.00			
Plot 5	1.73	97.50			
SD	0.10	7.11			

5.2.4. Historical Conditions

The 2017 water year had the greatest average stage difference for both meteorological spring and summer based on stage data for the USGS gage at Vista over water years 2008 to 2022, where the stage difference is calculated from the beginning stage value to the end of the season. Spring had a difference in stage of +0.9 $\frac{cm}{day}$, and summer had a difference in stage of -2.0 $\frac{cm}{day}$. The lowest average stage difference during spring occurred in 2015 where the difference in stage was 0.0 $\frac{cm}{day}$; during summer, the difference in stage was -0.4 $\frac{cm}{day}$. For 2022 (study year), the average daily stage difference was +0.3 $\frac{cm}{day}$ in spring and -0.4 $\frac{cm}{day}$ during the summer.

For the Central Sierra, the water year with the highest SWE value on March 1st was 2017 (125 cm (49 in)). The year with the lowest SWE on March 1st was in 2018 (17.0 cm (6.7 in)). During the study water year of 2022, the SWE on March 1st was 44.2 cm (17.4 in). Thus, this research was conducted in a relatively dry year, with respect to snow that supplies the Truckee River.

5.3. Discussion of By-Site Observations

Trees in Site C had faster leaf-expansion (Table 4), greater maximum leaf size (Table 4), and higher specific leaf area (Figure 20) than those in the rest of the sites. This is consistent with expectations given that these metrics can all be associated with shading due to competition (Givnish, 1984), and Site C had higher mean stand basal area (Figure 26), LAI (Table 11), LAI above saplings (Figure 27). All together, these data suggest that this site is resilient and productive, despite being further from the river (at 100 m away), at an elevation that is highest above the river (at 1.47 m) and having the fastest groundwater recession rate. Thus, interpreting the by-sites comparisons leads to the conclusion that sufficient access to groundwater is either maintained, despite spatial separation from the river, or is unimportant to these cottonwoods in this growing season. The predawn water potential data showing near-zero values suggests that connection to groundwater is maintained, and that they are still accessing the water table. Thus, even the root systems of the saplings must have been adequately established, which would lead us to expect the same at other sites as well. While the water table is typically shallow in floodplains, Frémont cottonwoods tend to also have deeper roots than other cottonwood species (J. Horton et al., 2003), apparently facilitating access across these substantial site variations. Regarding stand structure, being further from the river may facilitate higher sapling numbers if the distance lessens likelihoods of saplings from being washed away or buried by sediments (Asplund & Gooch, 1988); throughout the site, there is much evidence of floods moving through the floodplain, including regions of sediment deposits with no soil formation and woody-debris wrack lines, but such evidence of flooding does not extend up to site C (personal observation).

The finding that the drier conditions are associated with higher vigor is atypical in arid environments, but not necessarily in floodplains. In a study in northwestern China, in an arid environment with vegetation that relies on groundwater, greatest Normalized Difference Vegetation Index (NDVI) values were observed where groundwater depths were between 2.5-to-3.5 m on the floodplain, as opposed to the shallowest levels (Jin et al., 2011). At Site C, the groundwater levels were between 1 m and 2 m.

Whether trees are located in gaining or losing reaches can also be important; for example, *Populus trichocarpa* in an alluvial floodplain in western Montana was found to have significantly greater BA and tree growth in the gaining reach of the floodplain because of fertilization occurring due to hyporheic flow (Harner & Stanford, 2003). The research in this thesis was done at a smaller scale and only Site A was consistently at a gaining reach of the Truckee River (Figure 30), and Site A did not have the greatest BA (and did not stand out with respect to any metric). Site E also had plots with abundant vegetation like site C, and also high SLA values (Figure 20), additionally an inverse relationship was observed between predawn water potential and basal area across all sites (Figure 31; p =

0.026, $R^2 = 0.114$); thus, there was a pattern of positive covariation between stand-level vigor metrics and a physiological metric reflecting water access. Soil water was seemingly abundant across site E (Table 13), further indicating the stress introduced by solar radiation and highlighting the benefits of partial shade for saplings.

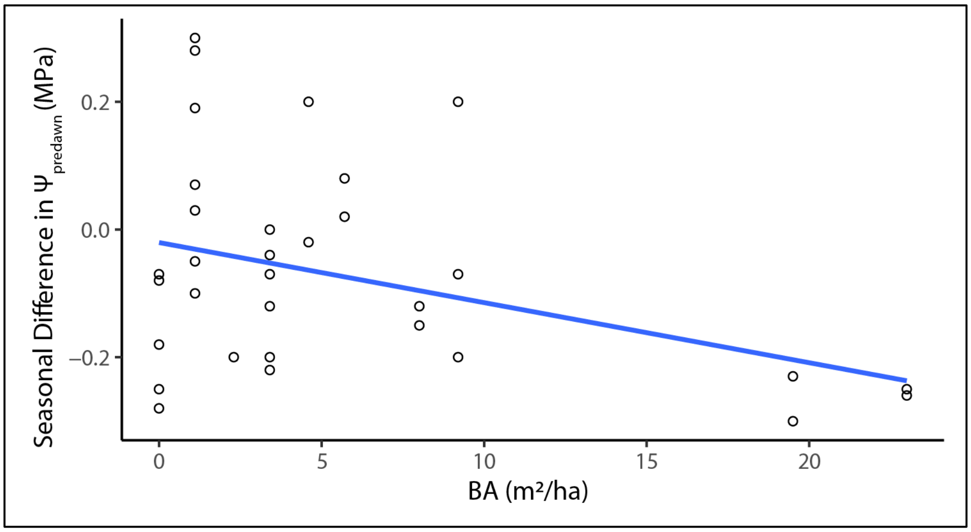

Figure 31. Linear regression of BA vs. the difference in predawn water potential across all sites (p=0.026, R2=0.114).

