Draft Report: Potential for Enhancing Recharge in the Carrizo Wilcox Aquifer by 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.

Oak savannahs are an important vegetation type in the Southern Great Plains (SGP) of the United States and are the characteristic vegetation type in both the Cross Timbers and Post Oak Savannah ecoregions (Figure 1). Together these two ecoregions extend from southern Texas into Kansas and make up some 120,000 km^2 (Griffith et al. 2007, Ansley et al. 2017). Over the past 150 years, these landscapes have been radically transformed by 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 savannahs, and dense woodlands. Fires are much less frequent and when they do occur can be catastrophic. This altered fire regime has allowed undesirable plants, such as eastern red cedar and yaupon, to invade the understory, creating dense thickets of vegetation—a process described by some as *woody plant encroachment* (WPE) or *thicketization* (Hoagland et al. 1999, Archer et al. 2017, Peinetti et al. 2019).

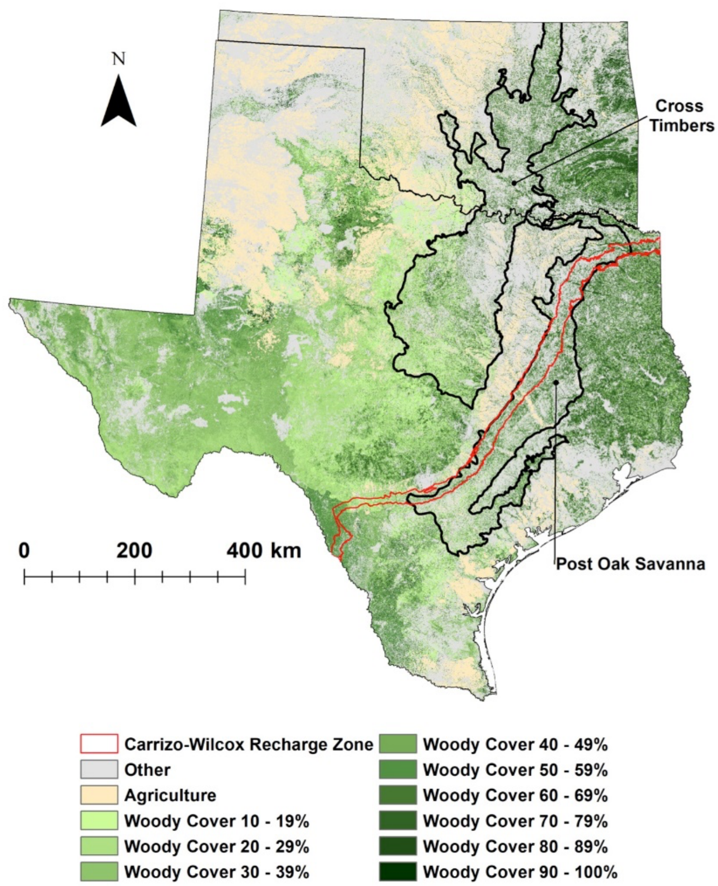

Figure 1. Extent of woody cover over the Southern Great Plains states of Texas and Oklahoma. The Cross Timbers and Post Oak Savanna ecoregions historically were predominantly oak savannas. The Carrizo-Wilcox recharge area, consisting of deep and permeable sands, overlaps with much of the Post Oak Savanna.

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). These changes in turn 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 its obvious importance, however, *very little is known about how thicketization of oak savannahs influences ecohydrological processes*—and in particular, changes to groundwater recharge.

In parts of Post Oak savannahs in Texas, deep sediments with water-bearing sands are common (Dutton 1999) and make ideal conduits for groundwater recharge. It stands to reason that an increase in woody vegetation over such sediments would reduce the amount of water available for recharging aquifers. But whether the restoration of thicketized oak savannahs would in fact increase groundwater recharge has been little studied.

