ECOHYDROLOGY OF THE POST OAK SAVANNA

An Undergraduate Research Scholars Thesis
by
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Research activities involving the use of human subjects, vertebrate animals, and/or biohazards must be reviewed and approved by the appropriate Texas A&M University regulatory research committee (i.e., IRB, IACUC, IBC) before the activity can commence. This requirement applies to activities conducted at Texas A&M and to activities conducted at non-Texas A&M facilities or institutions. In both cases, students are responsible for working with the relevant Texas A&M research compliance program to ensure and document that all Texas A&M compliance obligations are met before the study begins.

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This project did not require approval from the Texas A&M University Research Compliance & Biosafety office.

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ABSTRACT

Ecohydrology of the Post Oak Savanna

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There are few other regions that have been as significantly altered by woody plant encroachment (WPE) as the Southern Great Plains (SGP) of the United States. The transition from an oak savanna to a shrubland mosaic redistributes energy and water as the vertical and horizontal structure of the landscape change. In the POS, where underlying geology and sandy soils allow for groundwater recharge and active subsurface hydrology, the effect of woody shrubs is likely revealed within the near-surface soil matrix and modified by interception losses from the shrub canopy. However, almost no literature exists to detail the effect of woody invasion in the POS, and further there are no established interception losses for many dominating species. The dynamic transformation of the POS also warrants from time to time contemporary ecological description and documentation, for perpetuity sake. This project aims to determine (1) interception losses, and (2) near-surface soil moisture dynamics of yaupon holly (*Ilex vomitoria*) and other woody invaders of the POS at the Texas A&M University Ecology and Natural Resources Teaching Area. Interception rates are determined by measuring the volume of canopy throughfall in > 9 throughfall devices (TD) per canopy of shrub species and clusters, and then comparing these volumes to an unobstructed rain-gauge after each rain event. Continuous soil moisture is assessed with time-domain-reflectometry (TDR) sensors under 2 shrub clusters compared to 1 open savanna at 10, 20, and 40cm. Interception losses and soil water contents of different vegetation are reported. Contrary to my hypothesis, there is not significantly different soil-moisture contents in the 5-25 cm rooting zone between shrub and grass vegetation types. Therefore, the ecohydrological role of shrubs in this study shows that: First, these evergreen shrubs reduce a significant portion of rainfall to the subcanopy zone, nearly one-third of total rainfall in the case of yaupon holly. And secondly, that woody shrubs excel where deeper water is available for extraction, and in this process might alter sub-surface flows and connectivity across the landscape. The ecology of yaupon in the POS is further examined.

DEDICATION

To my wonderful campus community that has supported me along every step of the way. And to my parents, who instilled my desire to pursue the fundamental questions of life and strength to never back down from challenges.

ACKNOWLEDGEMENTS

Contributors

I would like to thank my faculty advisor, Dr. Bradford P. Wilcox, and his PhD student, Shishir Basant, for their guidance and support throughout the course of this research. Thanks be also to this wonderful spirit which drives us ever forward. Thank you also to Joe Boy, Chelsea Parada, and Pedro Liete for being the coolest lab partners.

Finally, thanks to my department and our awesome faculty and staff for their encouragement and continued inspiration. This experience was facilitated by many individuals and I am beyond thankful for the opportunity to learn more deeply what it means to be an ecologist.

The analyses depicted in this manuscript were conducted by me, Harrison R. Coker, with direction from Shishir Basant. Research was conducted at the Texas A&M University Ecology and Natural Resources Teaching Area (ENRTA). The former ENRTA manager, Jake Gaster, helped tremendously with my field efforts. These data are currently unpublished.

All other work conducted for the thesis was completed by the student independently.

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The materials used for this project were funded by Dr. Wilcox's Ecohydrology Lab.

NOMENCLATURE

POS	Post Oak Savanna
ENRTA	Ecology and Natural Resources Teaching Area
SGP	Southern Great Plains
LAI	Leaf-area index
WPE	Woody plant encroachment
TD	Throughfall device
CSC	Canopy storage capacity
ET	Evapotranspiration
θ_v	Volumetric soil water content
VWC	Volumetric soil water content

1. INTRODUCTION

1.1 Expansion of woody plants in the Post Oak Savanna

Oak savannas are an important vegetation type in the Southern Great Plains (SGP) of the United States and the characteristic vegetation type in both the Cross Timbers and Post Oak Savanna (POS). Together, these two ecoregions extend from southern Texas into Kansas and make up nearly 120,000 km^2. Over the past 150 years, these landscapes have radically transformed from cultivation and subsequent abandonment, altered fire regimes, urbanization, and fragmentation (Hoagland et al. 1999). These factors are, of course, interrelated; but the net result is a highly fractured patchwork of pasturelands, open savannas, and dense woodlands. Woody shrubs typically form clusters, or islands, which facilitate expansion into open savanna. Often times these shrub clusters are of low species diversity, especially when under invasion by yaupon holly (*Ilex* vomitoria). Typical species of the POS are outcompeted by shrub invaders creating unsuitable conditions for savanna grasses. Conversion from shrubland back to savanna will not occur unless chemical or fire management is employed, however fire is oftentimes viewed as a socially unacceptable practice throughout much of Texas. These compounding variables have led to the widespread invasion of undesirable woody plants, creating dense thickets of vegetation—a process described as woody plant encroachment (WPE) or thicketization (Hoagland et al. 1999, Archer et al. 2017, Peinetti et al. 2019). The success of these woody invaders, largely undocumented, warrants ecological description and documentation.

1.1.1 Ecohydrology of Post Oak Savanna largely unknown

The shift from a grass-dominated to a tree- or shrub-dominated landscape results in potentially profound changes to ecosystem function and processes, biogeochemical and energy budgets, and provisioning of ecosystem services (Barger et al. 2011, Eldridge et al. 2011, Wilcox et al. 2017). In turn, these landscape changes have important implications for the sustainability of pastoral societies and commercial livestock production systems, which are the foundation of rural economies and cultures (Archer and Predick 2014). Despite transformation in the structure of the vegetation community, however, we know remarkably little about how thicketization of oak savannas influences ecohydrological processes. Particularly, the quantity of rainfall lost to interceptive processes on woody shrubs and the distribution of water in the near-surface soil matrix. In the POS, where the establishment of woody plants is at the least remarkable, the redistribution of water in the environment is a primary concern lacking field study. Because landscape-scale ecological processes, such as total evapotranspiration (ET), remain fixed to many unknowns, the sustainability of this region will be difficult or even impossible to reach without a better knowledge basis of canopy interception losses of frequently occurring shrubs and their effect to near-surface soil moisture.

1.1.2 Lack of literature for Ilex vomitoria

Paudel and Battaglia (2015) found significant association between probability of occurrence and human disturbance for *I. vomitoria*. Facilitation of this shrub occurs primary from avian species that consume its fruit, which occur in mass-cropping events during the early winter and are distributed from cluster-to-cluster as birds fly between them (Stiles, 1980). However, there have been no studies that address the role of *I. vomitoria* on the water budget in oak savannas, and further no studies indicate interception losses of this shrub. Visual inspection of rangelands in the POS yields a startling revelation into the growth and expansion of *I. vomitoria* in the understory of forests and margins of rangelands, oftentimes occurring as a monoculture. Due to the lack of knowledge on this species, this study will include interception losses of three different canopies of *I. vomitoria* and continuous soil moisture monitoring under mixed-species clusters predominantly occupied by *I. vomitoria*. Along with these, interception losses of mixed canopies including I. vomitoria will also be evaluated due to the high prevalence of *I. vomitoria* occurring in tandem with other POS shrubs.

1.2 Project scope and goals

The fundamental goal of this project is to develop a better understanding of the ecohydrological implications of WPE in oak savannas. This will be done by evaluating interception losses and near-surface soil moisture dynamics under a variety of POS shrub species. Particular emphasis is placed on the invasive *I. vomitoria*, which currently retains an underappreciated role in POS ecohydrology as its expansion has evaded many studies. Quantifying these dynamics will offer direct support in establishing local water budgets and develop better knowledge on the relationships that govern rangelands of the SGP. Overall, this study will hopefully provide foundational support and knowledge for modeling shrub ecology as thicketization continues under further human induced disturbance and a changing climate.

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2. INTERCEPTION AND NEAR-SURFACE SOIL MOISTURE DYNAMICS OF WOODY SHRUBS IN TEXAS POST OAK SAVANNA

2.1 Introduction

The Post Oak Savanna (POS) of Texas is described as an oak-hickory forest (Mcmahan et al., 1984) that emerges from the Piney Woods in the east and borders Backland Prairie to the west. This biome is nestled at the far end of the Southern Great Plains and Cross Timbers ecoregions, situated as the transition zone from forestlands to the east and rangelands to the west (Fig. 1) (Harker et al., 1990). The POS has long been attractive to native peoples and especially early European settlers (Texas Parks and Wildlife) who introduced intensive grazing pressures and plowing practices, along with private property ownership, fence lines, roads, and urban settlement. Subsequently, fire as a normal landscape process was abandoned in what is a historically frequent fire regime (6.9 year mean fire interval) (Stambaugh, 2011). The rich disturbance matrix occurring throughout time has facilitated an ecologically unstable[†] vegetation community, and the net result is a rapid conversion from savanna to fractured woodland. The flora of the POS is usually described as tall grasses co-occurring with hardwood trees. Yet, the reality of grassland to shrubland transformation has not been thoroughly documented and remains a marvel of much needed study. Further, the sustainable use of local water resources relies upon better knowledge of how regional shrubland transformation may alter the water cycle. Further, the global change associated with woody plant encroachment (WPE) is one of the

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[†] Unstable refers to the post-disturbance process in which the biotic community is highly modified as a result of disturbance. In the POS, unstable rangelands give way to woody shrubs, but drivers of this change are not well understood.

most important challenges facing rangelands (Campbell & Stafford, 2000). This study follows suite in an emerging scientific discipline -- ecohydrology – which seeks to better understand the linkages between vegetation change and the water cycle (Wilcox & Thurow, 2006).

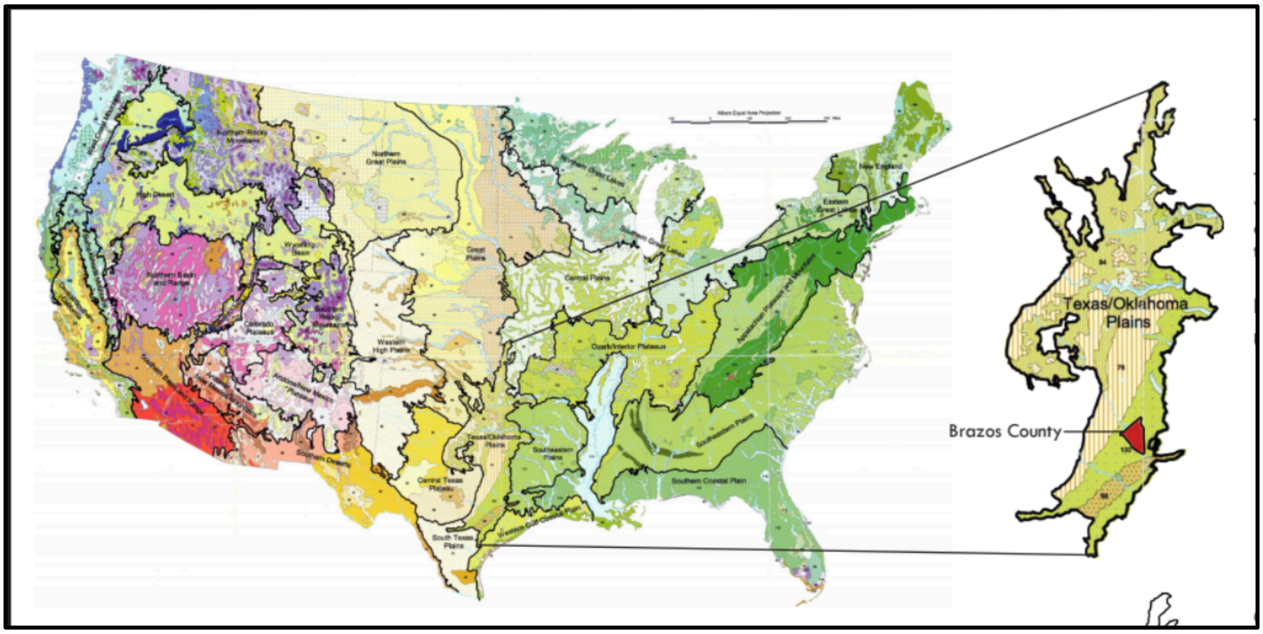

Figure 1: The location of the Post Oak Savanna is situated at the continental divide between humid forests to the east and arid rangelands to the west. Brazos county is depicted within the range of the savanna.