In contrast to both Site C and Site E, Site B, which is adjacent to the Truckee River, saw smaller tree-level leaf area (LA), a stress indicator that could be in response to the low LAI and thus low shading in the site (Figure 27). Site B also has a lower average length in growing season compared to other sites as well as a later leaf-out date which could also be indicators of stress (Figure 15, Figure 13). Variations in the groundwater mostly cohered with the river levels at Vista throughout the growing season, , despite spatial the separation between Mustang and the gage at Vista, suggesting that the river contributed to the groundwater levels remaining fairly close to the surface. At Site B, soil may also be a major control over the establishment and stress in cottonwoods, as demonstrated by this site having the highest gravel content and lowest field capacity (Table 13). This may be an indication that this soil is not ideal for cottonwood growth, or tree growth in general. Prior to restoration, this reach of the floodplain was agricultural land, but the original soil composition at this small scale prior to the channelization of the river is unknown since the geomorphology has changed. Even if groundwater is available, poor soil quality may prevent trees from establishing as frequently, driving an interplay between soil dryness and high radiation inputs due to the low canopy cover, considering that stress and reduced productivity can result from either (or both) factors related to soil-water limitations of water availability to roots or from atmospheric demand and potential evapotranspiration at a leaf surface.

Interestingly, variability among tree-function metrics were least for mature trees in mid-summer, whereas heterogeneities were larger in the beginning and end for saplings. For example, chlorophyll concentrations were least variable towards peak growing season (August 10) (Figure 16), which makes sense because of observed differences in rates of leaf out and senescence. The greater variation in stomatal conductance values observed in Figure 18 for saplings was also not surprising. Although there was an upper boundary of height to classify what is considered a sapling, aboveground size likely does not correlate to rooting depth (Goldsmith et al., 2019) and therefore the range in ages within the category of ‘sapling’ could imply differences in connection to groundwater, and this is unlikely to be true of the more established mature cottonwoods. That said, it should also be noted that chlorophyll concentrations values in the mature cottonwoods, which were generally lower, may reflect biases due to the leaves sampled at arms-reach and thus the shade leaves may poorly represent the entire tree productivity. The largest overall change in chlorophyll was observed in the saplings in Sites B and D (Figure 17), specifically between the peak and late season. The saplings in Site D had a shorter growing period (Figure 15) which is likely reflected in Figure 17, similar to saplings in Site B, with an increase of saplings at or near zero. These changes were more apparent in the stomatal conductance data, showing large changes in saplings from peak season to the late season; alternatively, the mature cottonwoods remained more stable between seasons (Figure 19). The large variability among Site C saplings may be due to the variety of age or vigor conditions seen there.

Vegetation surveys characterize stand conditions that reflect the resistance and resilience of the forest stands. Whereas many of the metrics used in this study reflect instantaneous conditions, and thus the scope of inferences is limited to understanding responses in this year, stand structure and crown characteristics integrate stress responses over prior years. The mature cottonwood foliage transparency survey is a good indicator of tree stand health, supported by the vigor survey results done for saplings. Site C had mature cottonwoods with slightly higher foliage transparency (Figure 22). This is expected as there is a higher mean basal area and higher density of trees around the study trees at this site (Figure 26, Figure 25), leading to competition for light, naturally prompting trees to self-prune and have shorter crowns (Oliver & Larson, 1996). The saplings at Site C, however, showed poorer conditions than in other sites (Figure 23), likely due to the higher shading caused by the density of cottonwoods. The sites with slightly lower transparencies include Site A, B, D, and E (Table 10), which also showed lower mean densities of saplings and mature trees at these sites (Figure 25, Figure 26). Surprisingly, the saplings had strong vigor in Site B, and poorer in sites D and E (Figure 25), showing that the study-tree saplings, all of which were established and apparently had access to subsurface waters

(Table 9, Table 10), benefitted from less shade (Table 12; Figure 25, Figure 26); those benefits of light may not extend to younger saplings or seedlings in denser locations.

The prolonged drought conditions likely did not allow the Truckee River water levels to meet the recruitment zone of the cottonwoods during the study period in 2022 (suggested by the initial stage of 1.20 m; Table 17), which include having the peak flow fully saturate the soil in mid-June during the period of seed dispersal, and have the river stage recede at a rate that allows the cottonwood roots to remain in contact with the water table (Mahoney & Rood, 1998; Rood, Gourley, et al., 2003). The initial stage was greatest for the summers of 2017 (2.33 m) and 2019 (2.34 m), in response to the high snowmelt (assumed from the SWE values measured on March 1st; Table 17). These conditions likely resulted in flows reaching the recruitment zone and are partially responsible for some of the saplings at our study site. During field visits in the 1990s, Rood, Gourley et al. (2003) saw unusual patterns of establishment in Frémont cottonwood saplings along the Lower Truckee River, where they lined the bank due to low flows following the 1987 recruitment year, as opposed to commonly being in the point bars of meanders. In our study, however, the 2019 water year also brought high water levels, potentially scouring the young saplings at lower elevations and along cut banks. This likely led to a more natural establishment pattern and is a possible explanation for the lower recruitment seen at Site B which is located along a cutbank. Since the USGS gage at Vista is approximately 9.5 km upstream of this site, it is difficult to know what stage would result in flooding at this location.

Table 17. Average of daily discharge between 2008 and 2022 at Vista for meteorological spring and summer along with snow water equivalent (SWE) averages between 2008 and 2022 for the Central Sierra (CDEC, 2023) (USGS, n.d.). A blue gradient exists for the change in stage, where the darker hue represents lower values.

