1. Student Researcher: Josh Lopez-Binder, jlopezbi@unm.edu
Faculty Advisor: Professor Marcy Litvak, mlitvak@unm.edu

2. Project Title: Investigation the Relative Limitation by the Two Major Types of Drought on Dominant New Mexican Tree Species' Water-Uptake and Carbon Sequestration Rates

3. Research problem and research objectives.

The purpose of this study is to investigate the impact of the two major components of drought on tree water-uptake and carbon sequestration for dominant New Mexican tree species. The two major components of drought are atmospheric demand for water (atmospheric drought, captured by vapor pressure deficit, VPD) and depleted soil water availability (soil drought, captured by soil water content, SWC). Increased temperatures in New Mexico over the past two decades have intensified both VPD and SWC drought. SWC has been shown to be more important than VPD for tree functioning in arid climates at the continental scale, but it is unknown if this trend holds for New Mexican trees and ecosystems. In addition, there is limited understanding of how tree's responses to VPD and SWC vary by species, elevation, ecosystem, forest structure, and season. This study will investigate the influence of both VPD and SWC on water-uptake and carbon sequestration for six dominant tree species in New Mexico: *Populus tremuloides* (quaking aspen), *Pseudotsuga menziesii* (Douglas fir), *Abies concolor* (white fir), *Pinus ponderosa* (ponderosa pine), *Juniperus monosperma* (one-seed juniper) and *Pinus edulis* (piñon pine).

4. Methodology employed.

My study sites are four ecosystems in the New Mexico Elevation Gradient: juniper savanna (US-Wjs), piñon-juniper (US-Mpj and US-Mpg), ponderosa pine (US-Vcp) and mixed conifer (US-Vcs). At each site, at least five trees of each dominant species have been instrumented with Granier probes (Lu, 2004), which have measured the rate at which sap moves through the boles (g-sap m^{-2}-sapwood s^{-1}) for the last 7-14 years, depending on the site. In each ecosystem we also collected land-atmosphere carbon, water, and energy exchange data as well as 30-minute averages of net radiation and its components, air temperature and relative humidity (used to calculate VPD), precipitation, 3 depths of soil water content (SWC), and temperature. I will use these data to quantify the impact of atmospheric drought (high VPD) and soil moisture drought (low SWC) in each species in the following steps: 1) employ wavelet coherence analysis to identify regions in time where VPD and SWC are de-coupled (Grinsted et al., 2004); 2) QA/QC and baseline sap flux time series (Lu, 2004); 3) Measure tree diameter (continuously with newly installed dendrometer sensors), sapwood depth and leaf area per unit leaf mass; 4) Using output from steps 2 and 3: calculate 30 minute averages of stomatal conductance (Gs), which serves as a proxy for carbon- fixation rate, using a simplified inversion of the Penman-Monteith model of evapotranspiration (Ewers & Oren, 2000) as well as calculate 30 minute averages of tree-level sap flux (Q, essentially tree-level water use); 5) Calculate relative importance of VPD, SWC, and the interaction between VPD and SWC on Gs and Q using the method in (Flo et al., 2022) as well as find differences in the effect of VPD and SWC on Gs and Q for different species, tree sizes, elevation and ecosystem. See figure 1 for a diagram of the data processing steps.

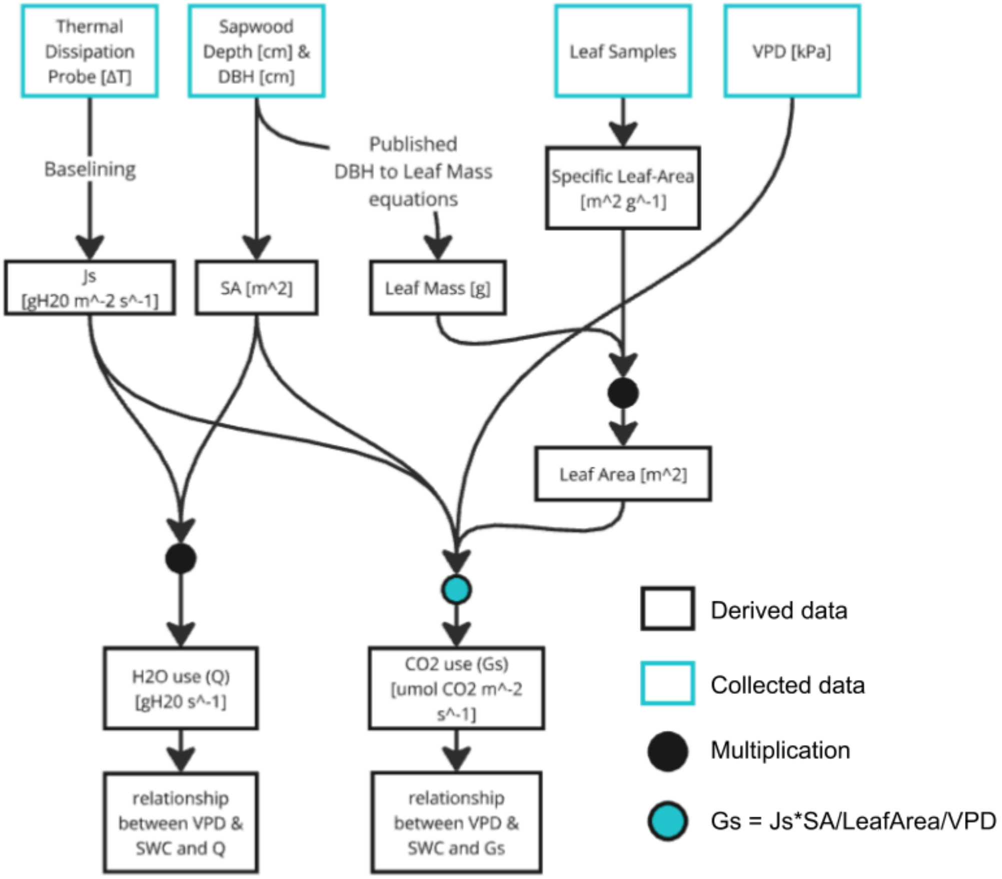

Figure 1 Data processing steps to go from collected data to the relationship between VPD & SWC and Q, Gs for each tree. Js: Sap Flux Density, DBH: Diameter of tree at breast-height, VPD: vapor-pressure deficit, SA: sapwood area, Gs: stomatal conductance, Q: tree-level sap flux. The equation for Gs and errors associated with its use are described in (Ewers & Oren, 2000)

With the help of this grant, I 1) developed and executed a methodology to safely collect leaf samples from high in the tree canopy, 2) applied a recently published method to obtaining sapwood depthod from increment cores using a thermal camera and 3) QA/QC and baselined all sap flux time series at US-Mpj and US-Wjs, comprising 14 years of at US-Mpj and 16 years of data at US-Wjs.