2.1.1 Implications of woody shrub encroachment in the Post Oak Savanna

Savannas are water-limited for at least part of the year -- it has therefore been widely assumed that competition amongst savanna flora is primarily for biologically available water within the soil profile (Scholes & Archer, 1997). Savannas are also coupled social-ecological systems (Briske, 2007) and provide a diverse array of ecosystem services to their inhabitants. Sustained overland and subsurface hydrologic flows are critical environmental processes for both private landowners, who recharge small lakes (“tanks”) for livestock or recreational use, and for recharge of the Carrizo-Wilcox aquifer. Across the POS and a significant portion of the Southern Great Plains, the widespread emergence of woody plants has transformed the POS from a grassland to shrubland mosaic (Hoagland et al., 1999). WPE is the result of the human footprint on the landscape; intersecting pressures of overgrazing, lack of fire regeneration, general mismanagement of arable soils, and a changing climate are often considered drivers leading to progressive establishment of woody shrubs (Asner et al., 2004). The emergence of a significant woody cover in place of grasses has far reaching effects into ecosystem function and processes, biogeochemical and energy budgets, and provision of ecosystem services (Barger et al., 2011; Eldridge et al., 2011; Wilcox et al., 2018). Therefore, exploring the burgeoning ecology of shrubland transformation is rightly Byzantine.

WPE induces a state transition from grassland to shrubland; the aboveground microcosm beneath the shrub canopy is transformed in nearly all aspects from that of the grassland. Woody plants may directly alter local and regional water fluxes through the processes of interception and transpiration (National Academy of Sciences, 2008) as well as to influence the energy budget by modifying latent energy, shading, and albedo (Bonan, 2008; Liete et al., 2020). As the overall structure of the ecosystem changes, its function follows. Woody shrubs have deeper rooting systems and higher evapotranspiration rates than grassy cover. Because water is intimately tied with land-surface vegetation, it is presumed this change in vegetative cover appreciably alters the quantity and quality of water distributed throughout the POS across space and time. It has been found that overgrazing in savannas leads to increased ecohydrological connectivity through amplification of the runon-runoff process, however, the relaxation of grazing pressures[‡]effectively collapses ecohydrological connectivity of the landscape (Basant et al., 2020). In the POS, where historical overgrazing occurred and is indeed relaxing, permanent

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[1] Stocking densities of cattle and other grazers on Texas rangelands have declined since the 20th century and are continuing to decline (Wilcox et al., 2012).

alteration of subsurface features, such as a compacted plow-pan or vastly eroded A-horizon, may be coupled to the success of WPE.

The POS, like other regions, hosts several woody shrub invaders. Prominent species include yaupon holly (*Ilex vomitoria*) (yaupon), deciduous holly (*Ilex decidua*), and Japanese privet (*Ligustrum japonicum*). These shrubs frequently occur along fence lines, lowland and riparian zones, and encompass taller trees and other shrub species forming discrete clusters or shrub islands dotting the landscape. Yaupon is a nuisance vegetation with very dense and irregular branching, evergreen foliage, and impressive re-sprouting ability post-mechanical treatment. This shrub excels as an edge-tolerant species and often rises as a vertical wall along forest margins and shrub islands (Fig. 2). Rangelands in the POS are typically managed for exotic grasses such as bermudagrass (*Cynodon dactylon*) and King Ranch bluestem (*Bothriochloa ischaemum var. songarica*). These grasses occur up to the margin of shrub dominated areas and are outcompeted by woody growth.

Figure 2: Woody plants dominate the understory of many lowland and forest areas in the POS. Here, yaupon holly occupies 5-10 feet of forest structure and creates nearly unsurpassable thickets. Oftentimes, POS shrubs can grow in excess of 20 feet tall. Despite its increasing frequency and magnitude, we know very little about this invasion by I. vomitoria and other woody invaders despite its rapid expansion into rangelands.

Region-wide expansion of yaupon and other woody species modifies the ecology of the landscape across many scales. Evergreen yaupon canopies provide shade to the subcanopy soil surface throughout the year. Altered subcanopy conditions demote the success of grasses, forbs, or other herbaceous vegetation. In shrub islands with yaupon, there will typically be no other vegetative life on the subcanopy floor including spring forbs.

2.1.2 Interception and soil moisture dynamics across an emerging shrubland

The first interaction of atmospheric rainfall occurs with vegetative surfaces in the plant canopy (Fig. 3). This process is known as canopy interception - an important and often overlooked portion of total evapotranspiration (ET). Intercepted rainfall adheres to vegetative surfaces and is lost to either evaporation or rain-splash, which in turn limits infiltration into the soil surface where it would otherwise become biologically available water (Lee, 1980). Intercepted rainfall that reaches the soil surface directly beneath the plant canopy is known as canopy throughfall. Several factors influence the quantity of canopy throughfall such as canopy storage capacity (CSC), leaf area index (LAI), leaf water repellency (hydrophobicity), and projecting tree crowns (Crockford and Richardson, 2000). Because tree canopies are spatially heterogenous, canopy throughfall is highly variable in the subcanopy zone with the highest distribution occurring near the margin of the canopy, called the drip line. Leaf litter also intercepts canopy throughfall by either repelling the water at the surface or storing water in the decomposing litter matrix.

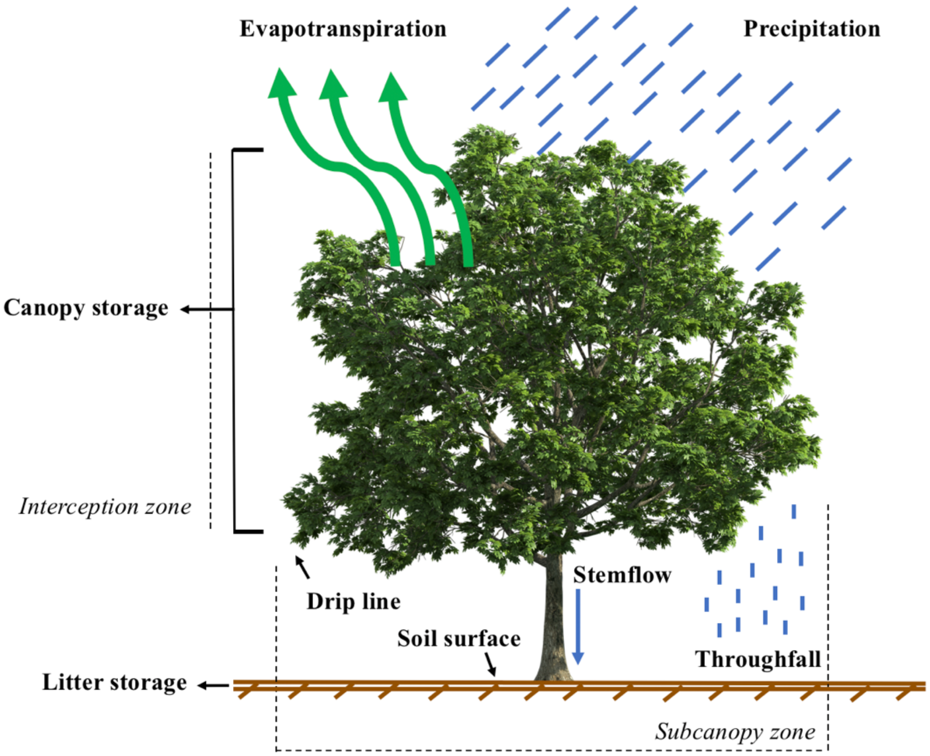

Figure 3: Precipitation is intercepted by vegetative and returned back to the atmosphere in a process known as canopy interception loss. In the evapotranspiration (ET) process, interception loss occurs from intercepted rainfall evaporating from the vegetative surface or as rain splash off vegetative surfaces. Interception loss s often an overlooked portion of total ET. Figure created by author.

Interception losses greatly differ between vegetation species, but also among individuals of a population. Thus, the habit and unique anatomy of each plant canopy make ascribing a definitive interception loss for a individual impossible. However, studies that determine interception dynamics from several isolated stands reveal the shrub canopies response to precipitation. This approach is the first step in understanding the complex dynamics of interception loss, but samples a very small variation of plants across what is a highly variable landscape. Yaupon in the POS differs remarkably from property to property; one stand may have a canopy with LAI similar to a trimmed ornamental, whereas other stands are elongated with low number of leaves (see Appendix). It is very common for yaupon to grow alongside shrubs of other species or trees in shrub islands; in the POS these mixed-species assemblages form most of the occurring WPE. Interception losses of these mixed-species shrub islands are seldom monitored in the field and no such studies exist for yaupon islands. Of more importance than individual shrub interception losses are those at the community-level. In emerging shrublands, there may be significant challenges to stream and groundwater recharge. Establishing field derived interception losses provides direct opportunities to better inform modeling efforts and to expand our understanding of interception dynamics in a highly fractured oak savanna. Despite this, there have been no field studies to determine canopy interception losses of prominent POS shrubs, so understanding of regional evapotranspiration remains fixed to many unknowns (Hassan et al., 2017). Basic field studies are therefore powerful tools for establishing knowledge.

Soil moisture conditions are likely tied to canopy interception losses and provide direct indications of a variety of ecological mechanisms and interactions. Water and nutrients are stored beneath shrub canopies in what are considered to be resource islands (Abrahams et al., 2003). Plants draw water from the soil for use in photosynthesis and energy balances. Because shrubs have deeper rooting systems and greater ET than grasses, the demand on soil moisture is expected to be higher under woody cover than grass cover. Huxman et al. (2005) notes that the movement of woody shrubs into oak savannas potentially increases evapotranspiration, especially when soil water tables are deep. Transects from the shrub main stem outward into the inter-canopy region generally show greater soil moisture close to the stem and canopy perimeter, and lower soil-moisture beneath the subcanopy (Stuart-Hill & Tainton,1987). Plants tend to absorb most soil water from shallower regions of the soil when the soil is moist; near-surface regions in the soil profile are also where roots are typically the densest (Bréda et al., 1995). Rooting depths also depend on soil water profiles along a drainage gradient (Fan et al., 2017). Because the POS has varying groundwater table depths, the rooting profiles of shrubs likely vary widely across the POS. Several notable dynamics resultant of woody shrub cover potentially alter soil moisture conditions. These include increased litter accumulation to the soil surface, reduced lighting conditions, and reduced temperatures above the soil surface. These physical components are also determinant factors in decomposition rates of soil organic matter (Yuste et al., 2007).

