BECOMING BOSQUE

Testing the benefits of mesquite restoration

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The Nature Conservancy in Arizona

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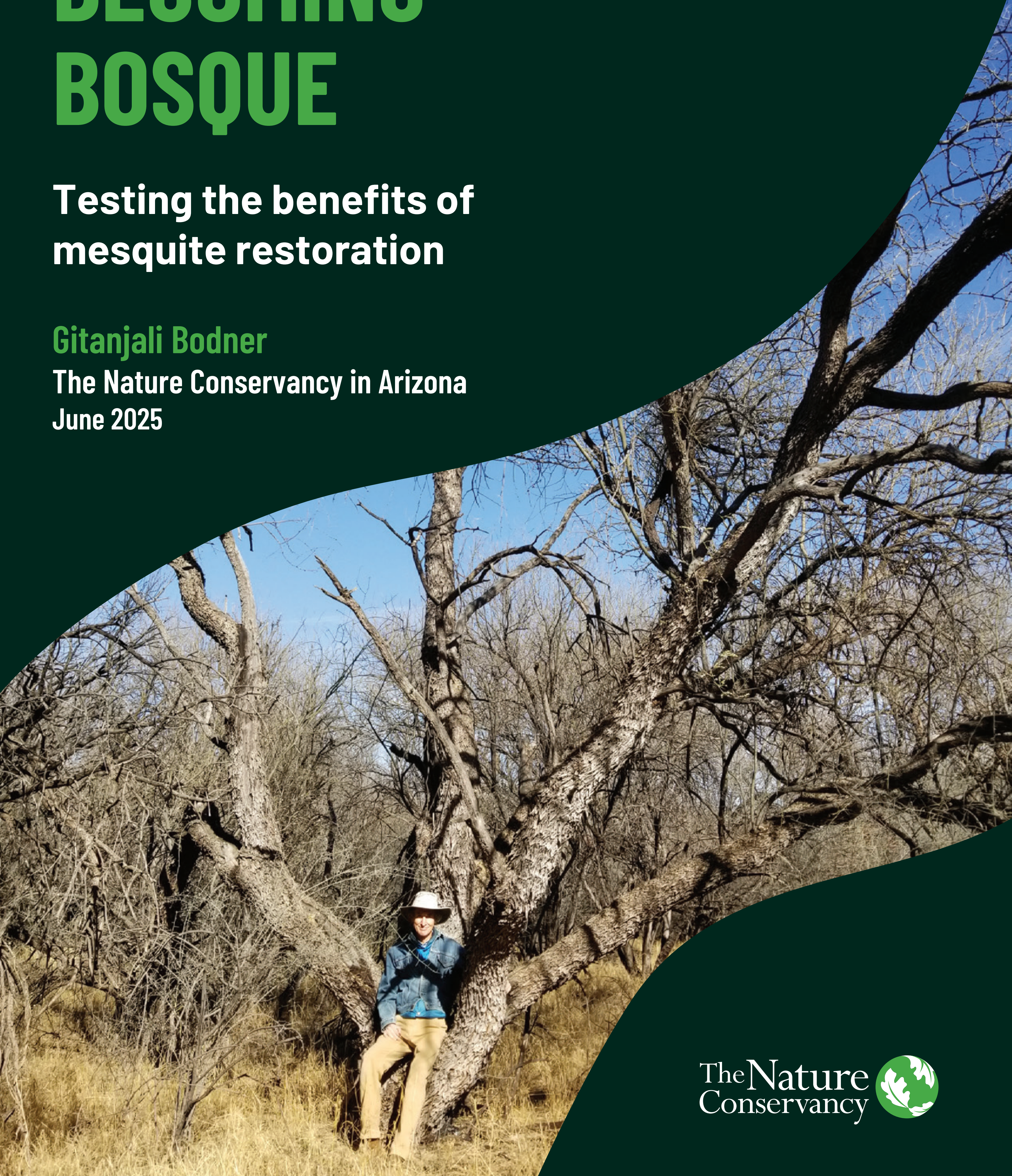

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Summary

In areas with appropriate growing conditions, restoration of mesquite thickets has succeeded in recovering habitat that resembles mesquite bosque form and function, in 20 years or less.

Abstract

This study evaluated ecological conditions of three types of mesquite-dominated habitats on a site along the San Pedro River in Arizona. Naturally-occurring vegetation at the site includes forests of large mesquite trees near the river; young mesquite thickets that re-colonized a retired agriculture field on a nearby river terrace; and upland desert scrub habitats on hillsides away from the river. Riparian and upland mesquite habitats have been studied before, though seldom at the same site; habitat values of young terrace thickets have been mostly undocumented. Comparisons of vegetation, birds, and ecohydrology across these three stand types – mature mesquite bosque, second-growth riparian mesquite thickets, and upland mesquite scrub — were designed to better understand natural habitat gradients, and to evaluate the success of restoration at re-establishing mesquite bosques on disturbed river terraces.

The study confirmed dramatic differences between mature riparian bosque and upland mesquite scrub stands, as has been documented elsewhere. Findings in young thickets were novel. In areas with appropriate growing conditions, we found that restoration was effective at recreating bosque-like habitat in as little as 20 years. Most of the site's young thicket stands (last plowed in 2002) already have vegetation structure and breeding bird assemblages that are more similar to mature bosques than to upland scrub stands. We attribute this rapid recovery to shallow groundwater that is within the reach of deep mesquite roots, a plentiful supply of seeds on adjacent lands, and management designed to encourage natural recruitment of native plants.

We also tested some targeted thinning practices to see whether this type of intervention could accelerate the full return to bosque form and function. Results suggest that selective removal of relatively small and densely-packed mesquite trees, aimed at replicating tree densities of mature bosques, can be compatible with managing for bosque wildlife. However, thinning was expensive, and its effects may be short lived. Where natural regeneration is successful, intensive treatments such as thinning may not be needed.

Suggested Citation

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Background

Low elevation valleys in the Southwestern US and northern Mexico are home to stands of mesquite trees that grow in a variety of forms (figure 1), from deep shady woodlands of tall trees ("mesquite bosques") in the riparian zones that flank our lush rivers, to open shrubby stands on the dry desert or grassland hillsides ("upland scrub" or "upland savannah"). This study focuses riparian mesquite bosques, but protecting and restoring these stream-side forests requires a clear understanding of how they differ from their upland counterparts (Johnson et al., 2020; Stromberg, 1993). Mesquite-studded upland scrub and savannah grasslands cover vast areas across the region (Brown and Lowe 1980; McClaran and VanDevender 1995; Enquist and Gori, 2008). As part of the global phenomenon of shrub encroachment in semi-arid lands, these upland grasslands have experienced dramatic increases in mesquite cover over the past 150 years (Archer, 1994; Archer et al., 2017; Enquist and Gori, 2008; McClaran, 2003; Van Auken, 2009). Shrub encroachment impacts livestock forage, watershed function, and wildlife habitat, which has made upland mesquites a widespread target for removal (Archer et al., 2011; Archer and Predick, 2014; Robinett, 2018). By contrast, mesquite bosques are much less common, occurring only in relatively narrow zones near rivers in areas with access to shallow groundwater (Johnson et al., 2020; Stromberg,1993). These ribbons of forest have long been prized for wildlife habitat (Gavin and Sowls, 1975; Villaseñor, 2006; Wilbor, 2010) and are beginning to be recognized for carbon capture (Martens and McLain, 2005). Nevertheless, the extent of mature mesquite bosques has been declining over the past two centuries. While percent loss estimates have been elusive (Tellman et al., 1997), many sources document loss and degradation of important bosque stands across the Southwest at the hands of land conversion for farming or housing developments, over pumping of groundwater that drops water tables out from under them, etc. (Johnson et al., 2020; Tellman 1997; Bahre 1991; Minckley and Clark 1984).