Leaf Samples

Leaf samples are necessary to calculate total leaf area, which is fed into the calculation for stomatal conductance at the canopy scale (see figure 1). I developed this methodology to retrieve a leaf sample from high in the canopy (the highest sample was 23.7m high) without climbing the tree, which was deemed unsafe, or using a shotgun, which is prohibited at the study sites. I used a large slingshot to set a low-friction cord (throw-line) over a twig. I then attached a double-sided chain-saw to one end of the throwline and hoisted it up to cut the twig (see figure 2).

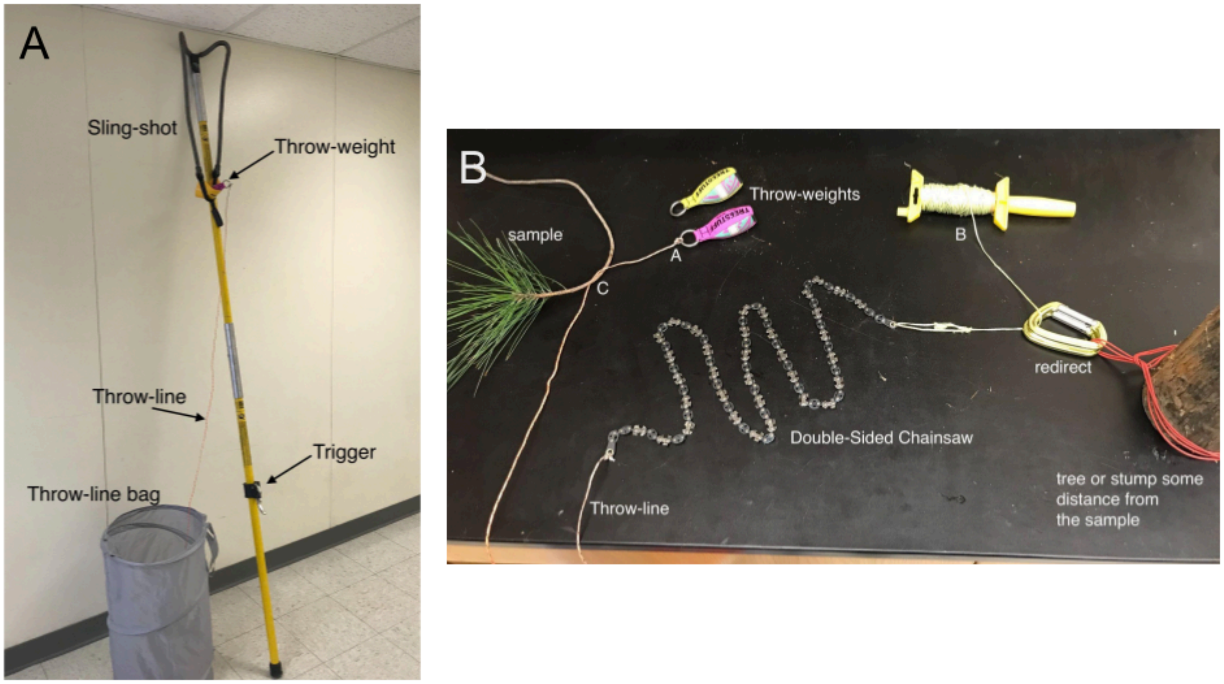

Figure 2 A) Equipment for setting the throwline over a twig. B) The equipment used to retrieve a sample after the throw-line has been set. Point C is cut by pulling on A to bring the chainsaw in contact with C. Then both A and B are alternatively pulled to create a sawing motion.

Thermal Data of Increment Cores

Due to practical limitations, a maximum of four Granier probes are installed in larger trees at US-Vcs and US-Vcp, which measure sap-flux in the outer 4 cm of sapwood. Up to two probes measure the outer 2cm of wood, and one probe measures the wood from 2cm to 4cm deep. The outer 10 cm of sapwood is measured in the smaller piñon and juniper trees at US-Wjs and US-Mpj. There are a number of reasons that additional information about the stem must be obtained to ensure the probe reading is accurate and useful for estimating stem or tree-level water use: 1) Sap is flowing over the entire sapwood area of a stem, and therefore these probe values must extrapolated to flow deeper in the wood in order to obtain a measure of whole-tree water use. 2) If probes extend into inactive heartwood the probe reading must be corrected (Clearwater et al., 1999). 3) It has been shown in many trees that sap flow varies spatially over the depth and circumferential position, as well as over the course of the day (Domec et al., 2005); (Ford et al., 2004); (Clearwater et al., 1999). This is why more than one probe is installed per tree, and at different depths where possible. A common way to calculate tree-level water use is by assuming: a) that multiple probes at the same depth and different circumferential positions may be averaged to find a good approximation of the true average value across circumference, b) the deeper probes are a good approximation of flow from their position up until the non-conductive heartwood; in other words, the sap flow rate is uniform with depth. However (Ford et al., 2004) showed that for some conifers this approximation can result in large errors, because sap flow can change significantly with depth, invalidating assumption (b). Similarly, evidence from a study of ponderosa pine wood properties (Domec et al., 2005) suggests that sap flow rates may vary significantly by depth. It is therefore important to 1) find sapwood depth and 2) validate the assumption that sap flow rate is approximately uniform with depth. Traditional methods for determining the sapwood depth are messy, expensive, or highly subjective (Gerchow et al., 2023). For these reasons I applied the methods described in (Gerchow et al., 2023) to quickly and objectively determine sapwood depth using tree cores sampled at our sites. With the support of this grant I purchased a thermal camera and supplies to take thermal imagery of increment cores in the field and analyze the data to find sapwood depth.

