Potential for Enhancing Recharge to the Carrizo–Wilcox Aquifer through Restoration of Oak Savannahs

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Presented to Post Oak Savannah Groundwater District

Introduction

In this report we highlight significant findings from our field assessment of soil water dynamics in the Post Oak Savannah ecoregion. The field work was concentrated in Milam County, Texas**,** and partially funded by the Post Oak Savannah Groundwater District (POSGWD). Other support was provided by Texas A&M University through the Sid Kyle Professorship of Bradford Wilcox and support for the research fellowship of Shishir Basant.

Project Scope and Goals

The overarching goal of our proposed project is to determine the extent to which recharge can be increased through vegetation management—in particular, the conversion of *thicketized* oak woodlands to pastures or open savannahs.

From June 2020 to April 2021, we carried out a series of preliminary field studies in the Post Oak Savannah ecoregion. This ecoregion overlies the Simsboro and Calvert Bluff formations in Milam County, Texas; both these formations are parts of the Wilcox Group within the Carrizo–Wilcox aquifer, one of the most important aquifers in the State of Texas. Both formations consist of over 60% sands, are among the most porous members of the Carrizo–Wilcox recharge zone (Dutton, 1999), and are representative of a large portion of the recharge zone's substrate.

Our specific goal for this preliminary field work was to understand the influence of woody plants on deep drainage (water percolation beyond the root zone). For humid or mesic systems, it is common to assume that groundwater recharge rates are equal to deep-drainage rates, but in semiarid and arid systems these rates may differ—owing to a thick vadose zone, which can mean large time-lags as soil water moves from the root zone to the aquifer (Scanlon et al., 1997). Even though the overarching goal of the proposed project is to understand the influence of vegetation on groundwater recharge, *for this preliminary work we limited the scope of our investigations to deep drainage (water movement and storage within soils to a depth of 3 m from the surface)*. Because a large proportion of the water used by shrubs and trees is coming from the upper 2–3 m of soil (Canadell et al., 1996), water movement beyond these depths is less likely to be influenced by trees. At the same time, an understanding of deep-drainage dynamics can provide valuable insights into the effects of vegetation on groundwater recharge.

Background and Site Description

The study area lies in the Post Oak Savannah—a widespread ecoregion typified by mosaics of Post Oak (*Quercus stellata*) forest stands and grasslands. Over the last few decades, many portions of this ecoregion have become increasingly dense with woody plants, due mainly to the encroachment of *Ilex vomitoria* (yaupon holly), an evergreen shrub species endemic to eastern parts of the United States. The more open areas and pastures have seen encroachment by eastern red cedar (*Juniperus virginiana*). The forest overstory is dominated by *Quercus stellata* and *Juniperus virginiana,* and the understory by *I. vomitoria.* Other understory woody and forb species include *Smilax bona-nox*, *Vtis mustangensis, Callicarpa americana, Ambrosia trifida, Cnidiscolus texanus, Helianthus annus, and Ilex decidua.* Species common in the grazed pastures include *Hordeum pusillum*, *Bouteloua rigidiseta*, *Croton lindeheimeri, Croton capitatus* and *Agalanis heterophylla.*

The preliminary field work was conducted on two adjacent ranches: the Keen Ranch and the Frock Ranch, located in Milam County, Texas (30° 47' 05'' N, 96° 53' 56" W, 159 m elevation). These properties, which both overlie the Carrizo–Wilcox aquifer recharge zone, were selected in collaboration and consultation with staff of the POSGWD. (The property described in our proposal to the POSGWD became unavailable soon after initiation of the project.)

The average annual temperature in this region is 15°C, with maximum temperatures of about 40°C during July and August. The average annual precipitation is 932 mm (http://www.ncdc.noaa.gov/cdo-web/datasets/). The dominant soil types in the study site include Edge series (fine, montmorillonitic, thermic Udic Paleustalfs), Padina series (loamy, siliceous, active, thermic Grossarenic Paleustalfs), and some areas of Rader series (fine-loamy, mixed, semiactive, thermic Aquic Paleustalfs)

Methods

Soil moisture measurements

Soil moisture was measured by means of neutron moisture meters (NMM) CPN 503 DR Hydroprobe (Instrotek Inc). These meters measure soil moisture (volumetric water content) indirectly, via neutron thermalization (Evett, 2003), which to date is considered the most robust way of measuring water content in soil (Oschner et al., 2013). Neutron probes are inserted into access tubes installed in the ground and measurements are made at various depths, each providing a neutron count ratio that varies linearly with the volumetric water content (VWC) of the probe's measurement footprint (radius of approximately 15 cm) at that depth.

Beginning in July 2020, we monitored soil moisture at the Keen Ranch and the Frock Ranch. We installed 24 access tubes to depths ranging from 140 to 270 cm in four different areas spread across the two properties (Figures 1 and 2). These areas were selected to enable us to make comparisons between pasture and thicketized woodland conditions as well as between open savannahs and woodlands. Four access tubes were installed in a pasture with no nearby woodlands (Pasture site (Independent)); seven tubes in a yaupon–oak woodland (Woodland Site-1); five in a pasture adjacent to Woodland Site-1 (Pasture Site-1); five in a pasture heavily encroached by eastern red cedar *(J. virginiana)* (Woodland Site-2); and three across a boundary of another woodland (two in Woodland Site-4, one in Pasture Site-4).

