Effects of Brush Clearing on Deep Drainage Using Soil Chloride; Identifying Potential Recharge and the Important Driving Variables

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Project Goals

The purpose of this study is to provide decision makers with qualitative data on potential recharge in managed rangelands in Texas. This study will facilitate insight into the fundamental elements and processes operating at a plot scale that might affect the potential for recharge at the local scale and ultimately help land owners better manage their land in order to replenish regional groundwater.

Introduction

The effects of groundwater recharge by removal of mesquite-dominated vegetation are currently under investigation in southwest Texas. Water recharge is important in the region since groundwater aquifer levels have lowered around 30 m in the last 85 years. Competitive xeric woody-shrub-dominated plant communities are also known to utilize the episodic rainfall events efficiently before water can penetrate below the rooting zone. Evapotranspiration is thought to be the dominant factor limiting groundwater recharge in semi-arid regions, such as La Salle County, where high rainfall events are rare and sporadic. There are two ways in which evapotranspiration is potentially reduced to a level that invokes groundwater recharge: reduced vegetation cover via land management, and reduced vegetation water use during winter dormancy. This study focuses on land management, particularly clearing of woody shrubs, as a potential mechanism to increase groundwater recharge. Around 70% of the annual rainfall of 555 mm (Soil Survey of La Salle County 1994) falls during the growing season (May-Oct). Warm, humid weather can, in some years, persist until late November, effectively reducing the dormant season to around four months. Winter precipitation has the capability of providing potential recharge, given favorable soil properties for water movement. The rooting depth of vegetation helps dictate the extent to which water can be removed from the soil profile through transpiration and is helpful in determining potential recharge or deep drainage below the root zone. In this study we use the Chloride Mass Balance approach (CMB) based on chloride concentration in the soil, chloride atmospheric inputs and precipitation, to compare deep drainage among areas managed for woody vegetation.

The water budget and soil properties

Deep drainage, or the percolation of water through the soil profile and beyond the root zone, can be expressed on an annual basis simply as:

$$D_D = P - (A_{ET} + \Delta S)$$

where D_D is the deep drainage, P is the water inputs by precipitation, A_{ET} is the combined loss of water through evapotranspiration, and ΔS is the change in root zone water storage. The units of the equation are expressed in depth per time (usually mm/yr).

Soil texture, bulk density and existence of impenetrable soil layers affect the movement of water through the soil profile. Other studies that model recharge rates (Scott et. al. 2000) use soil texture, bulk density and antecedent soil moisture at varying depths to estimate soil infiltration, percolation and subsequent recharge rates below the rooting zone. For potential recharge to increase there needs to be favorable soil properties to facilitate water movement down through the profile, beyond the maximum rooting depth. Coarser textured, low bulk density soils, with fragmented or no impermeable layers, are expected to provide faster water movement and greater recharge rates.

With the aid of volumetric soil moisture probes, and with a better understanding of the soil properties, actual soil moisture flux through the soil profile can be monitored following precipitation events throughout the year.

Vegetation effects on groundwater recharge

Recharge has been documented to have occurred where native vegetation of forest/ shrubland have been converted to grassland or pasture, or where forests or grassland have been cleared for agricultural practices, such as irrigation or dryland cropping. Subsequent shallow rooting depths, decreased canopy interception, potential decrease in evapotranspiration and periods of fallow, all allow for water infiltration and percolation to occur. Conversely, for vegetation to effectively move water upward and out of the soil as transpiration, plants must possess morphological and physiological adaptations which would allow for extended survival in the water-limited environment typical of semiarid and arid regions.

The buffering capacity of the vegetation to maintain soil water at depth is documented and likely to occur -- especially in semiarid regions, where rainfall is periodic and seasonal. But this affect is more likely during winter dormancy than in the active growing season. Rather, large precipitation events during the growing season tend to promote positive vegetation response, excess biomass production, increased root densities and deeper rooting depths. When rainfall occurs in-sync with high evapotranspiration, as it does in many semi-arid regions such as in southwest Texas, possible soil water gains from rainfall are countered by losses due to high temperature and subsequent evaporation. The problem is compounded by the fact that in a lot of these areas, vegetation responds actively to summer rain and associated increases in biomass utilize any excess water. Seyfried et. al. (2005) explains that it is possible for multi-year trends in annual precipitation to overwhelm the buffering capacity of the soil-plant system; however, excess rain during periods of winter dormancy are the most likely contributor, e.g. over a decade of wetter than average winters.