Cores were extracted 1.37 m above ground level using increment borers. Cores were placed in a plastic bag in the shade immediately after extraction to allow the heat generated by boring to dissipate. After a minimum rest time of 10 minutes and before a maximum rest time of 3 hrs, cores were exposed to the air for no longer than 10 minutes before thermal imaging, and a batch of 10-20 images were taken every 3 seconds. In order to quantify the sensitivity of the analysis to environmental conditions and a gradually drying core, multiple image batches were taken of the same core at different times, with the cores exposed to the air. After thermal imaging a normal photo was taken and cores were measured with a ruler to the nearest mm. An example of a core being thermally imaged can be seen in figure 3, and a thermal image in the analysis software along with a normal photo for reference can be seen in figure 4.

The first site sampled using this method was US-Vcp. In order to quantify the effect of resting time on calculated sapwood depth, cores were thermally imaged individually 10 minutes after coring, and then again all in the same tray after the final tree was sampled. An additional core was taken on the final tree (PP-1-318[1]) after finding rot in the first core (PP-1-9) (figure 9). For this reason many of the cores sampled at US-Vcp have multiple sets of data taken at varying durations after the core was extracted (figure 9). This allows for an estimate of how much time a

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[1] When a core is identified in a manner such as PP-1-318, the code is <species id>-<tree id number>-<core aspect in degrees>. This allows multiple cores from the same tree to be distinguished. For US-Vcp PP stands for *Pinus ponderosa.*

core can “rest” while still resulting in the same sapwood depth. From the US-Vcp data it was estimated that cores may rest for 3 hours, and likely longer, without significantly altering the results. Also, it appeared that 10 images were sufficient for a batch to capture sensor variation, and this standard was adopted for US-Mpj and US-Wjs.

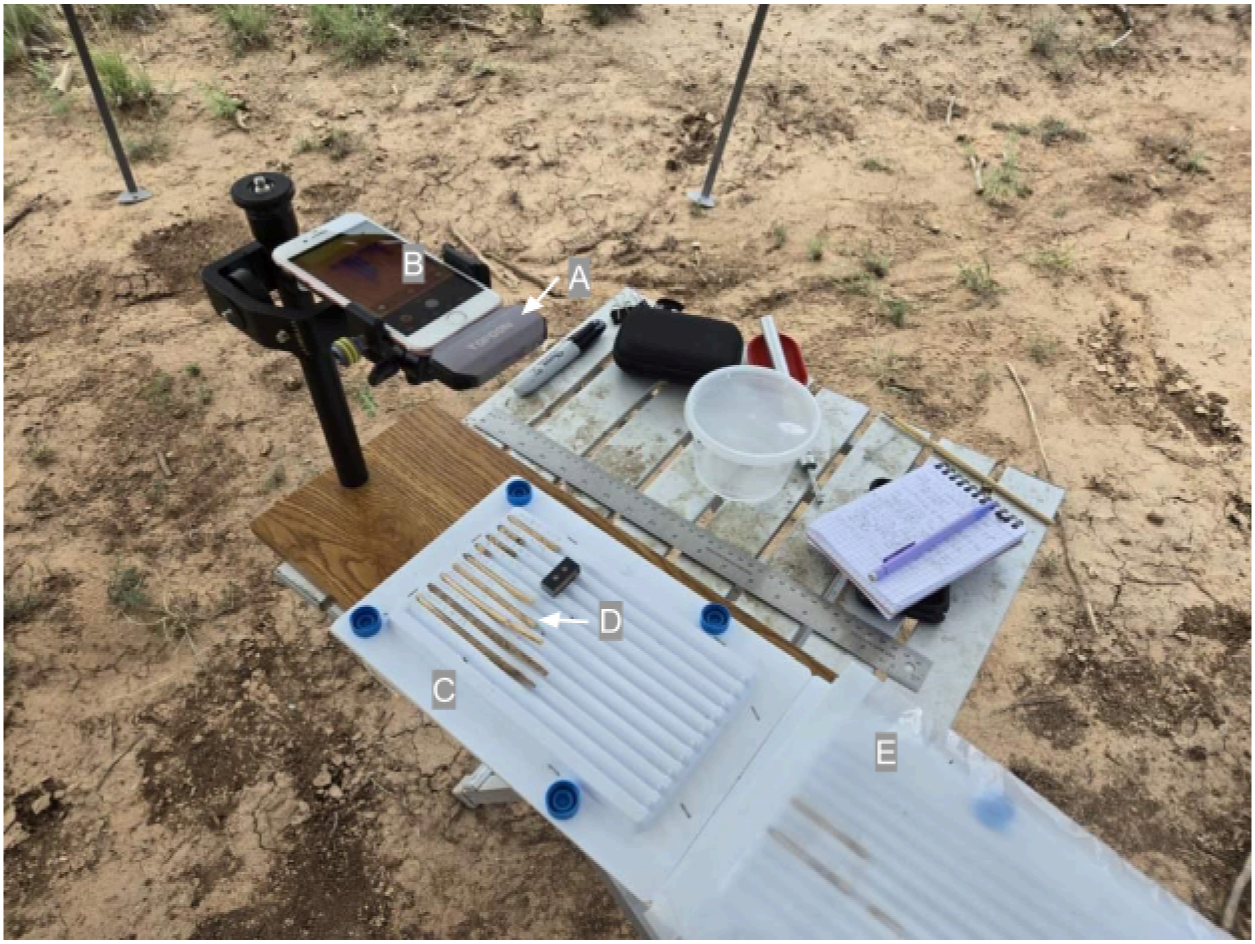
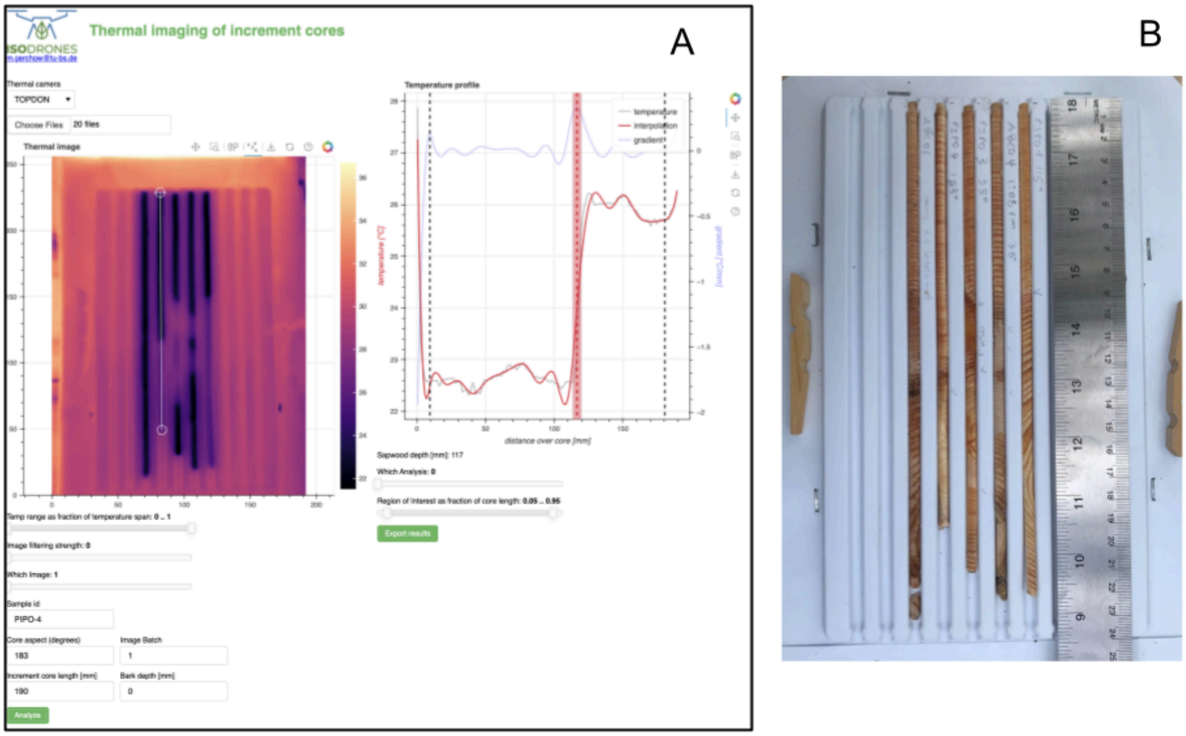