Readings were taken about every two weeks or, in the absence of any large rain events, at least once a month. We ensured that measurements were taken soon after every larger rainfall event. Neutron count ratios were recorded starting at a depth of 20 cm, and then every 20 cm to the final depth (140 cm or 270cm). Most of the access tubes were installed to the depth of 140 cm, and each of the sites contained at least one to the depth of 270 cm.

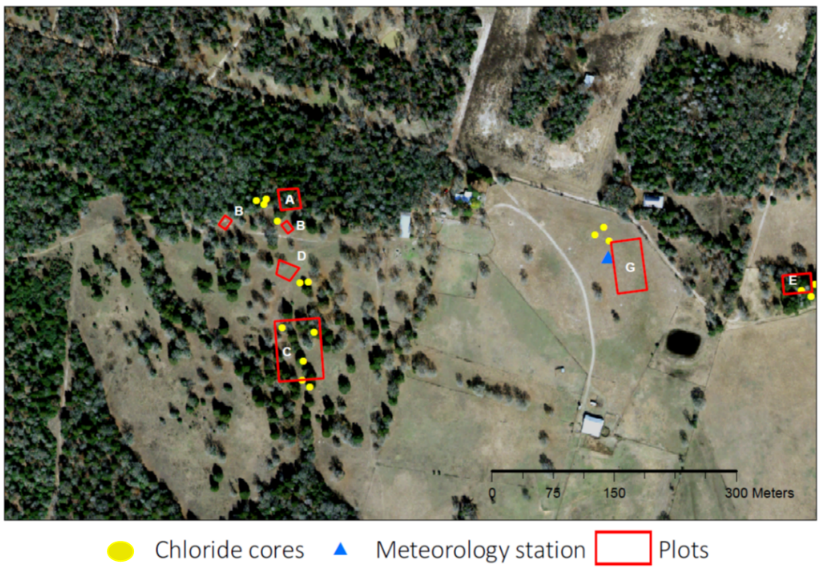

Figure 1. Locations of soil moisture monitoring and chloride sampling. Sites A-G; A – Woodland Site-1, B – Pasture Site-1, C – Woodland Site-2, D – Pasture Site-2, E – Woodland Site-4, F – Pasture Site-4, G – Pasture Site (Independent)

Because some of the access tube installations, including the ones at the Frock Ranch (Woodland Site-4, Pasture Site-4), were completed only in December 2020, there is not yet sufficient data to report from these sites. Additionally, during heavy rainstorms some of the access tubes filled with water, making it impossible to obtain measurements from all the access tubes on some occasions. The graphs in the main body of this report are based on soil water data selected to illustrate general patterns, but all the data from all the sites are provided in an Appendix 1 should the POSGWD want to do additional analyses.

The neutron count ratios were converted to VWC via a linear calibration equation that was developed for the same probes used for these field measurements (and used in previous work—see Basant et al., 2020). The VWC estimates are also used for calculating total water storage along the soil column—which is obtained by integrating soil moisture curve along the depth of soil or by summing up the product of VWC estimates with their respective weighted depths.

It should be noted that the calibrations applied here—even though very robust (R^2 - >75% and residuals <5%)—are a better fit for soils in drier climates, indicating that our soil moisture data most likely underestimate the wet conditions. For this reason, the patterns and differences are more important than the absolute numbers. To clarify further, we include the neutron count ratios in Appendix 1 (Neutron probe data). For more accurate soil moisture estimates, new field calibrations should be developed specific to the sites being monitored.

Chloride measurements and mass balance calculations

During the period September–November 2020, thirty soil cores were collected for measuring gravimetric water content, chloride concentrations, and other soil parameters. The cores, cut to a depth of 270 cm, were taken from locations across the two properties (yellow points in Figure 1), distributed to represent the different vegetation covers and landforms (Figure 2). Most of these locations overlap with the access tube locations. At least four soil cores were taken from each location. Of these, three were sampled at depths separated by about 20–30 cm and the samples were then analyzed for gravimetric water content and chloride concentrations (Appendix 2: Worksheet "All cores-Pore conc, Recharge"). One core from each location was used for determining soil texture (percentages of sand, silt, and clay), depth of rooting, and depth to the boundary of the argillic horizon. Bulk density estimates were derived from the specific soil series data available on the National Soil Survey Center database.

To measure gravimetric water content, a subsample of soils from every measurement depth was oven-dried for 24 h at 105°C. The remaining samples from each depth were dried, bagged and shipped to the Soil Testing lab at Oklahoma State University, Stillwater.