Much of the research on how woody vegetation removal affects water resources has focused on potential increases in surface water flow rather than deep drainage. Wilcox (2002) reviewed the literature and recognized the lack of evidence supporting the fact that removal of woody vegetation to favor grassland would increase water yield. Wilcox also identified the importance of knowing the influence that soil depth, soil morphology, and the depth to bedrock may have on increasing or decreasing water yield in streams. These same ideas help recognize that groundwater recharge may also be possible, under similar conditions, and indeed in some instances, while streamflow remains unchanged. Deep, sandy soils have the greatest potential for groundwater recharge following removal of woody vegetation.

Land use change is also a significant factor when trying to understand the historical dynamics of subsurface water flow. Pasture development, agriculture, irrigation and forestry all impact on how the water coming into the system will be utilized by the vegetation. Tolmie et. al. (2004) has suggested that with a change in land-use from native woodland to crop or pasture, water will be lost below the rooting zone and into the groundwater recharge zone. In temperate systems, when converting woodland to crops, enough water can be moved below the root zone in a matter of a few decades to flush carbonates, nitrates and chloride from the system. Flushing of chloride results in a shift of maximum concentration downwards as water escapes the root zone of the more shallow-rooting crop species compared to the more deeply-rooted woody species that occupied the soils previously.

In this study we track soil chloride concentration profiles in order to test the hypothesis that clearing shrub vegetation in a semi-arid Texas rangeland will increase deep drainage below the root zone. By comparing soil chloride among treatment plots that were cleared at different times in the past, a chronosequence can be established to see whether deep drainage has occurred in the period of time the shrubs take to regain dominance in the community.

Chloride: Historical Evidence of Recharge

Chloride is useful as an indicator to document recharge of water into saturated aquifers and beyond the root zone through deep drainage (Allison and Hughes 1978; Scanlon 1992; Phillips 1994, Allison and Hughes 1983; Reedy et. al. 2000; Scanlon 2000, Scanlon et. al. 2005). Chloride in precipitation, as well as dry deposition, is transported into the root zone with infiltrating water. Soil chloride concentrations increase within the root zone as a result of evapotranspiration because chloride is non-volatile and is not removed by evaporation or plant transpiration (Reedy et. al. 2000). White and Broadley (2001) indicate that chloride is largely moved through the soil by water flow due to its relative inability to form complexes and little adsorptive properties with soil. The distribution of chloride in the soil profile therefore represents the balance attained through downward percolation in solution and the concentration due to root uptake of water.

Low chloride concentrations in the soil indicate high water fluxes that flush chloride through the unsaturated zone, indicating either humid climate or unseasonably wet conditions in semi-arid settings. High chloride concentrations indicate low or upward moving water that allows chloride to build up in high concentrations. When mapping chloride concentrations with depth, a pattern can usually be seen where maximum chloride concentration represents the long-term maximum extent that water has reached. Below this depth, if water has been consistently removed from the profile, chloride concentrations drop as water has not been able to transport chloride lower. This “bulge” in chloride concentration, observed in chloride concentration profiles, signifies the removal of water at that soil layer due to evaporation or, more importantly, plant uptake and transpiration.

To quantify the rate of water movement, using soil chloride, a variety of techniques can be adopted, however the Chloride Mass Balance method (CMB) is a useful technique for semi-arid regions where recharge rates are expected to be below a few millimeters per year (Gee et. al. 2005). Others (Reedy et. al. 2000; Scanlon et. al. 2005; Scanlon 2000; Scanlon 1991; Scanlon 1994) have used the CMB approach to identify maximum extent of wetting fronts and recharge rates in semi-arid and arid areas to varying degrees of precision. The CMB method balances chloride inputs (through atmospheric deposition, both dry and in precipitation) with the chloride output (downward percolation through the soil). Confidence in recharge rate estimates require accurate estimates of atmospheric chloride input, precipitation and soil pore water chloride content . Chloride Mass Balance can be expressed as:

$$PC_P = D_D C_S \qquad (1)$$

where P is the precipitation (mm/yr), C_P is the chloride concentration by atmospheric deposition (mg/L), D_D is the rate of deep drainage (mm/yr), and C_S is the cumulative chloride concentration in the soil pore water to a depth of interest (mg/L). Rearranging for D_D gives:

$$D_D = PC_P / C_S \qquad (2)$$

Water flux can be estimated from the degree of chloride enrichment in pore water as a result of evapotranspiration relative to the chloride concentration in precipitation (Scanlon 2000). Estimates of recharge are possible if dry and wet deposition from the atmosphere is assumed to be the only source of chloride input to subsurface layers. An estimate of deep drainage can be calculated by dividing the cumulative amount of chloride down to a depth of interest by the chloride input (equation 2). Chloride concentrations in the soil profile are inversely proportional to recharge rates.