The Post Oak Savannah ecoregion in eastern Texas, which covers some 50,000 km^2 and was historically mostly an oak savannah, has been highly altered since the arrival of European settlers around 1850 (Griffith et al. 2007). Much of the area was plowed up and planted with cotton, then subsequently abandoned and/or converted into improved pastureland (Garza and Blackburn 1985). In the absence of fire, the abandoned lands have converted to a thicketized oak woodland with a dense understory of woody vegetation, as shown in Figure 2 (there are relatively few remnants of open oak savannahs that still have an understory of native grasses).

Figure 2. The remaining woodlands in the Post Oak Savanna are dense thickets of oak, yaupon, and juniper. Relatively few tracts of true oak savanna remain. A. A small patch of oak savanna in an abandoned cemetery. B. Eastern red cedar understory with an overstory of oak. C. Pastureland adjacent to a thicketized woodland.

The woody vegetation is dominated by post oak (*Quercus stellata*), blackjack oak (*Quercus marilandica*), and eastern red cedar (*Juniperus virginiana*). Yaupon (*Ilex vomitoria*) is a common understory plant. Prairie openings contain little bluestem (*Schizachyrium scoparium*). Average rainfall increases from west to east and ranges from around 700 to 1200 mm/year.

Project Scope and Goals

The overarching goal of our proposed project is to develop a better understanding of the ecohydrological implications of thicketization in oak savannahs (Figure 2). ***We are***

particularly interested in determining the extent to which groundwater recharge could be enhanced via reduction of thicketization and the creation of a more open structure.

For the first phase of this study, i.e., from June 2020 to April 2021, we conducted our field studies on the Post Oak Savannah ecoregion of Texas overlying the Simsboro and Calvert-bluff formation in Milano, Texas. Both these formations are parts of the Wilcox group within the Carrizo-Wilcox aquifer which is the third most important aquifer in the State of Texas. The Simsboro and the Calvert Bluff formations are both characterized by more than 60% sands and are one of the most porous members of the Carrizo–Wilcox recharge zone (Dutton, 1999)—and is representative of a large portion of the area underlain by this formation (personal communication, Post Oak Savannah Conservation District). In addition to supplying about 25% of the baseflow to streams in the region it is also a critical supply of water for irrigation and municipal use (Davidson et al. 2009, Huang et al. 2012). The aquifer extends from the Texas–Louisiana border to Mexico, underlies 66 counties, and has a subsurface area of 65,000 km^2. It is recharged through the predominantly sandy sediments of the Carrizo–Wilcox recharge zone, and much of the 29,000-km^2 outcrop area of this zone intersects the Post Oak Savannah ecoregion (Figure 1). Annual recharge increases from south to north and varies from a few millimeters in the south to over 100 mm in the wetter northern portions of the recharge zone (Reedy et al. 2009, Moore et al. 2012).

As a result of over-pumping, the level of the aquifer has declined by as much as 150 m in the last several decades (George et al. 2011). Pressure on the aquifer is expected to increase almost tenfold in the next 40 years. The growing demand for water is heightening tensions between agricultural users and water marketers who are eager to export water from the Carrizo–Wilcox to surrounding urban areas.

We believe that this ecoregion holds promise for increasing groundwater recharge at a regional scale because about one-third of its area is underlain by formations which are characterized by high proportion of sand and are known to have high hydraulic pressure as exhibited in lignite extraction pits (Dutton, 1999).

Specifically, our goal for this phase of the study was to understand the influence of woody plants on soil-water dynamics. Thus, we focused on investigating the soil water storage and movement (recharge) within 3 m of soil from the surface. We defined this as the scope for our study because this covers the root zone (largely expected to be within 2 m) and part of the unsaturated zone where we expect little to no influence of transpiration.

Out finding from this study can also be applied to other landscapes like the Cross Timbers ecoregion, where the vegetation and soils are very similar to those of the Post Oak Savannah (Hoagland et al. 1999, Griffith et al. 2007).

