SMART TREE WATERING IN ARIZONA'S URBAN ENVIRONMENT IN RESPONSE TO ARIZONA DEPARTMENT OF FORESTRY AND FIRE MANAGEMENT OPPORTUNITY STATEMENT OS #7 ON SMART URBAN TREE WATERING

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PROJECT SUMMARY

Nationwide, landscape irrigation consumes nearly 30% of all residential water. In Arizona, climate change has generated an enormous amount of interest in planting trees to increase canopy cover in order to make the urban environment more livable. However, an extended drought in Arizona calls for innovative solutions for tree watering that support increased water demand during establishment. The goal of this project is to provide mobile, efficient, and scalable urban tree watering solutions through place-based research in Tucson and Phoenix metropolitan areas. Specific objectives are: (1) to provide smart watering technologies that enhance tree survival during establishment, and (2) to quantify water savings resulting from new technologies for saplings as well as established trees.

We will compare the performance of status quo tree watering practices with proposed technologies that couple new watering techniques with conventional irrigation management schemes and optimizations. Using empirical data on tree survival and water savings, we expect to assess the benefits of water savings in tree plantings for city- and county-wide applications. In addition, we plan to broadly disseminate the research findings through a workshop that engages municipalities, counties, and community groups and to conduct field trips at the field experiment sites.

Various conventional tree watering strategies exist (e.g., flood, sprinkler, drip) with different ancient and contemporary products and techniques designed to hold water in the soil for plant establishment and for long term self-sufficiency (e.g., Olla, TreeDiaper, Groasis Waterboxx, rainwater harvesting). However, challenges remain, such as water draining too fast, high evapotranspiration loss, variability in rainfall, and irrigation products being unable to accommodate root systems—leading to product failure, root rot, and high costs that prohibit large-scale applications. In addition, solutions may be limited because of minimal understanding of the costs of urban forestry, such as irrigation, and by local residents' needs and preferences. The performance data on tree watering in Arizona's urban environment is even more sparse.

We propose a multi-scale study approach to address these challenges by integrating field experiments with numerical modeling. We will monitor individual tree survival, soil moisture and temperature, and basic micrometeorlogical data in a controlled experiment, in situ field experiment and at the city scale to capture variation in landscape typologies. At the site-scale, we will conduct controlled field experiments to test and collect performance data on innovative slow-watering materials based on hydrogels and other technologies identified as commonly used by municipal collaborators. In addition, through our current municipal collaborators, we have identified a community park in Tucson to conduct an in situ field experiment, where newly installed green stormwater infrastructure basins and saplings will be paired with innovative slow-watering materials and monitored for indications of water stress and survival over 8-10 months. At the city-scale, we will examine tree watering schemes at four distinct landscape types (oasis, mesic, xeric, and desert). At both scales, we will assess tree health and survival rates. We will use sensor technologies to collect data on soil moisture and soil temperature, which can inform the development and placement of the hydrogel and other watering treatment. Data collected will be used to calibrate and validate the numerical urban canopy modeling to forecast the performance

benefits of water savings and other co-benefits and tradeoffs in Arizona's urban environments at city and regional scales.

This study builds on collaborations with Tucson and Phoenix's urban forestry and water departments. The interdisciplinary team encompasses expertise areas of landscape architecture and planning (Yang), landscape ecology and GIS/remote sensing (Li), soil and plant science and sensor technology (Buzzard), green infrastructure and water harvesting (McCormick), materials science and chemistry (Loy), land/water modeling and sensor technology (Wang), and machine learning and optimization (Xu).

PROPOSAL ADVANTAGES

This study supports ADFFM's mission to create healthy urban forestry while promoting sustainable water practices. Outcomes of this project will demonstrate significant impacts by achieving the following three aims.

1. Provide a pathway for rapid development and prototyping of new products for tree watering.
2. Quantify product performance for watering in support of tree establishment directly following planting.
3. Create a framework for ADFFM-led engagement activities to enhance municipalities' capacity and preparedness toward drought resilience and urban heat island (UHI) mitigation.