There is growing interest in establishing new stands of mesquite bosque to compensate for mature stands that have been lost, but we have little evidence on what restoration practices can best accomplish this or how long it might take for new stands to regain bosque form and function (Turner and Gori, 2018). State and transition models suggest it may take 50-100 years to develop reference-condition bosques (Robinett et al. 2021), though few studies have attempted to test this timeline. We also have few tools available to recognize bosque potential in areas that have experienced disturbances (e.g. the clearing of near-stream fields for farming), since young trees cannot yet show the combination of large tree stature and high canopy cover that characterize mature bosques.

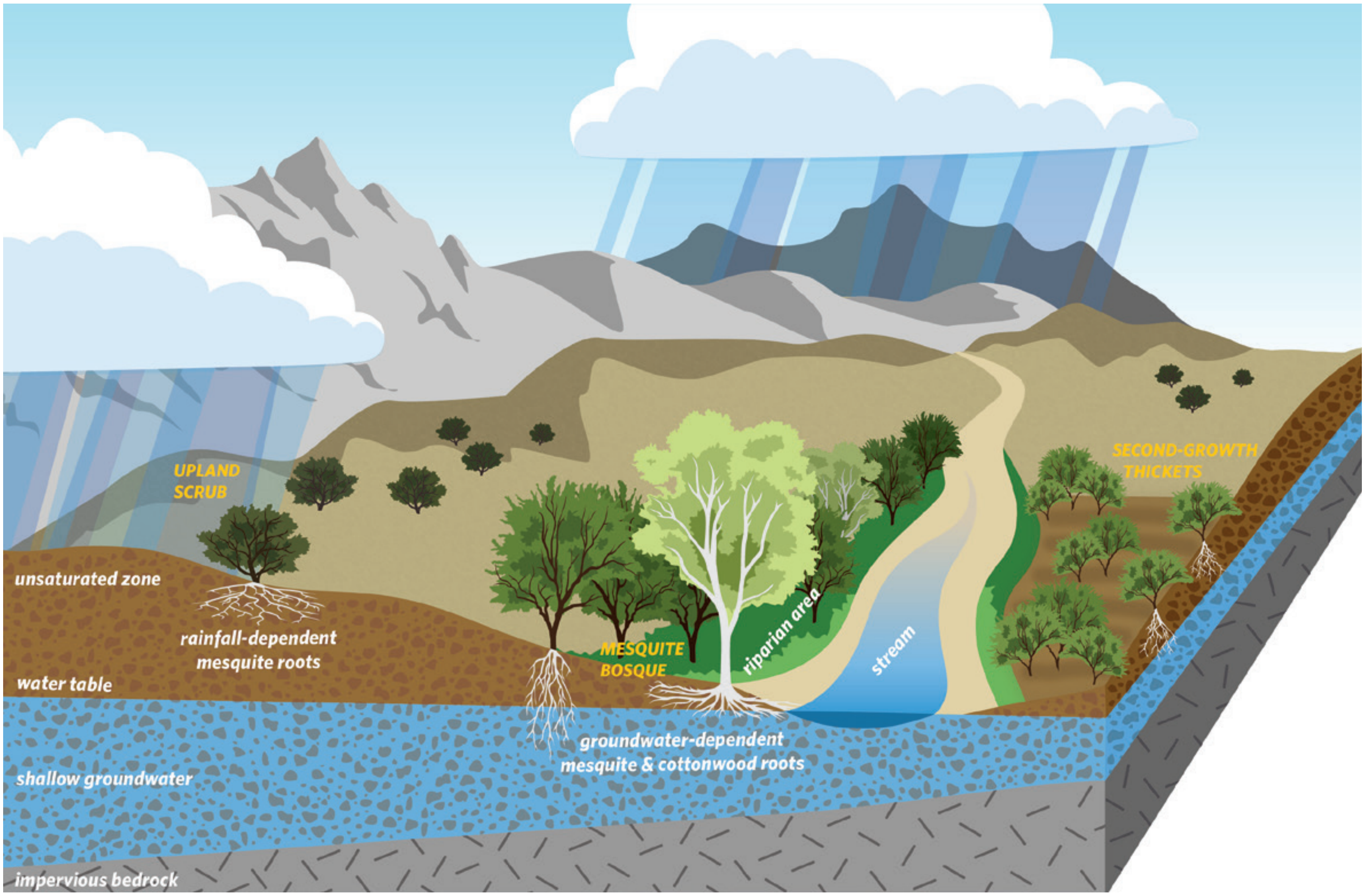


Figure 1. Mesquite forms differ across a watershed. Riparian Mesquite Bosques occur in a narrow band along rivers; roots have access to the same layer of shallow groundwater that supports other riparian trees like cottonwoods. Upland mesquites occur across much wider areas of desert and grassland farther from rivers; they depend on rainfall alone since their roots cannot reach groundwater. Farm field mesquites do not yet have the stature of Bosque trees; Are they becoming bosques, or are they limited by water and soils?

The fact that the same tree species can occur in such different forms –expanding within scrublands and declining in riparian woodlands—can cause confusion for land managers, researchers and policy makers. Efforts to characterize and classify stand types can help (e.g. Cornejo-Denman et al., 2020; Johnson et al., 2020; Scott et al., 2006), though no consistent framework and language has been reached. Contrasts within one study site may be especially useful to bring clarity to mesquite management conundrums.
This study looks at three types of mesquite-dominated habitats in close proximity. On TNC's Middle San Pedro River Preserve (MSPRP), velvet mesquites grow in both mature bosque woodlands on shady terraces near the river (figure 2a; 2c), and in upland scrub stands on dry hillsides (figure 2b). The Preserve also has areas near the river where mesquite bosques were cleared several decades ago to turn the floodplain terraces into farm fields, and where subsequent fallowing and conservation management (Clark, 2002) has allowed recovery of a natural plant community. In 2002, TNC purchased the property and retired irrigation of crops to leave more water for the river and allow native plants to recolonize. Thickets of young mesquite trees ("second-growth riparian thickets," figure 4) now cover most of these once-farmed fields.

In combination with nearby mature bosque and upland mesquites, these young thickets provide an opportunity to learn about how management actions can result in mesquite bosque recovery, and to explore potential tradeoffs in managing disturbed lands for wildlife, water, carbon capture and other values. This is important because disturbed lands like these are common along the San Pedro and nearby rivers, yet landowners have few resources that inform them of management choices.