In this study we used CMB to see if clearing of shrub vegetation changes deep drainage from mesquite-dominated rangelands in South Texas over time periods of 15 years or less. We expect to see a decrease in cumulative chloride with depth in plots that have been cleared of shrub vegetation compared to control plots. For plots that have been cleared longer, cumulative chloride concentrations should be less. The position of the bulge, or zone of greatest removal of water through evapotranspiration should be lower in the profile for plots that have been cleared than control plots. To test our hypothesis we will compare soil moisture and chloride profiles among a chronosequence of vegetation successional stages of woody dominance: recently cleared (<1 year), after 5 years of recovery from clearing, after 15 years of recovery from clearing, and mature sites that have never been cleared of large mesquite trees. In each stage of the chronosequence we relate differences in vegetative cover to differences in deep drainage that cannot otherwise be explained by soil properties. This project is a part of a larger study which aims to better understand deep drainage from a wider range of vegetation management scenarios with the primary goal of identifying which elements of this particular landscape might contribute to recharge and under what conditions deep drainage may occur.

Methods

The study area is located at the 400 acre Northcut Ranch, a private ranch approximately three miles east of Cotulla, Texas in La Salle County. Three treatment plots and a control have been established at three replicate sites on the ranch to represent a chronosequence, in which time is substituted for space, for a total of twelve experimental plots. The control plots are considered a native, undisturbed stand of rangeland brush dominated by mature honey mesquite (*Prosopis glandulosa*) and C4 grasses. The other three treatments were plowed of vegetation, using a horizontal blade that cuts the shrubs 30 cm below ground level, at different times in the past (2005, 2001 and 1991) and subsequently allowed to recover. This root plowing process is a common management practice in this region to remove woody vegetation and increase grass production. Thus, the treatment plots represent vegetative regrowth 1, 5, and 15 years since root plowing.

Precipitation records were obtained from the United States Department of Agriculture (Soil Survey of La Salle County 1994). The yearly average is 555 mm and the data consists of monthly averages for the period 1951-1984.

Over a period of one week in April 2006 and two weeks in July 2006, two soil cores were taken from each of three plots within each of the three sites for a total of 18 cores. The recently plowed plots in each site were not sampled since we expect that insufficient time has elapsed for water movement to have differed from the control plots to have affected chloride concentrations. A Giddings soil auger, mounted on either the back of a tractor or trailer, was used to excavate 50-mm diameter cores from depths up to 4.2 meters. The exact depth of each soil core was limited by the machinery's physical dimensions and power, and depended highly on the depth to rock or any other impenetrable layer encountered, such as gravel or highly-compacted silt.

Each soil core was sampled in 10-cm increments; however, not every increment of the core was sampled. Since we expected most of the chloride variability to occur in the first two meters, we spaced the increments further apart with depth, either 20 or 30 cm, as follows: 10, 20, 40, 60, 80, 100, 120, 140, 160, 180, 210, 240, 270 cm, etc. The number of samples per core ranged anywhere from nine to eighteen, depending on the total depth. If possible, the bottom 10 cm increment was sampled even if it fell outside the sampling protocol depths. Field observations were also made of soil morphology, including depth to calcium carbonate, color, mottles and soil structure, in order to aid soil classification once laboratory data had been obtained.

Soil profile samples were used to characterize a variety of soil descriptive parameters including volumetric soil moisture, bulk density, gravel fraction, particle size, fine roots, pH, electrical conductivity and chloride. Samples were oven dried at 105 C to a constant weight. Soil moisture was calculated on a percent by volume basis according to bulk density. Dry soil was then passed through a 2 mm sieve to remove gravel, carbonate nodules and large roots. The gravel fraction was determined as a percentage of the initial mass of dried soil. Homogenized and sieved soil samples were further sub-sampled, whereby 60 g was used for particle size analysis using the hygrometer method, the equivalent weight of soil in 50 cm^3 was allocated to measure fine roots, and 50 g of soil was taken for an aqueous extract. The sub-samples for particle size analysis and the aqueous extract were ground on a roller grinder (custom made by Kansas State University) for four hours prior to their further analysis.

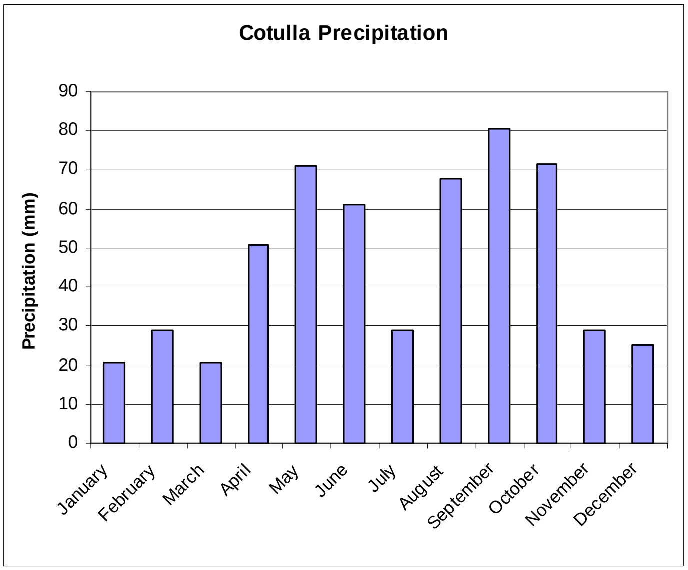
The particle size and fine root procedures of the study are in the process of being measured, results of which are yet to be determined. The results obtained from these analyses will to provide supporting evidence of the role that soil properties and maximum rooting depth play in affecting drainage rates.