Chloride concentrations were measured at the Soil Characterization Laboratory at Oklahoma State University, by means of the Flow Injection Analyzer Method (QuickChem 8500, Lachat Instruments, Loveland, CO, USA). Samples were prepared for the injection system by first being ground, then 10-g subsamples of soil were mixed with 0.01 M (Calcium Phosphate) $Ca_3(PO_4)_2$ and shaken at 200 rpm for 30 minutes. This soil solution was then filtered and treated with mercury thiocyanate, which frees the soil-bound chloride and forms mercuric chloride, thereby liberating thiocyanate ions in the solution. The thiocyanate binds with ferric radicals to form the orange ferric thiocyanate complex, which is proportional to the chloride concentration in the solution. The chloride concentrations obtained are in parts per million (ppm) or mg/Kg. To derive the concentrations in pore water *(Cl_w)* (mg/L), the ppm concentration is divided by the gravimetric water content for the respective depth (Kim and Jackson, 2012). This commonly employed standard methodology has been shown to have a precision of 90%–95%.

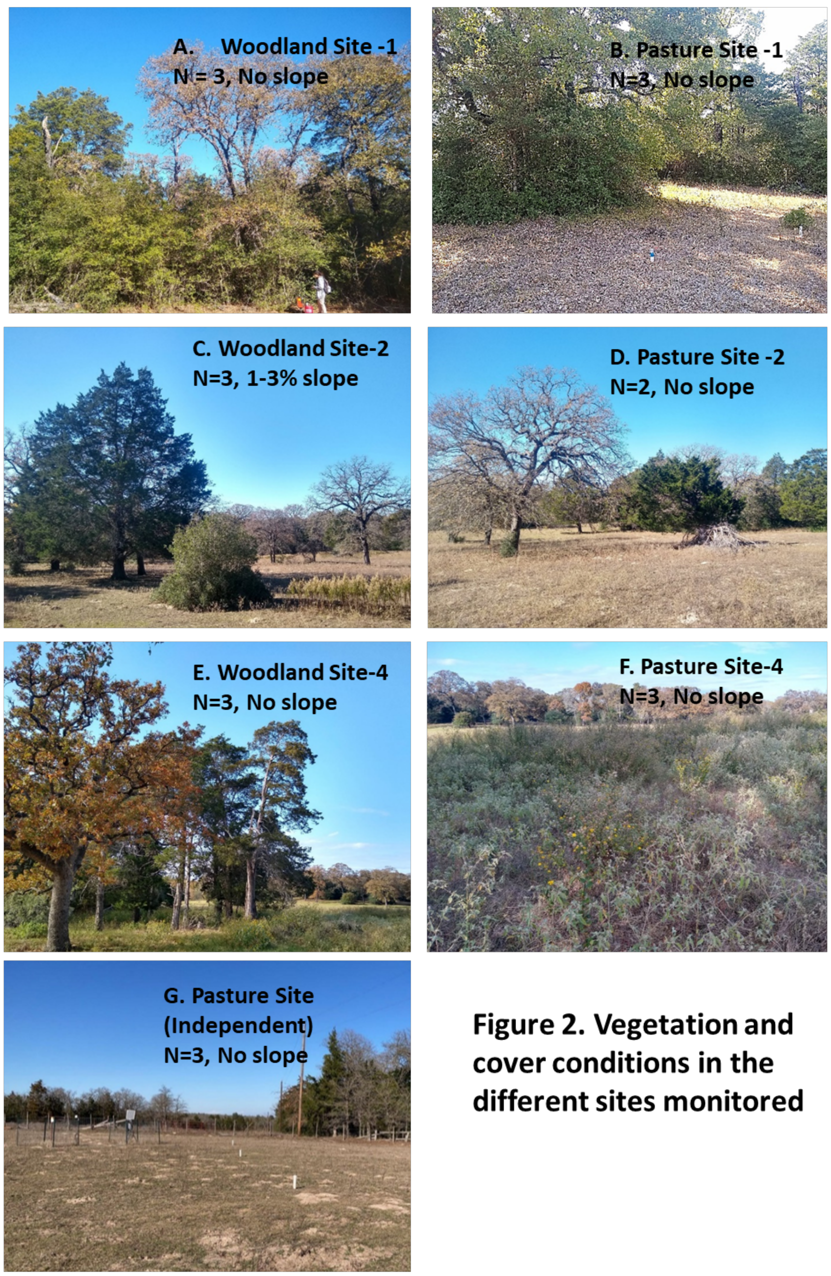

Figure 2. Vegetation and cover conditions in the different sites monitored

For the annual chloride deposition rates (Cl_p), we used the same estimates (0.98 mg/L) as Reedy et al. (2009) for the same aquifer and region. We used a mean annual precipitation of 944.88 mm/yr, based on precipitation data from the weather station at Little River near Cameron, Texas (https://www.texmesonet.org/).

Chloride mass balance (CMB) equation:

$$D \times Cl_w = P \times Cl_p \quad , \qquad \text{(Equation 1)}$$

where D = deep drainage, Cl_w = pore water chloride concentration at the specific depth, P = average annual precipitation, and Cl_p = annual chloride deposition rate (atmospheric dry and wet combined).

This equation uses Cl_w values from below the root zone to estimate recharge rates at specific depths. Root zone depths (determined on the basis of field and lab observations of soil cores) seemed to be primarily within 60–80 cm below the surface in herbaceous and pasture areas, and up to 100–150 cm cm in wooded areas. Note that these depths may vary and should be verified with detailed laboratory measurements of root presence and biomass estimations, which are beyond the scope of the current project.