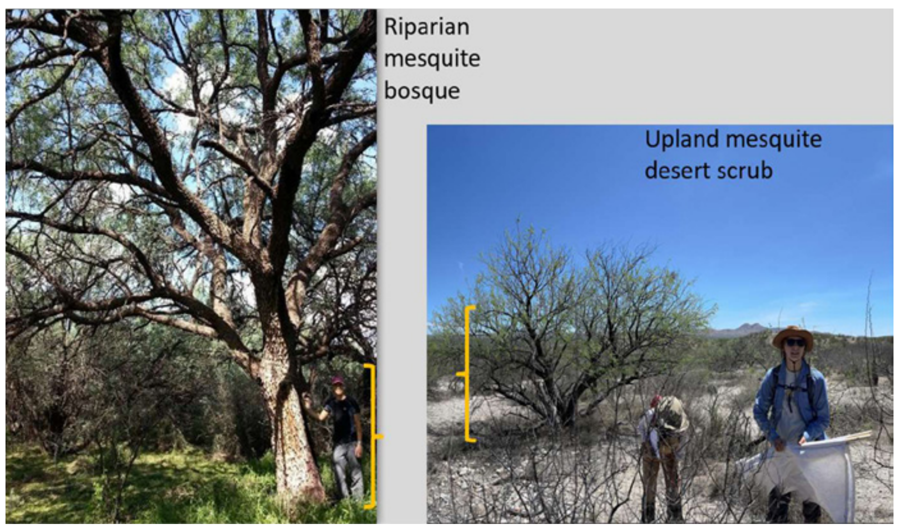


Figure 2a and b. Middle San Pedro Preserve. Mesquite trees growing in riparian bosques on a terrace near the river (left, a) and in upland desert scrub on slopes farther from the from the river (right, b). Yellow scale bar is 2m.

Figure 2c. Mature mesquite bosque, wintertime.

Since 2021, TNC and partners from the University of Arizona and the Agricultural Research Service have been studying mesquites on the MSPRP to better understand differences across landscape settings, tree ages and management choices. Our objectives in this study are:

- To *compare ecological characteristics* (bird diversity, vegetation structure and ecohydrology dynamics) across three main stand types — mature riparian mesquite bosques, second-growth thickets on a riparian terrace and upland scrub — to understand patterns of tree growth, water use and wildlife habitat.
- Conduct an *experimental thinning* of some second-growth thickets, to test whether selective thinning could accelerate the recovery to the form and function of nearby mature bosques.

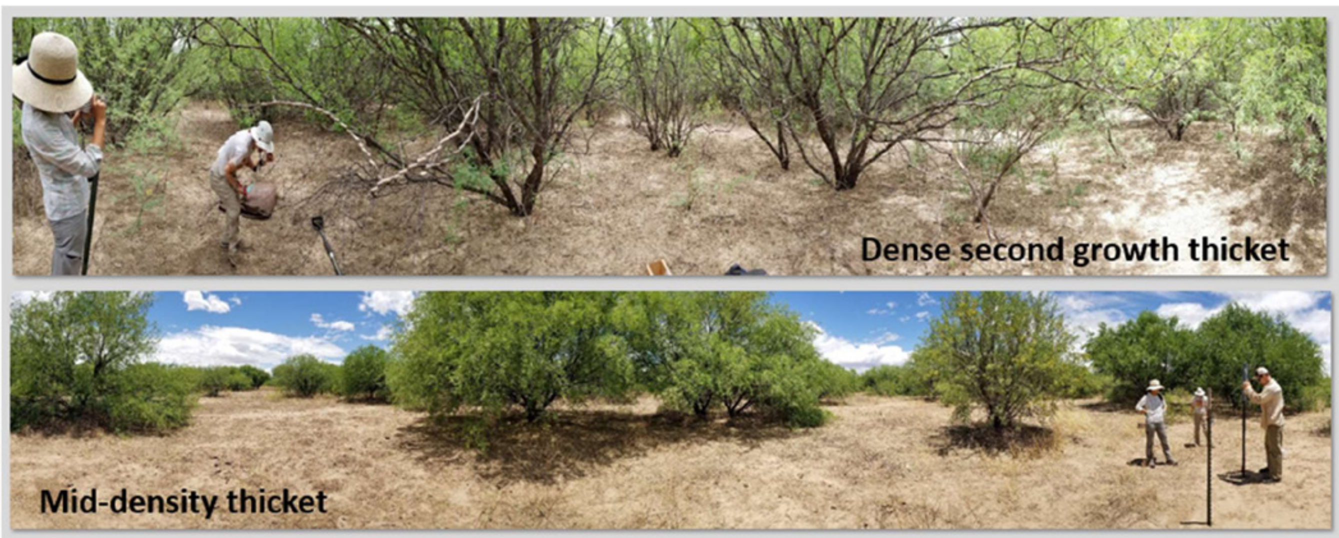


Figure 3. Second growth thickets on former farm fields east of the river. Trees in these stands date to 2002 or later. Natural differences in recruitment and growth resulted in large variations in stand densities.

Study design

This research design included 15 six-acre plots arrayed across the MSPRP's mesquite-dominated habitats (figure 4). Mature bosques (MMBs) on the west side of the river include some of the most extensive, intact bosque habitat in the region. Plots in this tall forest habitat were used to understand "reference conditions" to evaluate how similar other areas are to mature bosque form and function, and to establish desired condition targets for restoration prescriptions. Desert scrub habitat occurs on the hills above, including upland scrub mesquite (Uls). Upland plots are 15-20m higher in elevation than riparian terrace plots. Plots in this habitat provide a contrast that shows how different bosques are from the upland mesquite habitats that are much more widespread in the region. On the historic floodplain to the east, the property's 300-acre farm field was fallowed in 2002, resulting in second-growth thicket mesquite (SGTs) that range from dense thickets to strands of woodland winding through open terrain. Reasons for this variation are unclear. To incorporate this natural variability, we chose test plots that span this range of thicket density. Depth to groundwater ranges from 4m-12m across the floodplain terraces (TNC well measurements, 2002-2025).