There are two potential risks we have identified in this project and have outlined ways to address them. The first is unexplained sapling mortality, which may be due to unforeseen conditions such as disease without visible indicators. To mitigate this risk, we will use three sapling replicates for each experiment. The second risk is associated with vandalism and data loss which occur with the use of visible technologies, such as watering boxes or tree diapers, or hidden/buried sensors that may be subjected to heavy equipment during general maintenance or burrowing animals. Therefore, we will conduct frequent and robust site checks, prepare additional sensors and visible slow-water materials to swap if impaired or failure is identified, and ensure data logger are backup data regularly and stored in cloudbased software, such as Box and Google Drive.

SCOPE OF WORK

We propose to conduct a multi-scale study in three sequential/overlapping steps (Table 1). We will first summarize the current state of research, including tree demographic studies measuring survival, mortality, and removal patterns in the region. We will also examine species' response to disturbances such as drought and current irrigation management practices (e.g., use recycled water for irrigation).

We will procure similarly aged trees of the same species, work to develop simplified hydrogel cells, and identify additional slow-water materials through discussion with municipal collaborators from the City of Tucson and Phoenix. We have identified hydrogel cells because they are versatile products that can absorb water up to 500 times their weight and show potential as a cost-effective approach for concentrating water along tree roots ensuring water availability during dry periods. Hydrogel commercial products are in the form of small particles and have been used for amending soil in planting holes for young trees and to improve water use efficiency in grassland and agriculture fields. In this current study, we will develop hydrogel cells in shapes that are easy for 3D printing (e.g., rectangle) and easy to install in soils. Hydrogel cells will be placed relatively evenly surrounding the sapling/tree drip lines and at varying distances between the tree trunk and the drip line and at varying depths to test the watering efficiency. These cells will be installed when digging the hole for saplings at a width of 2-3 times the root ball width. 3D-printed hydrogel cells will include environmentally compatible organic and hybrid/inorganic-organic systems. The hydrogel cells can be readily tailored to manipulate water uptake and release (adsorption-desorption). They will be paired with control systems to provide actuation capabilities associated with volume change upon water uptake.

Table 1. Project scale, location, and timeline.

Scale & step	Location	Activity and task lead	Timeline
Literature review	UA & ASU	UA & ASU researchers	1-2/2023
Site-scale (saplings to install, spring 2023)	UA Agricultural Center, Tucson (controlled field experiments)	Data collection via sensors UA researchers	1-12/2023
	Gunny Barreras Memorial Park, Tucson (real-world setting)	Data collection via sensors UA researchers Tucson city partners	2-12/2023
City-scale (established trees)	Selected communities (four landscape types—oasis, mesic, xeric, and desert), Phoenix and Tucson	Sensors, GIS mapping ASU & UA researchers Phoenix & Tucson city partners	(varies) 3-12/2023
	Modeling scaling-up, optimization with surrogates	ASLUM & machine learning ASU & UA researchers	(varies) 6-12/2023
Results dissemination	UA campus for workshop; Tucson study sites for fieldtrips	Workshop, fieldtrips, publication UA & ASU researchers, ADFFM	8-12/2023

Figure 1. Experimental Design. Ground-based empirical data collected on individual trees at UA Ag Center (top panel) and in situ at Gunny Barreras park (middle panel). We will test slow-watering materials one native tree species from tree lists suggested by the City of Tucson Urban Forestry Program under controlled conditions at UA Ag Center and under natural environmental conditions in the field at Gunny Barreras Park to capture a broad range of impacts on product performance. We will integrate these empirical data into urban models to assess viability at city scales with respect to four landscape typologies.