Micrometeorological measurements

Precipitation was measured by means of a tipping bucket setup (Texas Electronics Rain Gauge, 0.2-mm resolution) and ambient temperature and relative humidity were measured with a plug-in probe (HMP155A, Vaisala, Helsinki, Finland). All the instruments were connected to a datalogger (CR-6, Campbell Scientific Inc., UT, US) that recorded data every 10 minutes (Figure 3).

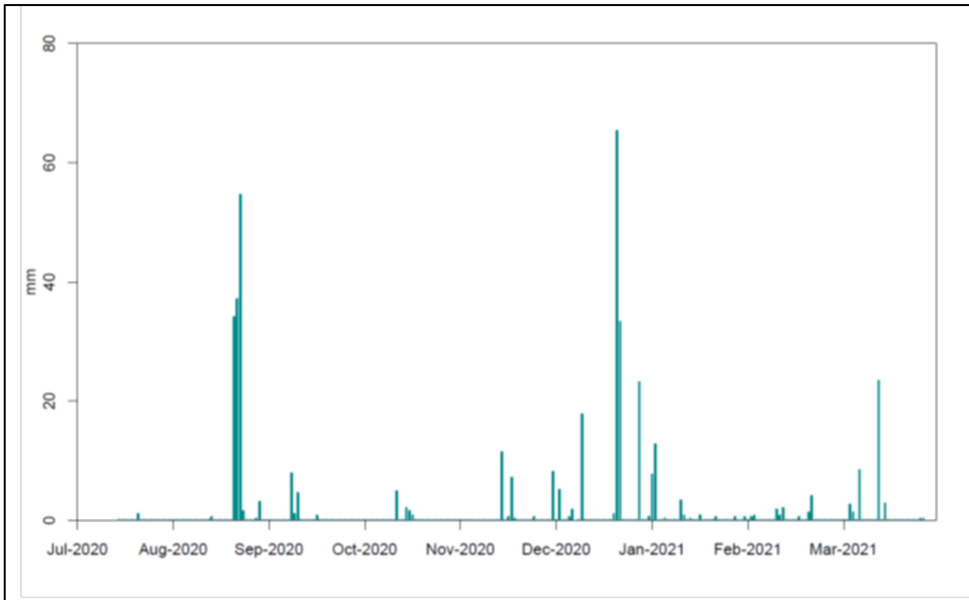

Figure 3. Daily rainfall recorded at the Keen Ranch from July 2020 to April 2021

Results

Soil chloride and texture

Chloride concentrations in pore water ranged from 0.05 mg/L to 3050 mg/L. Of the 256 soil samples analyzed, 90 had concentrations under 10mg/L, and only 28 samples exceeded 500 mg/L. The chloride concentration profiles showed obvious differences between the woodland and the pasture sites (Figure 4), the wooded areas having higher concentrations below 140 cm. Almost all the higher Cl_w were in deeper soils (>200 cm) in wooded areas. In contrast, pasture sites showed extremely low Cl_w in general—even at depths of 200 cm or more.