Project Rationale

The effects of WPE on water fluxes are entirely context-specific and depend on the precipitation regime, geology and soils, and proximity to groundwater (Huxman et al. 2005, Wilcox et al. 2006). For thicketized oak savannahs overlying deep sands, we believe that restoration to a more open structure has great potential for substantially increasing groundwater recharge. Our reasoning was based mainly on three factors: (1) Rainfall exceeds potential evapotranspiration for several months of the year; (2) the deep sands allow water to move beyond rooting depths, which is particularly consequential in recharge zones; and (3) conversion from a thicketized woodland to an open savannah will lessen the biomass of deep roots accessing vadose zone water (Figure 3). Further, the extensive overlap between the Carrizo–Wilcox recharge zone and the Post Oak Savannah ecoregion implies that restoration over a large area could substantially increase recharge at a regional scale. Obviously, since carrying out such a wide-ranging restoration effort would require regional planning and policy tools, a first step must be a detailed scientific evaluation of the potential for increasing recharge at a regional scale. Our proposed study would lay the groundwork for assessing that potential.

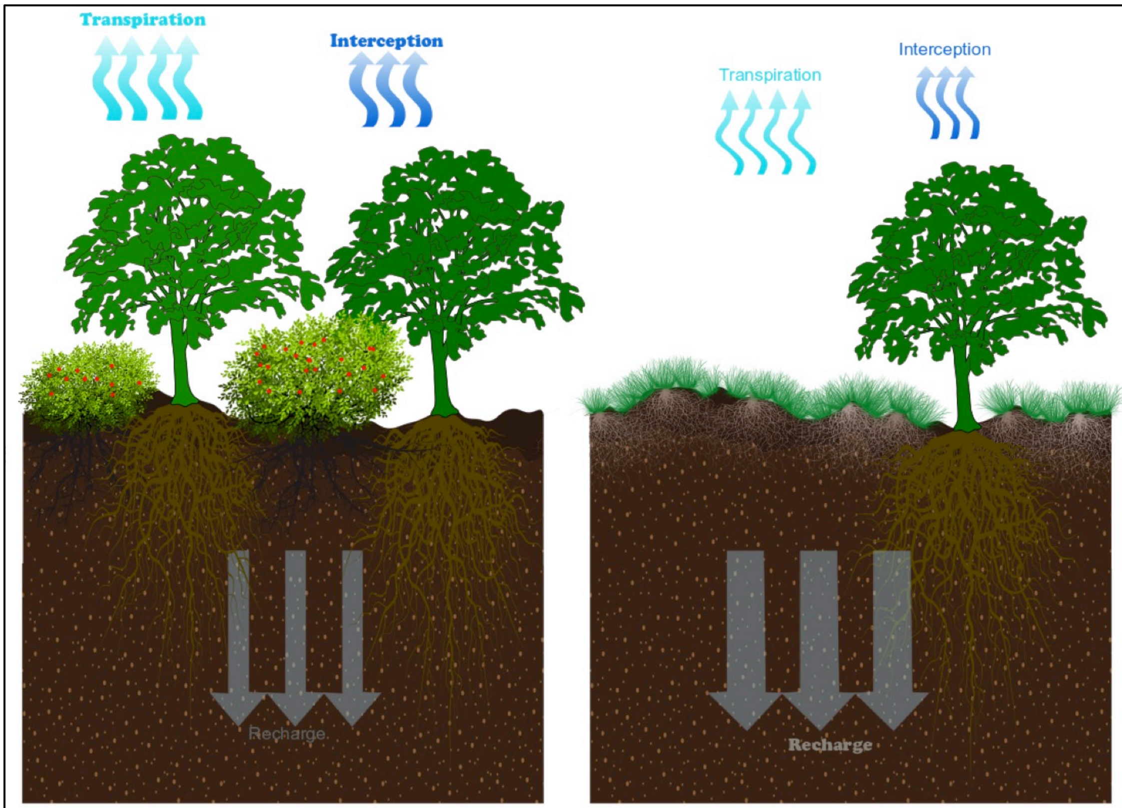

Figure 3. Conceptualization of water fluxes in a thicketized post oak woodland compared with those of a relatively open post oak savanna. Because of higher biomass and more deep roots, interception and transpiration will be greater in the thicketized woodland than in the savanna. As a result, groundwater recharge should be appreciably greater in the savanna than in the woodland.