Figure 3 The rig for positioning the mobile-connected thermal camera along with cores in a tray. A: thermal camera B: smart-phone C: increment core holder D: increment core. E: plastic bag for protecting cores while they “rest”.



Thermal camera: TOPDON

20 files

Temp range as fraction of temperature span: 0 .. 1

Image filtering strength: 0

Which Image: 1

Sample id: PIPO-4

Core aspect (degrees): 183

Image Batch: 1

Increment core length [mm]: 190

Bark depth [mm]: 0

Sapwood depth [mm]: 117

Which Analysis: 0

Region of Interest as fraction of core length: 0.05 .. 0.95

Figure 4 A) a screenshot of the webapp used to detect the sapwood depth. Note that the user clicks the start and end point of the core (white circles in thermal image) and enters the core length. This is used to determine which temperature values are sampled from the image, and their position along the core. B) A reference photo taken of the same cores. This is helpful for determining the presence and position of rot and if the core passed through the center of the tree.

Dendrometer Sensors

Two types of dendrometer sensors were purchased with the funds from this grant. One is a point sensor, which is fixed to the trunk and measures changes in the radius of the trunk at a single point. The other is a circumference sensor, which uses a metal band that encircles the trunk to measure changes in the circumference of the trunk. These were installed on trees at all our sites. See figure 5 for an example of dendrometers at US-Mpj. Data from these sensors will help us validate baselining for the sapflow sensors, as well as indicate periods of time when trees are growing or less active and dehydrated.

Figure 5 A: Circumference Dendrometer installed on a single-stemmed juniper at US-Mpj. Probe insulation was removed in this photo to take measurements. B: a point dendrometer installed on a multi-stemmed juniper at US-Mpj. Reflective insulation protects the sapflow probes from the sun.

5. Results

Results: Sapflow Data

I finished QA/QC of sapflow data at US-Vcs, US-Vcp, US-Mpj and US-Wjs. See figure 6 for an example of QA/QC'ed sap flux data in [g H20 / m^2 / s] and figure 7 for a summary of the data processed at each site.