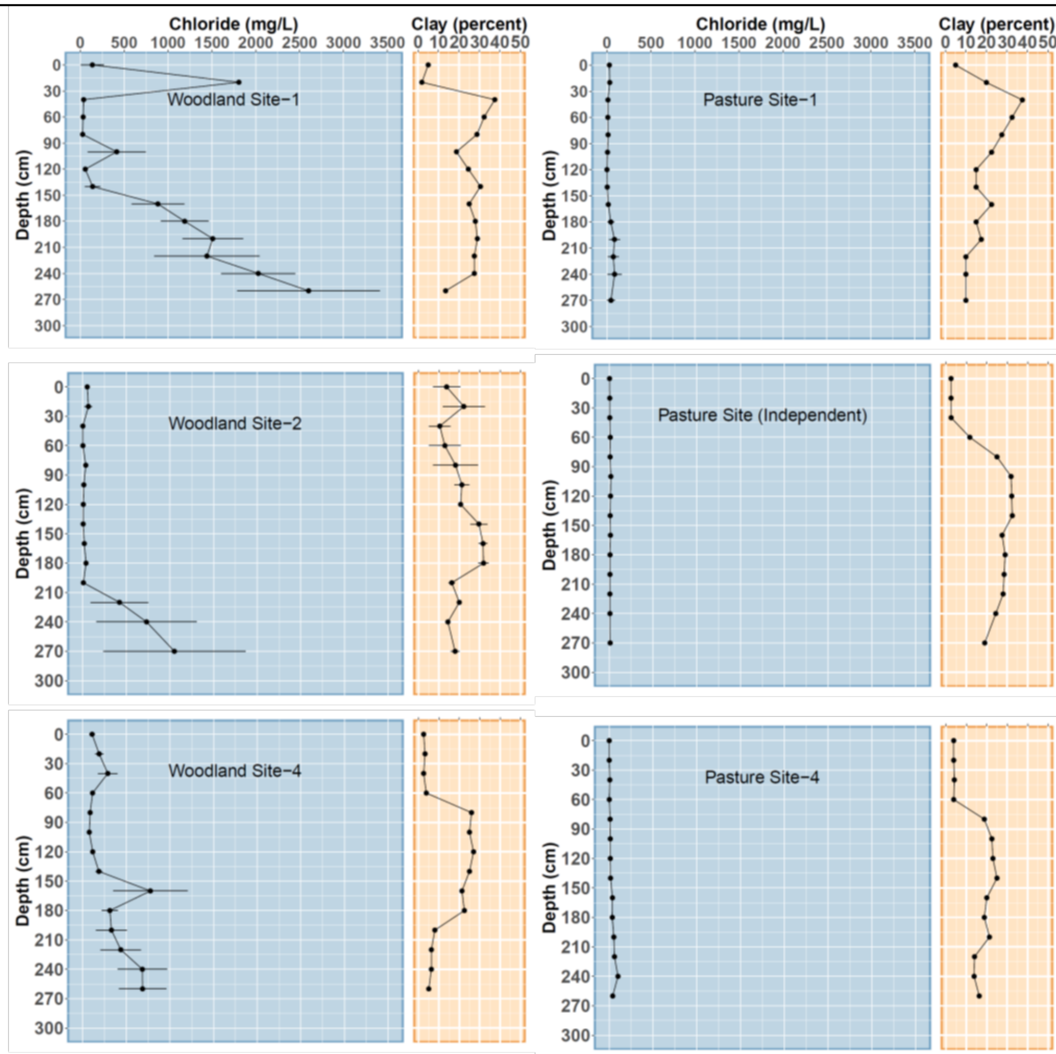

Figure 4. Chloride concentration profiles (pore water) for the different sites and their corresponding clay percentages with depth. Horizontal bars indicate the standard errors, which are in general lower for lower chloride concentrations (points without a horizontal bar were either an average of two data points or the SD is too small at this scale). Complete data and a summary are provided in Appendix 2.

Soil textures in the higher layers (30–40 cm depth) were mostly sandy to sandy loams. Below this depth, textures transitioned to sandy clays or sandy clay loams (Figure 4). Woodland Site-4 and Pasture Site-4, both in a different area from the other sites, had sandy soils to a depth of about 80 cm, below which there was an abrupt transition to sandy clay loams. Woodland Site-2, which also has more slope than the other sites, exhibited some variability in textures with some locations showing higher clay content even at depths of 20–30 cm.

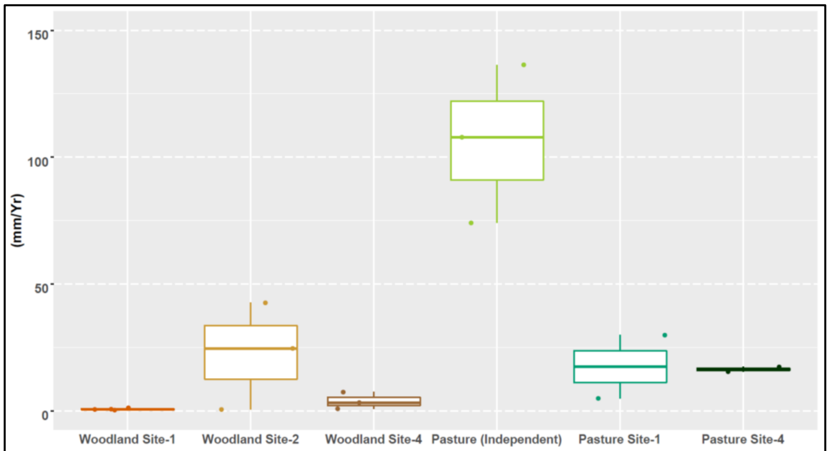

Figure 5. Deep drainage flux rates derived from Chloride Mass Balance (CMB)

Recharge rates

We use the term *recharge* to refer to water that is moving beyond the sampling depth—a usage consistent with that of other researchers conducting chloride studies. Our results showed that while there was considerable variability in the measurements, long-term recharge was in general much higher in the open areas than in the wooded ones (Figure 5). As shown in Table 1, the highest recharge was in a pasture site (>100 mm/yr), and the lowest was in a woodland site 1 (< 5 mm/yr).

Table 1: Recharge rates for the monitoring sites, based on chloride concentrations in core samples from different depths (in mm/yr, the standard reporting unit for chloride studies). Complete data on chloride concentrations can be found in the Appendix-1. Some cores are missing because of sampling malfunctions.

Site	Depths	120 cm	150 cm	200 cm	220 cm
Pasture (Independent)	Core-1	97.99	96.91	83.24	74.08
Pasture (Independent)	Core-2	88.33	92.99	105.56	107.84
Pasture (Independent)	Core-3	124.59	139.57	131.67	136.39
Woodland Site-1	Core-4	6.08	1.01	0.54	0.52
Woodland Site-1	Core-5	4.29	0.83	0.66	0.61
Woodland Site-1	Core-6	24.28	1.76	1.39	1.18
Woodland Site-1	Core-24	6.69	1.91	0.37	NA
Woodland Site-1	Core-23	19.91	7.94	0.49	0.26
Pasture Site-1	Core-22	438.21*	NA	16.42	29.83
Pasture Site-1	Core-21	NA	47.07	4.58	4.89
Pasture Site-1	Core-7	NA	408.05*	310.41*	257.69*
Woodland Site-2	Core-10	20.85	6.64	0.56	0.50
Woodland Site-2	Core-11	96.00	85.21	62.47	42.57
Woodland Site-2	Core-13	72.00	60.88	40.18	24.57
Woodland Site-4	Core-18	3.98	3.44	4.42	3.23
Woodland Site-4	Core-19	9.08	7.95	7.49	7.36
Woodland Site-4	Core-20	2.22	1.32	0.90	0.79
Pasture Site-4	Core-15	30.78	25.45	17.05	17.29
Pasture Site-4	Core-16	30.99	17.28	16.32	15.41

