CHAPTER 8

Enhancing Water Availability for Agricultural and Oilfield Applications

Lead Authors

Samuel A. Stormer
Institute for Public Policy Research and Analysis
University of Oklahoma
Norman, OK

Kevin Wagner
Oklahoma Water Resources Center
Oklahoma State University
Stillwater, OK

Mark Krzmarzick
School of Civil & Environmental Engineering
Oklahoma State University
Stillwater, OK

Contributing Authors, by Alpha

Clint Aichele
School of Chemical Engineering
Oklahoma State University
Stillwater, OK

Prem Bikkina
School of Chemical Engineering
Oklahoma State University
Stillwater, OK

Shellie Chard
Water Quality Division
Oklahoma Department of Environmental Quality
Oklahoma City, OK

Babu Fathepure
Department of Microbiology and
Molecular Genetics
Oklahoma State University
Stillwater, OK

Andrew S. Fox
Institute for Public Policy Research and Analysis
University of Oklahoma
Norman, OK

Hank Jenkins-Smith
Institute for Public Policy Research and Analysis
University of Oklahoma
Norman, OK

Preston Jones
Hydra Resources LLC
D&B Operating LLC
Ringwood, OK

Dayton Lambert
Department of Agricultural Economics
Oklahoma State University
Stillwater, OK

Lixia Lambert
Department of Agricultural Economics
Oklahoma State University
Stillwater, OK

Jarrod Maly
Hydra Resources LLC
D&B Operating LLC
Ringwood, OK

Owen Mills
Department of Environmental Quality
Oklahoma City, OK
Sushobhan Pradhan
School of Chemical Engineering
Oklahoma State University
Stillwater, OK

Xiangming Xiao
School of Biological Sciences
University of Oklahoma
Norman, OK

Chris Zou
Department of Natural Resource Ecology and Management
Oklahoma State University
Stillwater, OK

*This material is based on work supported by the **National Science Foundation** under Grant No. **OIA-1946093**, through the **Established Program to Stimulate Competitive Research (EPSCoR)** and the **Oklahoma State Regents for Higher Education**.*

This work represents a collaborative effort among researchers from the University of Oklahoma, Oklahoma State University, University of Tulsa, University of Central Oklahoma, Southwestern Oklahoma State University, Langston University, and the Noble Research Institute as well as affiliated organizations within the Socially Sustainable Solutions for Water, Land Use, and Infrastructure Resilience in Oklahoma (S3OK) project.

Acknowledgements

The authors extend their sincere gratitude to the members of the Opinion Leader Advisory Network for generously sharing their time, expertise, and insight—and for taking a chance on collaborating with us for the good of Oklahoma.

We are deeply appreciative of the participants in the Oklahoma Meso-Scale Integrated Socio-Geographic Network (M-SISNet) for contributing their time and opinions across eight surveys over the past five years. Their continued engagement provides an invaluable pulse check on the development of socially sustainable solutions to the state's most complex and "wicked" problems.

We also thank the members of the Extended Peer Science Advisory Network (EPSAN) for their expertise, insight, and commitment to advancing an empirically sound and socially relevant science.

Last, but not least, we express our appreciation to the dedicated research staff, students, and administrative professionals whose countless hours of collaboration, coordination, and creative effort ensure that this project remains strong, cohesive, and impactful.

CHAPTER 8

Enhancing Water Availability for Agricultural and Oilfield Applications

In the summer of 2020, Oklahoma received a National Science Foundation EPSCoR award to conduct research and collaborate with practitioners to address particularly complex issues ("wicked problems") facing Oklahoma in the areas of variable and marginal quality water supplies, land use, and infrastructure as they are impacted by changing seasonal and subseasonal weather patterns. The premise for this *Socially Sustainable Solutions for Water, Carbon and Infrastructure Resilience in Oklahoma* project, dubbed the "S3OK" project, is that socially sustainable solutions to complex societal problems will be found at the intersections of related but distinct problem areas, where diverse stakeholders can find agreement because the array of issues cuts across the usual narratives that frame social conflict.

The funded S3OK project created the foundation for the research and collaboration outlined in the case study and resource guide below.

To ensure iterative engagement between key stakeholders and scientists, the S3OK project team recruited nearly 70 distinguished practitioners from around Oklahoma to advise the project across its science focus areas; a significant subset of these practitioners (approximately 35) represented the water sector, including municipal officials, state officials, federal officials, private firms, nonprofit associations, and more. This practitioner group – the Opinion Leader Advisory Network (OLAN) – was instrumental in guiding the researchers' focus to ensure that the science undertaken through the project was of high relevance to Oklahomans and that this science could be applied directly to challenges currently faced by Oklahoma's water sector.

Enhancing Water Availability for Agricultural and Oilfield Applications

Through the S3OK opportunity, researchers and OLAN members collaborated over five years to define and discuss wicked problems of mutual high priority and select specific topic areas to work on in-depth in a 15-month working group format throughout years four and five of the project. Following a series of iterative selection processes, S3OK researchers and OLAN members decided to explore the topic of *Produced Water Reuse Potential for Oilfield and Agricultural Applications*.

> ***S3OK** emphasized not just research but systematic and iterative engagement between key stakeholders, the public, and researchers to identify convergent solutions in these key areas.*

Later, this focus was expanded to capitalize on S3OK research on improving soil health and management of Eastern Red Cedar, culminating in this chapter, *Enhancing Water Availability for Agricultural and Oilfield Applications*. Partners who contributed to this chapter's work included:

- Chickasaw Nation
- D&B Oilfield Services Inc.
- Noble Research Institute
- Oklahoma Department of Environmental Quality
- Oklahoma State University
- Oklahoma Water Resources Board
- University of Oklahoma

Nature of Water Quantity Problems

According to the 2012 Oklahoma Comprehensive Water Plan (OCWP), statewide consumptive demand for water will increase by 33% between 2010 and 2060. Much of this growing demand will occur in the crop irrigation sector. However, the oil and gas demand sector will experience the highest growth rate statewide, approaching 200%. Concurrently, surface water availability gaps, which occur when the demand for water is projected to exceed available supply, are forecasted in 67% of OCWP basins by 2060. At least minor depletions of alluvial and bedrock groundwater aquifers are predicted to occur in 78% and 41% of planning basins, respectively, by 2060 with many of these depletions occurring in western Oklahoma. Not surprisingly, the Oklahoma Meso-Scale Integrated Socio-Geographic Network (M-SISNet), a longitudinal survey of up to 2,500 geolocated households across Oklahoma that provides data on household perceptions on various issues, found that a substantial portion of the Oklahoma public is concerned with water quantity issues **(Figure 8.1)**. Per this survey, the western half of the state (particularly the southwest and Panhandle) perceive more issues with water quantity than other regions. This is consistent with the 2012 OCWP update, which found limited supply for growing demands in these regions.

To meet future demands, the 2012 OCWP recommends that the use of marginal quality water sources—such as brackish groundwater, treated wastewater effluent, production water from oil and gas operations, and stormwater runoff—have the potential to augment supply in many areas of Oklahoma. Similarly, the Working Group on *Enhancing Water Availability for Oilfield and Agricultural Applications* also identified **reuse of produced water**, or water that naturally exists in subsurface formations and is brought to the surface during oil and gas production, as a potential source of water to combat water scarcity. The current practice of produced water disposal was identified as a wasted opportunity for increasing water availability.