Background and Site Description

The study was conducted on two ranches – The Keen Ranch and The Frock Ranch, located close to Milano, Milam County, Texas (30° 47’ 05’’ N, 96° 53’ 56” W, 159 m elevation). Both these properties are located adjacent to each other in an area overlying the Carrizo-Wilcox aquifer recharge zone. The average annual temperature is 15° C (maximum temperatures of about 40 °C during July and August) and 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 fine sandy loam and Padina fine sand series with some areas of Rader loamy fine sand series. The Edge series soils are fine, montmorillonitic, thermic Udic Paleustalfs; Padina series soils are loamy, siliceous, active, thermic Grossarenic Paleustalfs; Rader series soils are fine-loamy, mixed, semiactive, thermic Aquic Paleustalfs. (web soil survey).

The study area lies in the Post-Oak Savannahs – a widespread ecosystem typified with mosaics of Post-Oak forest stands and grasslands. Over the last few decades, many portions of these landscapes have become increasingly dense with woody plants – mainly due to the encroachment of *Ilex vomitoria (*Yaupon holly), an evergreen shrub specie endemic to eastern parts of United States. The more open areas and pastures have seen encroachment in large numbers by *Juniperus virginiana*. Thus, the overstory in the forests are dominated by *Quercus stellata* and *Juniperus virginiana* and the understories are dominated 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 which are common in the grazed pastures include *Hordeum pusillum*, *Bouteloua rigidiseta*, *Croton lindeheimeri, Croton capitatus* and *Agalanis heterophylla.*

Methods.

Soil moisture measurements

From July 2020, soil moisture was monitored with a neutron moisture meter CPN 503 DR Hydroprobe (Instrotek Inc). 24 access tubes up to the depths of 140 to 270 cm were installed in four different areas spread across the two properties (Figures 4 and 5). Four access tubes were installed in a pasture with no surrounding woodlands (identified as Pasture (Independent site), 7 were installed in a Yaupon-Oak woodland (Woodland Site-1), 5 in a pasture adjacent to it (Pasture Site-1), 5 were installed in a pasture heavily encroached by Eastern Red Cedars *(J. virginiana)* (Woodland Site-2) and 3 were installed across a boundary of another woodland (2 in Woodland Site-4, 1 in Pasture Site-4).

Figure 4. Locations of soil water monitoring. Plots A-G; A – Woodland Site-1, B – Pasture Site-1, C – Woodland Site2, D – Pasture Site-2, E – Pasture Site (Independent), F – Woodland Site-4, G – Pasture Site-4

Readings were taken about every two weeks or at least once a month if there was not any big rain event, and we ensured to record soil moisture soon after all the larger rainfall events. Soil moisture was recorded starting at a depth of 20cm followed by increments of 20 cm up to the final depth (of 140 cm or 260 cm) of access tube. Most access tubes were installed to the depth of 140 cm with at least one 260 cm access tube in every plot.

The soil moisture data reported here is only from the Keen Ranch. 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 because of which there is not sufficient data yet to report from these plots. Additionally, because of frequent flooding (perched water table formations), it was not possible to record measurements from all the access tubes on some occasions. This especially happened for measurements deeper than 150 cm. Because these measurements were few and uneven, the results for total water storage and soil water storage have been shared as point-scatter plots and no statistical comparisons have been presented.

Figure 5. Vegetation and cover conditions for the different monitoring sites.