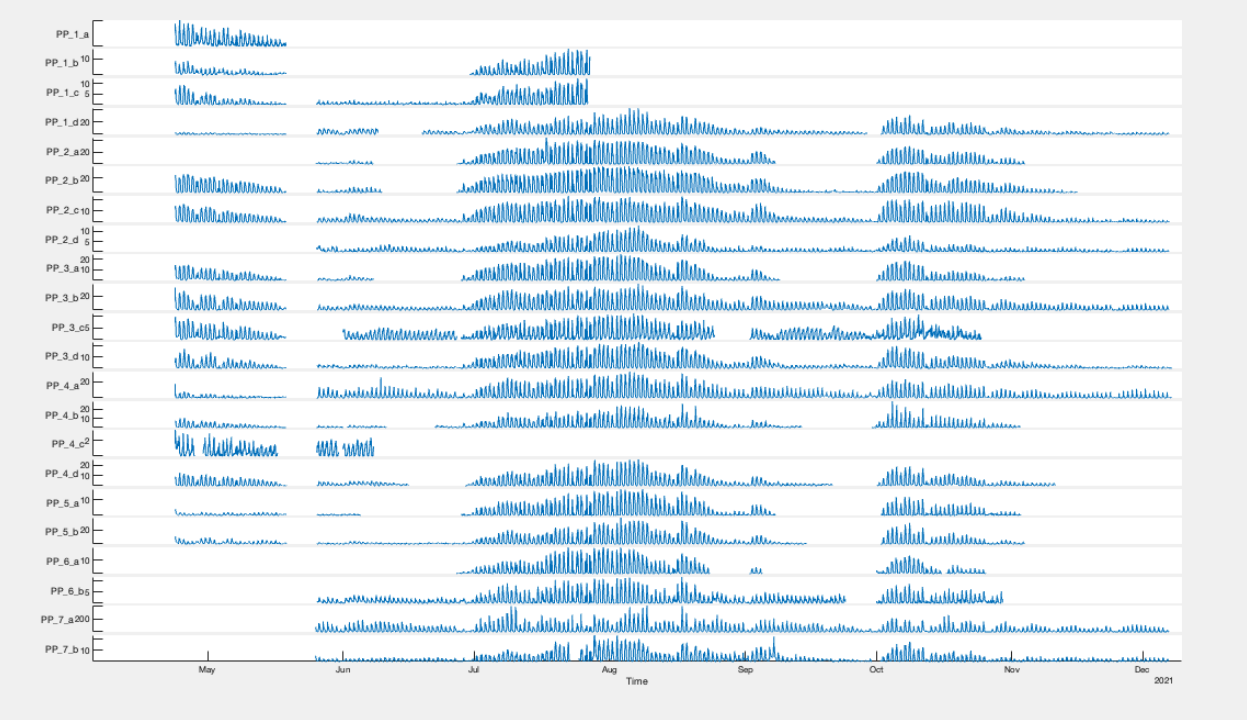


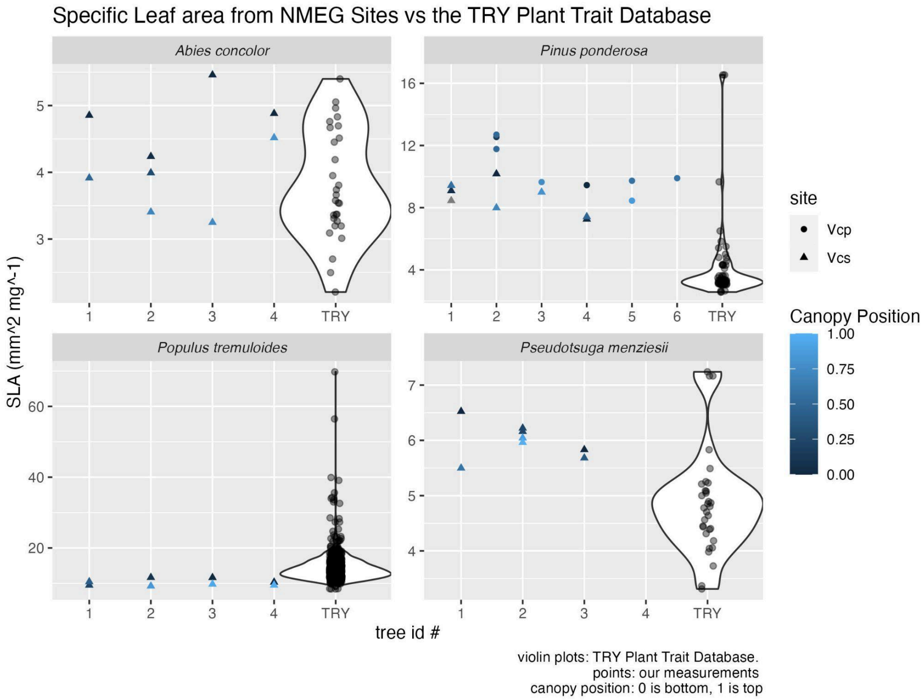
Figure 6 QA/QC'ed Sapflux density data [g H20 / m^2 / s] for all the probes at US-Vcp in 2020. Note some probes are in the same tree at different depths and circumferential positions.

Site	**Years**	**Number of probes**	**Number of trees**	**species**
US-Vcs	2016 to 2022	48	16	*P. tremuloides* *A. concolor* *P. ponderosa* *P. menziesii*
US-Vcp	2014 to 2022	22	7	*P. ponderosa*
US-Mpj	2009 to 2022	20	10	*J. monosperma* *P. edulis*
US-Wjs	2009 to 2022	10	5	*J. monosperma*

Figure 7

Results: Leaf Samples

I collected and processed leaf samples from our two high-elevation sites (US-Vcs and US-Vcp), a mixed conifer forest and a ponderosa pine forest. Specific Leaf Area (SLA) values calculated for each set of leaf samples are shown in figure 8. One interesting pattern is that samples taken from higher in the tree canopy tend to have lower specific leaf area, especially for P. tremuloides and A. concolor. This pattern can be observed in figure 8, where lighter colored points (higher in the canopy) tend to have lower SLA values. This is important because it implies that using a single value for specific leaf area for calculating leaf-specific stomatal conductance may result in significant errors.


Specific Leaf area from NMEG Sites vs the TRY Plant Trait Database

violin plots: TRY Plant Trait Database.
points: our measurements
canopy position: 0 is bottom, 1 is top

Figure 8 Specific Leaf Area for US-Vcs and US-Vcp, along with values for each species from the online TRY Plant Trait Database. Note the different y-axis limits in each plot, required by the different range in TRY values for each species.

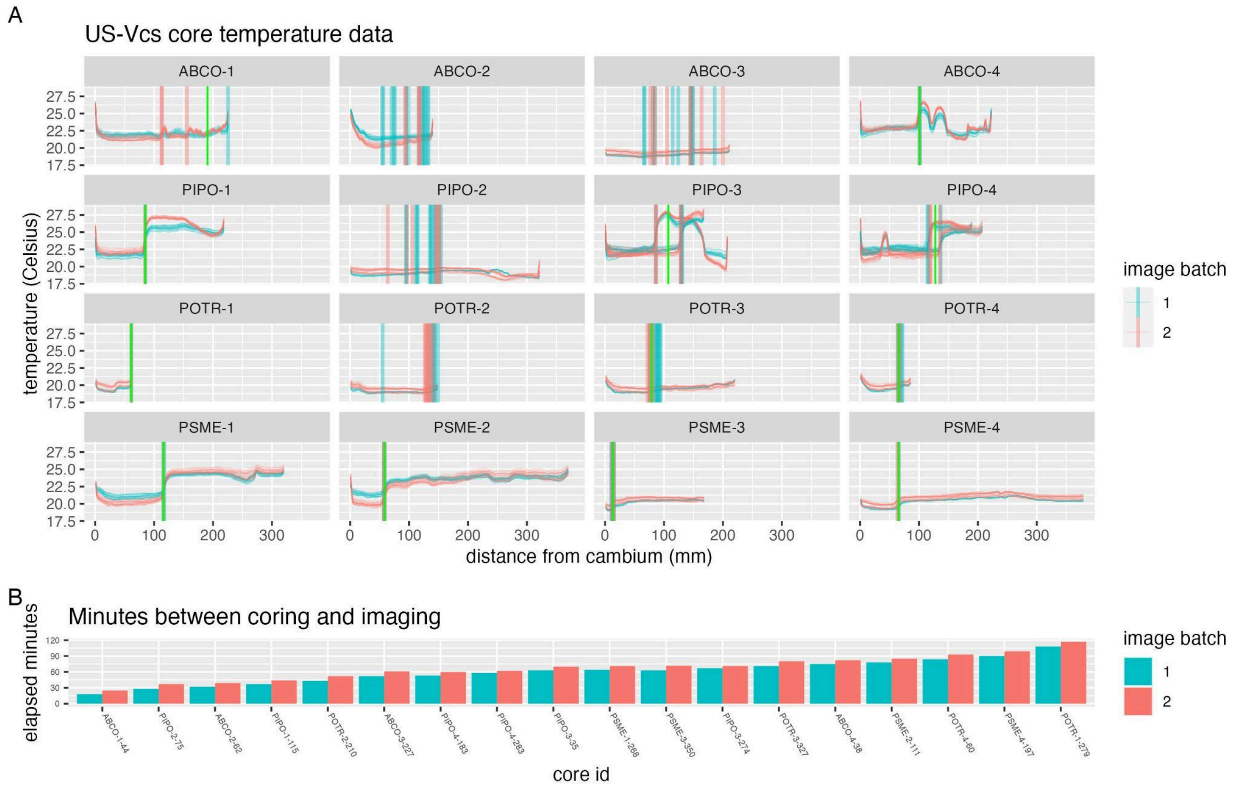
Results: Sapwood Depth from Thermal Data of Increment Cores