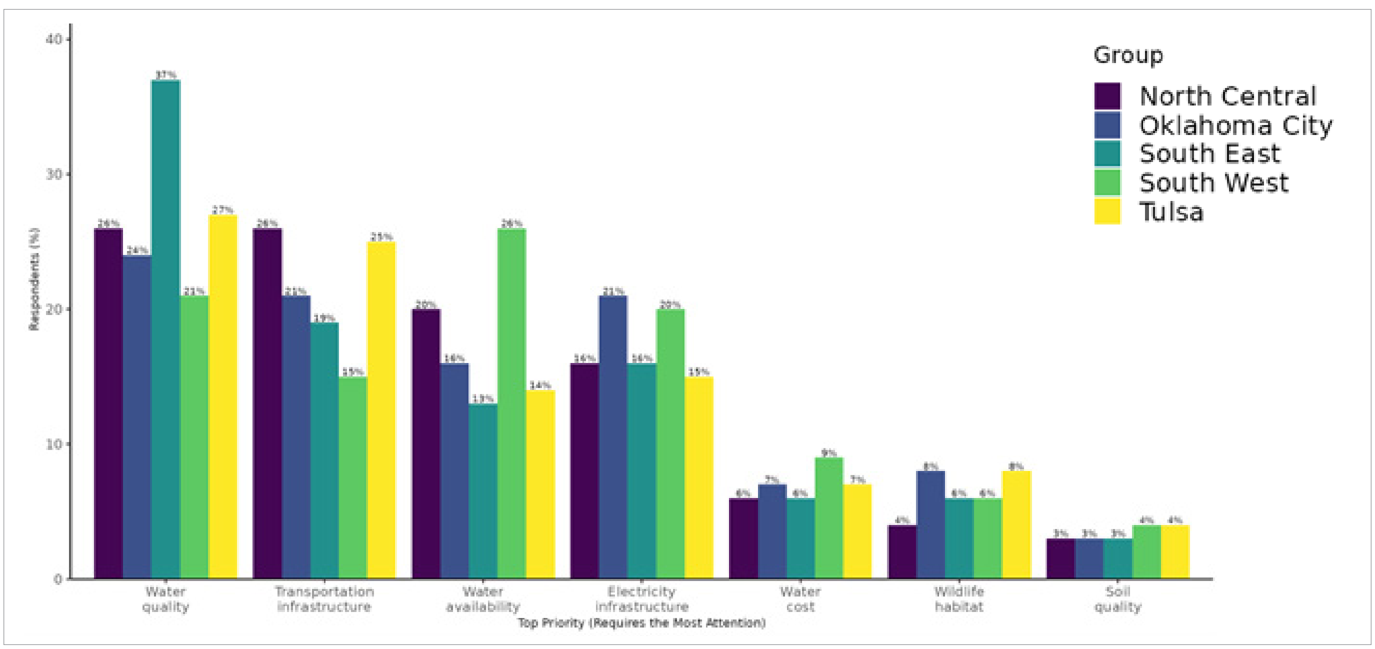

Figure 8.1. Oklahoma public responses to the question "If you were advising the scientists and policymakers who are working on this project, which of the following would you tell them require the most attention?"

Further, the Working Group identified three problems contributing to declining water availability to be addressed by S3OK Researchers (other challenges were noted, such as the need for water conservation, but other university researchers are addressing these thus it was determined that this work group not focus on them):

1. Reduced water availability due to changing weather/climate conditions
2. Increasing Eastern Redcedar encroachment contributing to water depletion
3. Reduced soil health due to past as well as present land management practices and changing climate conditions limiting water retention and agricultural land resilience to drought

Produced Water Opportunities

The oil and gas industry generates staggering volumes of wastewater which is called produced water (PW). PW includes both formation water and injection water. For every barrel of oil produced, nearly 9–10 barrels of PW (one barrel equals 42 gallons) are generated, totaling approximately 25 billion barrels per year in the US and 70 billion barrels globally[1,2,3]. Oklahoma is a leading US oil and gas producer, resulting in large amounts of water brought to the surface alongside oil and natural gas production.

PW contains a variety of contaminants, including oil and grease, dissolved hydrocarbons (BTEX, PAHs, phenols), heavy metals, naturally occurring radionuclides, corrosion inhibitors, biocides, and fracking chemicals, all of which pose significant pollution and health risks[4,5]. Additionally, PW often contains high levels of salt, ranging from <3% to over 30%. Conventional treatment methods are costly and often fail to meet environmental standards, as such, this water is generally disposed of via reinjection deep underground. Reinjection involves pumping the salt water into a porous geological layer capable of taking in the volumes of water. This layer is often deep, and high pressures are frequently required to pump the water into these deep layers. While we do not have exact numbers for more recent years, nearly 1.5 billion barrels of PW were disposed of underground in Oklahoma in 2014 via saltwater disposal (SWD) wells[6].

Deep well injection has become increasingly challenging due to stricter regulations, limited underground capacity, and the potential for seismic hazards[7,8]. Depending on location and facility availability, SWD costs range from $0.50 to $2.50 per barrel. Transporting PW to disposal sites adds additional costs—typically $1.00 per barrel for each hour of transport. Transport costs are lower in areas with abundant SWD facilities, around $0.50 per barrel. However, in areas with fewer facilities, PW must be transported to distant facilities, resulting in additional costs of $4.00 to $6.00 per barrel.

In Oklahoma and other oil- and gas-producing regions, PW represents a significant opportunity to supplement stressed water supplies for agricultural and other beneficial uses. Some PW sources also contain valuable metals and minerals that, if recovered during treatment, could provide a revenue stream to support the adoption of PW treatment technologies.

Oklahoma's PW, in particular, contains rare and critical elements such as lithium, bromine, and iodine—resources with important industrial and technological applications. In addition to mineral recovery, certain volumes of PW may be suitable for treatment and reuse in applications like agricultural irrigation, aquifer storage, and rangeland restoration.

With this potential in mind, the S3OK initiative was launched to explore dual opportunities: treating PW for reuse and extracting valuable minerals. Researchers have made progress in key areas such as oil-brine, metal-brine, and freshwater-brine separations. These processes can be integrated into a treatment train designed to meet specific goals—whether for water recovery, mineral extraction, or both.

S3OK evaluated a range of treatment and extraction methods that can be tailored based on the target resources and the desired water quality. In theory, this approach to resource recovery could create multiple economic incentives for the oil and gas industry to treat PW, ultimately enhancing regional water availability.

Reduced Water Availability Related to Weather and Climate

According to NOAA[9], Oklahoma is located in the central Great Plains and spans a climate transition zone—from the wetter southeast, which receives over 50 inches of rain annually, to the drier, semi-arid west, which gets less than 20 inches. This geographic position results in a wide range of average daily temperatures. Since the early 1900s, the state has warmed by about 0.6°F. In recent decades, rising temperatures in Oklahoma, Texas, and Kansas have been accompanied by fewer but more intense rainfall events[10].

Rainfall in Oklahoma varies greatly from year to year. The state has seen annual precipitation range from a low of 20.3 inches in 1910 to a high of 53.7 inches in 2015. The driest multi-year periods occurred in the 1910s, 1950s, and 1960s, while the wettest were in the 1990s and late 2010s. The driest five-year stretch was from 1952 to 1956, and the wettest was from 2015 to 2019. Most of the state's rainfall occurs in the spring and summer. Since 1985, the number of extreme rainfall events—those with 2 inches or more—has increased, peaking in 2015.

Droughts are a frequent and serious issue in Oklahoma. Since 2000, the state has been completely free of drought only about 21% of the time, while experiencing drought conditions over at least half its area about 28% of the time. Looking ahead, Oklahoma is expected to become warmer, with more intense heat waves and less severe cold spells. Although overall annual precipitation trends are unclear, summer rainfall may decrease slightly **(Figure 8.2)**. Even if rainfall remains steady, higher temperatures will lead to more evaporation and drier soils, worsening droughts and increasing the risk of severe wildfires.

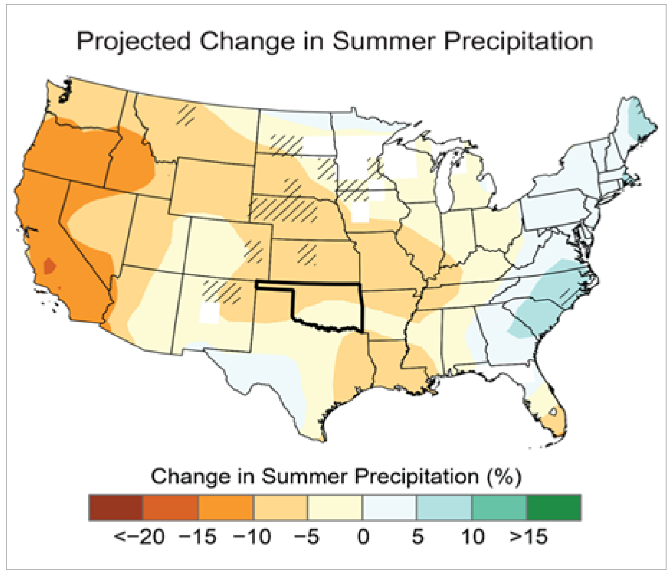

Figure 8.2. Projected change in summer precipitation *(Courtesy of NOAA)*.