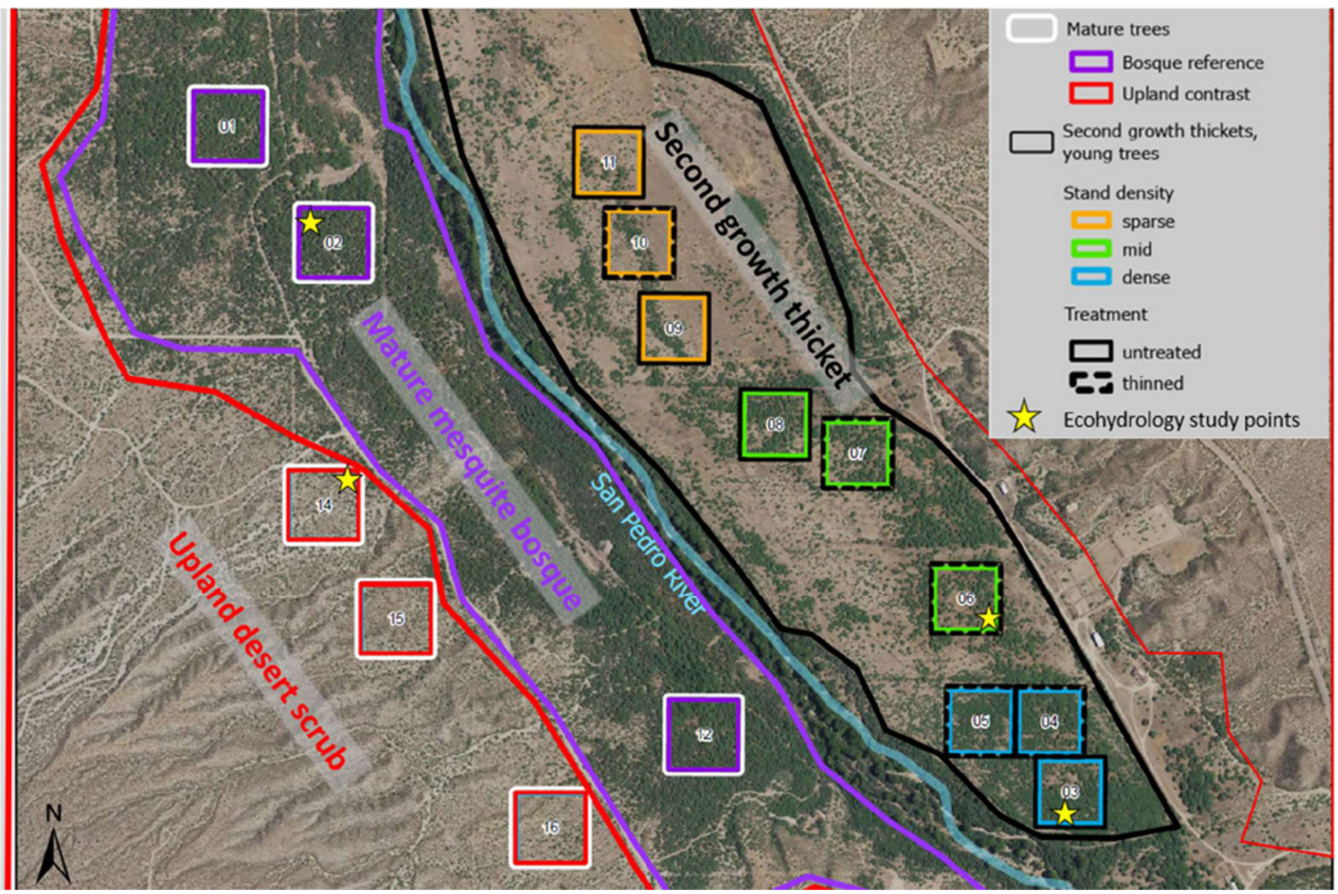


Figure 4. Study-wide plot map. A narrow line of tall cottonwood and willow trees flank the San Pedro River, with relatively undisturbed vegetation on the west — mature mesquite bosque on the riparian terrace and upland scrub on hillsides, with three study plots in each. Approx. 300 acres of former farm field areas are visible on the low terrace east of the river, with variations in tree densities from south to north that informed grouping of nine second-growth thicket plots into blocks of similar structure. Five of these plots were thinned in 2022. Map background is NAIP satellite imagery from May 2019.

Most measurements on these plots were made in the field, augmented with some remotely sensed attributes. Table 1 lists stand types and plot numbers, with field and remotely-sensed measurements. Detailed methods for measurements and statistical analyses are available upon request.

With help from partners, we studied several attributes on these plots, including:

- Vegetation structure (baseline comparisons of stand densities and cover, bark roughness, tree sizes; post-treatment changes and comparisons)
- Breeding bird communities (annual surveys 2021-2024; upland plots added 2023)
- Ecohydrology dynamics (comparisons across stand types and season, looking at water stress, source water and evapotranspiration)

Mesquite stand type	Plot#	Vegetation structure, field data	LiDAR canopy heights	Breeding Birds	Ecohydrology field data	Evapotranspiration, NDVI, remotely sensed	Plot Thinned
Mature bosque							
	Plot 01	x	x	4 years		x	
	Plot 02	x	x	4 years	x	x	
	Plot 12	x	x	4 years		x	
Upland scrub							
	Plot 14	x	x	2 years	x partial	x	
	Plot 15	x	x	2 years		x	
	Plot 16	x	x	2 years		x	
Second-growth thicket							
dense	Plot 03	x	x	4 years	x	x	-
dense	Plot 04	x	x	4 years		x	Spring 2022
dense	Plot 05	x	x	4 years		x	Fall 2022
medium	Plot 06	x	x	4 years	x	x	Spring 2022
medium	Plot 07	x	x	4 years		x	Fall 2022
medium	Plot 08	x	x	4 years		x	-
sparse	Plot 09	x	x	4 years		x	-
sparse	Plot 10	x	x	4 years		x	
sparse	Plot 11	x	x	4 years		x	Spring 2022

Table 1. Field and remotely sensed measurements taken between 2021 and 2024 in plots of each stand type.

Experimental thinning

In addition to comparing stand types, we designed an experimental treatment to test whether selective thinning could accelerate the recovery of second-growth thickets to the form and function of nearby mature bosques. Neighbors and partners were also interested in whether thinning could reduce water use of mesquite stands enough to benefit the local aquifer, without sacrificing valued habitat. Thinning prescriptions were designed to replicate the stand structure of nearby bosques in terms of tree density and spatial arrangement of trees. This meant reducing the number of small trees in dense areas, while retaining as much total canopy cover as possible. In each set of SGT plots, two plots were chosen for thinning, while one was kept as an untreated control; control plots allow us to better understand initial wildlife and plant responses to thinning and, in the future, to test whether longer-term effects of thinning were worth the cost and effort.

Prescriptions for selective thinning on thicket test plots:

- Remove trees to leave 10-20 feet between trunks
- Keep largest trees
- Keep some clusters of trees

Thinning was completed on a total of 30 acres in 2022, with some plots treated in early spring and some in the fall (table 1); this attempted to avoid disrupting birds during their breeding season. Trees were cut and stumps immediately treated with a contact herbicide to inhibit re-sprouting. Limbs were chipped and spread onsite. After sharing initial thinning prescriptions (see call-out box), contractors and TNC staff refined treatments on the ground using feedback and discussion over the first several days of the contract, and periodically throughout the thinning process. This prescription had the benefit of being able to be applied consistently across areas with very different initial conditions. Vegetation measurements before and after thinning allowed us to document how much the treatment changed stand density, canopy cover and other structure elements.

Figure 5. Results of thinning a dense thicket. Before, summer (top) and after, winter (bottom).

What we've found

Stand structure and tree comparisons

Structure and ***function*** of mesquites in upland scrub habitat are quite different from those of nearby stands of both mature bosque and second-growth thickets (table 2, figures 6,7,8). Compared with mature bosques, upland plots have significantly fewer mesquite trees, lower total canopy cover, and individual trees are smaller. Upland plots differ from most thicket plots in these same attributes, although the sparsest farm field areas have some characteristics (canopy cover, tree density) that overlap with the range seen in upland scrub. Notably, upland and mature bosque plots share attributes of older trees (rough bark) and more stable vegetation cover (few seedlings and saplings). We found that upland canopy cover is between 20-30%. This matches estimates from the literature of the maximum canopy cover that can be sustained by rainfall alone in this climatic zone (Archer et al., 2017).