Despite vegetation restructuring across the Southern Great Plains, the extent of WPE has evaded most POS and Cross Timbers ecological assessments. Dynamics of large-scale ecological processes such as evapotranspiration and soil-moisture conditions are often modeled, yet almost no studies provide field data in these areas. It is unfortunately still a common practice in hydrologic modelling to provide interception losses on selected tree measurements, limited studies, or even arbitrarily based on other studies, which can be a source of substantial error (Hassan et al., 2017). Therefore, experimentally based in-situ assessments of canopy interception losses are an important step in advancing literature about the role of shrubs in oak savannas.

The POS is an important site for understanding how vegetation change may influence local water budgets. The spatio-temporal reduction in grassy cover across the POS alters the overall quantity, quality, and energy of precipitation reaching the soil surface. Sandy-clay soils and the underlying geology of the POS allow for the contribution to deep groundwater recharge, so the canopy interception losses and demands on near-surface soil moisture become particularly interesting and important to investigate. The ecohydrological effect of shrub islands in place of grasses, I believe, will manifest in significant interception losses and greater demand to near-surface soil water. Due to the lack of knowledge on woody plants in oak savannas, there are many opportunities to collect meaningful field data in a region undergoing rapid vegetation restructuring. In this study, the significance of POS shrubs to the local water budget is investigated. The objectives are: (1) determining interception losses of common POS shrub species and mixed-species shrub clusters to establish literature than can be expanded into modeling and other studies, and (2) comparing near-surface soil moisture dynamics of mixed-species shrub clusters to intercanopy[§] savanna to determine if woody cover appreciably alters the soil water profile.

2.2 Methods

2.2.1 Site description

All monitoring and research were conducted at the Texas A&M University Ecology and Natural Resources Teaching Area (ENRTA) near College Station, TX (30.571593, -96.371669) (Fig. 3). ENTRA is an ecological unit currently managed for research and preservation of the POS biotic community by the department of Ecology and Conservation Biology. ENRTA is mostly heavily wooded and has undergone dramatic thicketization. Prior to being given to the university, the area was heavily overgrazed and cultivated for cotton (*Gossypium hirsutum*) production. Eroded sandy soils gave way to deep gullies scattered throughout the property, which is typical of the region. Climate is semi-arid with annual precipitation around 40in per year occurring mostly in spring. Rainfall comes in both intense gulf storms and light showers. Summers are hot and dry, so the timing of dry season rain events are crucial for sustaining primary production throughout the summer. Soils in the area are mostly of the Boonville series, characterized by a high-clay argillic horizon capped by a shallow, fine sandy loam (25–40 cm),

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[§] It is common to distinguish shrubs as occupying “canopy” areas while grasses occupy “intercanopy” areas. This ecological jargon can be misleading since all vegetation have canopies. However, ecologists use this terminology in primary reference to the highly altered subcanopy conditions of shrubs and trees.

inheriting both low fertility and water permeability. The underlying parent material is a claystone (USDA-Natural Resource Conservation Service, 2002).

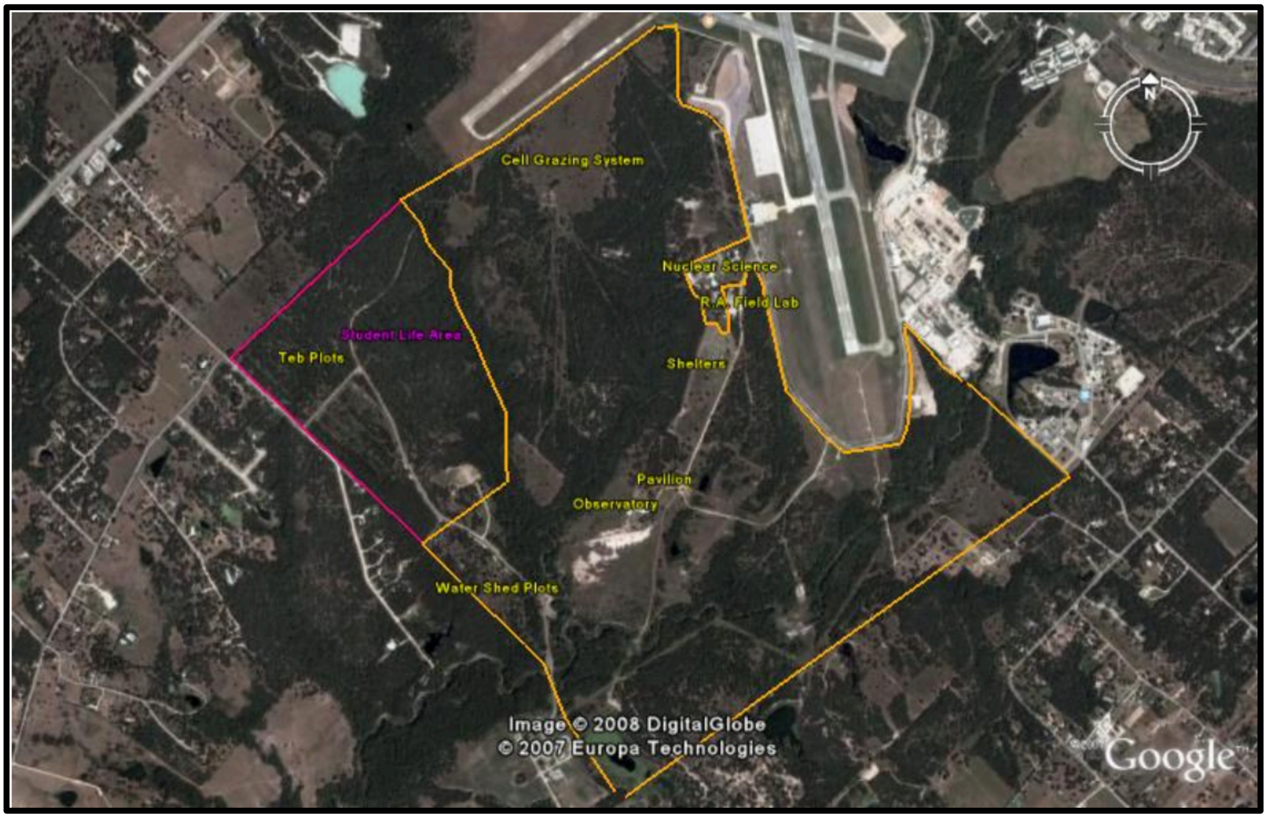

Figure 4: Ecology and Natural Resources Teaching Area (ENRTA) at Texas A&M University. This ecological unit is maintained as a conservation area of the Post Oak Savanna and is utilized for research and extension. Interception monitoring took place near the RA field lab and Watershed plots. Soil moisture dynamics were also assessed at the Watershed plots.

ENRTA has served various functions throughout its history. The Watershed Plots (n = 4, size =0.15 Ha) were investigated in the early 1990's, however the study could not be located. The plots were cleared of woody vegetation so that only mature post oaks (Quercus stelata) and grasses were present. The site was previously grazed, but for the last 35 years has seen minimal to no disturbance with no research activity or agricultural pressures. At the fringe of ENTRA and within several hundred meters of White Creek, this site has rested out of sight and undergone a remarkable transformation of woody shrubs. Regeneration of yaupon holly, deciduous holly, Eastern red cedar, and winged elm have effectively replaced tall-grass cover by 25-40% across all watershed plots. Satellite images from Dec. 1995 to Feb. 2019 reveal the extent of woody growth (Fig. 5).

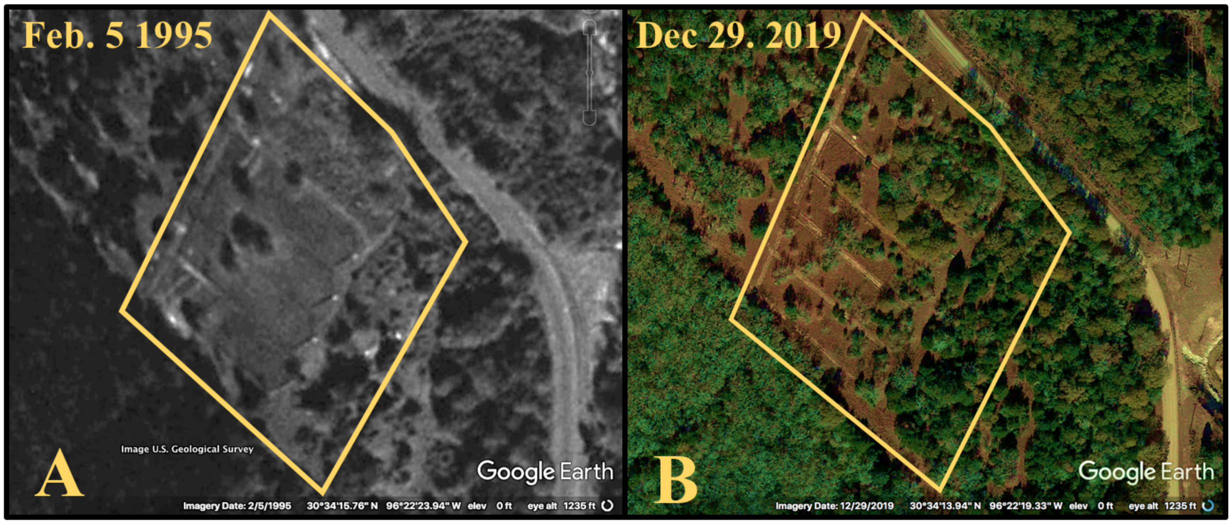

Figure 5: Satellite imagery of the watershed plots study area reveals shrubs dominating in place of tall-grasses from 1995-2019. These pictures were taken during the cool season, so green vegetation at these times are evergreen canopies. This site has been undisturbed for at least 20 years including lack of fire. This site represents a developing shrubland.

Both satellite images were taken in the cool season. The canopies seen in these images, therefore, are evergreens. Because this site has been resting, shrub domination likely represents a disturbance pulse-framework. Human intervention and then later relaxation permanently altered surface and subsurface soil features, likely a driver of WPE. The watershed plots represent an immature POS forest in transition and offers a valuable location for comparing woody cover to grassy cover on post-disturbance plots undergoing WPE.

2.2.2 Interception losses

Canopy throughfall was collected in throughfall devices (TD) under the canopies of both individual shrubs and mixed-species shrub islands. At least 9 TD's were distributed under the plant canopy to account for variations in canopy architecture (Fig. 6). TD's were constructed from reused plastic containers, funnels, insulating foam, sealing agent, ½ inch wire mesh, 1 inch wooden square dowels, and malleable wire. Funnels were attached to the top of plastic containers with sealing agent and channel canopy throughfall into the plastic container beneath. To prevent leaf litter accumulating in the TD, ½ inch wire mesh cages were built around each funnel. Insulating foam was wrapped around the plastic containers to minimalize evaporation losses before measurements were taken. Each TD was attached to a 1 inch x 1 inch wooden stake hammered into the soil. Wire was attached to a protruding screw head located on the opposite side of the wooden stake. Each TD maintained an affixed location under the shrub canopy throughout monitoring. TD's were periodically cleaned of fallen plant material and insects to prevent erroneous measurements.