The majority of cores at the sites (~30 out of 45, visual estimation) indicated a sharp transition between wet wood and dry wood. Wet wood is assumed to be conducting sapwood and dry wood is assumed to be nonconducting heartwood. (Gerchow et al., 2023) developed a method and a web application to find the sapwood/heartwood boundary, or “sapwood depth”. I modified the web app to allow multiple images to be processed simultaneously. The method defines the sapwood depth as the depth where the slope of the temperature profile is at a maximum and is increasing with depth. In some cases cores had sections of rot (for example ABCO-1-44 in figure 10). This method is confounded by such cases because regions with rot are still wet, but are not active sapwood. Cross validation with visual interpretation of core coloration and texture will be used to make a final estimate of the sapwood depth in these cases. At present the simplest assumption of uniform sap flow rate with depth will be used for lack of data proving otherwise. No clear pattern was visible in the cooler temperatures, suggesting core temperature alone does not indicate wood-conductivity. Some cores, such as PP-6 at US-Vcp and ABCO-2-62 at US-Vcs, were wet across their entire length, and so the method incorrectly identified small temperature increases as sapwood/heartwood boundaries. These cases suggest that sapwood extends to the center of the tree. Some other special cases are seen at US-Vcs. Some cores had dry sections that did not appear to be rot and were in between wet sections (for example ABCO-4-38). It could be that these are regions of cavitated wood. Other cores had rot sections that appeared dry and caused the core to brake on extraction (see PIPO-4-283). These regions are manually ignored. The average depth is taken in cases where more than one core was taken on a single stem (as in PP-1 at US-Vcp and PIPO-3, PIPO-4 at US-Vcs). Some junipers have probes installed on separate stems. In that case one core is taken for each stem and sapwood depth is not averaged. In some cases the sapwood depth coincided well with color changes in the core. This was especially notable for *Juniperus monosperma* cores, where wood was a much lighter color in the outer portion of the core. In contrast *Pinus edulis* cores were uniform in appearance, with no visual indication of sapwood depth. This method was therefore beneficial for detecting sapwood depth, especially in *P. edulis. P. edulis* and *J. monosperma* data can bee seen in figure 11 and figure 12.

two cores were taken from PP 1 because the first had rot and resin damage. The second one did as well.
Vertical lines are the identified sapwood/heartwood boundary.

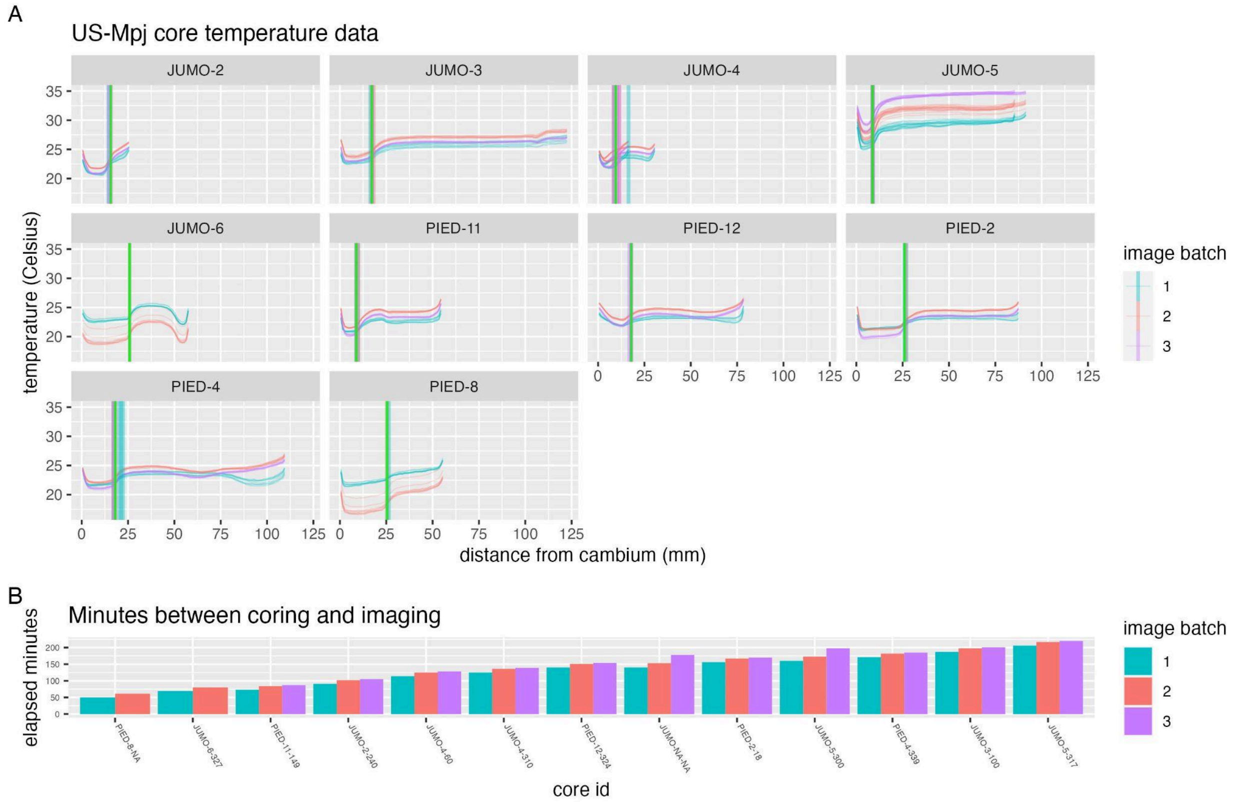
core id is: (<spps> <tree.id> <core.aspect>)