Chloride measurements and mass balance calculations

Nineteen different soil cores to the depth of 270 cm were collected from different locations across the two properties through September-November 2020 (yellow points on Figure 4). These locations were distributed to represent the various vegetation covers and differences in landforms – most of which overlapped with the access tube locations. Only the Pasture Site-1 was not sampled for chloride. Instead, another adjacent pasture area (Pasture Site-2) was sampled. Of the 4 soil cores from every plot, 3 were sampled at various depths separated by about 20 – 30 cm which were then used for estimating gravimetric water content and chloride concentrations (Appendix: Table A2). One core from each plot was used for determining the texture (percentage of sand, silt and clay), depth of rooting and depths to the boundaries of argillic horizon. Bulk density estimates were derived from the information available for the specific soil series available on National Soil Survey Center database.

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

Chloride concentrations were measured using the Flow Injection Analyzer Method (QuickChem 8500, Lachat Instruments, Loveland, CO, USA). To prepare the sample for the injection system, soil samples are first grinded, followed by mixing and shaking 10 g of soil in 0.01 M (Calcium Phosphate) $Ca_3(PO_4)_2$ at 200 rpm for 30 minutes. This soil solution is then filtered and then treated with mercury thiocyanate. The soil bound chloride is freed and forms mercuric chloride liberating thiocyanate ions in the solution. As thiocyanate binds with Ferric to form the orange Ferric thiocyanate complex, which is proportional to the chloride concentration in the solution. The method has been shown to be within 90-95% precise. The Cl- concentration obtained are in parts per million (ppm) or mg/Kg. To derive the pore water concentration *(Cl_w)* (mg/L), the ppm Cl-concentration is divided by the gravimetric water content for the respective depth (Kim and Jackson, 2012).

For the annual chloride deposition rates Cl_p, we used the same estimates (0.98 mg/L) as used in a 2009 report by Texas Water Development Board for the same aquifer and region. Mean annual precipitation of 944.88 mm/Yr was used based on the precipitation data from the weather station at Little river near Cameron, Texas (https://www.texmesonet.org/).

Chloride mass balance equation:

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

Where, D = Deep drainage

Cl_w = Pore water Cl- concentration at the specific depth

Cl_p = Annual Cl-deposition rate (atmospheric dry and wet combined)

P = Average annual precipitation

Cl_w values from below root zone were used in chloride mass balance (CMB) equation (Eq.1) to estimate recharge rates at specific depths. Root zone assumptions were made based on field and lab observations of soil cores. Roots in the herbaceous or pasture areas were confined to 60-80 cm and to 100 cm in wooded areas.

Micrometeorological and continuous soil moisture measurements

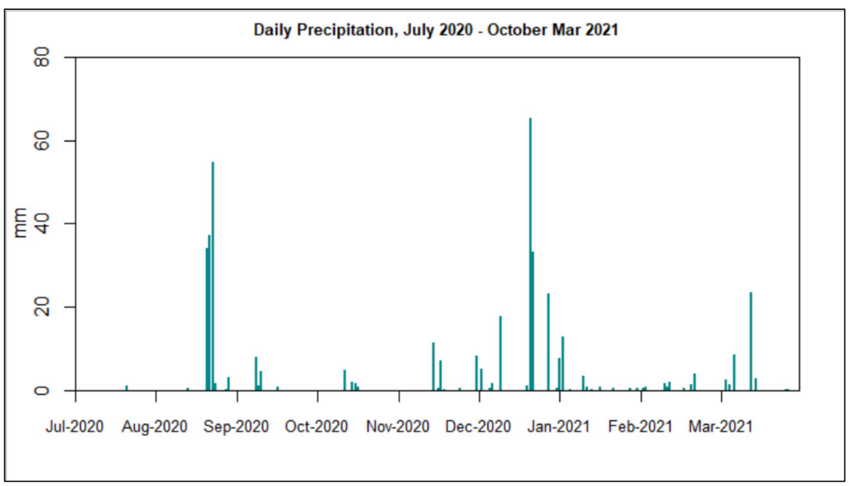

Figure 6. Daily rainfall at the Keen Ranch from July 2020 to April 2021.