Soil moisture measurements

During the period July 2020–Feb 2021, the area encompassing the study sites received a total of 359 mm of precipitation. The biggest rain events occurred in early September, mid-December, and early January (Figure 3).

The wettest conditions were observed for the winter months (December–February) and for the month of September. The general trend in soil moisture reflected the trends in precipitation for all the sites. Total water in 250 cm of soil column varied from 300 mm to 700 mm approximately (Figure 6). The independent pasture site and pasture site-1 usually remained the wettest of all sites. The water content in the wettest states at both these sites could not be measured and estimated because of water logging at the end of those access tubes. Woodland

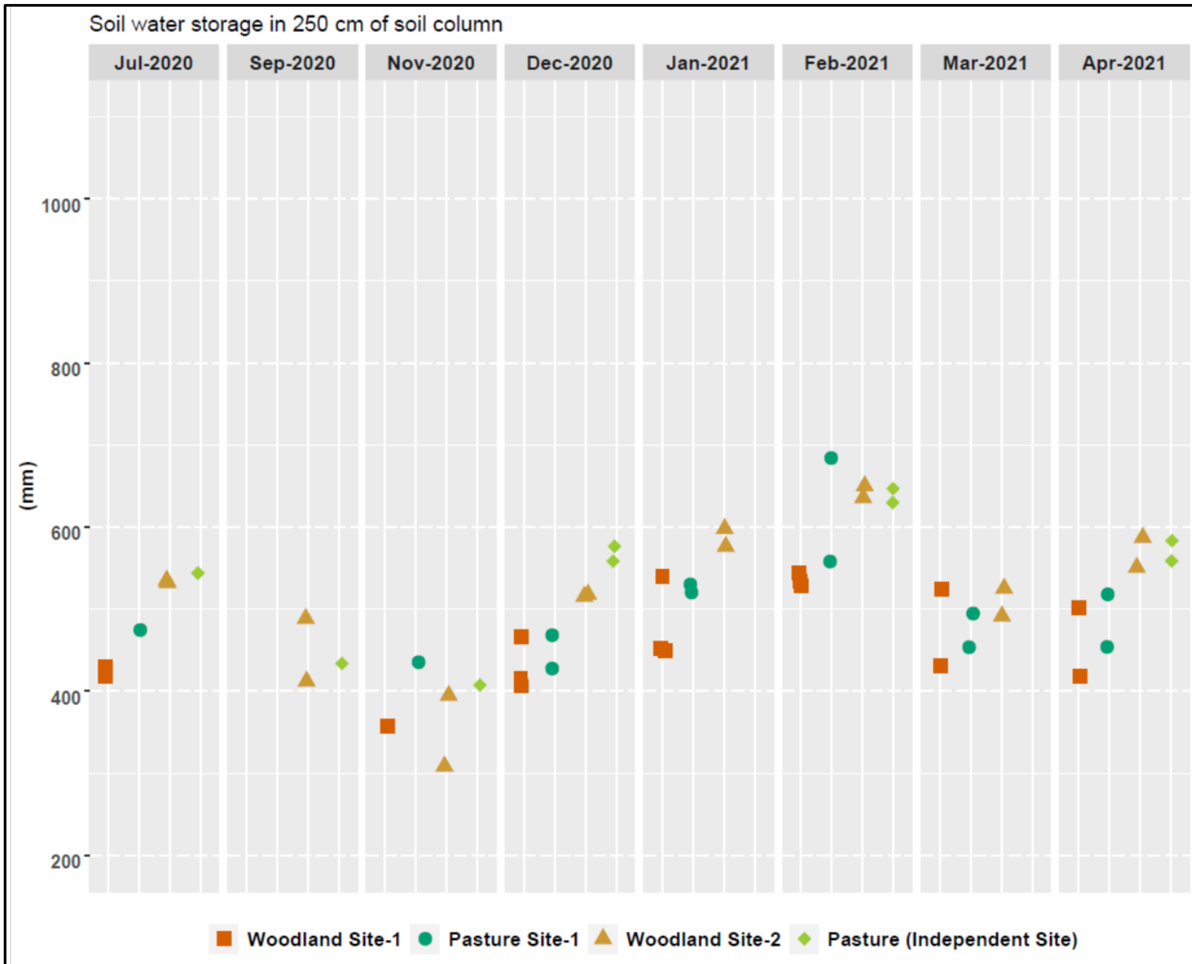

Figure 6. Total soil water in 250 cm soil column. Different symbols indicated different plots. Each point represents one location. Missing data points indicate lack of data from that month.