Structure of second-growth stands varies quite a bit across MSPRP. All but the sparsest thicket plots have significantly higher canopy cover than uplands, and individual trees are taller. Overall, attributes of forest structure in thicket plots have recovered at least part way towards those of mature bosque stands (table 2). For example, total canopy cover has reached 70 - 80% in dense young stands, within the range measured in mature stands (figure 6). Mid-density stands are nearing those levels, with sparse stands lagging behind but still growing quickly, as shown by aerial photo changes through time and by tree rings. Trees per acre in second-growth stands varies across the site, with some stands being considerably denser than their mature bosque counterparts, and some being similar or lower densities (figure 7). However, mature bosque and upland sites appear to have reached a stable density, while all second-growth stands continue to fill in with more seedlings and saplings (table 2). This suggests that even the sparse thickets will soon diverge from upland conditions and come to resemble the denser thicket and perhaps mature bosque conditions. Other aspects of structure are notably different in thickets than mature bosque stands, with shorter, smaller trees that have more stems per tree, and smoother bark that provides fewer resources for wildlife.

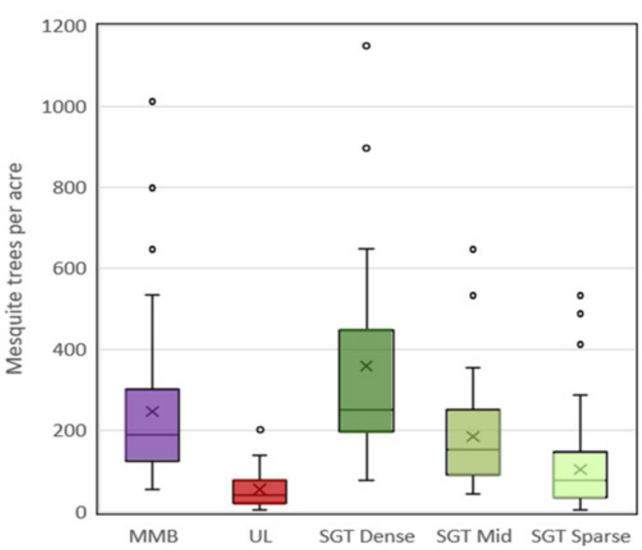


Figure 6. Tree densities. Uplands (UL) support many fewer mesquite trees per acre than mature bosques (MMB). All but the sparsest SGTs have densities that approach or exceed MMBs. Observations for each stand type include three plots, 12 to 16 observation points in each plot.

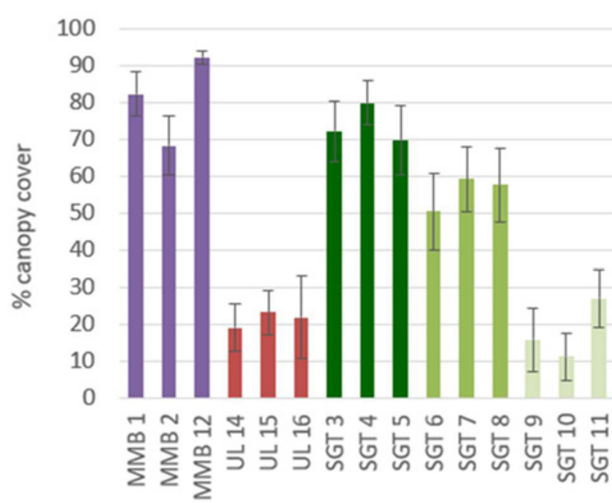


Figure 7. Canopy cover of trees and tall shrubs, measured by spherical densiometers at points across each plot. Error bars are standard error of the mean.

We also examined tree ring growth patterns in the SGTs. Mesquite trees are difficult to study using traditional tree coring methods (Shepard 2015). Cross sections taken while conducting experimental thinning show that most of the trees sampled, regardless of their diameter, were close to 20 years old. This suggests that the initial establishment of trees across this site happened quickly once plowing stopped and that young trees are growing at different rates.

Tree heights are notably different across stand types (figure 8; table 2). Average canopy height in mature bosque stands is taller than any other stand type. With smaller trees and more space between trees, upland plots had much lower average canopy heights. Thicket plots are in between. The largest trees in each plot in mature bosque stands are far taller than those of any other stand type (max height, not shown). Upland trees top out at just five to six meters. Most thicket plots already have some trees that have grown past seven meters.

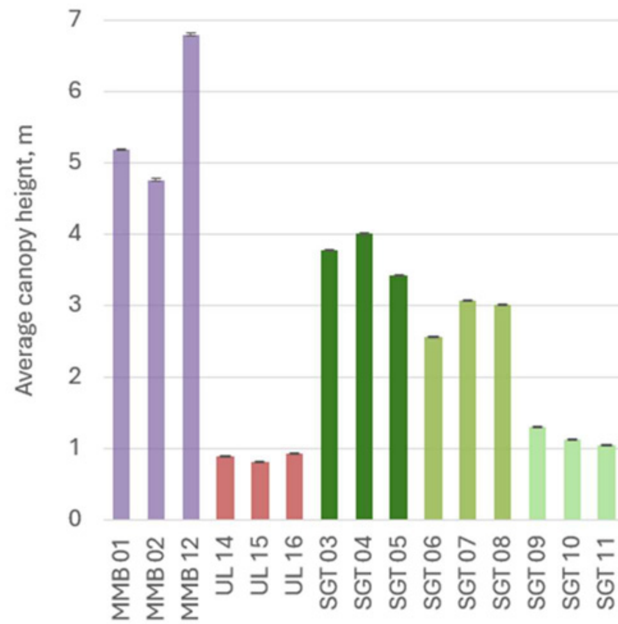


Figure 8. Overall canopy height of plants within plots of each stand type. Heights are estimated from 2020 USGS LiDAR data. With 24,000 pixels per plot, standard error of the mean are so small that error bars are hard to see.

	Mesquite trees per acre	Height class	Stem DBH	Stems per tree	Bark class	Mesquite seedlings + saplings	Canopy cover	Mid-story cover
Stand type	Avg density	Avg, m	Avg, cm	Avg count	Avg class, 1-6	Avg #, 3m radius	Avg %	Avg %
MMB Reference	247	5.7	17.9	2.8	3.9	0.3	81	47
Upland scrub	59	3.2	8.6	2.9	0.4	0.4	21	50
SGT Dense	419	4.2	7.2	2.6	2.0	2.7	76	51
SGT mid-density	186	4.6	8.7	4.8	2.2	3.4	55	34
SGT sparse	104	3.7	6.8	2.5	1.7	4.2	18	30

Table 2. Field-based metrics of stand structure and tree characteristics compared across stand types and density blocks. Details on statistically significant differences, and some additional metrics are available upon request.