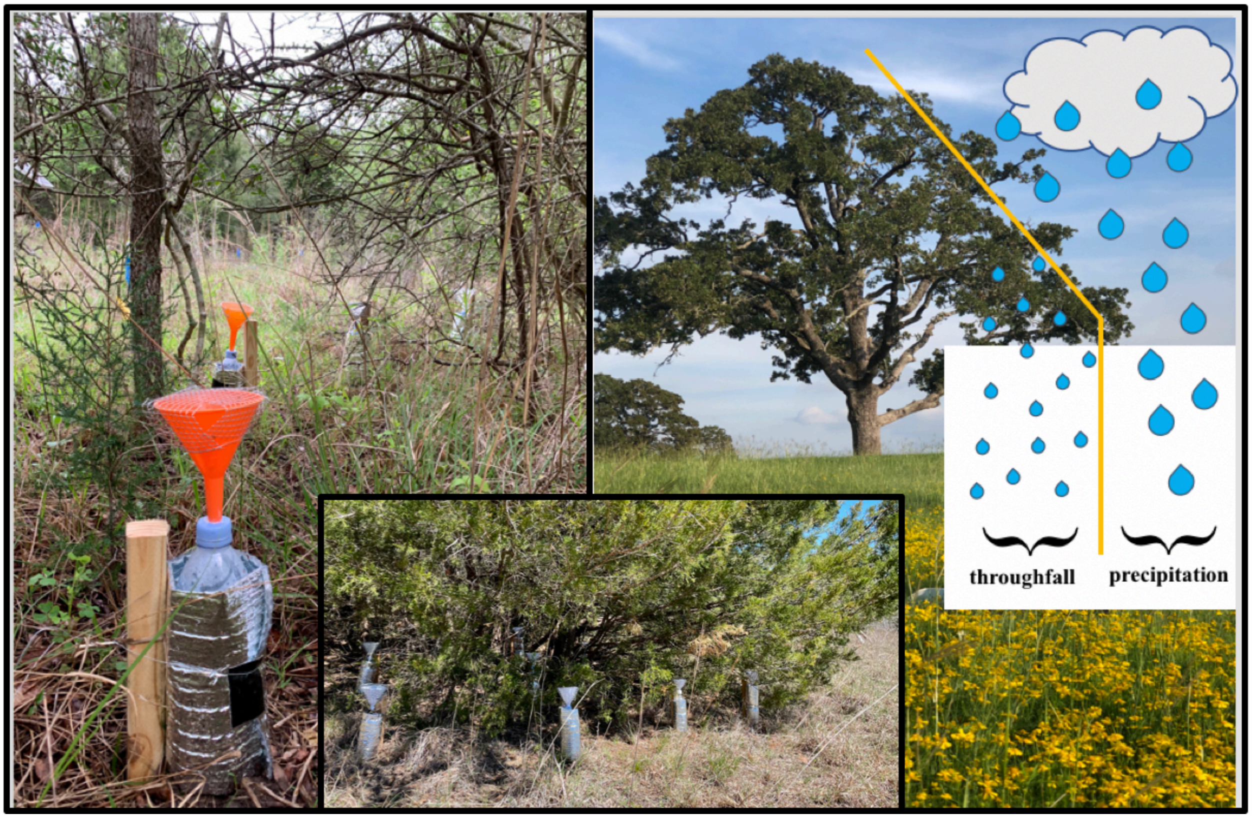

Figure 6: Interception research design showing: left) the throughfall device (TD), mid-bottom) the distribution of TD's under shrub canopy, and right) a diagram presenting the manner in which rainfall interacts with the plant canopy to become throughfall.

Canopy throughfall was recorded as the volume of water collected in the plastic container no more than 36 hours after the cessation of a rain event. Unobstructed rain-gauges were placed less than 200 meters from clusters to serve as a reliable control for throughfall comparison. These rain-gauges were horizontally located greater than two-three tree heights away from the nearest trees. It is assumed that the rain-gauge adequately sampled gross rainfall and provides an independent variable measured without error (Helvey and Patric, 1965). Volumetric measurements were taken with a 100 mL (small rain events) and 200 mL (large rain events) graduated cylinder and recorded in a field notebook.

Varying filter sizes were used for TDs. Measured water volumes were normalized to the area of the rain gauge for each observation in Equation 1:

$$T_n = T_o \times N_f \tag{1}$$

Where, T_n is normalized throughfall, T_o is observed throughfall, and N_f is normalization factor as a ratio of rain-gauge surface area to TD surface area. Normalized throughfall was averaged from all devices at each monitoring site for each rain event. Interception loss per rain event was calculated from Equation 2:

$$I_c\% = \left\{100 - \left[\left(\frac{T_a}{P}\right) \times 100\right]\right\} \tag{2}$$

In which canopy interception loss, I_c *%*, is determined from dividing the average throughfall per canopy (T_a) by the total precipitation per rain event (P) measured in the rain-gauge. This value is multiped by 100 and then subtracted from 100 to obtain the interception loss as percent of rain event. This value reflects the reduced quantity of rainfall that reaches the soil surface as modified by the shrub canopy.

Rainfall intensity is thought to have a significant effect on interception losses. A tipping bucket rain-gauge was located at the experimental watersheds where interception losses were obtained. However, high resolution minute-wise data from the rain gauge cannot be extrapolated with certainty to the interception plots. Rainfall rate per event was instead determined as the number of recorded tips (mm) divided by the duration of the rain event in hours following Equation 3:

$$P_r = \frac{number\ of\ recorded\ tips\ (mm)}{duration\ (hours)} \tag{3}$$

P_r values are a quantitative metric derived as a ratio for representing rain rate, or the overall quantity of rain divided by the number of hours rain fell. Precipitation, *P*, is obtained each time the tipping bucket records 1 mm of water. Because there is occasionally false measurements from in intra-period events, I filtered out and removed hourly data that did not contain more than 3 mm of tipping-bucket activity. This was successful in removing nearly all of the noise. precipitation in the POS is often not a singular discrete event, so the P_r value is effective with pairing to my field study on interception losses. These values were distributed, and I decided a designation based on three reasonable rainfall rates. Rain rates determined from P_r values are presented in Table 1.

Table 1: Determination of rain rates[C]

P_r value thresholds[a]	***Average Rain Rate***[b]	***Rain Events***	***Classification***
< 10	4.7 (1.9 – 7.5)	20	Light
≥ 10 < 20	13.5 (11.0 – 17.9)	7	Moderate
> 20	26.2 (20.0 – 45.5)	9	Intense

[A] Values are determined by [(mm event^{-1})/(duration of event in hours)]

[B] Data are presented for each group as: median (range)

[C] Rain rates are determined from the p_r values obtained in equation 2.3. The threshold designation for rain rate was arbitrarily assigned based on the distribution of events.

2.2.3 Continuous near-surface soil moisture measurements

Campbell Scientific water content reflectometers (CS 655) were installed at three locations – two directly under mixed shrub cluster canopies and another in open savanna in order to assess soil water contents beneath each vegetation type. A total of nine sensors were installed at depths of 10 cm, 20 cm, and 40cm beneath the soil surface. Each sensor relays volumetric water content (VWC) to a Campbell Scientific data logger operating from a small 12v battery and solar panel. Stored data is collected every several months with a USB cable and laptop through the LoggerNet software application. A physical layout of the soil-moisture monitoring design is included in Figure 7.

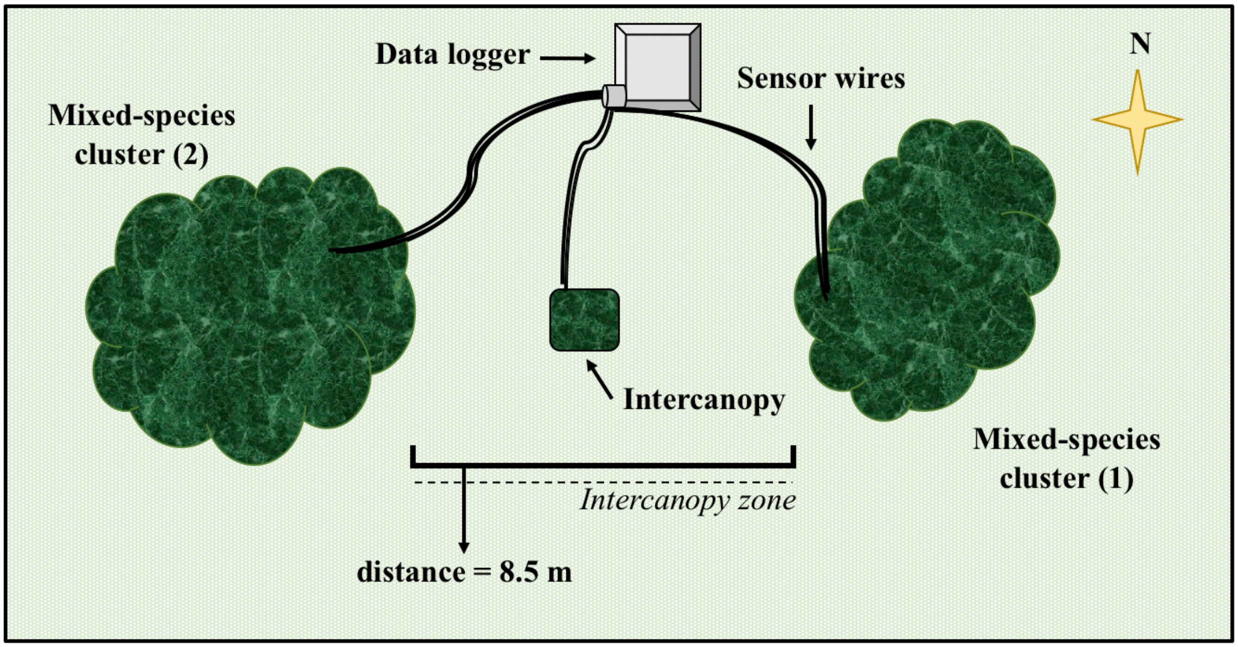

Figure 7: Two shrub clusters and a grassy location were selected to monitor near-surface soil moisture dynamics. Mixed-species shrub clusters (1) and (2) were also monitored for interception losses. The Intercanopy grassy site is located approximately midpoint between shrub clusters. The distance from shrub canopy to shrub canopy is 8.5 m. Sensors wires were tied together and run along the surface of the soil to the nearby data logger.

Mixed-species cluster (1) and mixed-species cluster (2) from the interception study were selected for continuous soil moisture monitoring. Mixed-species clusters are separated by 8.5 m (canopy margin to canopy margin) of grassy “Intercanopy” near the runoff flume of the furthest southern watershed plot. Approximately equidistant to both canopy margins is the Intercanopy monitored site which has a dense standing cover of little blustem (*Bothriochloa barbinodis).* Because of the close proximity of monitoring sites, it is likely that environmental variation is low, so comparison between plots should yield insight into the hydrologic dynamics across sites.

Sensors installed at each site are depicted in Figure 8.