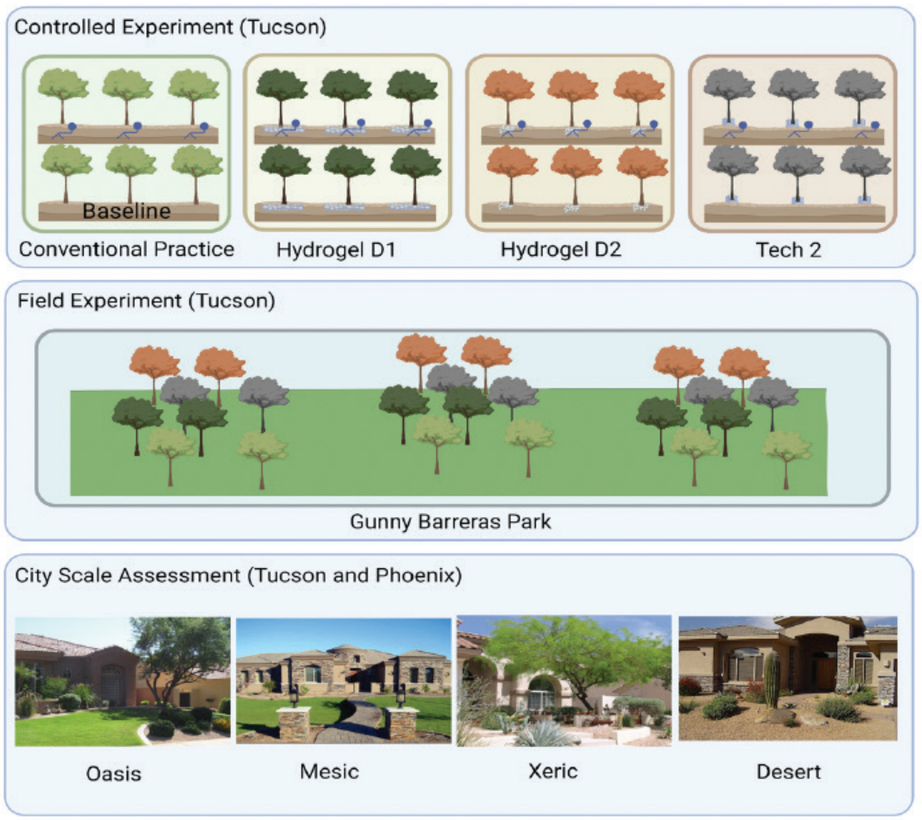

Figure 1. Study sites in Tucson and Phoenix. (1) Site scale (UA Agriculture Center, controlled experiment)—to compare four different situations with three saplings for each (24 saplings total in Tucson)—current practice (e.g., sprinkler/drip irrigation); irrigated by the new hydrogel technology (D1 (drip line) and D2 (between drip line and tree trunk): placed at two different distances [D] to tree trunk; and Tech 2 (current/emerging practice such as Groasis Waterboxx). (2) Site scale (Gunny Barreras Park, field experiment)—to replicate the research design in (1). (3) City scale—to compare two different situations (current practice vs. new hydrogel technology) across four distinct landscape types (oasis, mesic, xeric, and desert) using three established trees for each (24 trees in Tucson and 24 in Phoenix; 48 total). Integration with existing green stormwater infrastructure (e.g., rainwater harvesting basins) and mulch practices will also be considered based on the individual site conditions.

We will deploy sensor networks surrounding the saplings/matured trees (see Figure 1) to measure the soil moisture and temperature. It is hypothesized that watering saplings/matured trees using hydrogel cells can maintain higher and more stable levels of soil moisture and lower temperatures than more natural conditions between rainfall events. In addition, the hydrogel cells are expected to support better tree health, yield higher tree survival rates, provide long-term water self-sufficiency, are cost-effective and easy to install, and require low maintenance. We will compare water meter data among watering schemes to assess water savings.

At the site scale (both controlled and field experiments), we will examine the temperature andmoisture thresholds and ranges that would significantly influence tree establishment and growth. Three sets of data will be collected: (1) hourly soil moisture and temperature (iButton sensors placed in-situ), (2) bi-weekly data on tree health (field measurements), (3) monthly water use data (water meters and study records/logs) and naturally occurring rainfall data. We will also survey each site to obtain the information of building arrangement, tree locations, crown size, and types and coverage of vegetation and pavement. We will conduct weekly site visits and observations at all sites in Tucson and Phoenix throughout the study period (1/2023-12/2023).