Ecohydrology

After comparing ***structure*** of vegetation, we compared ***function*** of different mesquite stand types by looking at how these stands and their trees use water (ecohydrology), and how the stands are, in turn, used by wildlife (see Birds below). Evapotranspiration (ET) estimates show differences in how trees respond to rainfall and season (figure 9). Dominant plants in all sites go semi-dormant for up to four months in winter, though timing varies some from year to year. In warm seasons, upland plots' water use is clearly tied to recent rain. By contrast, mature bosques are transpiring much more water than can be accounted for with rainfall, and their activity rises steeply in warm seasons even in periods with little to no recent rainfall, which indicates that they have access to the shallow groundwater of a healthy riparian area. The similar ET patterns of MMBs and STGs (especially high and mid-density stands) suggest that these younger stands also use additional sources of water—presumably some combination of groundwater and older rainfall stored in deep soils. Note, however, that average water use of all these mesquite stands is still well below that expected in irrigated crops, as shown by the "crop reference" line that illustrates expected water use of crops whose growth is not limited by rainfall.

Two years of ecohydrology field research using plant stress and water isotope measurements provide additional evidence that trees in the young thickets already function much like their mature bosque neighbors, with relatively stable access to moisture despite highly variable rainfall across seasons and years (Gillespie, 2023). As indicated by leaf water potential that was measured in riparian terrace stands (plots 2,3, and 6), trees' seasonal water stress was similar across stand ages and densities, and between the two water years, despite

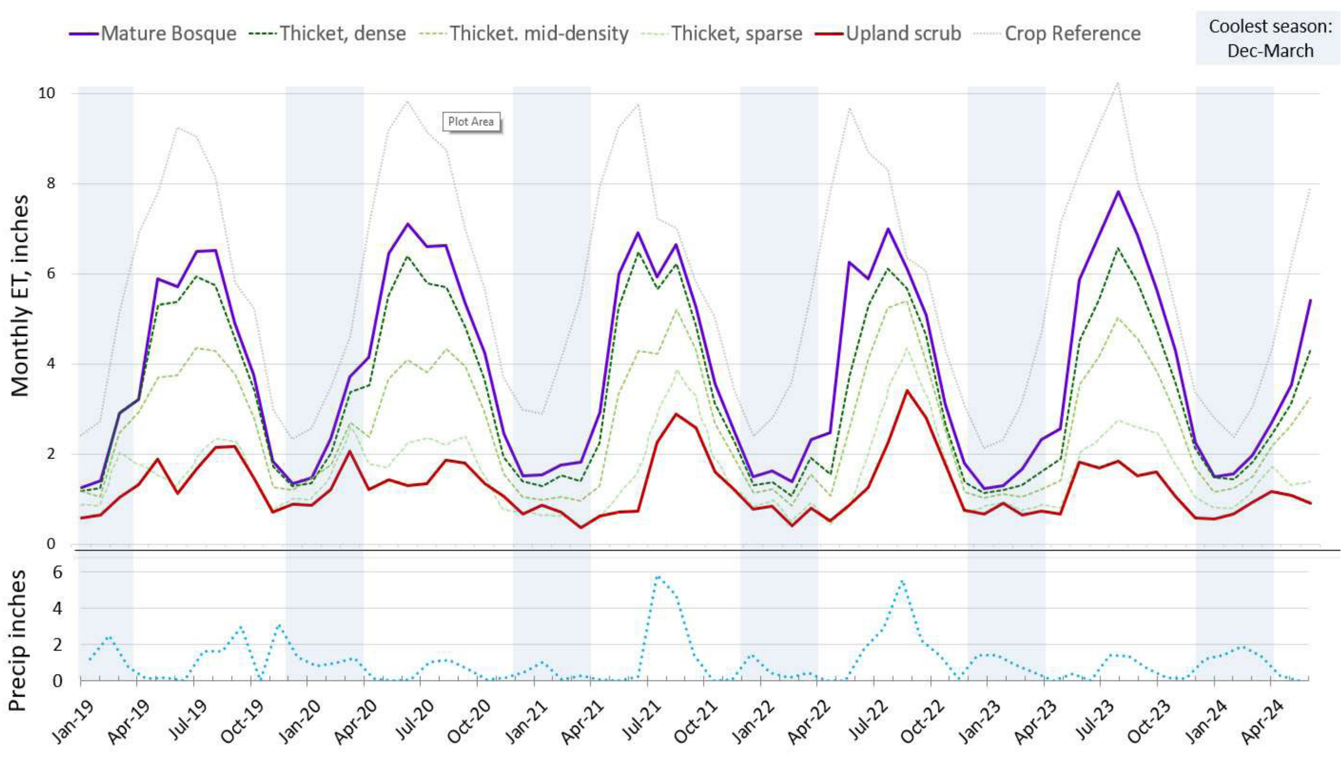


Figure 9. Monthly evapotranspiration estimates for each stand type; colored lines represent averages across the three plots in each strata. Grey dashed line is Reference ET, expected in well-watered crops. All data is from OpenET, ensemble model estimates for ET

summer precipitation in 2023 being less than half that of 2022. This suggests that 2023's higher winter precipitation helped to buffer the trees from water stress of the drier summer. The fact that mesquite trees can use prior-seasons rainfall to survive and grow through drought times is a source of remarkable resilience. This ability could serve mesquites especially well as the ongoing effects of climate change amplify variability in rainfall and groundwater, potentially allowing riparian mesquite forests to persist through conditions that are too extreme for their cottonwood and willow neighbors.

Water isotope signatures show that trees on all plots opportunistically used both deep and shallow water sources, depending on the time of year (Gillespie, 2023). Isotope values for water in tree xylem tissues is highly variable across time, suggesting that trees both mix and switch water sources depending on conditions. Clustering around precipitation values in monsoon season of 2022, less so in the drier summer of 2023, suggests that trees were using more of prior-seasons rainfall in 2023. Also notable is that all trees had xylem isotope values that were quite different from the values found in groundwater; this suggests that even trees that can access groundwater are getting a substantial portion of their water from other sources.

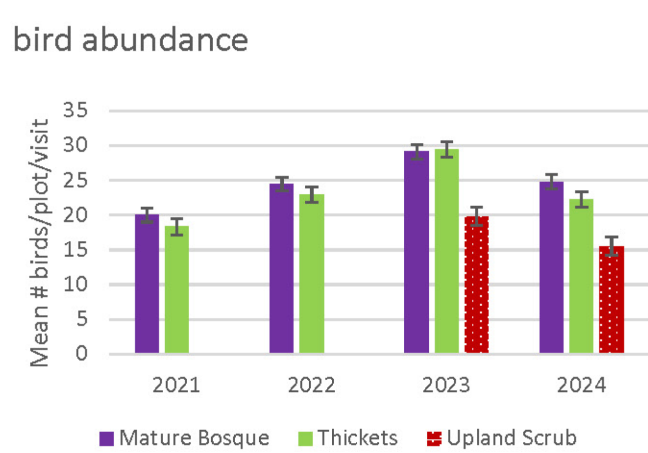
Birds: comparisons across strata

Yellow warbler © Jim Rorabaugh

Four years of breeding bird surveys give insight into wildlife values of the various mesquite stand types and habitat conditions present across this experimental array. Overall, results suggest that second-growth thickets on riparian terraces are providing excellent bird habitat, and that these areas function much more like their rare mature bosque counterpart than like the more common upland scrub. Point-count surveys tallied over 3,700 birds from 86 species. Riparian terrace mesquite stands had large diversities and densities of birds, with 84 species detected, and as many as 71 individual birds per 6-acre plot in any given eight-minute point count survey. With a smaller survey effort, upland scrub plots totaled 308 birds in 28 species.