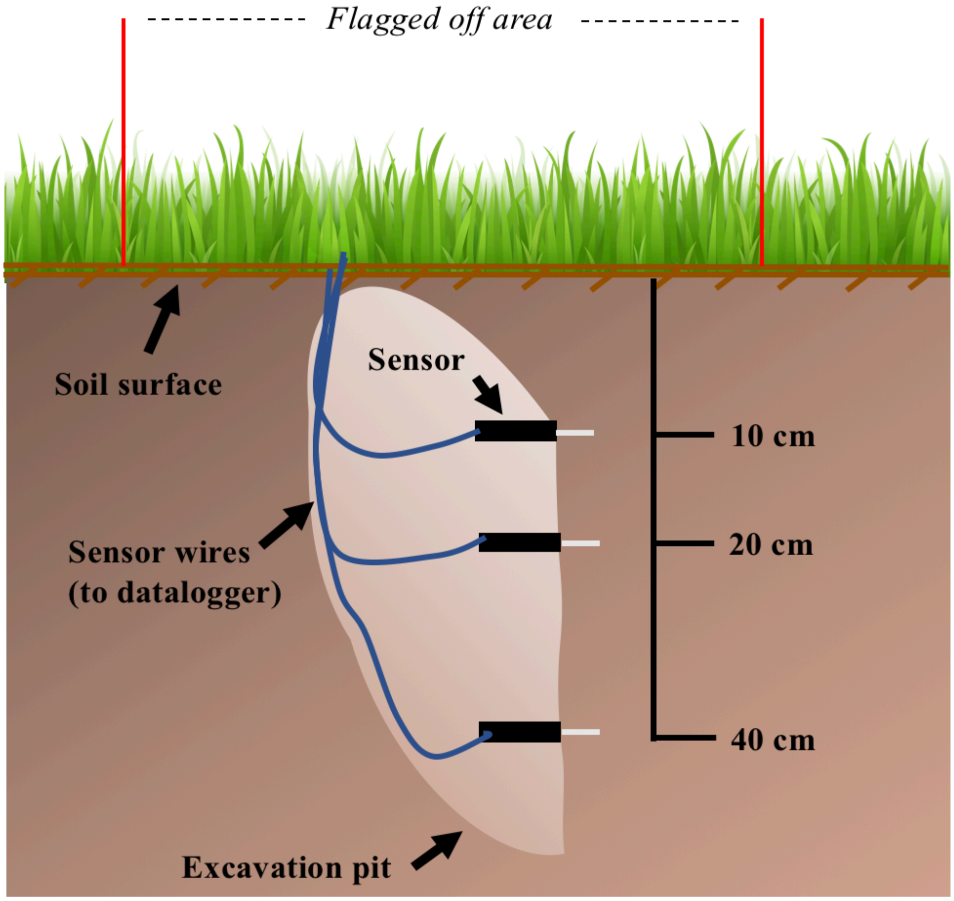

Figure 8: Campbell Scientific TDR sensors (CS 655) are inserted into the undisturbed soil profile from within the excavation pit to monitor volumetric water content (θv). Sensors are installed parallel to the soil surface at 10, 20, and 40 cm. These sensors take a data point every 10 minutes and supply this information to a local data logger via sensors wires. Obtaining the volumetric portion of soil water from stacked sensors allows for the estimation of water content under differing vegetation types.

TDR sensors were installed at depths of 10 cm, 20 cm, and 40 cm beneath the surface at three locations. A 50 cm excavation pit was carefully hand dug to expose an undisturbed vertical soil profile facing the primary stems of the shrub cluster. Sensors were installed parallel to the soil surface with the metal prongs oriented horizontally as recommended by the manufacturer. Soils removed from the excavation pit were carefully backfilled in the correct order. For the canopy clusters, surrounding leaf-litter was carefully reapplied to the surface following excavation to recreate surface conditions. Cables attached to the sensors were run along the opposite profile face of the excavation pit to prevent water from flowing into the sensor's monitoring range. The monitoring area was flagged off to prevent soil compaction during their monitoring period. Code was supplied to the Campbell Scientific CR300 data logger to obtain volumetric water content (θ_v), bulk electrical conductivity (EC), soil temperature (TS), bulk dielectric permittivity (Ka), period average (PA), and voltage ratio (VR) every 10 minutes through SDI-12 cables. Soil water content was averaged per day (May 1 – November 23).

The CS 655 sensors produce volumetric soil water content by converting the dielectric permittivity of the sampled soil body with oscillation period of the sensors digital onboard microprocessor. Despite claims from the manufacturer that this sensor works well without calibration, it is recommended that all sensors be calibrated (Hignett et al., 2008). To do this, a user-derived calibration equation was attempted in the field. However, the range of soil-water conditions required for a successful calibration was not met. Instead, the equation by Topp et al. (1980) was used to calibrate sensor output. This equation has become a standard in the field of measurements in coaxial transmission lines and is recommended by the manufacturer (Campbell Scientific) and available literature (Vaz et al., 2013). Using a third-degree polynomial, the relationship between dielectric permittivity and volumetric water content for mineral soils is represented through Topp's equation (Equation 4):

$$\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} K_a - 5.5 \times 10^{-4} {K_a}^2 + 4.3 \times 10^{-6} {K_a}^3 \tag{4}$$

Where θ_v is the predicted sensor observation and K_a is the dielectric permittivity of each observation. Root mean squared deviations (RMSD) and mean average error (MAE) of θ_v transformation were computed to assess quality-of-fit and accuracy. RMSD is a measure of the difference between values, often reported for calibrating sensors (Vaz et al., 2013) and MAE is the average of the absolute values of the errors between data sets (Hyndman & Koehler, 2006). The result of applying Topp et. Al (1980) equation was average RMSD = 0.1076 and MAE = 0.109. Although literature sources often able to obtain lower RMSD values (Hignett et al., 2008), this value is not unreasonable and results reflect the expectations soil-water conditions based on the soil texture present.

Sensors provide VWC at the sensor point. To compare sites, the 10 cm and 20 cm sensors were ascribed a depth factor of 10 cm, so that the 10 cm sensor represents 5-15 cm beneath the soil surface and the 20 cm sensor represents 15-25 cm. Averaged daily VWC was multiplied by the depth factor, and the results of the two sensors were added together to produce water depth of a 40 cm soil column under each vegetation type. Rooting densities were not quantitatively accessed; however, excavation pits for the sensors revealed larger, more course roots in the mixed-species canopies down to lower layer whereas the intercanopy grassy site had much finer and shallow roots.

2.3 Results

2.3.1 Interception

Canopy throughfall was monitored from Oct. 2019 – Mar. 2021 under eight different shrub canopies at the ENRTA in Texas A&M University. These include 3 yaupon holly stands, 1 Eastern red cedar, 1 water oak, and 3 mixed-species shrub clusters. These vegetation types were selected as representative samples of POS shrub communities. Characteristics of the monitored shrubs are included in Table 2.

Table 2: Physical characteristics of interception monitoring sites.

MONITORED VEGETATION	***NO. OF STEMS***	***DIAMETER OF STEMS (cm)***	***CANOPY AREA (m^2)***	***MONITORING PERIOD***
Ilex vomitoria (young)	4	[A]6.5 (4-10.5)	8.12	Nov. 29 - Dec. 12 (2019-2020)
Ilex vomitoria (mid-stage)	12	7 (4-12.5)	13.14	Oct. 29 - Dec. 12 (2019-2020)
Ilex vomitoria (mature)	21	7 (5-10.5)	20.12	Nov. 12 - Dec. 12 (2019-2020)
Juniperus virginiana	17	8.5 (4-15)	31.99	Jan. 1 - Mar. 18 (2021)
Quercus nigra	1	26.5	29.34	Jan. 1 - Mar. 18 (2021)
Mixed-species cluster (1)			36.44	Apr. 4 - Mar. 6 (2020-2021)
Ilex vomitoria	13	5 (3-8.5)		
Ulmus elata	3	8 (7-10)		
Juniperus virginiana	1	8		
Mixed-species cluster (2)			44.7	Mar. 21 - Mar. 6 (2020-2021)
Ilex vomitoria	14	4 (2-12)		
Ulmus elata	3	12.5 (12-13)		
Prosopis glandulosa	5	9 (8-10.5)		
Mixed-species cluster (3)			62.39	Jan. 1 - Mar. 18 (2021)
Juniperus virginiana	7	16 (4.5-25)		
Ilex vomitoria	20	2 (1.5-4)		

[A] Data presented as: average (range)

Rainfall was captured in both rain gauges and canopy throughfall devices (TD). Rainfall and canopy throughfall were measured with a graduated cylinder less than 24 hours after the cessation of all rain activity. Rain gauge volume was directly compared to the reduced volume captured in TD. Figure 9 presents the volume (mL) of rainfall captured by independent rain gauges throughout the interception monitoring period.

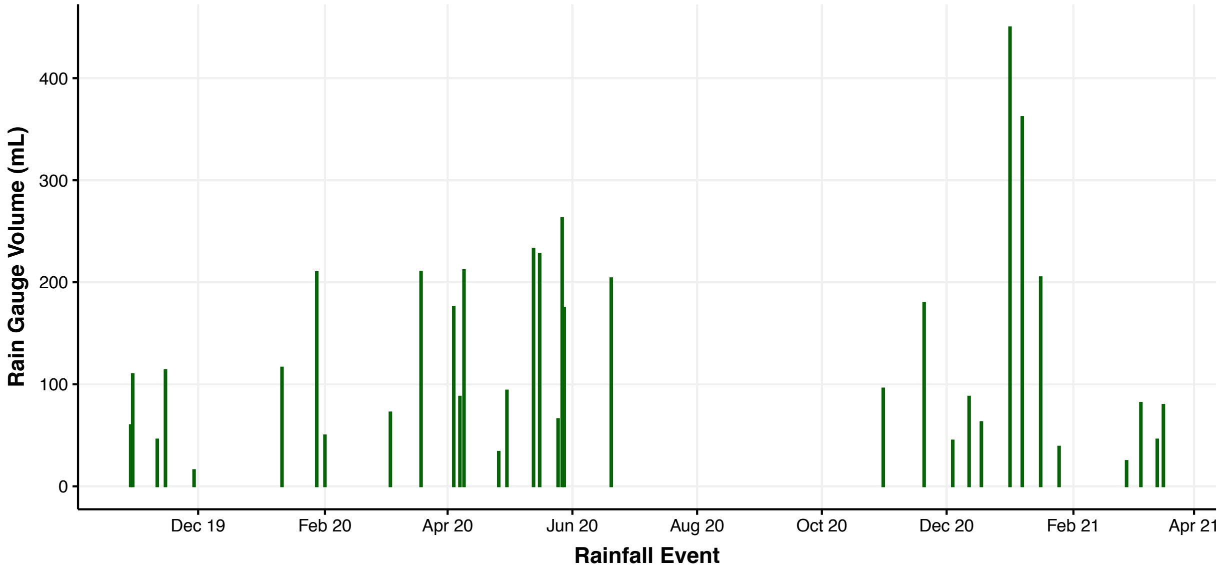

Figure 9: Rainfall volume captured by the rain gauges throughout the interception monitoring study. This data was used for direction comparison to canopy throughfall. Some rain events are not recorded because they could not be measured within 24 hours of the rain event. Snow events are also excluded.

Below average annual precipitation occurred during both 2019 (36.29 in) and 2020 (30.69 in) in College Station, TX. Canopy throughfall observations (N = 1191) of 34 rain events were conducted across a wide array of precipitation events ranging from light suspended showers to intense storms. A summary of the monitored events is included in Table 3.

Table 3: Descriptive information of interception study.

Monitored vegetation	***No. of observations***	***No. of rainfall events***	***Monitoring Period***
Ilex vomitoria (young)	*113*	20	Nov. 29 - Dec. 12 (2019-2020)
Ilex vomitoria (mid-stage)	*221*	24	Oct. 29 - Dec. 12 (2019-2020)
Ilex vomitoria (mature)	*219*	22	Nov. 12 - Dec. 12 (2019-2020)
Juniperus virginiana	*78*	8	Jan. 1 - Mar. 6. (2021)
*Quercus nigra**	*75*	8	Jan. 1 - Mar. 6. (2021)
Mixed-species cluster (1)	*189*	25	Apr. 4 - Mar. 6 (2020-2021)
Mixed-species cluster (2)	*222*	25	Mar. 21 - Mar. 6 (2020-2021)
Mixed-species cluster (3)	*74*	8	Jan. 1 - Mar. 6. (2021)

*water oak was defoliated throughout the sampling period

Because TD's were not designed for snowfall, two snow events (Jan. 10 and Feb. 15, 2021) were excluded from analysis. Along with these data, negative interception losses were excluded (n = 123). During some storms with high wind speeds, collectors placed near the dripline of the canopy likely captured nonintercepted rainfall at a steep angle -- similar to the study by Herbst et al. (2006). This produced a measurement of canopy throughfall which exceeded the total rainfall, so thus the data is not representative of the canopy interception process. Stemflow was also not measured during this study. Further, I visually observed very little to no stemflow from any major stems in Mixed-species canopy (1) during a moderate intensity precipitation in April. Reported interception losses represent the reduced volume of rainfall reaching the subcanopy floor. Field derived canopy interception losses of POS shrubs are presented in Table 4.