	Spring			Summer			Snow Water Equivalent (March 1)		
Year	$Stage_{initial}$	$Stage_{final}$	Δ stage rate (cm/day)	$Stage_{initial}$	$Stage_{final}$	Δ stage rate (cm/day)	% normal for date	inches	Stations Reporting
2008	1.29	1.48	0.20	1.47	1.29	0.20	107%	29.2	44
2009	1.34	1.61	0.30	1.61	1.21	-0.44	74%	19.5	42
2010	1.41	1.63	0.24	1.63	1.29	-0.38	91%	24.1	45
2011	1.33	2.23	0.99	2.23	1.30	-1.02	123%	33.6	39
2012	1.32	1.63	0.34	1.63	1.22	-0.46	32%	8.5	41
2013	1.34	1.55	0.24	1.55	1.34	-0.23	64%	17.2	40
2014	1.34	1.71	0.41	1.71	1.00	-0.78	36%	9.7	41
2015	1.24	1.26	0.02	1.26	0.90	-0.40	21%	5.3	44
2016	1.32	1.65	0.36	1.65	1.12	-0.59	87%	21.7	39
2017	2.33	3.12	0.86	3.12	1.33	-1.97	191%	49	42
2018	1.28	1.60	0.36	1.60	1.21	-0.43	25%	6.7	42
2019	2.34	2.87	0.58	2.87	1.32	-1.70	155%	40.1	43
2020	1.16	1.29	0.14	1.80	1.20	-0.66	43%	11.4	44
2021	1.23	1.29	0.06	1.29	0.95	-0.38	68%	17.7	41
2022	1.20	1.51	0.34	1.51	1.14	-0.41	67%	17.4	43

5.4. Evaluation of Research Question 1: Mature Trees versus Saplings

A series of T-tests, ANCOVA tests, linear regressions, and data representing plant physiological traits and independent data related to water availability were used to test whether collocated Frémont cottonwoods in differing life stages experience water stress similarly.

For specific leaf area (SLA), one t-test was run for each site between mature trees and saplings. The five t-tests showed significant differences in Site A ($t = 2.807$, $df = 93$, p-value = 0.006) where mature cottonwoods had greater values, in Site C ($t = -7.535$, $df = 125$, p-value < 0.0001) where saplings had greater values, and in Site E ($t = 3.188$, $df = 105$, p-value = 0.0019) where mature cottonwoods had greater values. Differences were not significant in Sites B (t = -0.5088, df = 91, p-value = 0.61), or D (t = 1.385, df = 85, p-value = 0.17).

ANCOVA tests were done at the site level, plot level, site and tree level with plant physiological traits as the dependent variable, the maturity of trees as the independent variable, and hydrological data as a covariate. This tested to see whether a relationship exists between the hydrological and plant physiological parameter, and if it is due to cottonwood age. Table 18 visualizes the tests and variables used for each test.

Table 18. List of ANCOVA tests done, with plant physiological traits on the top row, and hydrological drivers on the left column.

Analysis X|Y	SLA	Max chl	Length of Growing Season	Late season $\Psi_{predawn}$	Seasonal difference in g_s
Late Season GW Table Depth	plot|plot	plot|plot	plot|plot	plot|tree	plot|tree
Soil θ (lower 50% quartile)	plot|plot	plot|plot	plot|plot	plot|tree	plot|tree
Elevation Above the Truckee R.	plot|plot	plot|plot	plot|plot	plot|tree	plot|tree
Distance from the Truckee R.	plot|plot	plot|plot	plot|plot	plot|tree	plot|tree
Soil Field Capacity	site|site	site|site	site|site	plot|tree	plot|tree
% Gravel in Soil	plot|plot	plot|plot	plot|plot	plot|tree	plot|tree

The relationship between SLA and distance from the Truckee River significantly depended on the maturity of the cottonwoods (F = 12.58 , df = 1, p < 0.001). For the mature cottonwoods, SLA did not decrease significantly as distance to the Truckee River increased (F = 0.12, df = 1,17, p = 0.735, R^2 = -0.01), but for the saplings, the SLA did increase significantly as the distance to the Truckee River increased (F = 19.6, df = 1,16, p = 0.0004, R^2 = 0.52) (Figure 32). This trend, however, appears driven by one site (Site

C) which had especially high SLA values for saplings (possibly in response to density or competition for solar radiation); otherwise, the sapling and mature SLA values were quite similar.

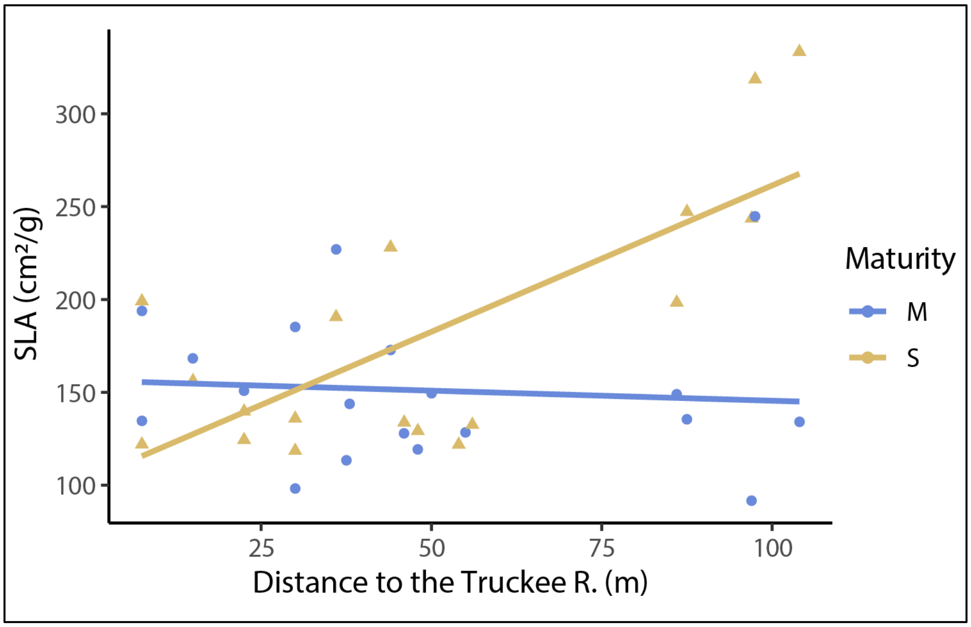

Figure 32. The relationship between SLA and distance to the Truckee R for both mature cottonwoods and saplings (ANCOVA: $F = 12.58$, $df = 1,92$, $p < 0.05$).

Significant relationships were also seen between the late season water potentials and the distance to the Truckee River. The late season predawn water potential significantly decreased as the distance to the Truckee River increased ($F = 8.449$, $df = 1,92$, $p = 0.005$), and the influence of cottonwood maturity on water potential was significant ($F = 5.87$, $df = 1,92$, $p = 0.02$), although there was no significant interaction effect (i.e., by-maturity-class differences in the dependence of predawn water potential on the distance to the Truckee R; $F = 0.14$, $df = 1,92$, $p = 0.71$) (Figure 33). Saplings had higher water potentials (i.e., closer to zero), implying that they experienced slightly better water status across the site gradients; however, the effects of height may influence these small differences, and in all cases the predawn values were minor.