Precipitation was measured using a tipping bucket setup (Texas Electronics Rain Gauge, 0.2-mm resolution) and ambient temperature and relative humidity were measured using a plug-in probe (HMP155A, Vaisala, Helsinki, Finland). In addition, continuous soil moisture was measured using an array of time-domain reflectometry sensors (CS-655, Campbell Scientific Inc.) which were installed in the 'Pasture' site at the depths of 15, 30, 50, 70, 90 and 110 cm. All the instruments were connected to a datalogger (CR-6, Campbell Scientific Inc., UT, US) where the data was recorded every 10 minutes (Figure 6).

Results

Soil chloride and texture

Pore water Cl- concentration profiles showed obvious differences between the woodland and the pasture sites (Figure 7) with relatively higher accumulation under the woodlands after 140 cm. The pore concentrations 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 the concentration of 500 mg/L. Almost all the higher Cl_w were in deeper soils (> 200 cm) and under the woodland sites. In contrast, pasture sites showed extremely low Cl_w in general – even at depths of 200 cm or more.

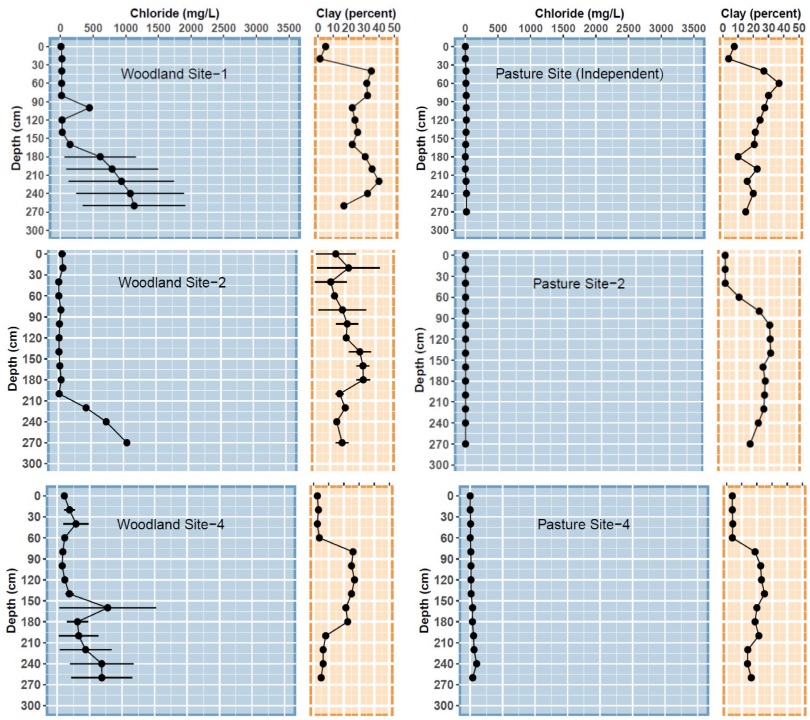

Figure 7. Chloride profiles and clay composition for the different plots. Bars are standard deviation.

Textures were mostly sandy to sandy loams in the first 30 to 40 cm after which they transitioned to sandy clay loams or sandy clay soils (Figure 7). Woodland Site-4 and Pasture Site-4 – which were on a different property than the rest of the sites, had sandy soils until 80 cm after which there was an abrupt transition to sandy clay loams. Woodland Site-2 – which also has more slope than other sites, exhibited some variability in textures with some locations showing higher clay content even at depths of 20-30 cm.