Increasing Eastern redcedar encroachment

Eastern redcedar (Juniperus virginiana L.) is a native evergreen tree that is rapidly encroaching upon the Great Plains, particularly the grasslands of Oklahoma. In recent years, evergreen species—especially junipers—have been expanding in Oklahoma at a rate five to seven times faster than in other regions of the United States.

As of 2018, Eastern redcedar covered more than 4.5 million hectares in Oklahoma, with projections estimating an increase to over 6.3 million hectares by 2028[11]. Satellite imagery analysis conducted by our team revealed that between 2016 and 2020, Oklahoma's forested area grew by 243,893 acres (a 1.9% increase), primarily in the central and northeastern parts of the state.

This rapid expansion is largely driven by fire suppression and changes in land management practices, such as overgrazing and the abandonment of cropland. The encroachment of Eastern redcedar has had significant ecological consequences, including the displacement of native plant and animal species, reduced forage availability for livestock, altered soil hydraulic properties, and an increased risk of wildfires.

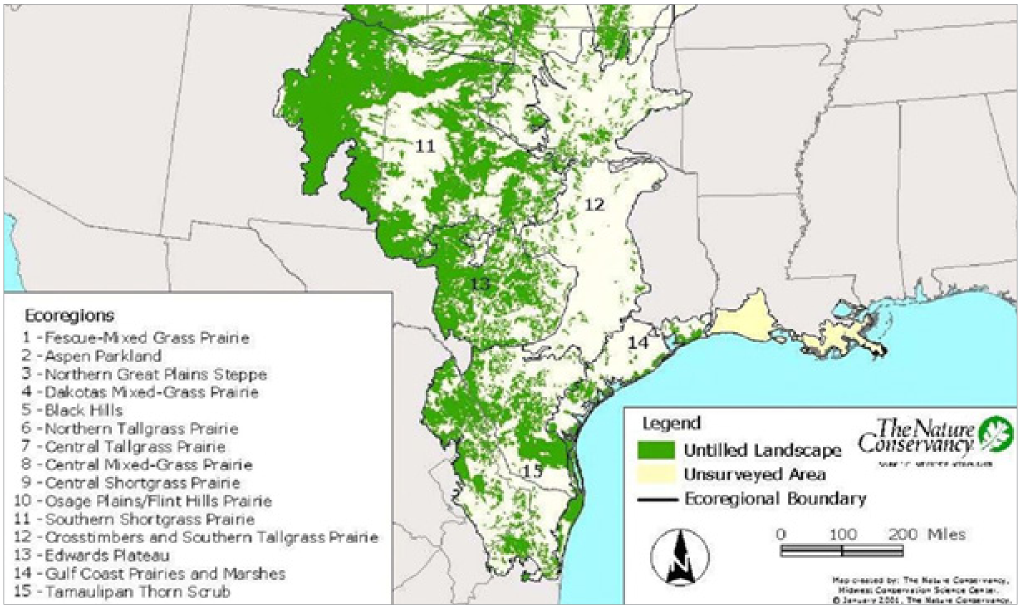

Figure 8.3. Untilled lands in Oklahoma, New Mexico, and Texas. *Courtesy of the Nature Conservancy.*

Economically, the impact is substantial. In 2001 alone, the estimated annual losses due to catastrophic wildfires, reduced cattle forage, diminished wildlife habitat, decreased recreational opportunities, and lower water yields amounted to approximately $218 million[12].

Reduced Soil Health

Much of Oklahoma has been previously tilled **(Figure 8.3)**. This previously cropped land has been converted to or reverted back to grassland. This land typically has lower productivity (approximately half) and greater erosion than grasslands never cropped. This is due to a large extent to the loss of soil organic matter during the initial years after breaking the land out (50% of soil carbon lost in first 5 years of initiating cropping) [13,14,15,16] and loss of soil fertility which may take decades or even centuries to restore. Soil organic matter is a key attribute of soil quality and impacts water infiltration.

Burke et al (1995)[17] found that restoration of soil N required 50 years after reintroduction of native perennial grasses. Kindscher & Tieszen (1998)[18] found that even 35 years after restoration of tallgrass prairie on a previously cultivated site, soil organic matter remained lower that native prairie. Fuhlendorf et al. (2002)[19] found that soil carbon, total nitrogen, organic matter, nitrate, and potassium were significantly lower and percent bare ground higher in grasslands previously cultivated and restored. Soil nitrogen and soil carbon on these previously cultivated mixed prairie sites were 30–40% lower than native prairies, while bare ground was 40% higher.

Heavy grazing can further impact and prolong restoration by increasing carbon allocation to leaves, reducing litter accumulation, increasing bare ground, decreasing root biomass, and ultimately lowering nutrient inputs into the soil. On previously cultivated sites, soil nitrogen and carbon were higher with moderate grazing than with heavy grazing. In comparison, grazing minimally impacted soil nutrients on native sites. This suggests that greatest benefit of grazing management to soil fertility and health should be realized on previously cultivated grasslands.

Key Science Advancements/ Proposed Solutions to Reduced Water Availability

The working group identified eight potential solutions to the problems of eastern redcedar encroachment, reduced soil health, and reduced water availability related to weather and climate. These solutions are discussed in the sections that follow. Each solution was researched, resulting in significant scientific advancements.

Eastern Redcedar (ERC) Encroachment

The working group proposed several solutions to address eastern redcedar encroachment:

- Support continued funding and expansion of programs to remove harmful woody species (i.e., the Terry Peach North Canadian Watershed Restoration Act and Terry Peach Watershed Restoration Act) by **quantifying how restored native prairie improves water availability** using targeted monitoring and improved modeling
- Support planning and control efforts **using satellite imagery to monitor ERC** presence across Oklahoma
- **Understand and quantify social acceptance, adoption barriers, and public willingness to enhance ERC removal** programs, particularly using controlled burns for smaller trees

To support continued and expanded funding for removing harmful woody species in watersheds, decision makers need data on its benefits. S3OK research highlights that restoring native prairie by mechanically removing encroached juniper significantly improves water availability through increased root zone soil moisture and watershed runoff. Using a paired watershed approach, we observed that soil water storage in the top 1-meter profile doubled, and annual runoff increased by more than fourfold following restoration. Ongoing monitoring of soil moisture and runoff dynamics across various phases of restoration provides valuable empirical data to refine hydrological models and enhance predictions of water availability under different land-use scenarios[20]. Conversely, S3OK modeling assessed the impacts of doing nothing and not controlling ERC. Yang et al. (2024)[21] found that if all grasslands in Little River Watershed were allowed to convert to forests, it would lead to a 41% reduction in streamflow.

ERC management efforts require accurate monitoring of ERC presence. Our study shows the potential of using satellite-based remote sensing to measure, monitor, report, and verify the spatial-temporal dynamics of eastern redcedar trees and forests in Oklahoma and the Southern Great Plains at high spatial resolution (30-m) and annual temporal resolution[22] (Yang et al., 2023). The resultant annual maps of eastern redcedar forests can assist agencies in monitoring management efforts and areas experiencing continued expansion, and support stakeholders' communication and decision on the removal and/or control of eastern redcedar trees/forests. Yao et al. (2025)[23] showed that expansion is not uniform across the state **(Figure 8.4)**. Most expansion is occurring in the eastern half of the state, filling in areas among existing forests.