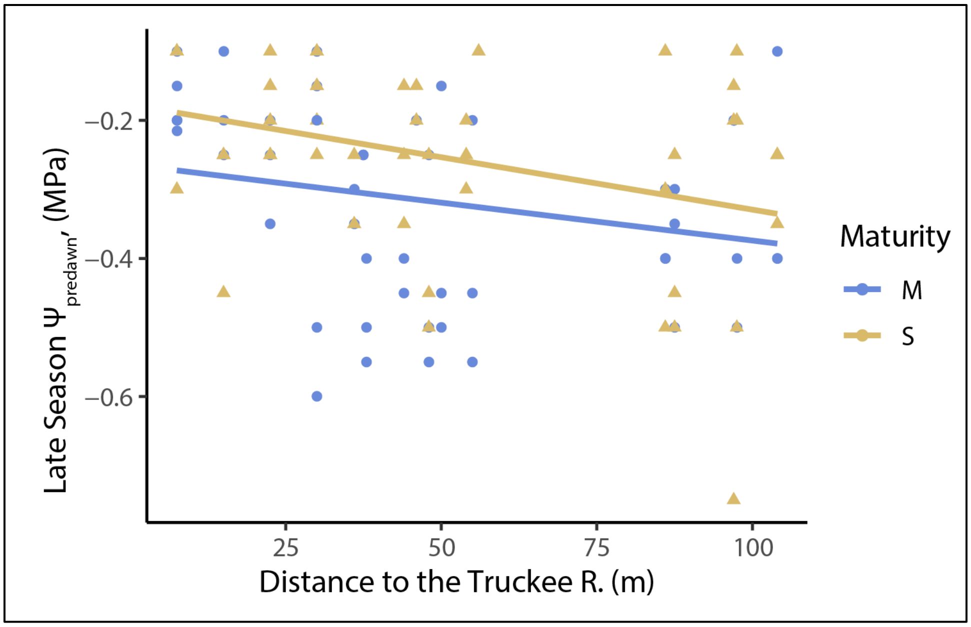

Figure 33. The relationship between the late season Ψpredawn and distance to the Truckee River for both mature cottonwoods and saplings (F = 8.45, df = 1,92, p = 0.005).

Finally, significant relationships were also seen between the late-season predawn values and the depth-to-groundwater values. The late-season predawn water potential decreased as the depth to groundwater increased significantly (F = 7.153, df = 1,92, p = 0.009), and the influence of cottonwood maturity on water potential was significant (F = 4.92, df = 1,92 , p = 0.03); there was no significant interaction effect (i.e., by-maturity-class differences in the dependence of predawn water potential on the distance to the Truckee R; F = 0.69, df = 1,92, p = 0.41) (Figure 34). Thus, these data suggest that groundwater availability to roots declines (somewhat) with depth of groundwater, and that effect has similar influences on both mature and sapling trees.

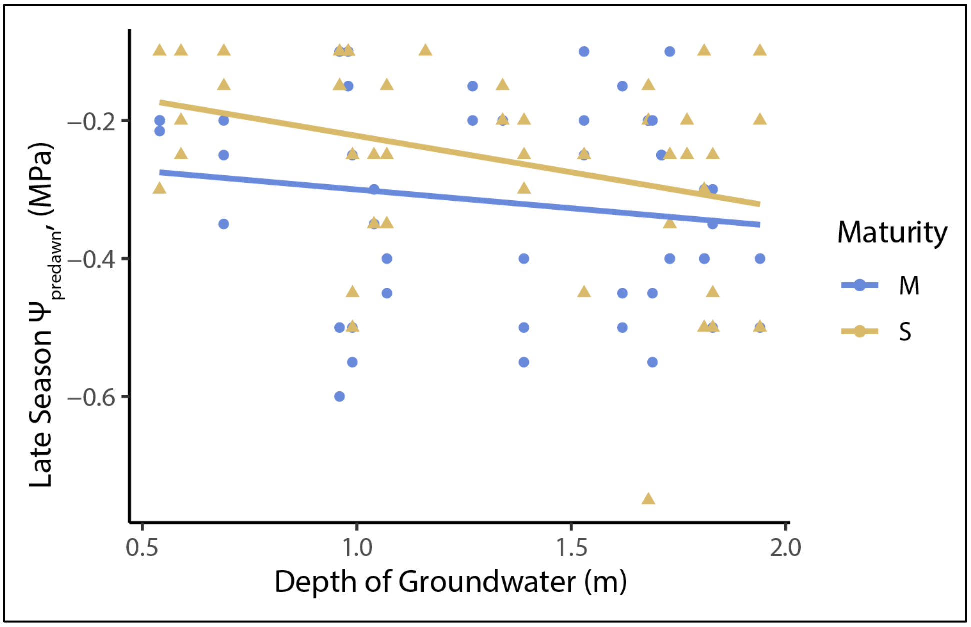

Figure 34. Relationship between late season Ψpredawn and depth to GW for both mature cottonwoods and saplings ($F = 7.15$, df = 1,92, $p = 0.009$).

Paired t-tests at the plot level were done on the variables for which the ANCOVA tests failed to show a linear dependence of physiological variables on any of the variables related to water access. There were 6 tests done in total testing for differences by-maturity-class between physiological traits, including SLA, maximum chl, difference in g_s, growing-season length, and late-season predawn water potential. The average SLA for mature cottonwoods (159 ± 11 cm^2/g) was not significantly lower than the average SLA for saplings (198 ± 18 cm^2/g) (at $p < 0.05$), although differences may be revealed by a larger dataset (paired t-test, $t = -1.973$, df = 13, $p = 0.07$) (Table 19). There was no significance difference found between maturity levels of cottonwoods for maximum chlorophyll (paired t-test, $t = -0.951$, df = 13, $p = 0.36$), seasonal change in g_s (paired t-test, $t = -0.858$, df = 13, $p = 0.41$), seasonal change in predawn water potential (paired t-test, $t = -0.88$, df = 13, $p = 0.39$), growing period length (paired t-test, $t = -1.732$, df = 13, $p = 0.11$), or late-season predawn water potential (paired t-test, $t = -1.46$, df = 13, $p = 0.17$) (Table 18).