Abundance and species richness of birds varied across years and across stand types (fig 11). Thickets were comparable to mature bosques in all years; upland scrub supported significantly fewer bird individuals and species than either ($p<0.05$ for 2023, 2024). Results are presented as averages across survey bouts, to account for differences in sample sizes across stand types.

Indices of overlap show that species assemblages of thickets were more similar to those of mature bosques than to upland scrub sites ($\beta_{\text{sør}}$, Sørensen pairwise dissimilarity indices: thicket * mature bosque: 0.273; thicket * upland scrub: 0.495; mature bosque * upland scrub: 0.483). While many βeta-diversity indices exist, the $\beta_{\text{sør}}$ index incorporates both species turnover and nestedness of one assemblage within another (Baselga 2010), so seemed most appropriate here. While there was a broad overlap of species found across the site, composition of species varied across stand types and years (Figure 12). Additional analyses of point-count and territory mapping data is outside the scope of this report but may provide insights into which aspects of stand structure affect bird abundance and species composition. More nuanced analyses may be able to further guide restoration actions and inform predictions about specific stand characteristics needed to support particular species. Integrating this data with other studies (e.g. Andersen and Steidl, 2019; Wilbor, 2010) into larger regional analyses could also help understand variations seen across time and space.



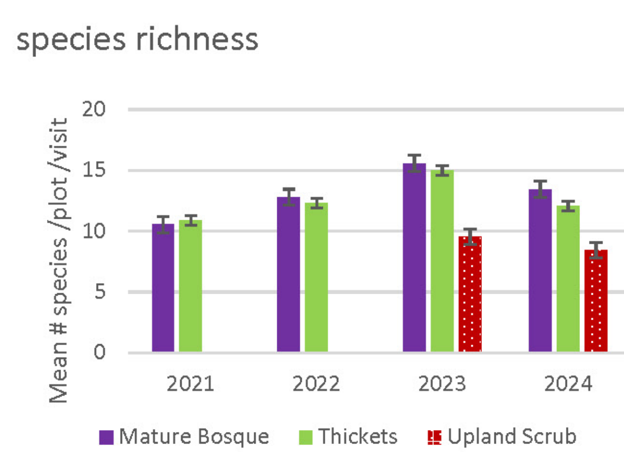


Figure 11. Abundance (left) and species richness (right) of birds observed during the breeding season, in different stand types of mesquite habitats on the Middle San Pedro Preserve. Bars represent the mean number observed in each eight-minute point-count survey, across multiple plots and visits; error bars are standard errors around those means.

Figure 12. Examples of species showing strong habitat preferences among stand types. Top row: Species typically considered mature bosque specialists; none of these species exclusively used mature stands without also occurring frequently in younger thickets. Middle row: Thicket specialists. Bottom row: Upland scrub specialists, with varying degrees of spill-over into sparse thickets and other stand types. Uplands were only sampled 2023-2024.

Results of experimental thinning

Aims of selective thinning were to replicate mature bosque structure, with high canopy cover coming from well-spaced, large trees. This meant trying to keep most of the overall canopy cover while removing some of the smaller trees, expecting that the trees that are left will grow enough to fill in gaps in canopy quickly. Overall, selective thinning reduced average tree densities by 30% (figure 13) and canopy cover by about 25% (figure 14). Changes in mid-story vegetation cover (not shown) was more dramatic than canopy cover; this is a key habitat variable for birds and other wildlife who use understory plants and low branches to nest, forage and hide from predators.

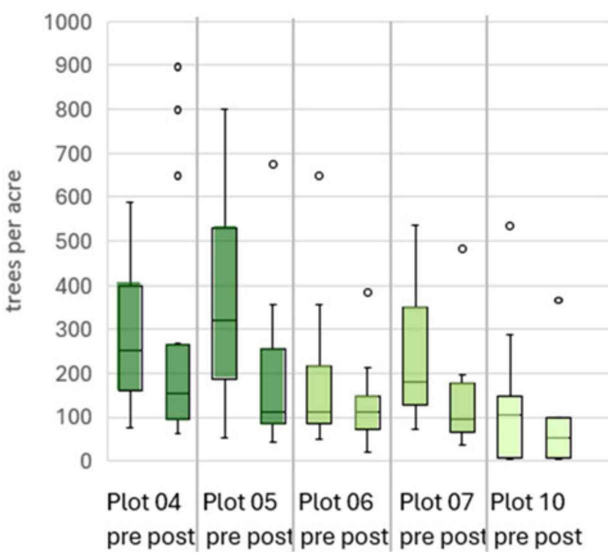


Figure 13. Changes in tree density with thinning.

Our thinning prescription allowed for these effects to differ across plots, with largest numbers of trees removed from the densest plots (plots 4,5); a smaller number removed from mid-density plots (6,7), concentrated in parts of the plot with the most trees to begin with; and relatively few were removed from the sparsest plot (10), all within a single dense band that runs through that plot. The apparent increase in canopy cover from plot 6 was probably due to a delay in measuring post-treatment conditions until after the wet monsoon of 2022, showing the potential for rapid growth in these trees.

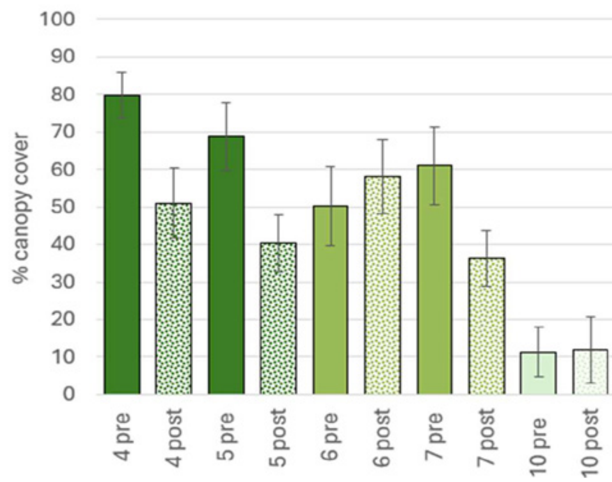


Figure 14. Changes in canopy cover with thinning.

Selective thinning had some short-term effects on usage by certain bird species, but was largely successful in retaining overall bird habitat values while attempting to shape stand structure. Lucy's warblers continued to use thinned plots, although at lower abundance relative to control plots. Shrub-loving Bells Vireos declined in thinned plots. Three species (yellow-breasted chat, summer tanagers, vermillion flycatchers) increased in thinned relative to control plots. Removing a higher percentage of tree cover would likely have had different bird responses, at least in the short term. Future repeat surveys (say, 5 and 10 years from now) will be required to determine longer-term effects of targeted thinning on birds.

Top: Lucy's warbler; bottom: Yellow-breasted chat
© Jim Rorabaugh

With limited time for before/after measurements, on-site ecohydrology research used differences in starting stand densities as a proxy for thinning effects. However, satellite-based estimates of evapotranspiration (ET) were used to go back and forward in time to look at how much thinning decreased overall water use of mesquite stands. This method showed some decline in ET after thinning, but with tree growth quickly returning thinned stands towards pre-treatment ET levels.