For this figure, the total soil water (250 cm) could not be calculated for Woodland Site-1 and Pasture Site-1 on Sep 10th-2020. These access tubes were flooded at the bottom. However, data for 150 cm of column is available for most points. Refer to Appendix 1-Neutron probe data; worksheet "Water storage_depth" for more details.

sites (Site-1 and Site-2) had the driest locations and showed significant variability which reduced during the winter months. Soil moisture profiles (volumetric water content in Figure 7) also indicated similar patterns – with the woodland site-1 being drier than the adjacent pasture (Pasture site-1) – which was especially true for the upper 60-90 cm of soil column. The depth-wise volumetric water content values varied from less than 0.1 cm^3/ cm^3 (very dry) to a little over 0.3 cm^3/ cm^3 . The highest values were most likely underestimated due to limitations on calibration – but were also only noted in the pasture sites and not in the woodland sites. This is indicative of field capacity or saturation – a phenomenon also indicated by the frequently flooded access tubes in both the pasture locations.

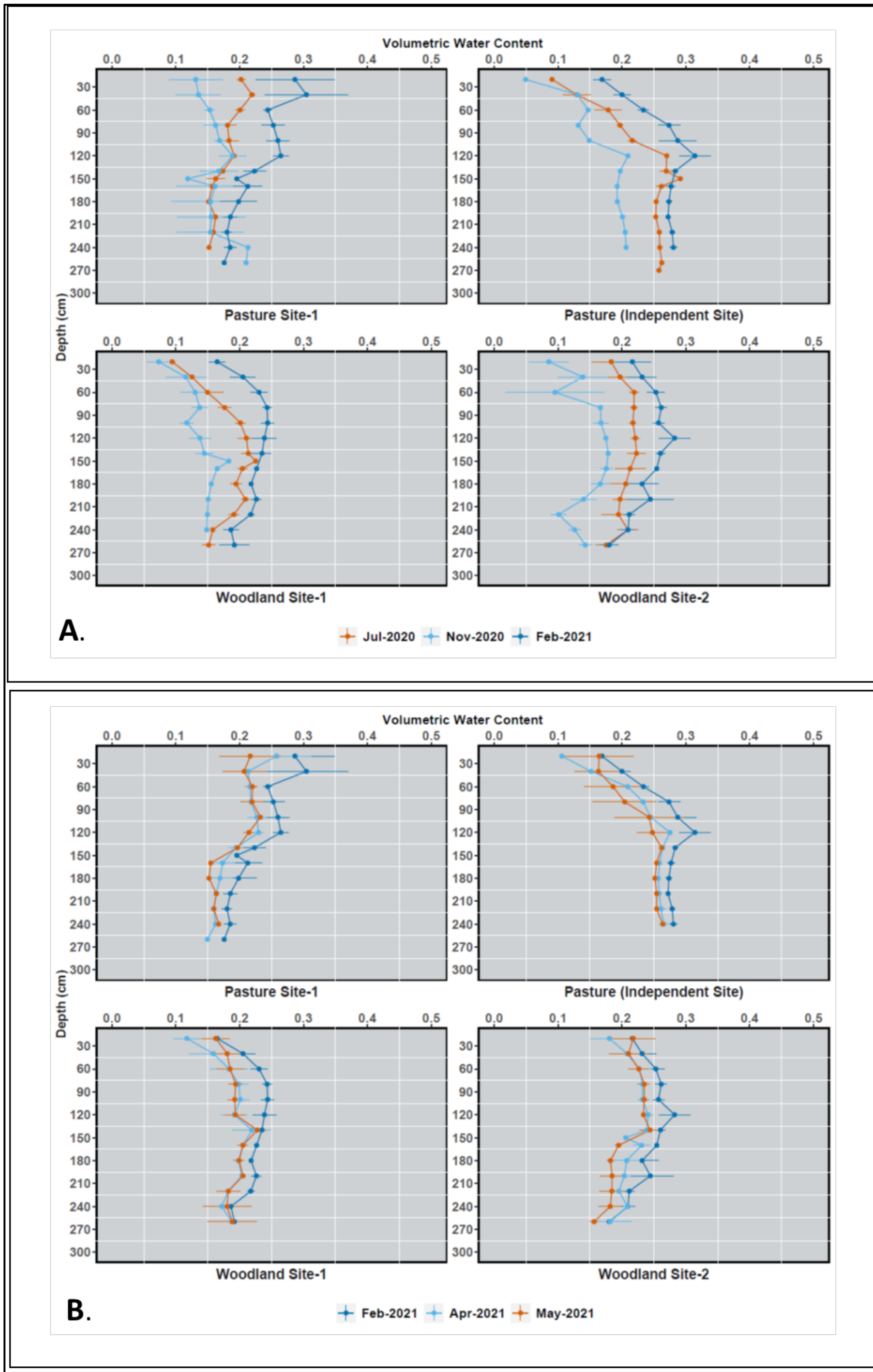

Figure 7. Change in soil moisture profiles during the course of the study; A. Summer to Winter , B. Winter to Spring
Horizontal lines indicate standard error.
Data from Woodland Site-4, Pasture Site-4 has not been presented here because of insufficient data points from those plots. Data from Pasture Site-2 is not included because the plot seemed to have some significant runoff confounding our infiltration/deep drainage interpretations. However, raw data including neutron count ratios for all the plots are provided in Appendix 1 (Neutron probe data)