Table 19. Summary table of paired t-tests that include SLA, maximum chl, Seasonal difference in g_s, difference between predawn Ψ, length of growing season, and late season $\Psi_{predawn}$.

	Mature			Sapling			Paired t-test	
Variable (units)	Mean	SD	N	Mean	SD	N	t	p-value
SLA (cm^2/g)	160	42	14	198	69	14	-1.973	0.07
Max chl (mg/m^2)	470	52	14	484	39	14	-0.952	0.359
Seasonal difference in g_s ($mmol/(m^2s)$)	83	84	14	106	74	14	-0.858	0.406
Length of Growing Season (days)	181	8.0	14	189	18	14	-1.732	0.107
Late season $\Psi_{predawn}$ (Mpa)	-0.31	0.1	14	-0.26	0.10	14	-1.46	0.169

5.4.1. Discussion

Overall, the data showed a mixed story. While there were a few significant differences observed between mature cottonwoods and saplings, we consider this study to fail to reject the null hypothesis $H1_0$. SLA can be used as an indicator for water stress in vegetation, where a lower SLA is seen in water-conservative plants leading to smaller yet thicker leaves. However, there were no consistent differences in SLA between saplings and mature trees, even if differences were seen in Site A, Site C, and Site E. Similarly, the ANCOVA test run to test maturity difference between SLA and distance to the river showed significant differences, but these results are likely confounded by the significant variations in LAI (Table 27) and how the degree of shading influences SLA confounding its use as a stress metric. Distance from river also significantly related to the late season predawn water potential, and that relationship differed for cottonwoods of differing maturity levels. It was unexpected that the saplings would show higher predawn water potentials, suggesting greater access to subsurface waters. A similar significant relationship with predawn water potentials was observed for depth to groundwater. The rest of statistical tests of saplings versus mature trees were non-significant. Given that the predawn water potential data were the only data indicative of water stress differences between the maturity classes, and that effect was small even if it was significant, we conclude that we failed to reject the null hypothesis and cannot conclude from this study that there were functional differences in the effects of water stress amongst collocated Frémont cottonwoods of different ages.

5.5. Evaluation of Research Question 2: Does Subsurface Water Availability Matter (across the observed range of variation)?

A series of forty-two linear regressions were done between cottonwood physiological data and hydrological data (Table 20). Twelve were used to test floodplain hydrology influences on stomatal conductance and photosynthetic potential ($H2_A$), twelve to test floodplain hydrology influences on tree-level growing season length ($H2_B$), 24 to test floodplain hydrology influences stand-level density and stand-level productivity in Frémont cottonwoods ($H2_C$), and 21 from the aforementioned 42 were additionally used to test the influence of soil characterization on cottonwood productivity and vigor ($H2_D$) (Table 19).

There were one significant p-values found of the 12 linear regressions run to test hypothesis $H2_B$, regarding tree-level stress indicators ($p < 0.05$) (Table 20), but none related to stomatal conductance. Stomatal conductance was used to quantify the cottonwood water use and characterize plant water status throughout the season and was compared with soil moisture (Table 21). Shallow soil moisture was reported as an average of values at 30 cm and at the surface, and, along with g_s data, were aggregated to be associated with early season (June 1st, June 4th) and late season (September 25th). A Pearson coefficient and a Spearman coefficient was calculated for 'Mature vs Soil Moisture at the Surface', 'Mature vs Soil Moisture at 30cm, 'Sapling vs Soil Moisture at the Surface', 'Sapling vs Soil Moisture at 30cm'. Average of both the stomatal conductance and soil moisture values were taken per plot. Both the Pearson coefficient (r) and the Spearman coefficient (r_s) showed no significant relationship found between g_s and shallow soil moisture (Table 21). Alternatively, when examining chl, there were two significant p-values in the tests of hypothesis $H2_A$ ($p < 0.05$): maximum chl increased with elevation above the river ($p = 0.003$, $R^2 = 0.204$), and maximum chl increased with distance from river ($p = 0.012$, $R^2 = 0.143$) (Table 20). Overall, this data suggests that subsurface water availability does not result in a tree-level stress response in Frémont cottonwoods.

Table 20. List of linear regression tests done, with plant physiological traits on the top row, and hydrological drivers on the left column. *The soil moisture data lower than the 50th quartile was used for this analysis.

		$H2_A$		$H2_B$		$H2_C$		
	Analysis X|Y	Seasonal difference in g_s (plot)	Max chl (plot)	Growing Period Length (plot)	Foliage Transp. of mature cottonwoods (plot)	Basal Area (plot)	Saplings within 1m of study trees (plot)	LAI (plot)
	Late Season Depth to GW (Site)	p=0.483 R^2=-0.014	p=0.054 R^2=0.076	p=0.488 R^2=-0.014	p=0.171 R^2=-0.055	p=0.289 R^2=-0.005	p=0.097 R^2=0.050	p=0.091 R^2=0.053
	Elevation Above River (plot)	p=0.622 R^2=-0.021	**p=0.003** R^2=0.204	p=0.589 R^2=-0.020	p=0.083 R^2=0.118	p=0.056 R^2=0.080	p=0.065 R^2=0.068	p=0.202 R^2=0.019
	Distance from River (plot)	p=0.800 R^2=-0.027	**p=0.012** R^2=0.143	p=0.993 R^2=-0.029	p=0.098 R^2=0.103	p=0.521 R^2=-0.017	**p=0.002 R^2=0.217**	**p=0.034** R^2=0.097
$H2_D$	Field Capacity (plot)	p=0.058 R^2=-0.073	p=0.165 R^2=0.027	p=0.973 R^2=-0.029	P=0.805 R^2=-0.055	p=0.172 R^2=-0.027	p=0.817 R^2=-0.027	p=0.547 R^2=-0.018
	% Gravel (plot)	p=0.397 R^2=-0.007	p=0.550 R^2=-0.018	p=0.217 R^2=-0.016	p=0.492 R^2=-0.029	P=0.077 R^2=0.064	P=0.400 R^2=-0.008	p=0.532 R^2=-0.017
	Soil θ* (plot)	p=0.464 R^2=-0.013	p=0.446 R^2=-0.011	p=0.605 R^2=-0.021	**p=0.044** R^2=-0.011	**p<0.001 R^2=0.403**	p=0.503 R^2=-0.032	p=0.427 R^2=-0.010

Table 21. Summary table of Pearson coefficient (r) and Spearman coefficient (rs) for stomatal conductance versus shallow soil moisture data averages (at surface and 30 cm) per plot, coefficients with a p-value < 0.05 are in bold.