Implications, lessons learned, and future questions

Overall Implications

This study showed that with the right growing conditions, many of the ecological values of mature mesquite bosques can be restored in a practical time frame – in this case, 20 years or less. It also suggests that other near-stream areas of second growth mesquite thickets may be providing more wildlife benefits than is commonly recognized. Success at this site indicates that this particular riparian terrace still has the conditions needed to support mesquite bosque habitat, including relatively shallow groundwater and deep alluvial soils. Evaluation of other restoration sites for bosque potential could use these site conditions as a benchmark. Variability in regrowth patters at this site showed that some second-growth riparian areas can naturally re-create bosque tree densities, while other areas quickly form overly-dense thickets. This suggests that some second-growth stands will not need interventions to reach bosque-like structure and function, while other areas might benefit from mechanical thinning. We showed that selective thinning aimed at replicating bosque tree densities could be done without dramatically degrading habitat for bosque-specialist birds in the short term. However, long-term effects of our thinning are yet to be determined. Repeating some plot measurements in five to ten years would provide much insight into whether thinning changed the trajectory or timing of forest recovery. Revealing conditions under which expensive interventions are not necessary would be a useful outcome for land and wildlife managers.

Attempts to evaluate potential water savings of thinning in riparian thickets were inconclusive, since we were not able to estimate relative amounts of groundwater used by different stands. Results did support the general idea that bosques and riparian terrace thickets use more water than upland sites, but use less than irrigated cropland. However, the cost of treatments, and rapid re-growth of remaining trees, suggests that this style of selective thinning that retains bird habitat value is unlikely to provide enough water savings for a long enough time to be worthwhile at scale.

Lessons learned: Implementing thinning

The selective thinning itself was an expensive and time-consuming endeavor. This style of thinning is not to be taken lightly, and may not be easily replicated across large areas without dedicated funding and compelling reasons. Due to contracting limitations, we did not have the luxury of individual marking of trees, nor of continual oversight of thinning crews. Results on the ground therefore varied over time as crew members learned from one another and from TNC staff feedback. While some areas came closer to our target prescription than others, our experience with this loosely-supervised thinning is likely to be similar to most landowners who contract with commercially available crews.

Resprouts from tree stumps continue to be a challenge. Despite being treated with herbicide within minutes of cutting, many cut stumps resprouted with live stems. This is not unexpected; the tenacity of mesquite is well known, and our project plan includes re-treatment of cut trees for at least two years. However, this re-treatment may have to be extended in order to maintain the effects of thinning into the future. In addition, managing these thinned stands into the future may also face challenges relating to the tendency of thinning crews to default to "firewise" treatment that involves removing lower limbs from trees. Such heavy pruning often triggers mesquites to sprout dense clumps of thorny shoots. Some birds may prefer stands with the dense, thorny mid-story vegetation that these trunk sprouts create; human land managers likely will not.

Potential future directions

Birds: We found bird use of second-growth riparian thickets to be more like that of mature bosque than we had expected. However, we were not able to compare our finding with those in the published literature because most other studies we found did not characterize the habitats they sampled in sufficient detail. In some cases, it may be possible to do after-the-fact classification of habitats in published studies, e.g. by looking at vegetation data within those studies or by comparing their specific sampling locations with other information (e.g. site photos, time series of remote imagery, LiDAR data on canopy heights, remotely-sensed greenness indices and evapotranspiration estimates). For future bird studies, we encourage researchers to include a gradient of mesquite stand types wherever possible, and to describe those in terms that would allow them to be compared across sites, as we do here.

Tree rings: This study suggests that additional tree-ring research could be fruitful, taking into account the sampling lessons learned here. We had hoped that tree rings would give insights into how these mesquites have responded to variable climates in the past two decades (which years' weather was good for growth, which were stressful), and perhaps show when the young thicket trees first started accessing groundwater (we predicted rings would be more consistent and wider after they were no longer relying solely on rainfall). Unfortunately, different trees' relative ring widths were not consistent across years, so could not give insights into climate or water access. Climate signals are likely more consistent in the rings of older trees (Shepard 2015), but we were not willing to cut old trees in the mature bosque to take necessary cross-section samples, and did not have equipment capable of taking cores from mesquite's exceptionally dense, sticky wood. Adding samples from old trees in both bosque and upland settings (taking cross-sections if old trees are cut for other reasons, or using appropriately-robust tools for coring) could reveal or disprove differences in climate relationships between trees that have access to groundwater and trees that do not. Comparing our thicket cross-section samples to older trees, and to samples collected elsewhere (e.g. Shepard 2015's samples from upland savannah at the Santa Rita Experimental Range), might help interpret dynamics of young riparian thickets despite the lack of obvious consistencies across trees in our samples.

Carbon: Prior studies suggest that mesquite bosques can develop large stocks of carbon over time (Martens and McLain, 2005; Throop et al., 2022). We took pilot data on tree biomass and soil carbon, in order to get ballpark estimates of carbon storage and capture across the site, and to enable design of more rigorous comparisons in the future. Additional data on soil carbon, and modeling to extrapolate tree biomass to the stand level, would enable estimates of whole-site carbon stocks. Adding measurements of tree growth, from dendrometers that we currently have tracking diameter growth in a dozen trees, and from future vegetation measurements, would enable estimates of the rate at which these stands are continuing to capture carbon.

Ecohydrology: In examining tree water use, the study was unfortunately not able to clearly distinguish between deep soil moisture and groundwater, so has limited application to estimating effects of mesquites on basin water budgets. We had hoped that this study would allow us to estimate how much of mesquite tree water use came from recent rainfall and how much from the groundwater aquifer that supports streamflow and riparian vegetation. It did show that trees use recent rainfall when available, so are not solely drawing on groundwater, but isotope values were not able to distinguish between deep soil moisture and true groundwater. Deep soil moisture can come from wicking up of the groundwater table (aided by tree roots), but can also come from somewhat older precipitation that infiltrated past shallow soil layers—also sometimes aided by tree roots via the active water storage process of "hydraulic redistribution" that mesquites are known for.

In the case of on-site infiltration of water into deep soil layers, it is important to note that water used by trees may not be taking away from groundwater budgets, since we cannot assume that this water would have become aquifer recharge had it not been transpired by trees. Aquifer recharge requires very specific conditions – notably continuously saturated conditions all the way to the water table. This is extremely rare in upland areas that have high evaporative demand and are situated far above the water table. On-site aquifer recharge is possible on alluvial terraces like the bosque and thicket sites in this study but still requires a rare combination of rainfall events (and/or flooding) sufficient to wet the soils down to the 4.4-10m depths at which this site's water table typically lies.

Additional studies that include both upland and riparian mesquites in a full set of ecohydrology measures could help us better understand the natural gradients between these categories of trees, and improve the broad-scale water budgets that rely on distinguishing between them. If future studies can find ways to better distinguish trees' use of between aquifer groundwater and deep soil moisture, this would also improve water budgeting and would better inform strategies to conserve both habitat and water supplies.

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Additional information is available upon request, including methods for measurements and statistical analyses; more results from bird analyses; time series of historic imagery; and more detail on the thinning prescriptions.

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