Figure 9 Core data for US-Vcp. A) temperature profile along the cores. All trees are *Pinus ponderosa*. HRM is a different sensor type used in a different study. PP are ponderosas with granier probes installed. B) Time elapsed between coring and imaging for the two image batches. Twenty images were taken per batch. Note that PP-1-318 was taken after try1, so has a negative duration for try1 and can be ignored. It is notable that for all trees, except PP-6 and PP-5, the sapwood depth is nearly identical for all three image batches. PP-6 is an exception simply because it is wet along its entire length. In the case of PP-5 it appears that the 10minuteAfter batch had an anomaly that was resolved in the later batches; in that case waiting longer resulted in clearer data.



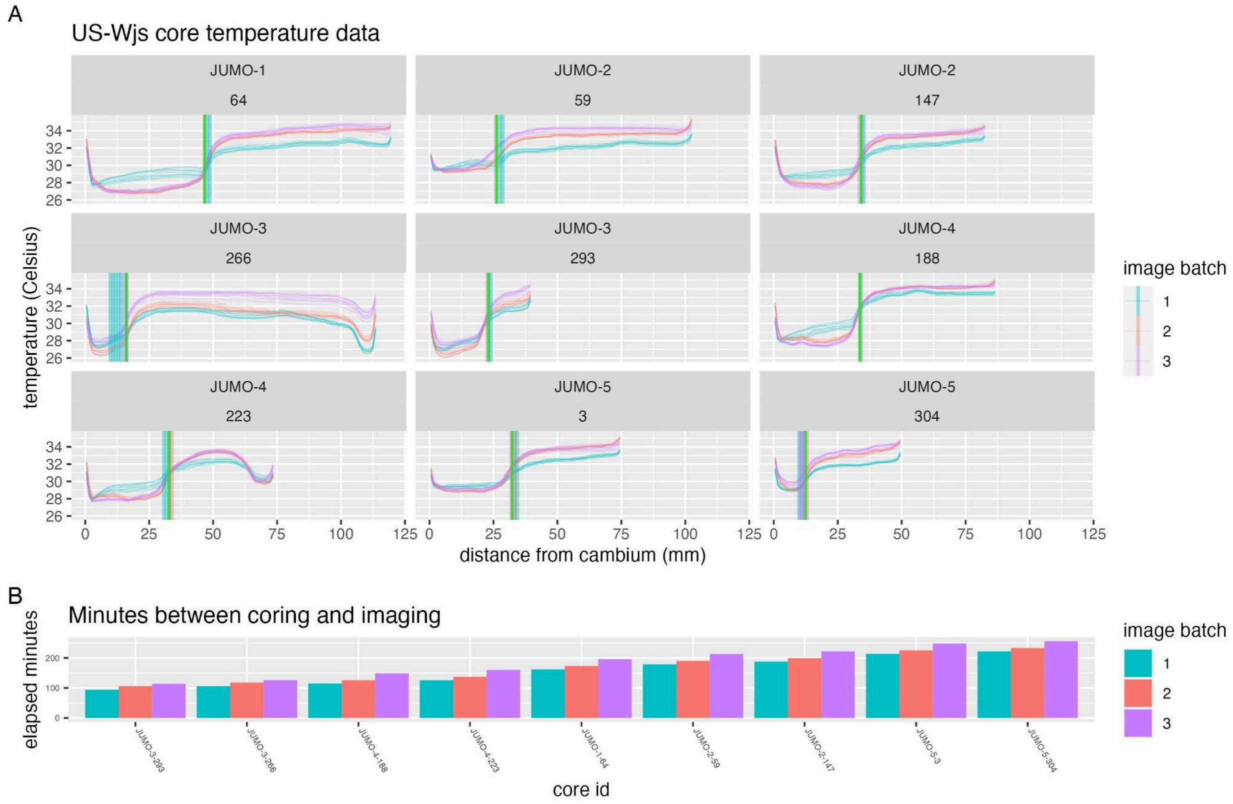
core id is: <species code>-<tree id>-<core aspect>
Batch 1 was taken no more than 10 minutes after all the cores were exposed while positioning in the rig.
Batch 2 was taken no more than 10 minutes after Batch 1.
Green line shows the sapwood depth determined by thermal data.

Figure 10 Core data for US-Vcs. A) Temperature profile along the cores. Species codes are: ABCO=*Abies concolor,* PIPO=*Pinus ponderosa*, POTR=*Populus tremuloides,* PSME=*Pseudotsuga menziesii*. B) Time elapsed between coring and imaging for the two image batches. Twenty images were taken per batch.



core id is: <species code>-<tree id>-<core aspect>
Batch1 was taken no more than 10 minutes after all the cores were exposed while positioning the rig.
Green line shows the sapwood depth determined by thermal data.

Figure 11 Core data for US-Mpj. A) Temperature profile along the cores. Species codes are: JUMO=*Juniperus monosperma,* PIED=*Pinus edulis.* B) Time elapsed between coring and imaging for the three image batches. Ten images were taken per batch. There was no visual indication of sapwood depth for *Pinus edulis* cores.



core id is: <species code>-<tree id>-<core aspect>
Batch1 was taken no more than 10 minutes after all the cores were exposed while positioning the rig.
Green line shows the sapwood depth determined by thermal data.