	Early Season		Late Season	
	r	r_s	r	r_s
Mature vs. @ Surface	-0.18	0.16	-0.24	-0.35
Mature vs. @ 30cm	0.01	0.11	-0.04	-0.05
Sapling vs. @ Surface	-0.14	0.31	0.09	0.14
Sapling vs @ 30cm	0.17	0.14	-0.07	0.05

Of the 24 linear regressions run to test hypothesis $H2_C$, four showed significant p-values. Significant findings included the following: the foliage transparency increased with decreasing soil θ ($p=0.044$, $R^2=0.011$), basal area increased with soil θ ($p < 0.001$, $R^2 = 0.403$), the number of saplings within 1 m of study trees increased with distance from river ($p = 0.002$, $R^2 = 0.217$), and plot-level LAI increased with distance to the river ($p = 0.034$, $R^2 = 0.097$). Two showed relatively strong covariation between the independent and dependent data ($R^2 > 0.2$), basal increasing with soil θ ($p < 0.001$, $R^2 = 0.403$), and the number of saplings within 1 m of study trees increased with distance from river ($p = 0.002$, $R^2 = 0.217$) (Table 19).

Finally, of the 21 linear regressions run to test hypothesis $H2_D$, examining relationships between stress indicators and other site variables, two resulted in significant p-values. Significant findings included the following: the foliage transparency decreased with increasing soil θ ($p = 0.044$, $R^2=0.011$), and basal area increased with soil θ with a strong covariation between the independent and dependent data ($p < 0.001$, $R^2 = 0.403$) (Table 20).

5.5.1. Discussion

As with the H1 tests, the data evaluating H2 shows a mixed story.

There were two significant differences observed between floodplain hydrologic data and chl data suggesting that productivity (per leaf area) may substantively differ across the floodplain. Surprisingly, the data showed significant increases in chl with distance from and height above the river. Chlorophyll is a metric for photosynthesis, or leaf productivity, and was expected to decrease with a distance increase. Thus, although no data supported

$H2_A$, a difference in leaf productivity was observed. No data supported $H2_B$. Regarding H_2C, there was substantial supporting evidence, with strong relationships observed between the independent water-access metrics and stand-level metrics of structural density (BA), crown vigor (transparency), stand productivity (LAI), and recruitment potential (sapling density). Lastly, there was also substantive suggestion that soil characteristics are important to stand-level metrics, in support of $H2_D$.

Nonetheless, there were few significant results overall. Moreover, there are potential confounding factors within the significant findings. The maximum chlorophyll values increased with distance and elevation from the river, but chl levels are likely also influenced by vegetation density. Additionally, some of the relationships were opposite of what we observed in the field, warranting further scrutiny. We reject the null hypothesis, because there were indeed variations in trees and stands across the floodplain, but we also do not conclude that the alternative hypotheses capture our observations, and thus further research is warranted.

6. Conclusion

6.1. Overview

The results were mixed for the two research questions we addressed, with marginal evidence that the saplings and mature trees behaved differently, and some data showing variations in various characteristics associated with soils, soil moisture, and floodplain position (pertaining to river connectivity). Regardless, our results inform us of the eco-hydrological processes occurring in this section of the floodplain. Therefore, future research could lead to more targeted and informed hypotheses and hypothesis tests, and those in charge of restoration efforts can refer to our results to track the success of restoration, and thus adjust management practices accordingly.

6.2. Study Design

There were various ways the selection of sites and plots could have been established. For example, there could have been fewer sites but more trees and plots within sites, to improve resolution in comparing plot-scale variations. This, however, could limit the stretch of the floodplain that would be sampled and may not have captured the variation in cottonwood health that was observed. A challenge to our site selection that was designed to reflect various positions relative to the Truckee River was the variability within sites and between plots that existed, making it difficult to treat sites as a unit for comparison, which was an initial intent of the design. In all the sites, for example, there was at least one plot with noticeably less vegetation than the rest, often devoid of cottonwoods. These small-scale variations suggest how floodplain position is not the dominant control over the structure of the ecosystem.

An improvement to this research would be to conduct instantaneous measurements, such as chlorophyll and stomatal conductance, in a more organized manner. Although the sampling occurred in generally the same area each visit, in some instances the values between leaves were variable. Three leaves were used for chlorophyll to get a better representation of the tree values, but for other measurements such as stomatal conductance and water potential where only one leaf was used per study tree, more measurements would improve the research design. Time limitation and field assistance became a concern when selecting the sampling dates and the number of measurements taken for each cottonwood.

However, retrospectively, the variability among measurements and trees were too great to detect plot- or site-level differences.

Another important consideration is the use of one field season. Although it was a dry summer, which might be expected to enhance variations among trees, the predawn water potential measurements provided robust evidence that all trees had access to highly available subsurface waters. However, the variations among stand structure, sapling density, and crown transparency all indicate functional differences among the conditions experienced by these trees, and perhaps those differences require more severe drought conditions to manifest.

6.3. Final Remarks

These results contribute to the knowledge of the micro-scale variation of floodplain tree physiology, specifically in an environment where large-scale restoration work has been done, and their relationship with hydrological processes. Also, this research being conducted during multi-year drought conditions was beneficial to see how floodplain systems behave in response to regulated minimum flow.