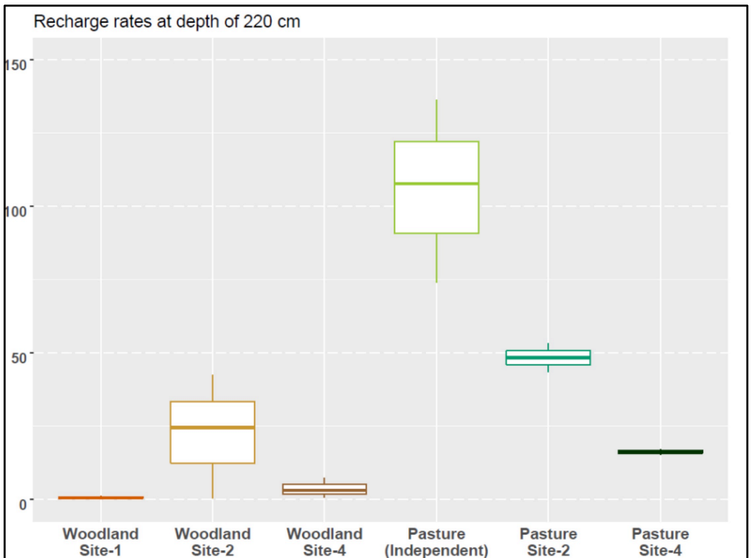

Figure 8. Recharge rates derived from Chloride Mass Balance.

Recharge rates

Estimates of long term recharge were considerably higher for open areas. The highest recharge was in the pasture site (>100 mm/yr) and the lowest was in the woodland site 1 (< 5 mm/yr) (Table 1). As highlighted in Figure 8 there was considerable variability in the recharge measurements but in general, recharge was much higher in wooded areas.

Table 1: Recharge Rates (in mm) at 120, 150, 200 and 220 cm based on pore water Cl- concentrations

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
Pasture Site-2	Core-7	NA	NA	NA	43.68
Pasture Site-2	Core-8	NA	NA	NA	53.21
Pasture Site-2	Core-9	NA	NA	NA	NA
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

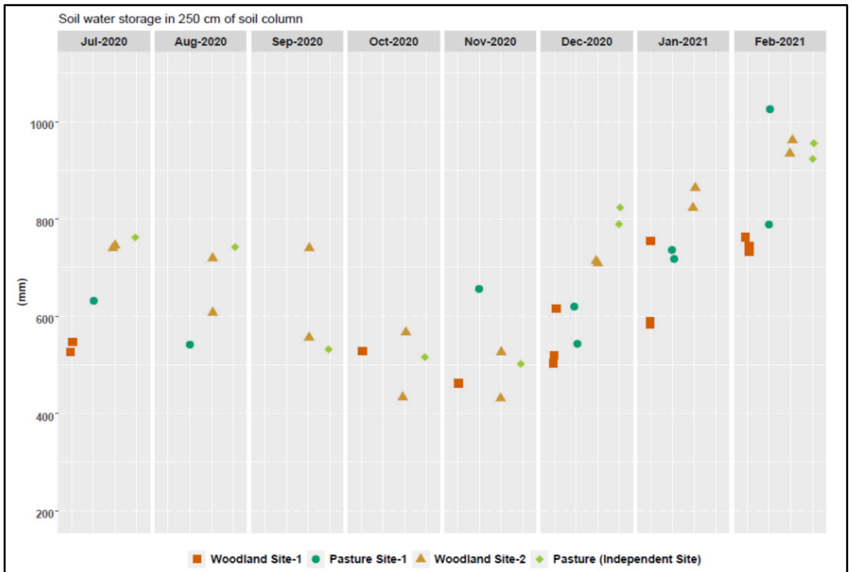

Figure 9. Total soil water to a depth of 250 cm

During the period of observation reported (Jul 2020 – Feb 2021), the site received a total of 359 mm of precipitation. The biggest rain events occurred in early September, mid-December and early January (Figure 6). The wettest conditions were observed for the winter months (Dec-Feb) and for the month of September. The general trend in soil moisture reflected the trends in precipitation for all the sites (Figure 9).