Table 4: Interception losses reported for different vegetation

Monitored Vegetation	***Mean****	***Rainfall (mm)***				
		0-100	*100-200*	*200-300*	*300-400*	*400-500*
Ilex vomitora (average)	32.0 ± 23.0	36.5 ± 26.7	28.3 ± 18.7	27.2 ± 19.8	-	-
Ilex vomitora (young)	26.3 ± 20.7	28.1 ± 21.8	25.4 ± 17.6	24.1 ± 21.3	-	-
Ilex vomitora (midgrowth)	35.3 ± 24.3	40 ± 26.7	31.4 ± 20.8	29.7 ± 20.7	-	-
Ilex vomitora (mature)	31.5 ± 22.3	37 ± 25.6	26.6 ± 16.9	26.7 ± 18.2	-	-
Mixed-species cluster (1)	23.3 ± 19.3	25.1 ± 20.7	18.8 ± 21	25 ± 17.1	20.9 ± 13.1	13.8 ± 15.8
Mixed-species cluster (2)	37.8 ± 20.5	45.5 ± 19.1	35.9 ± 13.2	22.1 ± 19.1	40.9 ± 17.8	35.8 ± 15.7
Mixed-species cluster (3)	56.7 ± 25.0	61.4 ± 23.7	-	56 ± 19.7	23.3 ± 20.1	62.2 ± 17.8
Juniperus virginiana	52.9 ± 20.9	54.2 ± 21.7	-	55.2 ± 11.9	37.3 ± 24.5	60.8 ± 12.6
Quercus nigra	19.7 ± 23.3	21.8 ± 25.7	-	6.0 ± 9.0	16.8 ± 24.2	18.8 ± 10.2

[*] All data presented as: mean (I_c%) ± SD; final interception loss is averaged from all data and presented in the "Mean" column. Averages of storm-size events are presented.

The storage capacity of plant canopies is the inherent ability to capture and store rainfall on vegetative surfaces such as leaves and bark. The efficiency of canopy storage capacity decreases as the duration and intensity of a rain event increase. For very small rain events, the canopy storage capacity can be determined when no canopy throughfall is generated. Unfortunately, rain events throughout this study never yielded 100% interception losses, but Mixed-species canopy (3) came very close with the smallest precipitation event (25 mL). Interception losses occur across both space and time, and as a result can have high variation across events. Variation in interception losses represent spatially heterogenous rainfall and canopy characteristics. Averaged canopy interception losses as a percent of total rainfall

(Equation 2) are plotted against the size of each rain event in Figure 10. Three yaupon holly shrubs at different growth stages were monitored. Yaupon interception losses are presented in greater detail in Figure 11.

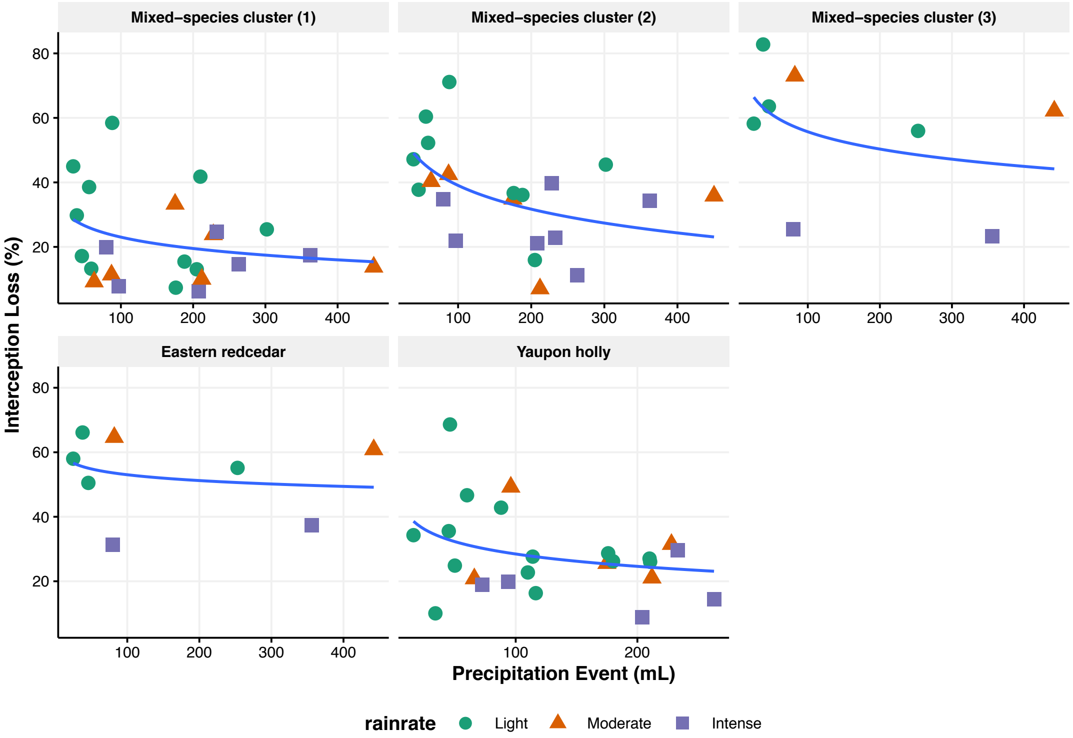

Figure 10: Interception losses as percent of total rainfall for monitored POS shrubs. Data points represent the reduced percentage of rainfall reaching the subcanopy surface. Rainrate data are displayed from the values in Table 1. Trendlines are only for visualizing the effect of rainrate on interception loss.

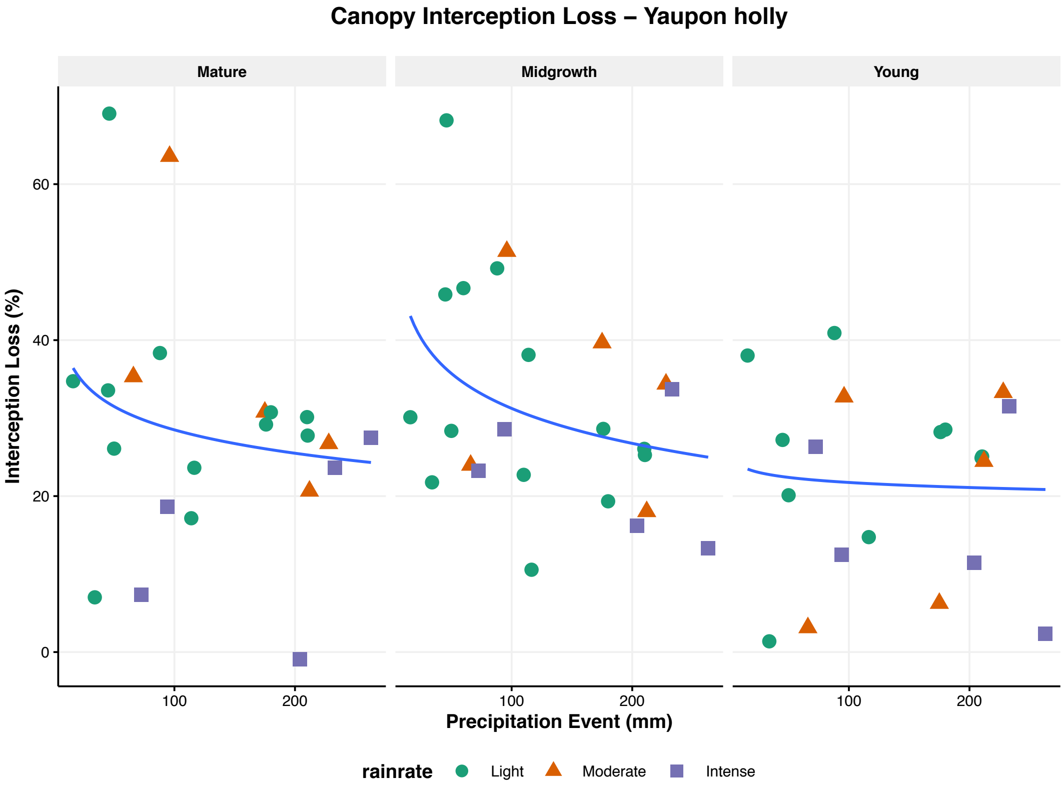

Figure 11: Interception losses of three yaupon holly shrubs. These shrubs differ in their growth stage. Trendlines are only for visualization. Rainrate geoms were produced from values obtained in Equation 2.3 and their respective designations from Table 1.

The percentage of rainfall intercepted and lost back to the atmosphere is represented by *Interception Loss %.* on the x-axis. The quantity of rainfall captured in the rain-gauge represents *Precipitation Event (mL)* on the y-axis.

The efficiency of the plant canopy to store rainfall becomes reduced as the intensity and duration of rainfall increases. In most interception studies, a logarithmic reduction in interception losses occurs with increasing precipitation events. This is slightly indicated by the visual trend lines, but the variation in subcanopy throughfall as a result of shrub canopies is an important ecological process of vegetation change. Therefore, “normalizing” this data debases its natural tendencies. It appears that across most of the interception plots, plant canopies intercepted more rainfall in light rainrate events than intense events, with moderate rainrates indicating no significant pattern but occurring between light and intense events. Yaupon shrubs show an interesting trend with age; the midgrowth yaupon intercepted the most rainfall (35.3 ± 24.3), followed by the mature yaupon (31.5 ± 22.3), and lastly with young yaupon (26.3 ± 20.7). Yaupon in shrub islands and throughout the forest floor matures to and morphologically alters to gain vertical advantage of lighting conditions. As a result, canopy density decreases and a void fills the previously occupied subcanopy region.

Calculated interception losses of *J. virginiana* (52%) are similar to Duesterhaus (2008) observation of 52% canopy interception loss in Kansas. Zou et al. (2015) calculated a lower amount in Oklahoma of 36.3%, and Owens et al. (2006) observed 40% in Texas in *J. ashei.* Interception losses are varied across the literature, but this similarity likely verifies the authenticity of this research method and the results produced for other vegetation types.

Kruskal-Wallis Test was conducted to examine the differences of interception losses according to the types of vegetation. A significant effect size (H =0.147, df = 7) was found for the differences of interception loss between species and mixed-species clusters.

2.3.2 Near-surface soil moisture dynamics

Volumetric soil water content (θ_v) was monitored from May 1 – November 23, 2020 across three vegetation types. TDR sensors (Campbell Scientific 655) were installed at 10 cm, 20 cm, and 40 cm beneath the soil surface of each vegetation type. Soil volumetric water content was recorded every 10 minutes and averaged by day. Sensor output was calibrated from Equation 2.4 (Topp et al., 1980). An intercanopy grassy area is compared to Mixed-species cluster (1) and Mixed-species cluster (2) from the interception monitoring design. A time-series of soil volumetric water content between vegetation types is presented in Figure 12.