Figure 12 Core data for US-Wjs. A) Temperature profile along the cores. JUMO=*Juniperus monosperma*. Each graph represents a different core, with aspect displayed below the tree-id. In many cases probes were on two different branches, or even stems of the tree, so data is kept separate to reflect this. B) Time elapsed between coring and imaging for the three image batches. Ten images were taken per batch

Recommendations for Further Research: Sap Flow probes and Sapwood Depth

Studies suggest that sapflow rates may vary significantly by depth and circumference for many conifers (Domec et al., 2005); (Ford et al., 2004); (Clearwater et al., 1999). For this reason it would be advised to measure the variation as directly as possible. One way would be to construct a probe as described in (Ford et al., 2004) which measures sap flux density at a series of points along the radius of the bole. Considering the high cost of constructing and analyzing data from such a probe a fewer number of representative trees could be instrumented and a relationship could be defined to correct values from a single probe. In addition, granier probes are known to be poor estimators of zero-flow conditions, and they have consistent magnitude errors when compared to more accurate measurements (Rabbel et al., 2016); (Peters et al., 2018). For this reason it would be useful to install more accurate probes alongside granier probes to validate granier data and possibly provide corrections for past and future data. More reliable sapflux magnitudes would allow tree-level sap flux (Q) to be scaled up to the ecosystem level with more certainty and compared to flux tower measurements of evapotranspiration.

6. Who will benefit from the Research Results

Leaf area will be used to obtain stomatal conductance (Gs), which acts as a proxy for carbon sequestration rates. The results from US-Vcs and US-Vcp suggest that leaf area can vary by position in the canopy, and therefore tree-wide Gs must use an integrated measure of leaf area for the entire tree. Sapwood depth has been objectively determined for trees that have granier-type sapflow probes. Sapwood depth allows tree-wide sap flow rates to be calculated, in other words tree-wide water use. Tree-wide water use data can then be used to answer a wide variety of questions including: How is tree water use impacted by both atmospheric dryness and soil-moisture? How does tree water use change by tree size, tree species, ecosystem type, elevation and local forest density? How has tree water use changed over time, and by season? Analogous questions can be answered about carbon-sequestration rates using Gs. The answers to the water-use form of these questions will help us understand what trees, ecosystems and forest structures may be most vulnerable to future changes in climate and how ecosystem water-balance may change. The answers to the carbon-sequestration form of these questions will help us understand how feedbacks between climate and forests are operating in semi-arid regions like New Mexico. On a smaller scale, these results could help us identify species that tend to use high amounts of water despite high stand density or drought. Other results could indicate if certain species have altered water-use patterns at different elevations (ponderosas and junipers exist at two different elevations at our sites).

One agency that could use these results is the NM Environment Department, possibly in collaboration with the US Forest Service and the NM Energy Minerals and Natural Resources Department (EMNRD). Selective thinning based on which trees are expected to overdraft water in the future could reduce water losses to transpiration and increase stream flows and groundwater recharge, as well as release remaining trees from competition. These results could also inform reforestation efforts by identifying forest structures and climates where trees will maintain a healthy amount of groundwater withdrawal or maximize carbon sequestration.

7. Budget Balance and Remaining Funds.

Describe how you have spent your grant funds. Also provide your budget balance and how you will use any remaining funds. If you anticipate any funds remaining after August 30, 2024, please contact Carolina Mijares immediately. (575-646-7991; mijares@nmsu.edu)

The grant funds have been used to buy supplies to aid in collecting leaf data and thermal core data. They have also been used for travel to sites. The funds also supported half of my salary during the spring 2024 semester, allowing me to be a graduate teaching assistant for one lab section as opposed to two, and thereby devote more time to sample collection and data analysis. They also were used to attend the 68th Annual New Mexico Water Conference and present a poster. No significant funds remain.

Total: Budgeted: $7,386.22, Used: $7,383.51, Remaining: $2.71

Salary: Budgeted: $3,806.62, Used: 3,773.14, Remaining: 33.48
This covered one half of the salary awarded under a 0.5 FTE graduate assistantship position at UNM. I took a 0.25 FTE assistantship position for the Spring of 2024, allowing an additional 10 hours of work to be allocated to this project.

Fringe Benefits: None

Health Insurance: None: Covered by 0.25 FTE graduate assistantship

Travel: Budgeted: $1,029.60, Used: $656.54, Remaining: 373.06

expense	cost
site visits	606.54
68th Annual NM Water Conference	50
total	656.54

Supplies Budgeted: $2,550.00, Used: $ 2,953.83, Remaining: -403.83 (Note that the deficit is accounted for by Travel)

item	cost
tomst point dendrometer	2201.17
p2 pro thermal camera purchase and return (difference)	6.5
field supplies: ruler, notebook, tape, wooden boards, clipboards	40.71
camera clamping hardwear	62.47
pole pruner	117.49
forestry angle gauge	37
supplies for getting leaf samples from high trees	159.36
hand rope saw: double-sided chainsaw	36.98
increment core holders (trays)	63.15
topdon TC002 thermal camera	229
Total	2953.83

Services: None
Equipment: None

8. Presentations related to the project.

- Poster presentation at the 68th Annual NM Water Conference
- Poster presentation at 33rd Annual UNM Biology Research Days

9. List publications or reports, if any, that you are preparing. For all publications/reports and posters resulting from this award, please attribute the funding to NM WRRI and the New Mexico State Legislature by including the account number: NMWRRI-SG-FALL2023

- UNM Masters thesis

10. List any other students or faculty members who have assisted you with your project.

- Professor Will Pockman (UNM)
- Professor Alex Webster (UNM)
- Research Professor Rae DeVan (UNM)
- PhD Student Malkin Gerchow (Technical University of Braunschweig)
- Rachael Auer (UNM, Research Scientist I)

11. Provide special recognition awards or notable achievements as a result of the research including any publicity such as newspaper articles, or similar.
None

12. Degree completion and future career plans.

My plan is to complete my degree by the end of Spring of 2025. In the process of doing this research I have discovered I am interested in Eco-Hydrology. Eco-hydrology is interesting to me because ecosystems have an important impact on the precious water resources in New Mexico. I want to work in a setting where science is applied to management and my efforts contribute to effective management of water resources in our state.

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