As highlighted in Figure 9, there was significant scatter in the soil moisture data, however there do appear to be some general differences between woodlands and pastures (Figure 10). Soil moisture profiles were very distinct when woodland and an adjacent pasture were compared (Woodland Site-1 vs Pasture Site-1). Pastures generally had higher water content in the first 1.5 m of soil. This depth was a lot less in the sum (Jul-2020). This reduced depth could probably be attributed to plant water use being limited by the depth during the summer as the soils got drier (and hence, more difficult for plants to draw). However, the differences in water content closer to the surface between pasture and woodland were a lot more pronounced during the summer. Even though the water content increased during fall (Nov-2020), the differences between pasture and woodlands were still evident. Woodland Site-2 showed a similar change in soil moisture profiles and as well as the shape as Woodland Site-1. This was expected because of similar soil texture in these two sites.

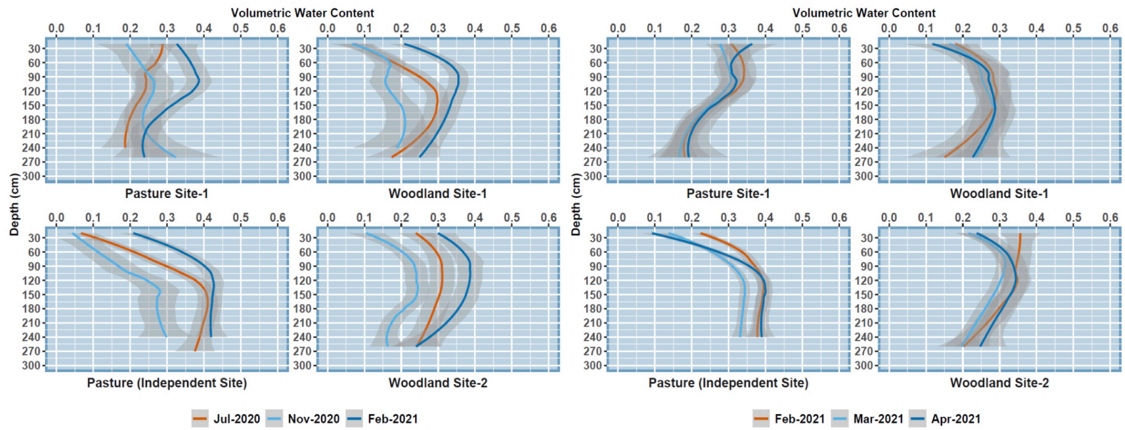

Figure 10. Change in soil water for woodland and pasture sites for the duration of the study

The independent pasture site (not to be compared with Woodland Site-2) showed very distinct behavior compared to the rest of the plots. Relative to other plots, these plots had frequent issues of perched water table formation (as seen in the field with access tubes flooding from inside). The soil moisture profile showed a consistent pattern of increase – and 'plateauing' with depth, which was indicative of drawdown of water into deeper profiles – which is further evidenced by decrease in deeper soil water content as seen in spring 2021 (Figure 10). Because there are no roots at these depths, this water has to be moving downward. More on this downward flux can be said with soil water observations from soils deeper than 260 cm (which is what our current installations allowed us to do).

Overall, the comparison of soil moisture profiles between the woodland and the pastures indicate an obvious influence of transpiration with the effects being limited by the rooting depth and saturation in the deeper soils.

Conclusions

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 suggested that recharge can be 20 to 50 times higher in open pastures than in closed woodlands. The soil water measurements have been ongoing for almost a year and indicate that soils in the pastures are in general wetter than in the woodlands. The data will be strengthened with longer-term measurements, deeper soil cores, and more locations. In addition, the soil moisture measurements should be complemented with measurements of soil flux and direction of flow.

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