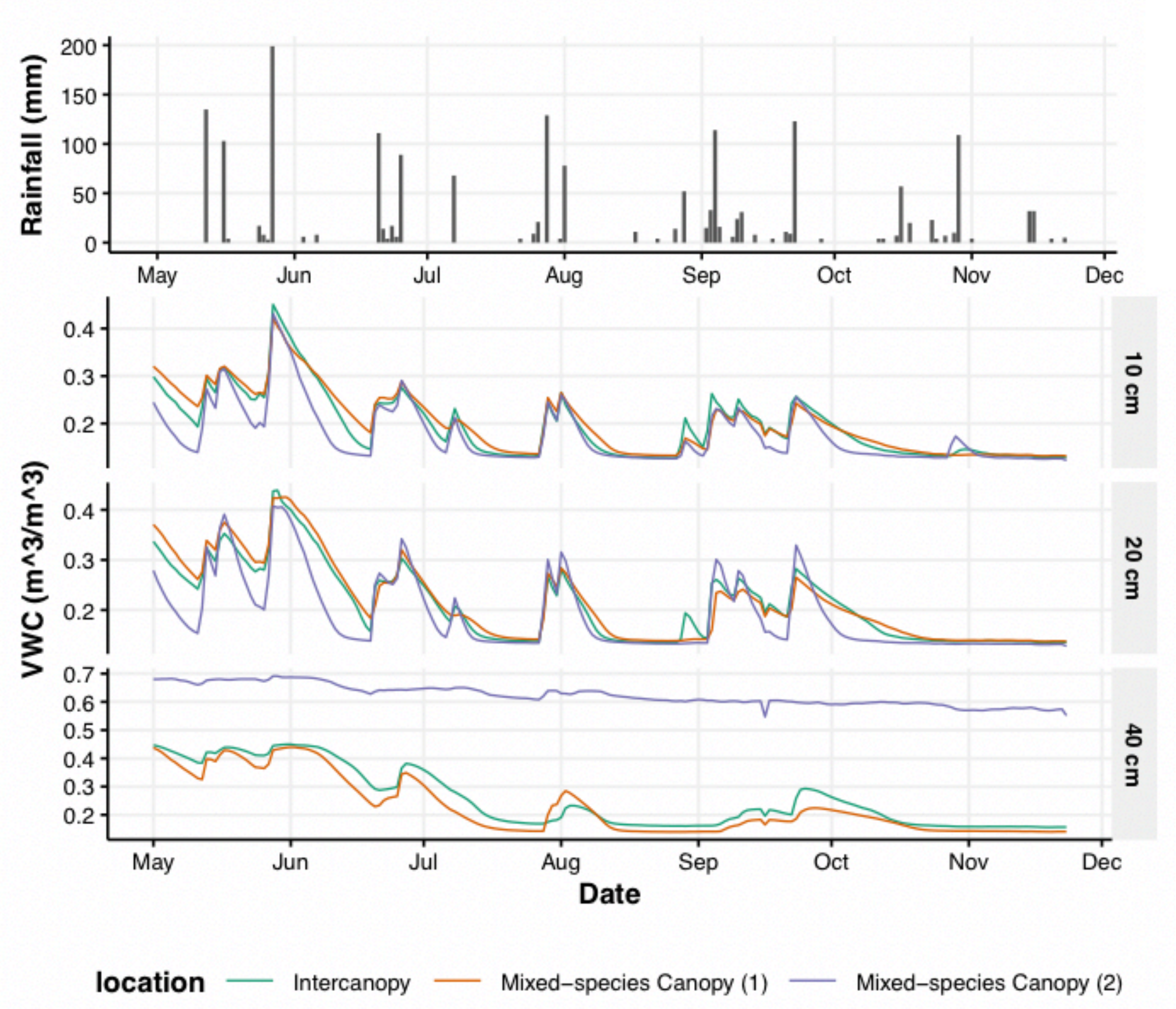

Figure 12: Time-series of soil volumetric water content (taken at three depths across three vegetations types from May 1 to November 23 (2020). VWC data is topped with a precipitation bar graph showing how the depth of a rain event corresponds to fluctuation in soil water.

VWC ranges form from 13-47% across sensors during the sampling period. Soil water typically decreased as distance from the soil surface increased. Mixed-species cluster (2) shows faster water depletion at 10 and 20 cm after rain events, but also faster recharge of soil water at 20 cm. At 40 cm, the intercanopy site retains more water for nearly the entire study. On October 29 a 109 mm rain event occurred, yet only the 10 cm Mixed-species canopy (2) appreciably responded to this event, then followed by a small response from the intercanopy site. The interception loss for this cluster was 50.7%, greater than the average, but temperature for that day was low (36-60F) and wind speed average was around 10 mph during the event. After the beginning of October, there appears to be almost no response to precipitation across any of the sites.

At the 40cm sensor of Mixed-species canopy (2), the sensor was installed on top of the clay-argillic horizon and subsequently sampled the water table throughout the study. A neutron probe access tube located less than 5 m away from this site cross-validates this observation as the tube frequently fills with water and remains filled for long periods of time. Additionally, the sensor pit was carefully excavated to examine if there was physical damage to the sensor, and at 40-45 cm from the soil surface water pooled into the pit (performed in March 2021). Therefore, to obtain comparable data between sites, only the 10 cm and 20 cm depth sensors were utilized for obtaining soil water columns. Soil water contents represent the depth of water in the 5-25 cm soil profile. Soil water content of the driest days are presented in Figure 13 and responses to several rain events are presented in Figure 14.

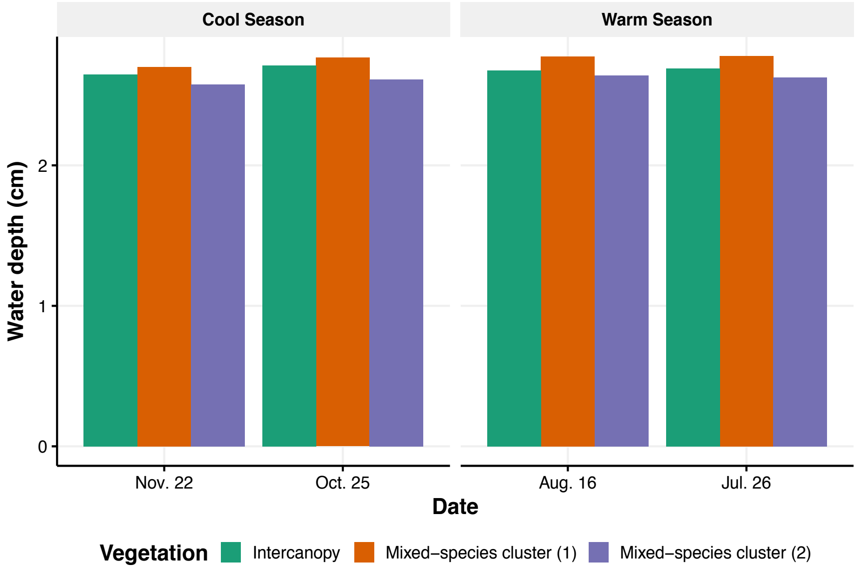

Figure 13: Water column of 5-25 cm rooting zone beneath three vegetation types at discrete dates. These water columns were the most depleted during the study for the cool and warm season.

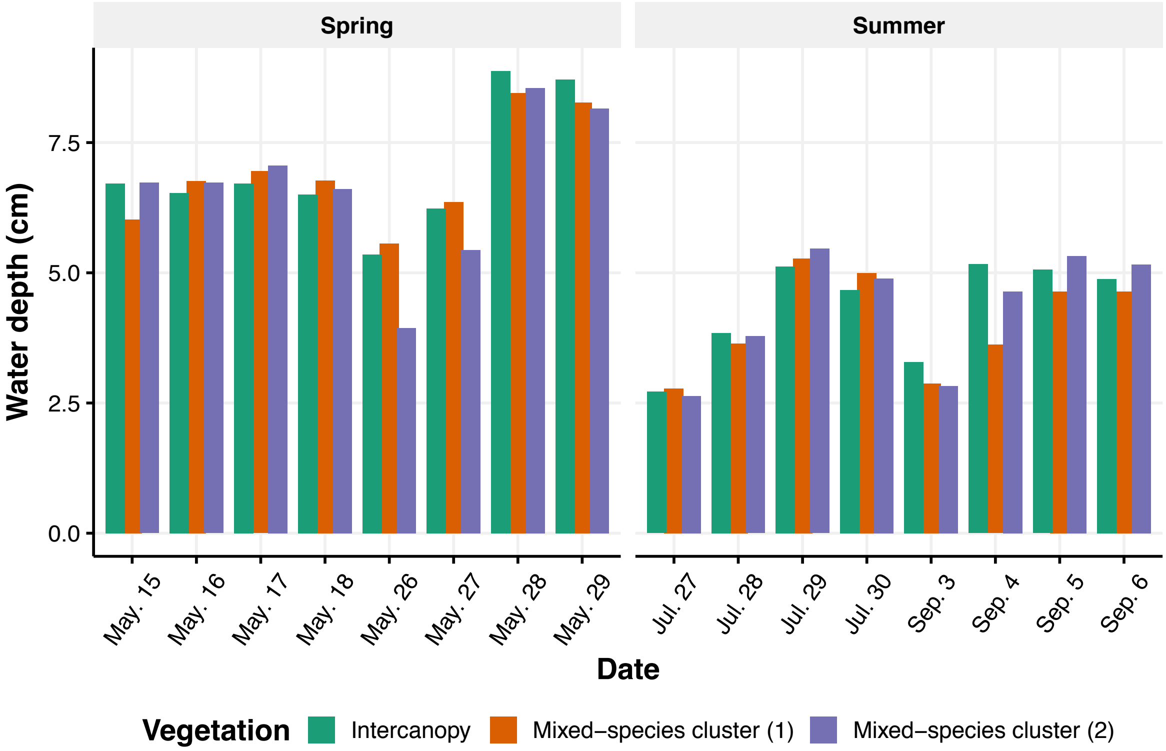

Figure 14: Water column of 40 cm rooting zone beneath three vegetation types at discrete dates. The dates are presented as: day prior to a rain event, day of rain events, and the two days after the rain event. Precipitation is as follows: May 16 → 103 mm; May 27 → 199 mm; July 28 → 129 mm; September 4 → 114 mm

Discrete dates were chosen to represent the driest periods during the study along with several rain events, including the largest rain event recorded on May 27. Dry periods in the warm and cool seasons retain nearly identical water columns; approximately 2.6-2.8 cm of water depth in the observed 20 cm soil profile indicates a 13-14% water-to-soil volume at the driest periods (Fig. 12). Comparable rain events in the spring and summer (ranging from 103-199 mm) indicate similar saturations of the soil profile and no significant differences among vegetation types. The highest soil moisture content throughout the study was measured during May 26 – May 31; this is approximately 8.4-8.8 cm of water depth in indicating a 42-44% water volume (Fig. 13). The May 16 rain event did produce soil moisture responses similar to the other rain dates, but the soil was already highly saturated prior to this event.