This research would benefit from a multi-year study to track the geomorphological changes following extreme restoration efforts as the environment transitions to a more natural system. One finding of potential importance to managers is that the trees performed relatively similarly physiologically, despite poor soil conditions existing (e.g., at Site B) in some areas, and yet this did not show detrimental effects to the established individuals. Thus, as both a pioneer species and a drought tolerant tree focusing on getting cottonwoods into the ground may be more of a priority than concern over their specific microenvironmental conditions. It is unclear how these results translate to other floodplains and other floodplain tree species in semi-arid environments, or other members of the genus *Populus* that inhabit riparian areas in North America and elsewhere (Blasini et al., 2021; Sankey et al., 2021).

Questions that arose from conducting this research included: how often, or what percentage of cottonwoods experience above-ground mortality; when is the best time to plant vegetation meant for restoration efforts; and do certain planting patterns garner greater success in establishment? Restoration management practices are constantly evolving with various arguments on what is the best approach to address environmental concerns. Interestingly, what we have learned about cottonwoods, including even these specific cottonwoods we studied, may not help in mitigating the threats to this system because various invasive species have also become prevalent vegetation types over the study reach. A non-native species can be introduced to an ecosystem and create disorder, and thus there can be large consequences from small actions, as has been seen continuously throughout the history of environmental management (EPA, 2022). Thus, despite the apparent overwhelming success of the Truckee River restoration project on cottonwood resistance and resilience, limitations will continue to exist. Continued monitoring and understanding of changes is key to mitigating issues early; thus, as a post-restoration survey of various characteristics, this study also provides a key step in measurements and record-keeping that can serve to support identifying changes yet to come.

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8. Appendix

Appendix Table 1. Summary statistics for peak leaf area and leaf growth rate. Plot-level data were compared to calculate the Pearson and Spearman correlations at the site-level. Correlation values between -0.7 and -1, and 0.7 and 1, are shaded in light red. Correlation values with a p-value ≤0.05 are bolded. Data omitted include sites with less than 3 values, and plots that were not present in both mature and sapling data.

		Mature vs. Sapling	
	Site	r	r_s
Peak Individual Leaf Area	A	0.14	-0.50
	B		
	C	0.08	-0.20
	D		
	E	-0.86	-0.50
	Total	**0.83**	0.70
Leaf Growth Rate	A	0.99	0.87
	B		
	C	0.80	**0.90**
	D		
	E	**0.96**	1.00
	Total	0.71	0.80

Appendix Table 2. Summary statistics for chl (mg/m^2) values throughout the season, and between seasons. In addition to SD and SE values for site, a total SD and SE is calculated for the total matures and saplings, and a sitewide total.

		Early Season		Peak Season		Late Season		ΔPeak-Early		ΔLate-Early		ΔLate-Peak	
		SD	SE	SD	SE	SD	SE	SD	SE	SD	SE	SD	SE
Mature	A	61	20	44	15	78	26	63	21	80	27	66	22
	B	31	10	43	14	99	33	39	13	85	28	77	26
	C	64	17	61	16	135	36	56	15	122	33	114	30
	D	50	15	80	24	65	20	66	20	66	20	57	17
	E	47	21	43	19	99	44	19	8	68	30	59	26
	Total	64	9	104	15	104	15	62	9	99	14	83	12
Sapling	A	23	7	42	12	97	28	46	13	102	30	122	35
	B	44	15	65	22	84	28	74	25	80	27	82	27
	C	55	14	86	22	85	22	71	18	84	22	89	23
	D	30	17	52	30	91	53	42	24	109	63	85	49
	E	29	9	50	15	91	27	61	18	96	29	56	17
	Total	57	8	64	9	110	16	70	10	121	17	106	15
Sitewide Total		48	5	64	6	108	11	66	7	111	11	96	10

Appendix Table 3. Summary statistics for g_s (mmol/(m^{2}s) values throughout the season, and between seasons. In addition to SD and SE values for site, a total SD and SE is calculated for the total matures and saplings, and a sitewide total.

		Early Season		Peak Season		Late Season		Δ(Peak-Early)		Δ(Late-Early)		Δ(Late-Peak)	
		SD	SE	SD	SE	SD	SE	SD	SE	SD	SE	SD	SE
Mature	A	38	13	237	79	108	36	252	84	115	38	311	104
	B	105	37	158	56	141	50	162	57	145	51	130	46
	C	94	25	255	68	292	78	226	60	268	72	251	67
	D	65	20	323	97	167	50	295	89	129	39	255	77
	E	112	56	79	40	108	54	226	113	182	91	232	116
	Total	92	13	248	36	204	30	226	33	182	26	232	34
Sapling	A	83	24	222	64	149	43	216	62	156	45	299	86
	B	167	56	220	73	112	37	324	108	154	51	292	97
	C	134	36	228	61	193	52	248	66	161	43	254	68
	D	92	41	379	169	214	96	342	153	173	78	330	148
	E	159	41	275	71	179	46	256	66	162	42	222	57
	Total	148	20	269	36	166	22	280	38	170	23	281	38
Sitewide Total		127	13	268	27	185	18	259	26	180	18	274	27

Appendix Table 4.
Post hoc Tukey test results for growing period data that is organized by site and maturity. All p-values<0.05 are in bold and results are highlighted.