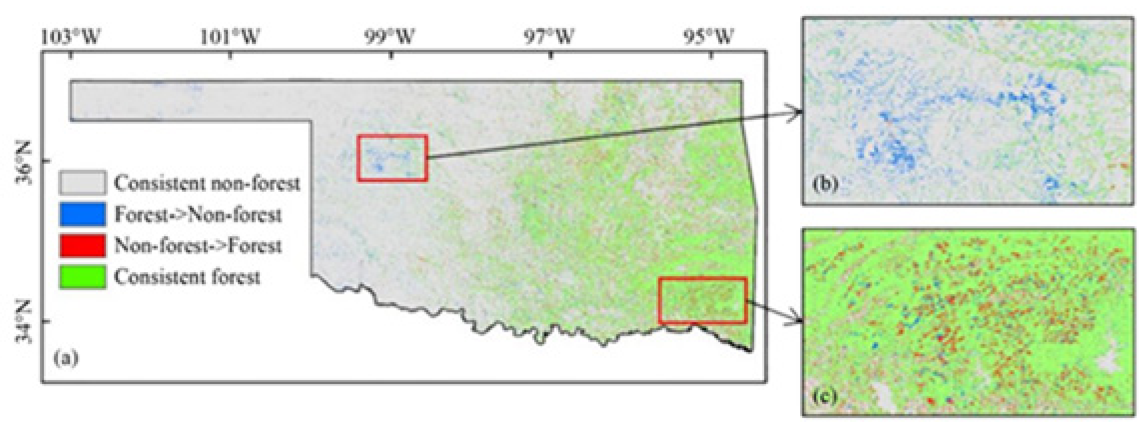

Figure 8.4. Spatial distribution of forest cover changes for Oklahoma from 2016–2020 (from Yao et al., 2025).

Our study also shows the potential of using satellite-based models, which estimate gross primary production (GPP) and evapotranspiration (ET), to assess the impacts of woody plant encroachment on the carbon fluxes and water fluxes (Yang et al., 2024). The resultant GPP and ET data products can also be used to support stakeholders' communication and discussion on the ecological and environmental effects of woody plant encroachment.

Finally, our study indicates that public willingness to support Eastern Redcedar (ERC) removal programs using controlled burns is influenced by several social and demographic factors. While rural residents are more knowledgeable about ERC encroachment and its risks, both rural and non-rural residents express concerns about wildfire hazards. Controlled burns are recognized as effective management tools, but liability and safety concerns are major barriers to their acceptance.

Results suggest that residents who have experienced prolonged droughts or expressed concern about water availability are more likely to support prescribed fire as a management practice. However, non-rural residents, particularly those living in areas with a high wildland-urban interface (WUI), are less familiar with controlled burning practices and may need targeted educational outreach to increase their support. Public-private partnerships and community-based fire management programs could help address liability concerns and improve public acceptance of prescribed fire[24]. Further, a statewide study to identify areas of lowest risk for prescribed fire could be helpful for targeting areas for prescribed burning and related outreach efforts, as well as areas of high risk which should be targeted for mechanical control.

Reduced Soil Health

The working group recognized the need for improved soil health across all land uses in Oklahoma, particularly on grazinglands (rangeland and pastureland) and cropland. Ongoing USDA funded projects are evaluating the benefits of soil health practices to cropland. Thus, S3OK and the working group focused on identifying solutions to the problem of reduced soil health in rangeland and pastureland systems (the largest land use in Oklahoma).

The solution evaluated was: **implementing regenerative livestock grazing** to improve soil water infiltration, as well as drought resiliency and soil health. S3OK research compared two grazing management systems, adaptive and prescriptive, to determine the best method for improving soil health and overall sustainability. Regenerative livestock grazing is a management practice designed to sustain grassland ecosystems and soil health. This approach emphasizes balancing grazing pressure with adequate vegetation recovery periods, ensuring the continuous presence of living root systems in the soil. Such practices promote the sustained growth of soil microbial communities, leading to increased soil organic matter content.

Consequently, improvements in soil structure, aggregation, and porosity are anticipated, resulting in enhanced water-holding capacity and infiltration rates, providing resilience to drought and flooding. When combined with increased plant diversity, this practice extends the growing season, boosts producers' income, and enhances ecosystem services such as carbon sequestration and wildlife habitat improvement.

Our study in rotationally grazed pastures in southern Oklahoma revealed a positive correlation between the dominance of oligotrophic microorganisms and soil organic matter content. This finding suggests that under proper grazing management, the addition of fertilizers may not be necessary for maintaining soil health (manuscript in preparation).

We also observed a decrease in soil microbial biomass and respiration immediately following grazing events, attributed to the reduction in aboveground plant biomass. However, after two years of rotational grazing, these microbial indicators consistently increased, demonstrating the long-term benefits of this management approach (manuscript in preparation).

Finally, our work emphasized the importance of aligning grazing intensity and frequency with the soil's nutritional characteristics. In grasslands relatively deficient in organic nitrogen, higher grazing frequencies (e.g., nine grazing events over two years, with at least 60-day resting periods) positively influenced microbial biomass compared to lower frequencies (e.g., four grazing events over two years) (manuscript in preparation).

Produced Water Treatment, Resource Extraction, and Reuse

To better meet long-term oilfield and agricultural water needs and create potential for year-round production, potential solutions identified include:

- **Microbial pre-treatment** to remove hydrocarbons
- Improving **oil-produced water separation** techniques
- Pilot testing and further development of cleaning produced water **using membrane distillation to remove salinity** and making it available for irrigation
- Develop and enhance **new techniques for resource extraction**
- Evaluate **carbonated produced water** for enhanced oil recovery

Microbial Pretreatment to Remove Hydrocarbon

Economically removing dissolved hydrocarbons from produced water is challenging but ultimately necessary for any land-application reuse of the water. Bioremediation (using microbes to degrade contaminants) is often used in soils, sediments, and groundwater as an effective, sustainable, socially acceptable, and safe means of destroying toxic compounds from spills, leaks, and other contamination sources. There have been extensive research and application showing degradation of hydrocarbons by microorganisms in freshwater, soils and low-salt environments[25,26,27]. PWs are, however, very salty, far beyond the salt-tolerance limits of those bacteria.

Recent studies have shown the ability of salt-loving (halophilic) and salt-tolerant (halotolerant) organisms to degrade hydrocarbons at salinity ranging up to 30% salt[28,29] suggesting their potential application in bioremediation of PW. We have enriched several hydrocarbon-degrading microbial cultures from various locations including oil-contaminated sediment from Rozel Point at Great Salt Lake (UT), crude-oil-contaminated soil (Kuwait), soil from Salt flat (OK), and an oil production facility in Seminole County (OK)[30,31]. These enrichment cultures are robust and capable of degrading a mixture of petroleum compounds at high salinity.

Recently, we successfully isolated a salt-loving (halophilic) bacterium, *Modicisalibacter* sp. strain Wilcox from the First Wilcox formation in Payne County. This bacterium degrades a variety of petroleum compounds in the presence of salt up to 24%[32]. In addition, strain Wilcox can withstand high levels of heavy metals that are typically found in PW. Furthermore, the strain has the ability to remove some of the toxic heavy metals such as Mn, Zn, Se, Pb, Cu, and Cr by biosorption and bioaccumulation mechanisms. Also, the bacterium has the capacity to recover 98% of 2 mM lanthanum present in the medium through a combination of biosorption and bioaccumulation mechanisms. This ability is particularly significant for resource recovery from PW (discussed later), offering a sustainable approach to extracting valuable elements from wastewater. Overall, this bacterium holds significant promise for the development of a sustainable bioremediation process for the removal of toxic hydrocarbons and heavy metals in PW-fed bioreactors. However, this technology is not pilot-scale ready because of the growth rates, settling time, and robustness to changing water chemistries, the 'completeness' of the hydrocarbon removal still needs to be tested.

Improving Pre–Treatment Oil–PW Separation Techniques

Our work sought to gain a deeper understanding of the interface and its related properties in produced water and oil systems. The interfacial dynamics between oil and water play a pivotal role in the efficiency of separation processes within the oil and gas industry, particularly in the management of PW, which is a complex aqueous byproduct of hydrocarbon extraction enriched with salts, hydrocarbons, and dissolved ions. We investigated the intricate interplay between interfacial viscoelastic properties and emulsion behavior, focusing on optimizing separation techniques. Using synthetic PW and cyclohexane systems as a model, we analyzed the interfacial tension and dilatational viscoelasticity under varying surfactant (sodium dodecyl sulfate, SDS) concentrations.