2.4 Discussion

2.4.1 Implications of study

This study couples the monitoring of interception losses with near-surface soil moisture dynamics under woody shrub clusters and grassy intercanopy in the Post Oak Savanna. Interception losses to the subcanopy are reported for *Ilex vomitoria*, *Juniperus virginiana*, *Quercus nigra*, and mixed-species shrub clusters commonly occurring in the POS in Table 4. This study takes place in a lowland area with unusual subsurface hydrology. The determination of a near-surface water table occurring at the compacted plow-pan is interesting for a number of reasons. Primarily, the physiological response of shrubs to this altered feature are most likely very interesting, and by further understanding the disturbance history, we can elucidate why woody shrubs have succeeded so well in such a short amount of time. It is likely the hyper-moist conditions likely limit rooting depths due to a lack of oxygen below the water-table (Fan et al., 2017). Therefore, the 5-25 cm subsurface region is assumed to be the primary “rooting zone”, or region where rooting density and water demand is high. Contrary to my hypothesis, it does not appear that woody shrubs significantly reduce soil water in the near-surface regions as compared to grassy intercanopy. However, the availability of water less than 1 meter below the surface is certainly extractable to shrubs, and shrubs use more water than grasses. Therefore, the question advances: *how does the belowground ecology of these shrubs interact with deeper soil moisture to alter savanna subsurface flows?*

Evapotranspiration is a highly complex process in savannas. A substantial shift from transpiration to more evaporation is likely to occur in subhumid biomes as the ratio of bare ground to vegetated ground decreases with WPE (Huxman et al., 2005). Zou et al. (2015) reports a very high interception loss of tall-grass prarie – 44% - but acknowledges the variation is within a high range of values reported across the literature. The reality of grass interception loss across rangelands in the POS, where overgrazing continues to persist, and thus, across any rangelands where herbaceous cover is reduced, is that the ability for aboveground biomass to intercept and evaporate rainfall is reduced by grazing. In this study, the field site has been undisturbed for around 25-30 years, so the dense little bluestem cover monitored in the intercanopy area does not represent most working rangelands of the region. However, along the margins of rangelands and in canopied sites, these conditions likely do exist as the landscape contains many micro-habitats. Shrub expansion occurs where most landowners are not looking; along the less utilized areas of property, such as the field site. Because there were not obvious signs of near-surface soil water depletion by the shrub clusters, it is likely that these sites are removing moisture from deeper within the profile. Yet with reason to believe that deeper rooting density may be limited by the shallow soil water table, the rooting habit of this shrub is likely highly dynamic and capable of responding to environmental stimuli such as a compacted clay-horizon. Regional yaupon encroachment, then, could possibly alter subsurface flows and reduce stream recharge where there might otherwise be more connectivity across the landscape. The POS lies on top of the Carizo-Wilcoix aquifer, thus, this study supports the need for deeper assessments of soil water conditions under differing vegetation types.

2.4.2 Ecological description of woody shrub encroachment in the POS

To accurately perceive the complex ecology of developing shrublands requires looking beyond the ecological community as simply a result of neutral theory or niche theory as suggested by Stokes and Archer (2010). Wilcox et al. (2018) provides two theoretical and conceptual frameworks for understanding the underlying mechanisms of shrub transformation – alternative stable state theory (ASST) and pyric herbivory. Soil moisture results comparing canopy and intercanopy sites satisfy the first key concept of ASST, which is that alternative stable states governed by strong stabilizing feedbacks may exist under the same exogenous environmental conditions. The framework of pyric herbivory, being that fire once removed may not have the capacity to regenerate the landscape, is also supported with visual observations of recent prescribed burning at ENRTA failing to burn woody plants as shown in Figure 15.

Historical management of rangelands is often a key component to their current status, with high variation in management conditions leading to heterogenous responses of land units and the evolution of a fractured landscape. In central Texas, where private-land ownership is nearly universal, structures such as fence lines provide ample opportunity for the recruitment of woody species. To better understand the facilitation of yaupon holly and WPE in the POS, it is important to view the POS as a coupled socio-ecological system (Briske, 2007). Nuisance vegetation, either woody or spiny, is oftentimes appreciated by the landowner as it plays a role in providing physical support for delipidated fencing structures. As the landowner finds benefit from keeping nuisance vegetation along fence lines, birds that consume fruit from woody species will further optimize the shrub-fragmented landscape from these recruitment corridors.

I. vomitora, *J. virginiana*, *I. decidua,* and *Ligustrum japonicum* constitute a vast majority of woody invaders in the POS. Shrub islands have an interesting structure with woody species occurring most prominently along the margins and decreasing in density towards the interior of the island. Shrub islands occur across most of the POS and usually contain some form of climax tree species surrounded by woody plants. Shrub islands occur most frequently is lower lands and typically blend into forest. Typically, the margins of shrub islands are composed of very compact shrubs. Inside the shrub islands, a vast vertical structure develops as understory shrubs become less dense and elevate above the forest floor. Yaupon holly often obtains a 25 ft vertical extent within shrub islands in the POS. These less dense sites may provide beneficial protection to grazing undulates looking to provide shelter for their newborn calves or to wildlife looking to escape human-production pressures. Shrub establishment also reduces the ability for successful fire management as local managers have reported the cessation of fire along margin boundaries of *I. vomitoria* and *L. japonicum*. At the Ecology and Natural Resource Teaching Area, prescription removal of shrubs (utilizing a skid steer with brush cutter) in late 2019 have been ineffective in both stopping the regrowth of understory invaders and improving conditions for savanna grasses – further supporting the theory for pyric herbivory (Fig.15).

Figure 15: The short woody regeneration seen here (L. japonicum) comes from 90-100% mechanical treatment with a brush cutter in late 2019. In early 2020, a prescribed fire was ineffective across most areas of the prescribed burn with dense I. vomitoria and L. japonicum. This is an issue for properties with extensive woody encroachment seeking to restore native grasses with fire.

2.4.3 Yaupon ecology

A prominent POS landscape interaction is the product of deciduous oak (*Quercus spp.)* trees surrounded by evergreen yaupon holly. Each year, large *Quercus* trees defoliate, and leaves accumulate in the yaupon-oak subcanopy zone. The emergent property of this species pair is what appears to be an extremely high leaf-litter accumulation sustained on the soil surface. Leaf litter is primarily made up of *Quercus* leaves and is in much higher accumulation than in areas without year-round shading from evergreen species. Under the canopies of *Quercus* trees surrounded by native grasses[**], it appears that biomass loading of leaf litter does not surpass microbial decomposition rates, so grasses are able to persist. It has been shown that belowground biomass carbon pools increased markedly with grassland-to-shrubland state change (Archer et al., 2019). Under the emerging yaupon-oak niche, leaf-litter accumulation becomes a prominent component of the subcanopy zone that actively restructures the ability for grass species to survive. Although the "island of fertility" phenomena is recognized throughout the scientific community, there is still very little known about nutrient enrichment under tree canopies (Scholes and Archer, 1997). Because of this interacting shrub and tree dynamic, soil-moisture conditions in shrub islands are reasonably tied to litter conditions at the soil-surface and other belowground factors, such as the microbiome. Few studies have investigated below-ground factors such as soil physical characteristics and root density in relation to water infiltration under open grass areas to vegetated patch areas of two-phase mosaic vegetation (Archer et al., 2002). Additionally, the landscape change in soil microbiome is almost never evaluated when discussing WPE. The amount of water held in litter-storage, hydrophobicity of surface litter, and development of the soil O-horizon, and the microbiome and its communication with surrounding species are important ecological aspects for understanding how yaupon and other evergreen shrubs alter the hydrosphere.

2.4.4 Observations of litter decomposition under I. vomitoria and soil temperature

Shrub canopies accumulate dry deposition and organic residues that are removed by intercepted rainfall. This process alters the chemistry of canopy throughfall that reaches the soil

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[**] Native grasses surrounding oak trees can be found at the ENRTA but are often difficult to find in private rangelands

profile. A study in India observed 25-30% increase in throughfall pH as compared to rainfall in their interception study (Guar and Kumar, 2018). Qualls (2020) posits that reduction in quantity of precipitation and alteration of throughfall chemistry are the main external factors affecting litter decomposition rates. In ecosystems with interception losses of appreciable magnitude, the reduction of litter decomposition rates is especially possible under evergreens (Qualls, 2020). Soil temperatures collected by the continuous soil moisture sensors at 10 cm depth beneath the soil surface are presented in Table 5. The inter-canopy prairie grass site maintains higher temperatures than shrub clusters containing *I. vomitoria.* This observation relates to Breshears et al. finding of higher soil temperatures in intercanopy patches vs canopy patches between the warmer months of May – September (1998).

Table 5: Averaged soil temperature measured at 10cm beneath the soil surface under different vegetation.

Vegetative cover	***Apr. 29 - May 31 (2020)***	***Jun. 1 – Aug. 31 (2020)***	***Sep. 1 – Nov. 23 (2020)***	***Feb. 1 – Feb. 8 (2021)***
Intercanopy	24.99	29.17	22.59	11.73
mixed-species shrub cluster (1)	21.79	26.64	21.58	11.00
mixed-species shrub cluster (2)	22.06	26.90	21.40	11.01

2.4.5 Concluding remarks

POS shrubs intercept and loss a significant portion of total rainfall to environmental processes. *I. vomitoria* intercepts one-third of rainfall reaching the subcanopy zone. Litter accumulation and decomposition remain interesting ecological features of POS shrub encroachment and are likely tied to interception losses but were not evaluated. Because canopy interception loss is a significant ecological process of the monitored shrub vegetation, but results do not vary from grassy-to shrub sites, there is very likely substantial draws on deeper soil-water tied to the compacted argillic clay-horizon. Thus, this study affirms the need to evaluate shrub water demands at deeper depths within the soil water profile. Access tubes located across the watershed plots are used for neutron probe measurements and will help further elucidate this behavior. Recharge of the Carizo-Wilcox aquifer is likely tied to land-surface vegetation, and thus *woody shrubs may play a complex role in altering deep groundwater recharge*.

The continued research and knowledge on the community role of WPE is essential for the sustainable growth of Texas. This study hopefully encourages others, particularly undergraduates, to further elucidate the role of woody shrubs in the POS.

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APPENDIX: PHOTO GUIDE OF YAUPON HOLLY IN THE POST OAK SAVANNA

This photo guide is included to provide documentation of yaupon holly (*Ilex vomitoria*) across rangelands and forest sites in the Post Oak Savanna of Texas. These pictures highlight the growth habit of yaupon. Pictures are freely reproducible with correct attribution.

These pictures were taken at the Ecology and Natural Resources Teaching Area[††] (ENRTA) (Range Area) at Texas A&M University, College Station, TX on March 20, 2021 by the author, Harrison R. Coker. The site was formerly heavily overgrazed and was presented to the university in very poor health in 1946. For the past 25-35 years, most of the Range Area has been resting without grazing pressures. However, legacy disturbances still guide vegetation community to this day. Pictures included in this appendix come from sites across the Range Area with varying histories since given to the department.

The Range Area remains a valuable resource for research and aesthetic appreciation of Texas oak savannas. Those interested in visiting or with questions should contact Dianne Robinson, the current ENRTA Manager.

[††] The address of ENRTA is 1183 Fishtank Rd, College Station, TX 77845.

Figure A.1: Yaupon holly forms dense canopies at the edge of forested areas. Yaupon often appears forming vertical walls with its dense, irregular branching.

Figure A.2: Another example of yaupon holly forming dense walls against grassy areas. Pictured here, the grasses are mowed for aesthetic appeal. The expansion of yaupon into frequently mowed areas is most likely very fast.

Figure A.3: The evergreen leaves of a yaupon holly are in a simple, opposite arrangement with elongate foliage that has smooth margins and rounded teeth.

Figure A.4: The growth habit of yaupon showing long stems with foliage at top optimizing lighting conditions.

Figure A.5: In many forested areas the growth of yaupon can become very branching.

Figure A.6: Some areas exhibit a very high number of stems per area ground surface. This growth form of yaupon is usually light-limited by a superior canopy above it.

Figure A.7: A view of a lowland drainage area. Yaupon aggressively colonizes sloped areas and fills in nearly all available roome.

Figure A.8: A different view of the same lowland area presented in Figure A.5.

Figure A.9: Leaf litter from Post oak (Quercus stelata) is loaded to the subcanoy zone each fall. The evergreen canopies of yaupon holly protects this litter year round, and it accumulates in abundance.

Figure A.10: Oak leaf litter that accumulates in the subcanopy does not quickly decompose into soil organic matter (SOM). Nearly all of the litter is still being physically broken down into smaller elements. Exposing the mineral surface reveals surprisingly slow development of the O-horizon.