Discussion

Our results strongly suggest that thicketization of post oak savannas Influences soil water dynamics and deep drainage fluxes. We found that in wooded areas chloride accumulation rates were significantly higher than in the pasture areas, with differences on the order of 100 to 1000 times. This difference is reflected in the deep drainage fluxes—the pasture sites showing rates higher than those of their adjacent woodland sites, by 5 to 50 times. In addition, the woodland sites frequently showed higher variability in chloride accumulation deep in the profile, probably owing to the more heterogeneous vegetation cover (both in species and canopy cover), which would mean heterogeneity also in root density, biomass, and water uptake.

The different woodland sites also differed from each other in their chloride concentrations and depths of accumulation. These differences can be explained by differences in soil texture. For instance, the site-1 had higher clay content (sandy clay to sandy clay loams as early as 30 cm) than the other sites, where textures in the upper horizons varied from fine sands to sandy loams (Figure 4). However, soil textures do not explain the differences seen in chloride concentrations between woodland sites and the pasture sites adjacent to them (Woodland Site-1 vs Pasture Site-1, Woodland Site-4 vs Pasture Site-4).

The concentrations and patterns of the chloride profiles we found are comparable with those found by previous studies in the region using CMB. The low chloride concentrations observed to depths of 260 cm in the pasture sites are most likely due to faster water movement along these profiles, flushing out the chloride. Similar profiles with “flushed out” chloride have been observed in other regions following conversion of natural ecosystems to croplands or on irrigated fields (Scanlon et al., 1997, Acharya et al., 2017). Our Independent Pasture site has such a history as well, the area having been cleared of vegetation and converted to pasture some 50 years ago (per conversation with the landowners). This site exhibited the highest deep drainage rates of all the sites (mean = 106 mm/yr at 220 cm). Pasture Site-4 was an exception in this regard, having deep drainage rates significantly lower than those of the other pasture sites—most likely due to its greater herbaceous cover and ungrazed conditions, which would mean higher transpiration and greater rooting densities.

The effects of transpiration on deep drainage were obvious in the woodlands, in particular the yaupon-oak woodland (Woodland Site-1), which had the highest chloride accumulation (Figure 4). While the higher chloride may be attributable to higher clay content at this site, we suspect that the evergreen nature and greater density of yaupon stands could be a factor too. In addition, field observations during sampling suggested much drier soils under these stands—as was also revealed by the soil moisture profiles (Figure 7 A, July–November 2020, shows greater depletion of moisture in the wooded areas than in the adjacent pastures).

Chloride concentrations in Woodland Site-4 (juniper-oak) and in Woodland Site-2 (juniper) – were much lower than in Woodland Site-1 (yaupon–oak), which may be explained by lesser water uptake from shallow soils or faster drainage in the upper horizons owing to the finer textured soils. Occasional drainage throughout the profile (following large storms or a sustained period of wetness and low evapotranspiration) may be a common feature for all the sites. The soil moisture profiles (Figure 7) for the period November 2020–February 2021, during which rainfall was frequent and there were two snowstorms, shows a "recovery" in moisture at all the sites, all the way to 260 cm.

Higher soil moisture in the pasture sites also explains the extremely rapid deep drainage rates from some of these sites. Soil moisture measurements in all three pastures indicated VWCs of 25%–30% during the wettest periods. Given that these are already underestimates (due to calibration limitations) and that the access tubes in pastures were often inundated (indicative of saturation pressure), these horizons must be getting saturated often—leading to rapid downward movement of water. In contrast, for the wooded areas we never found any evidence of saturation (no flooding of access tubes), and the VWCs in the upper soil horizons were also much lower (less than 0.15).

Overall, our findings provide compelling evidence for (a) higher deep drainage rates in the pastures compared with their adjacent woodlands, and (b) the importance of transpiration and seasonality in regulating downward fluxes. As noted earlier, there is generally expected to be a large time-lag between deep drainage and aquifer recharge. However, deep drainage fluxes are a strong—if not a certain—indicator of the effect of land cover on recharge rates. For estimation of recharge rates, chloride profiles (which extend deeper into these soils and closer to the underlying formations) will be crucial. The soil moisture and total soil water data are essential to our understanding of the processes responsible for the differences in chloride concentrations and deep drainage fluxes. Further, they indicate that larger rain events and long wetting periods with suppressed evaporative demand may significantly alter deep drainage dynamics.

Conclusions and Future Work

The data presented here are preliminary but do strongly suggest that recharge rates are higher in open areas than in closed-canopy woodlands. The chloride mass balance evaluation indicated that recharge can be 20 to 50 times higher in open pastures than in closed woodlands. The soil water measurements, which have been ongoing for almost a year, indicate that soils in the pastures are in general wetter than in the woodlands. These data will be strengthened with longer-term measurements, deeper soil cores, and more monitoring sites. In addition, the soil moisture measurements should be complemented with measurements of continuous soil measurements and actual evapotranspiration fluxes.

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