The experimental approach involved synthesizing PW based on established compositions and pairing it with cyclohexane, a representative hydrocarbon phase. Interfacial tension measurements revealed a significant divergence from pure water–cyclohexane systems. Notably, the baseline interfacial tension for PW–cyclohexane was found to be 44.47 ± 0.32 mN/m—approximately 4.5 mN/m lower than the 47.94 ± 1.26 mN/m observed in pure water–cyclohexane systems. This reduction highlights the complex ionic composition of PW, which significantly enhances surfactant activity.

The interfacial tension and dilatational viscoelastic properties were examined through a systematic analysis of sodium dodecyl sulfate (SDS) concentrations. Key findings indicate that the critical micelle concentration (CMC) for SDS in the PW–cyclohexane system is 0.1 g/L, markedly lower than the 1.8 g/L observed in water–cyclohexane systems. Dynamic dilatational studies further revealed that at optimal SDS concentrations (0.01 g/L for PW and 0.1 g/L for water), interfacial moduli peaked, signifying a balance between elastic and viscous responses essential for emulsion stabilization or destabilization. Furthermore, as illustrated in **Figure 8.5**, the phase angle steadily increases with SDS content in both systems, and a change toward more viscous–dominant behavior at the interface is observed. However, the interfacial behavior in PW systems shifted more rapidly, underscoring the unique impact of PW's ionic complexity.

Further insights were derived from dilatational rheology analyses conducted at oscillatory frequencies ranging from 0.1 to 0.5 Hz. These experiments quantified the viscoelastic response of the interface through the storage modulus (E′, elastic component), loss modulus (E″, viscous component), and complex modulus (E*). In pure water–cyclohexane systems, peak moduli occurred at an SDS concentration of 0.1 g/L, reflecting an optimal balance of elasticity and viscosity. Conversely, in PW–cyclohexane systems, the maximum moduli shifted to 0.01 g/L, with a notable increase in the phase angle—indicative of a transition toward viscous–dominated behavior. This shift, accentuated in PW, suggests that ionic interactions accelerate surfactant saturation at the interface, limiting dynamic molecular rearrangement and reducing elasticity at higher concentrations.

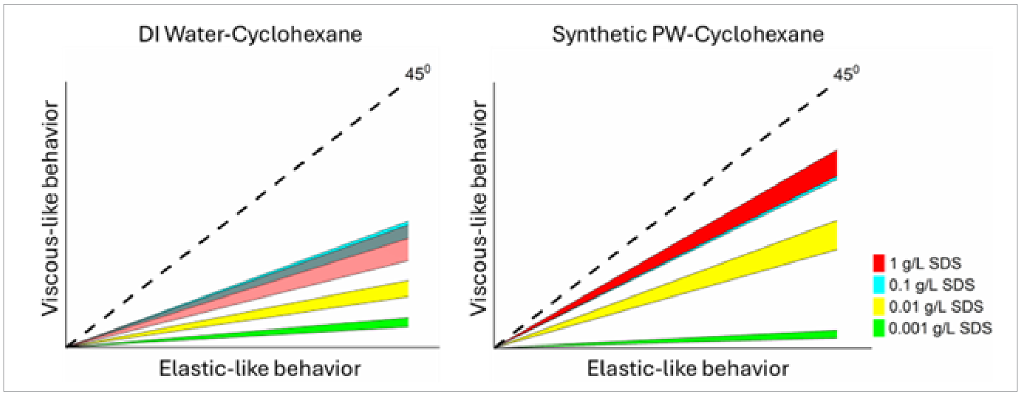

Figure 8.5. Variation in phase angle: each region represents the range of minimum and maximum phase angle values recorded for the solutions at frequencies between 0.1 and 0.5 Hz.

These findings have significant implications for improving separation processes in oilfield operations, where stable oil-in-water emulsions impede efficient phase disengagement. The lower CMC and altered viscoelastic profile in PW-cyclohexane systems indicate that minimal surfactant dosages can destabilize emulsions, facilitating oil-water separation with reduced chemical input. This enhanced sensitivity to SDS in PW highlights the critical role of water chemistry in interfacial dynamics, offering a strategic framework for tailoring surfactant applications in enhanced oil recovery, wastewater treatment, and emulsion management.

By bridging fundamental interfacial science with practical applications, this research provides a robust foundation for advancing separation technologies. Future investigations will explore additional surfactants and environmental variables, such as temperature and pressure, to further refine these interfacial systems, aligning with the industry's pursuit of efficiency and sustainability.

Membrane Distillation (MD)

MD is a promising "next-generation" desalination technology that is still being developed for commercial uses. One unique advantage of MD over other membrane systems is its ability to recover water from practically any salinity level. The unique advantage of MD over systems like conventional reverse osmosis is that energy input into the system is heat, which can come from a variety of sources. Many oil fields do not possess the infrastructure to capture natural gas co-produced with petroleum. These fields produce waste heat when the natural gas is flared. In addition to flare gas, solar thermal technologies, heat produced from 'stranded electrons' in wind-producing areas, heat from compressors and pumps in the oil field, and natural geothermal heat associated with oil production wells are all options at several sites. After successful development in the laboratory scale system proposed herein, our prototype will be piloted at a deep well injection site with high solar radiance, contains active oil production wells producing waters with high geothermal temperatures (~60°C), and is within a wind turbine field (with the major transmission station within a quarter mile of the site). This provides many promising options for providing the energy needed to drive a full-scale operation system.

We have made significant progress in investigating MD systems for PW treatment. In our work to date, we have used MD to treat PW from six formations in Oklahoma, Colorado, and Texas. We achieved 60-86% water recovery in this raw PW, which ranged from 20,800-154,000 mg/L total dissolved solids (TDS), proving that the process can desalinate at practically any salinity; however, we found that crystallization of the inflow should be avoided to avoid membrane fouling from salt crystallization. In this process, we also increased the concentrations of valuable elements [e.g., lithium (Li), iodine (I), bromine (Br), and manganese (Mn)] in the supersaturated brine. For example, we increased Li concentrations in one PW from 8.9 mg/L to 52.5 mg/L. Further, valuable rare earth elements (e.g. lanthanum, neodymium, and europium) have been found to be present in salt crystals generated from the brine concentrate. We have also tested raw incoming waters to D&B's facility and waters after their gravity separation process. We found that even the existing crude pretreatment step onsite leads to drastic improvement of membrane quality and performance. This demonstrates the importance of a unit-operations design that removes organics prior to desalination.

Resource Extraction Using Modified Silica Particles

A major advancement was made through S3OK in resource extraction technology, especially for recovering rare earth elements (REEs) such as lanthanum (La^{3+}). We focused on La^{3+} due to its significant value in the electronics industry. REEs are crucial for producing renewable energy technologies, sophisticated electronics, and essential infrastructure materials. However, their extraction has often been inefficient and harmful to the environment. Our research centers on utilizing chemically modified silica particles for the selective and efficient recovery of lanthanum. By modifying the surface chemistry of silica particles with Pr–EDTriA groups in alkaline conditions, we significantly enhanced their ability to bind La^{3+} specifically. At an optimal pH of 11.3, these particles showed improved stability and functionality, validated by thermal gravimetric analysis (TGA) and zeta potential measurements.

A particularly exciting feature of this research is the remarkable selectivity of modified silica particles in challenging saline environments. Many industrial waste streams, such as those from produced water treatment, often have competing ions like Na^{+} that can disrupt traditional recovery techniques. Our experiments showed that the modified silica particles achieved a La^{3+} recovery rate exceeding 98 wt.%, even in the presence of Na+ ions (100 ppm) **(Figure 8.6)**. This result motivates our future work that focuses on utilizing more selective ligands to remove La^{3+} at higher salt concentrations. By customizing the surface characteristics of silica particles, this technology enhances extraction efficiency, decreases energy use, and minimizes chemical waste, making it an attractive option for industrial use.