Tukey Results - Length				
Site Maturity	diff	lwr	upr	p-adj
A S-A M	-13.722	-36.052	8.607	0.607
B M-A M	-15.322	-38.589	7.945	0.509
B S-A M	-13.667	-37.538	10.205	0.699
C M-A M	-7.222	-28.857	14.413	0.985
C S-A M	-5.289	-26.640	16.062	0.998
D M-A M	0.051	-22.710	22.811	1.000
D S-A M	-34.389	-61.078	-7.700	**0.003**
E M-A M	-7.722	-38.152	22.708	0.998
E S-A M	-6.556	-27.907	14.796	0.992
B M-A S	-1.600	-23.282	20.082	1.000
B S-A S	0.056	-22.274	22.385	1.000
C M-A S	6.500	-13.421	26.421	0.988
C S-A S	8.433	-11.179	28.046	0.926
D M-A S	13.773	-7.365	34.911	0.524
D S-A S	-20.667	-45.986	4.653	0.212
E M-A S	6.000	-23.236	35.236	1.000
E S-A S	7.167	-12.446	26.779	0.973
B S-B M	1.656	-21.611	24.922	1.000
C M-B M	8.100	-12.866	29.066	0.962
C S-B M	10.033	-10.640	30.706	0.858
D M-B M	15.373	-6.753	37.498	0.430
D S-B M	-19.067	-45.216	7.083	0.360
E M-B M	7.600	-22.358	37.558	0.998
E S-B M	8.767	-11.906	29.440	0.932
C M-B S	6.444	-15.191	28.080	0.994
C S-B S	8.378	-12.973	29.729	0.958
D M-B S	13.717	-9.043	36.478	0.633
D S-B S	-20.722	-47.411	5.967	0.274
E M-B S	5.944	-24.486	36.374	1.000
E S-B S	7.111	-14.240	28.462	0.986
C S-C M	1.933	-16.885	20.751	1.000
D M-C M	7.273	-13.130	27.676	0.977
D S-C M	-27.167	-51.876	-2.458	**0.020**
E M-C M	-0.500	-29.209	28.209	1.000
E S-C M	0.667	-18.151	19.485	1.000
D M-C S	5.339	-14.762	25.441	0.997
D S-C S	-29.100	-53.561	-4.639	**0.008**
E M-C S	-2.433	-30.929	26.063	1.000
E S-C S	-1.267	-19.757	17.224	1.000
D S-D M	-34.439	-60.139	-8.739	**0.001**
E M-D M	-7.773	-37.339	21.794	0.997
E S-D M	-6.606	-26.707	13.495	0.987
E M-D S	26.667	-6.020	59.354	0.213
E S-D S	27.833	3.373	52.294	**0.013**
E S-E M	1.167	-27.329	29.663	1.000

Appendix Table 5. Tukey test results for bulk density, field capacity, and gravel content. The table highlights and bolds relationships with a significant difference ($p<0.05$).

Tukey multiple comparisons of means 95% family-wise confidence level									
Bulk Density 0-10cm					**Bulk Density 25-35cm**				
Site	**diff**	**lwr**	**upr**	**p-value**	**Site**	**diff**	**lwr**	**upr**	**p-value**
B-A	**0.430**	**0.091**	**0.770**	**0.009**	**B-A**	**0.544**	**0.203**	**0.886**	**0.001**
C-A	0.257	-0.083	0.597	0.198	C-A	0.244	-0.098	0.586	0.242
D-A	0.297	-0.043	0.636	0.106	D-A	0.155	-0.208	0.517	0.704
E-A	-0.251	-0.591	0.089	0.217	E-A	-0.080	-0.422	0.261	0.952
C-B	-0.173	-0.513	0.166	0.558	C-B	-0.300	-0.642	0.041	0.102
D-B	-0.134	-0.473	0.206	0.764	**D-B**	**-0.390**	**-0.752**	**-0.027**	**0.032**
E-B	**-0.681**	**-1.021**	**-0.341**	**0.000**	**E-B**	**-0.625**	**-0.967**	**-0.283**	**0.000**
D-C	0.040	-0.300	0.379	0.997	D-C	-0.089	-0.452	0.273	0.944
E-C	**-0.508**	**-0.847**	**-0.168**	**0.002**	E-C	-0.324	-0.666	0.017	0.068
E-D	**-0.547**	**-0.887**	**-0.208**	**0.001**	E-D	-0.235	-0.598	0.127	0.326
Field Capacity 0-10cm					**Field Capacity 25-35cm**				
Site	**diff**	**lwr**	**upr**	**p-value**	**Site**	**diff**	**lwr**	**upr**	**p-value**
B-A	-0.105	-0.241	0.032	0.186	**B-A**	**-0.185**	**-0.275**	**-0.095**	**0.000**
C-A	-0.056	-0.193	0.080	0.735	**C-A**	**-0.100**	**-0.190**	**-0.010**	**0.025**
D-A	-0.086	-0.222	0.051	0.361	D-A	-0.051	-0.146	0.044	0.510
E-A	-0.032	-0.168	0.105	0.956	E-A	0.000	-0.090	0.089	1.000
C-B	0.049	-0.088	0.185	0.819	C-B	0.085	-0.005	0.175	0.069
D-B	0.019	-0.117	0.156	0.993	**D-B**	**0.134**	**0.039**	**0.229**	**0.004**
E-B	0.073	-0.063	0.210	0.510	**E-B**	**0.184**	**0.095**	**0.274**	**0.000**
D-C	-0.030	-0.166	0.107	0.965	D-C	0.049	-0.047	0.144	0.551
E-C	0.024	-0.112	0.161	0.982	**E-C**	**0.099**	**0.009**	**0.189**	**0.026**
E-D	0.054	-0.083	0.190	0.761	E-D	0.051	-0.045	0.146	0.518
Gravel Content 0-10cm					**Gravel Content 25-35cm**				
Site	**diff**	**lwr**	**upr**	**p-value**	**Site**	**diff**	**lwr**	**upr**	**p-value**
B-A	**0.401**	**0.142**	**0.660**	**0.001**	**B-A**	**0.336**	**0.092**	**0.579**	**0.004**
C-A	**0.261**	**0.002**	**0.520**	**0.048**	**C-A**	**0.261**	**0.017**	**0.504**	**0.032**
D-A	0.224	-0.035	0.483	0.111	D-A	0.111	-0.133	0.354	0.660
E-A	-0.008	-0.267	0.251	1.000	E-A	0.001	-0.243	0.245	1.000
C-B	-0.140	-0.399	0.119	0.507	C-B	-0.075	-0.318	0.169	0.887
D-B	-0.177	-0.436	0.082	0.283	D-B	-0.225	-0.469	0.019	0.079
E-B	**-0.409**	**-0.668**	**-0.150**	**0.001**	**E-B**	**-0.335**	**-0.578**	**-0.091**	**0.004**
D-C	-0.037	-0.296	0.222	0.992	D-C	-0.150	-0.394	0.093	0.376
E-C	**-0.269**	**-0.528**	**-0.010**	**0.039**	**E-C**	**-0.260**	**-0.503**	**-0.016**	**0.033**
E-D	-0.232	-0.491	0.027	0.093	E-D	-0.110	-0.353	0.134	0.668