We will use empirical data collected from site-scale experiments to inform an urban canopy model (UCM) that can evaluate “what if” scenarios at the city scale. The UCM is designed to represent the built environment at the neighborhood scale (~100-1000m), and it is scalable to address city level processes. At the city scale, the urban area can be simulated as gridcells with spatial resolution of neighborhood scale; each gridcell represented by its own buildup (e.g., low- , medium-, or highresidential) class with landscape data obtained from the aforementioned site-scale survey. Specifically, we will model different watering schemes using a state-of-the-art UCM (ASU Single-Layer Urban canopy Model; ASLUM v4.1) over typical landscapes in Arizona (desert, xeric, mesic, and oasis). ASLUM features holistic representation of physics and transport of heat, moisture, and carbon emissions, urban hydrological processes, and advanced parameterization of biogenic functions of urban vegetation. This numerical modeling can identify the optimal watering schemes to increase the survival rate of saplings (1-2 years), and to reduce water use for established urban trees.

The “what if” scenarios will be developed based on the configuration of parameters in ASLUM (e.g., tree coverage, tree crown size, soil type, and material properties). Next, we will simulate the water use and vegetation response to various watering schemes facilitated by machine learning (ML) fast surrogates of ASLUM. Our previous studies have shown that ML-based surrogates can emulate ASLUM outputs at high accuracies with negligible computational cost in Phoenix. We will train and validate the ML surrogates using ASLUM simulation results and sensor data and apply the surrogates throughout Phoenix and Tucson.

Key outcomes of ASLUM and ML surrogates include soil-, surface- and air-temperatures of the site around trees, evapotranspiration loss, amount of irrigation, and amount of water savings due to smart watering schemes, presented in GIS spatial maps and descriptive statistics. Furthermore, we will perform multi-objective optimization and use genetic algorithms to determine the optimal portfolio of watering schemes that minimize the addition of supplemental water and tree mortality, and maximize tree health. The optimization leads to Pareto solutions, meaning any of the objectives cannot be further minimized/maximized without jeopardizing other objectives, thus characterizing the tradeoffs between tree health and water use.

Finally, we will assess the overall project success through several comparisons. (1) Compare the tree health across different study sites using the US Forest Service's Tree Health Metrics. (2) Compare tree mortality rates of the study sites with the typical mortality rates in Arizona and national averages. (3) Compare the cost of each tree watering scheme and the benefit of water savings for the short- and long-term. These comparisons will help municipalities to make informed decisions on urban tree watering. The Urban Forestry and Water departments of Tucson and Phoenix will help leverage resources to facilitate the study.

Deliverables & Metrics of Success

Performance Period	Anticipated Deliverables	Metrics (if applicable)
Year 1	• Sensor data collected from field experiments with summary statistics • Percent of water savings at two scales • Tree health data Recommendation for products and technologies for tree establishment watering. • GIS spatial mapping of tree watering needs based on landscape types • Urban modeling framework for tree watering through various smart watering schemes • Model simulated city-scale tree health and water savings • Machine learning-based surrogate models for fast simulations at city-scale • A multi-objective optimization tool to identify optimal tree watering strategies	•Soil moisture and temperature • Tree DBH • Canopy width • Tree crown health • Trunk cross sectional area • Tree height • Tree mortality rate (1st year) • Tree mortality rate compared to state and national averages • Water savings (1st year) • Projected water savings (long-term) • Cost vs. benefit of each tree watering scheme (short- and long-term) • Co-benefits and tradeoffs
Final Product(s) / Deliverable(s)	• A final report submitted to ADFFM • A stakeholder workshop jointly organized with ADFFM • Field trips to experiment sites • 1-2 journal publications	

The research team will conduct monthly meetings and will meet regularly with the ADFFM designee (at least bi-monthly; total 6-7 meetings) to discuss progress on the project. In addition, the team will coordinate with the UArizona Research, Innovation & Impact office and ABOR on bi-university coordination on at least a quarterly cadence.

Team Members

Name	Department	Institution
Bo Yang	School of Landscape Architecture and Planning	University of Arizona
Shujuan Li	School of Landscape Architecture and Planning	University of Arizona
Vanessa Buzzard	School of Natural Resources and the Environment	University of Arizona
Grant McCormick	Planning, Design & Construction; Department of Environmental Science	University of Arizona
Douglas Loy	Department of Materials Science and Engineering; Department of Chemistry and Biochemistry	University of Arizona
Zhihua Wang	School of Sustainable Engineering and the Built Environment	Arizona State University
Tianfang Xu	School of Sustainable Engineering and the Built Environment	Arizona State University

Budget: 3-year budget $752,100