The kinetic improvements achieved by modifying silica particles represent a significant advancement in the recovery of La^{3+} ions from aqueous solutions. Our experiments showed that unmodified silica particles took 20 hours to reach equilibrium, while the modified silica particles, optimized at pH 11.3, reached maximum recovery in just 2 hours—a tenfold boost in adsorption speed. This notable enhancement is further underscored by the modified particles' ability to resist the negative effects of Na^{+} ions, which slowed the sorption rates for unmodified silica but did not affect the performance of the modified particles. The faster kinetics are due to the improved surface chemistry of the modified silica particles; the introduction of TMS–EDTriA groups enhanced binding strength through multivalent interactions and uncovered additional active sites for adsorption **(Figure 8.7)**. Furthermore, the more negative zeta potential at pH 11.3 has heightened the electrostatic attraction between La^{3+} ions and the particle surface, promoting quick and effective binding. This advancement in kinetics leads to increased throughput in practical applications, significantly decreasing processing times and enhancing the feasibility of selective ion recovery from complex aqueous systems.

We have successfully refined and validated this technology by incorporating characterization techniques like thermal gravimetric analysis (TGA) and scanning electron microscopy (SEM), ensuring it remains reliable under various operating conditions. These innovations open up possibilities for sustainably recovering essential materials from waste streams, aiding in reducing dependence on imports and traditional mining practices for

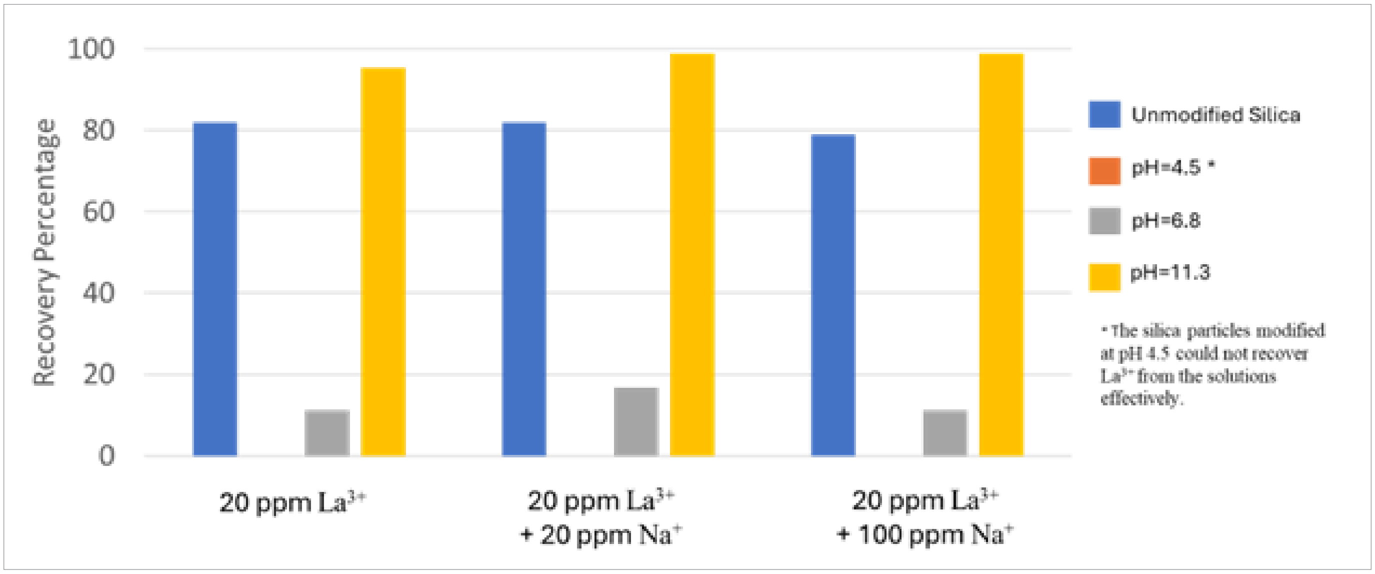

Figure 8.6. La^{3+} recovery after 24 hours of mixing.

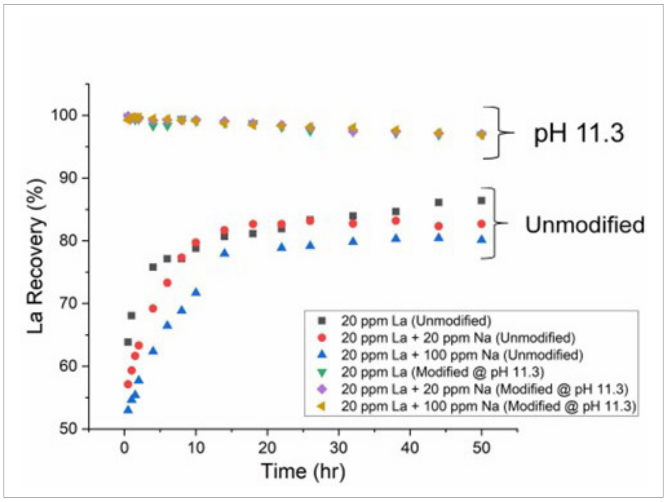

Figure 8.7. La^{3+} recovery percentage over time for unmodified and modified silica particles at pH 11.3 in different solutions.

lanthanum while also meeting the increasing global demand for clean energy and advanced technologies.

Carbonated Produced Water for Enhanced Oil Recovery

Members of the working group also investigated the potential of high salinity carbonated water flooding (HS-CWF) for enhanced oil recovery (EOR), CO_2 storage, and produced water disposal using microfluidics and conventional coreflooding experiments. They demonstrated that CO2 solubility in the brines increases significantly with pressure from 150 to 1000 pounds per square inch gauge (psig), with minimal changes observed between 1000 and 1200 psig. Experimental results aligned well with established thermodynamic model predictions, and a new correlation was developed linking CO2 solubility to brine density at ambient conditions.

In hydrocarbons, both CO2 solubility and the swelling factor increased with pressure (150–700 psig), while the swelling factor decreased with increasing hydrocarbon molecular weight. Interfacial tension (IFT) measurements revealed a linear decrease in IFT with increasing pressure across all the salinities tested and a linear increase with brine salinity across the pressures tested. Microfluidic experiments showed pressure-dependent EOR performance, with greater reductions in residual oil saturation observed at 700 psig compared to 150 psig across the oil-water systems studied. Coreflooding experiments indicated that low-salinity waterflooding (LSWF) and carbonated waterflooding (LS-CWF) were more effective for oil recovery compared to high-salinity waterflooding (HSWF) and carbonated waterflooding (HS-CWF), respectively, and Bentheimer sandstone cores exhibited superior performance over Berea sandstone cores under identical test conditions. CO2 sequestration potential also varied with salinity and pressure: high-salinity CWF performed better at 700 psig, whereas low-salinity CWF was more effective at 150 psig.

This multi-scale experimental approach demonstrates the complex interplay between pressure, salinity, oil type, and rock type in determining the effectiveness of carbonated produced water flooding for EOR, CO2 storage, and produced water disposal. Findings support the use of CWF as a viable low-carbon EOR strategy, particularly under high-pressure conditions and with optimal brine salinity.

Annotated Treatment Train for Produced Water

The work group produced a vision for a produced water treatment system that is:

- Flexible to handle variant water chemistries found in PWs and similar oily briny groundwater formations,
- Reliant on low-grade energy sources (heat) as the primary desalination mechanism to allow for flexibility around site-specific economic considerations of available energy resources (i.e., site specific geothermal, solar, electric, industrial, and waste heat resources),
- Scalable to the current and future water reuse needs and influent water availabilities at a given site (i.e., the system can upscale or downscale without significant site-specific capital investment) and
- Incorporates considerations for add-on processes for simultaneous water recovery and elemental recovery goals (Elemental

recovery operations taken off of side streams, when feasible, have the potential of creating net value more than offsetting any cost of treatment; similarly, microbes can at times sorb certain heavy metals of economic interest).

The overall schematic of the current vision is provided in **Figure 8.8**.

Currently, step 1 (pretreatment processes to capture recoverable oil) is ready for pilot-scale testing. For the second step (biological degradation of organics and membrane distillation), work in the laboratory is still needed to determine appropriate scales and robustness during continuous flow operations of the processes (~1–2 years of work). For step 3 (elemental recovery processes), data on Lanthanum recovery is encouraging enough to field test the ability to capture the metal on modified silica nanoparticle membranes and from the microbial sorption; however, Lithium, Iodine, and other metal recoveries still need development in the lab (~2–3 years of development and testing). Our goal is that with sufficient financial resources to proceed with laboratory-scale development, in 3 years, a fully built-out pilot plant with integrated water and metal recovery will be tested in the field. As we progress with the pilot scale evaluation, we will:

- Evaluate how useful resource extraction can be from a geopolitical and economic standpoint; and
- Identify/delineate optimum conditions for implementation and potential limitations.

Future Work/Considerations

Continued work is needed to improve soil health, including expanded support for state (Oklahoma Conservation Commission) and federal cost share and technical support programs (USDA Natural Resource Conservation Service). Research is needed to better understand the effects of soil health practices, particularly in semi-arid environments (western Oklahoma) and grazinglands. In particular, a better understanding of the impacts of soil health practices on farm/ranch economics, soil nutrient

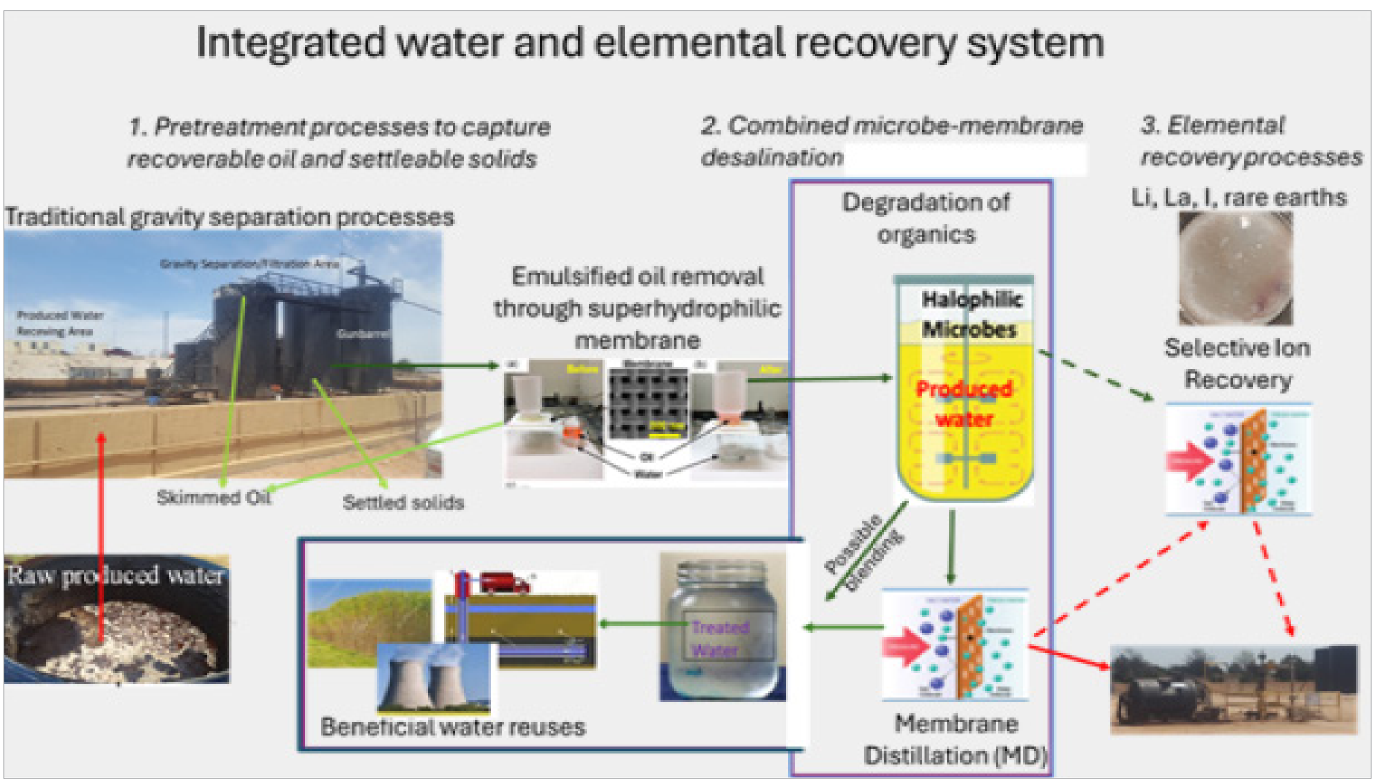

Figure 8.8. Produced Water Treatment train.

cycling and availability, agricultural production/yields, water resources, and other ecosystem benefits is needed. Additionally, effects of soil health practices on grazinglands and their ability to restore degraded sites, particularly those previously cropped, is needed. Finally, a better understanding of barriers to adoption and incentive structures is needed in order to develop and implement appropriate programs to encourage adoption.

Similarly, expanded efforts are needed to manage eastern redcedar and halt its expansion. An improved understanding of the ecosystem, grazing, and economic impacts of ERC control is needed, appropriate incentives, and barriers to adoption are required. Incentive programs are certainly needed to encourage control efforts statewide (i.e., passage of the Terry Peach Watershed Restoration Act), along with outreach and an identification of areas most suitable for prescribed fire versus mechanical controls.

With PW treatment and reuse, our goal is to make demonstrable progress towards implementation of a small-scale pilot treatment opportunity for produced water reuse, and lay the groundwork for a five-year time horizon implementation guide that underscores future regulatory considerations, resource recovery opportunities, potential for agricultural use, and reduced treatment costs, new economic opportunities, and enhanced environmental benefits. Authorization of an Oklahoma Produced Water Consortium is proposed to enhance development and adoption of PW treatment and reuse.

Current Regulatory Environment for PW Reuse in Oklahoma

The Oklahoma Corporation Commission Oil and Gas Division regulates oil and gas development, including the management of PW. In 2020 the **Oil and Gas Produced Water and Waste Recycling and Reuse Act** was enacted to support the reuse and recycling of PW. This law grants operators and non-operators the right to manage, transfer, sell, or treat PW, giving them exclusive rights to any resulting proceeds. Ownership of PW is retained by the operator until transferred, at which point it becomes the property of the new handler. The bill also protects entities that recycle and transport PW from liability, encouraging the transformation of PW from a waste product into an economically valuable resource. Additionally, changes to drilling permits and injection well applications were introduced, including stricter requirements for well integrity, elimination of the Area of Review (AOR) requirement for gravity flow injections, and the need for radioactive tracer surveys to ensure mechanical integrity in simultaneous injection operations.

This regulatory framework provides a good foundation for future use. However, as PW treatment and reuse progresses, additional work will be needed by agencies, industry, and university partners to **identify and help implement needed policies and regulations to support the proper use of produced water.**

Resource Recovery Potential

Produced water (PW) can include valuable elements such as lithium, magnesium, barium, strontium, boron, bromine, iodine, zinc, and other rare earth elements (REEs). These components are regarded as vital minerals essential for advancing clean energy technologies and various industries[33,34], indicating PW's potential as a source for their recovery. In addition, recovering these minerals from PW can have serious national security ramifications. Since several of the elements in PW are used in defense technology and vital sectors, the US government has designated them as "critical minerals," indicating that disruptions in their supply chain might majorly affect national security. Since almost all REEs are now imported into the United States, there is much interest in locating alternate domestic sources of these elements[35]. Additionally, as per the report by the US Department of Commerce[36], the United States is highly dependent on foreign nations, such as China, to supply critical minerals. Over-reliance on foreign countries and foreign sources for essential minerals and materials presents serious national and economic security risks.

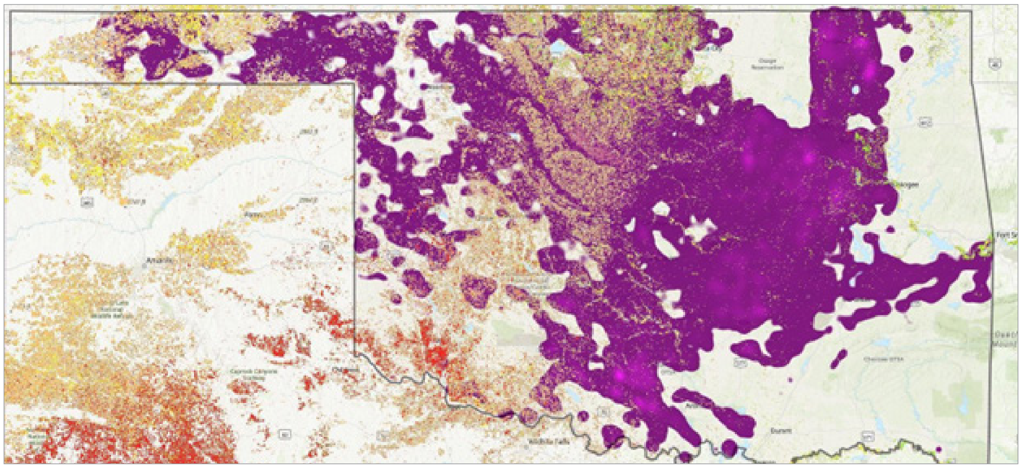

Figure 8.9. Locations of Oklahoma and Texas Panhandle cropland (granular dots) and oil and gas wells (purple heat mapping).

The amount of PW produced in the U.S. has been increasing, as has the demand for its management or recycling. When valuable components are extracted from it, what was once thought of as a waste product from the production of oil and gas is transformed into a potential resource necessary for clean energy technologies while reducing the environmental impact of disposing of large amounts of PW[37]. During oil and gas production in the U.S., almost 2.8 billion gallons of PW were produced daily in 2017[38], which rose to almost 3.0 billion gallons daily in 2021[39]. Resource extraction from PW would give the country a domestic supply of vital minerals like lithium and rare earth elements (REEs), lessen import dependency, generate new employment in the processing and treatment industries, cut disposal costs for oil and gas companies, and boost clean energy technology by supplying vital components.

Potential Agricultural Use of Treated PW

Treated PW presents a potential, though complex, opportunity for agricultural use, especially in water-scarce regions like western Oklahoma. Oklahoma produces approximately 1.5 billion barrels of produced water annually, equivalent to 487,650 acre-feet—a volume theoretically capable of supporting over 200,000 acres of high water-demand crops, assuming a 2-foot-per-acre annual water requirement. However, several factors limit the direct application of this resource.

Treated PW has potential uses in the irrigation of non-food crops, tree plantations, and landscape projects. However, its use requires careful management to ensure water quality meets the necessary standards to avoid negative impacts on soil health and crop productivity. Identifying optimal treatment methods and appropriate agricultural applications is essential for maximizing the benefits of produced water while minimizing risks.

A primary challenge is the spatiotemporal mismatch between PW availability and agricultural demand. Transporting produced water long distances for agricultural production is generally cost-prohibitive. This limits its application to areas near treatment facilities. Fortunately, much of Oklahoma's cropland sits comfortably in areas dense with oil and gas wells **(Figure 8.9)**.

Another challenge of PW use for agricultural production is the temporal differences in PW production and crop needs. While produced water generation is relatively constant, agricultural water needs, particularly for crops, are concentrated during specific growing seasons (typically spring and summer). This seasonality makes consistent, year-round utilization difficult. Even with high water-use crop rotations, periods of low demand will exist while treatment facilities operate continuously.

Despite these challenges, certain agricultural applications in western Oklahoma show promise. Cotton production, both favored by the region's land use history but limited by water availability in the region's dry climate, offers a viable option because of its wide planting, high water needs and potential to be co-located with potential produced water facilities. Similarly, turf grass and bioenergy crops could be considered. Rangeland restoration and localized irrigation of alfalfa or pasture near produced water facilities are also possibilities, though the latter requires careful consideration of potential impacts on the food chain. Soil productivity near treatment facilities also plays a role. In some areas, like the Permian Basin, soils may require substantial investment to become suitable for irrigated cropland.

A potential solution to the mismatch in time might be solved in a hybrid mode of agriculture use induced artificial recharge of aquifers. That is—locating treatment plants near alluvial aquifers, using grasslands or other agriculture use for final filtration and allowing excess treated produced water to percolate into the aquifer, providing long-term storage and a means of distributing water when needed. This approach requires further investigation to determine its logistical and environmental impact.

In conclusion, while the sheer volume of PW in Oklahoma suggests a significant potential resource for agriculture, the spatiotemporal mismatch between supply and demand, coupled with transport limitations and soil conditions, necessitates innovative approaches. Artificial aquifer recharge and carefully selected crop applications, such as cotton, offer promising avenues for further exploration.

Finally, careful consideration of water quality, treatment methods, and the specific agricultural context is essential to ensure the sustainable use of produced water in agriculture. Further research is needed to address knowledge gaps and develop guidelines for its safe and efficient application including:

- What types of non-food crops (e.g., bioenergy crops or fiber crops) can be effectively irrigated with treated produced water, and how does salinity impact their growth and productivity?
- How can treated produced water be integrated into reforestation and erosion control efforts, such as tree nurseries, shelterbelts, and riparian buffer zones?
- What are the potential benefits and risks of using treated produced water for landscape irrigation in highway and municipal projects, particularly regarding soil health and water conservation?
- What are the necessary treatment processes to ensure that produced water is safe and sustainable for agricultural use, and how do these vary across different crop types and soil conditions?

Improved Treatment Cost, Economic Opportunities, and Environmental Benefit

Treatment cost for produced water varies depending on the characteristics of the produced water, treatment technology, and purpose of reuse[40]. Capital investment for treatment plants and pipeline infrastructure is high. Newfield Exploration, a PW treatment company located in Oklahoma, estimated that the capital cost of a piping and treatment network was approximately $90 million. Newfield's treatment cost for produced water was estimated at $1.26/m^3 ($0.20/bbl). The treatment costs could range from $0.09/m^3 to $12/m^3 to use produced water for irrigation[41].

There are also potential revenue streams to offset some of the treatment costs, such as extracting valuable minerals or chemicals from produced water and selling the treated water to be used in agriculture or other industries[42]. For example, Eureka Resources, a company in Pennsylvania, recovers marketable byproducts during treatment, such as methanol, sodium chloride, and calcium chloride[43]. Methanol is an organic chemical compound that can be used as a solvent, fuel, and pesticide. Its global market price ranges from $346–$372 per ton in 2025. Sodium chloride (NaCl) can be used for road deicing. The global market for this chemical was valued at $18.97 billion in 2023 and is projected to reach $25.37 billion by 2032. Calcium chloride (CaCl) can be used as drilling fluids in addition to deicing, construction, and pharmaceuticals. The U.S. is the world's largest importer of CaCl. In 2022, the US imported almost $73 million of these compounds. The global CaCl market size was valued at $1.7 billion in 2023 and is projected to be $2.3 billion in 2030. Research in Kern County of California has shown that diluted low-saline produced water for irrigation is of comparable quality to the local groundwater in the region[44]. This could be a potential revenue stream for treatment plants, especially during drought years.

In Oklahoma, limiting reinjection of produced water could mitigate environmental damage, especially the induced seismic events. Induced seismic events in Oklahoma have negative impact on Oil & Gas industry's infrastructure as well as residential property values[45]. FEMA (2023)[46] estimates the annualized earthquake loss (AEL) in Oklahoma is 24 million $ and ranked 27 in the nation. AEL provides a long-term average of expected annual damages.

PW Consortium/Regional Efforts

To hasten advancement of PW treatment and use, a coordinated effort will be needed. An Oklahoma Produced Water Consortium is proposed to support this cause and help advance research, development, and piloting PW treatment and resource recovery. The S3OK Produced Water Research Team already joined the New Mexico Produced Water Research Consortium in early 2025 to enhance collaborative opportunities with researchers and industry from surrounding oil-producing states. Through participation in this consortium, we have begun meeting monthly with leaders of the Texas-, New Mexico-, Colorado-, and Wyoming-produced water consortiums. These collaborations are expected to yield new opportunities for joint research, enhanced resources for technology development, elimination of duplication of effort, and increased speed of development and deployment of new treatment technologies and, ultimately, reuse of produced water.

Members of the S3OK Produced Water Research Team are discussing with university administrators, agency partners and industry, the possibility of formally forming an Oklahoma Produced Water Research Consortium. Through formal formation of consortiums in New Mexico, Texas, and Colorado, state and federal resources have been secured by these states to enhance needed research, testing, and policy development. We would strive for a similar outcome to advance produced water treatment and reuse in Oklahoma to support agricultural and industrial (O&G) needs while supporting new industries (resource recovery, treatment technology, etc.).

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