The ground samples allocated for aqueous extracts were then shaken in flasks for 4 hours with 100 ml of distilled water. In mixtures where the soil swelled, absorbing much of the water, an additional 100ml of distilled water was added and noted. The 1:2 soil water slurry (similar to that used by Dyck et. al. 2003 and described by Dellavalle 1992) was then left to settle for approximately 30 minutes and pH and electrical conductivity measurements recorded using a hand-held YSI and Hanna instrument, respectively. The soil slurry was then filtered through a Bachar Funnel with a #2 Whatman filter using a vacuum flask. The water extract was then bottled and later analyzed for chloride using the ion chromatography method described by Pfaff 1993 and employed by the New Mexico Bureau of Geology and Mineral Resources.

Chloride deposition data was obtained for a seven year period (1999-2005), from the National Atmospheric Deposition Program, and collated to provide average chloride depositions for the two closest known observation points to Cotulla, La Salle County, Texas. Cotulla lies between Beeville, which is nearer to the coast, and Sonora, which lies further inland. Cotulla is located approximately 80 miles from Beeville and 160 miles from Sonora. A distance-weighted interpolation of monthly chloride deposition values was made from those values obtained for each of the two observation stations at Beeville and Sonora. The monthly values for Sonora are around one quarter of those values at Beeville, which is nearer to the coast. The interpolated rate of monthly chloride deposition in rainfall for Cotulla was 0.7 mg L^{-1} month^{-1} (8.4 mg L^{-1} yr^{-1}).

Two methods were adopted to describe the above-ground vegetation pattern, represented in each of the twelve study plots: line transects and quadrats. Observations were made in July and so represent the relative growth distribution at that time of year. Shrub percent cover by species was classified along three 15-meter line transects placed in random directions, each from a randomly located point near the center of each plot. Vegetation intersecting the entire transect length in each plot was described to a 5-cm resolution and expressed as a percentage of the total linear distance. Along each line transect, five 0.25 m^2 quadrats were placed randomly to further classify ground cover of vegetation, bare ground, rock, and leaf litter, expressed as a percent of the soil surface area. The middle of the first quadrat along the line transect was randomly selected within the first 3 meters of the transect. The side of the line was also determined randomly. Each successive quadrat was then placed every 3 meters down the transect, alternating sides.

Figure 1. Average monthly precipitation for Cotulla, TX (Soil Survey of La Salle County 1994)



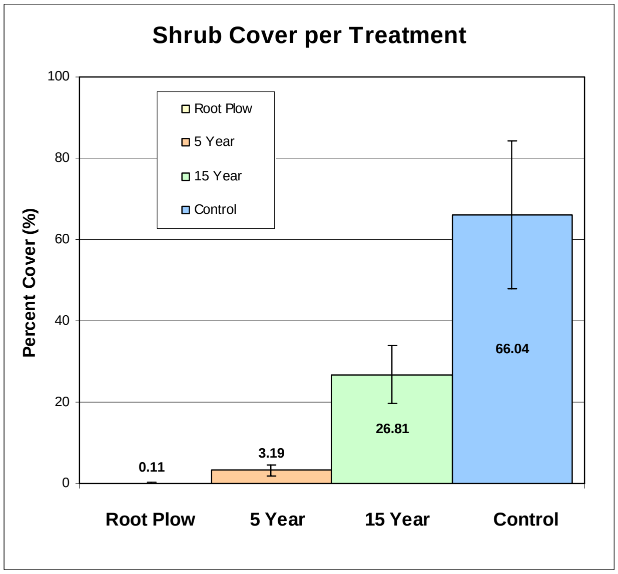


Figure 2. Percent shrub cover and standard error between treatments for the three sites combined**.**

Results and Discussion

A summation of precipitation is presented in Figure 1 and shows the average monthly precipitation for Cotulla. Total annual precipitation in La Salle County, as reported by the United States Department of Agriculture is 555 mm^{-1} $year^{-1}$. Around 70% of the annual precipitation falls in the summer months (May-October) and 30% falls during winter (November-April).

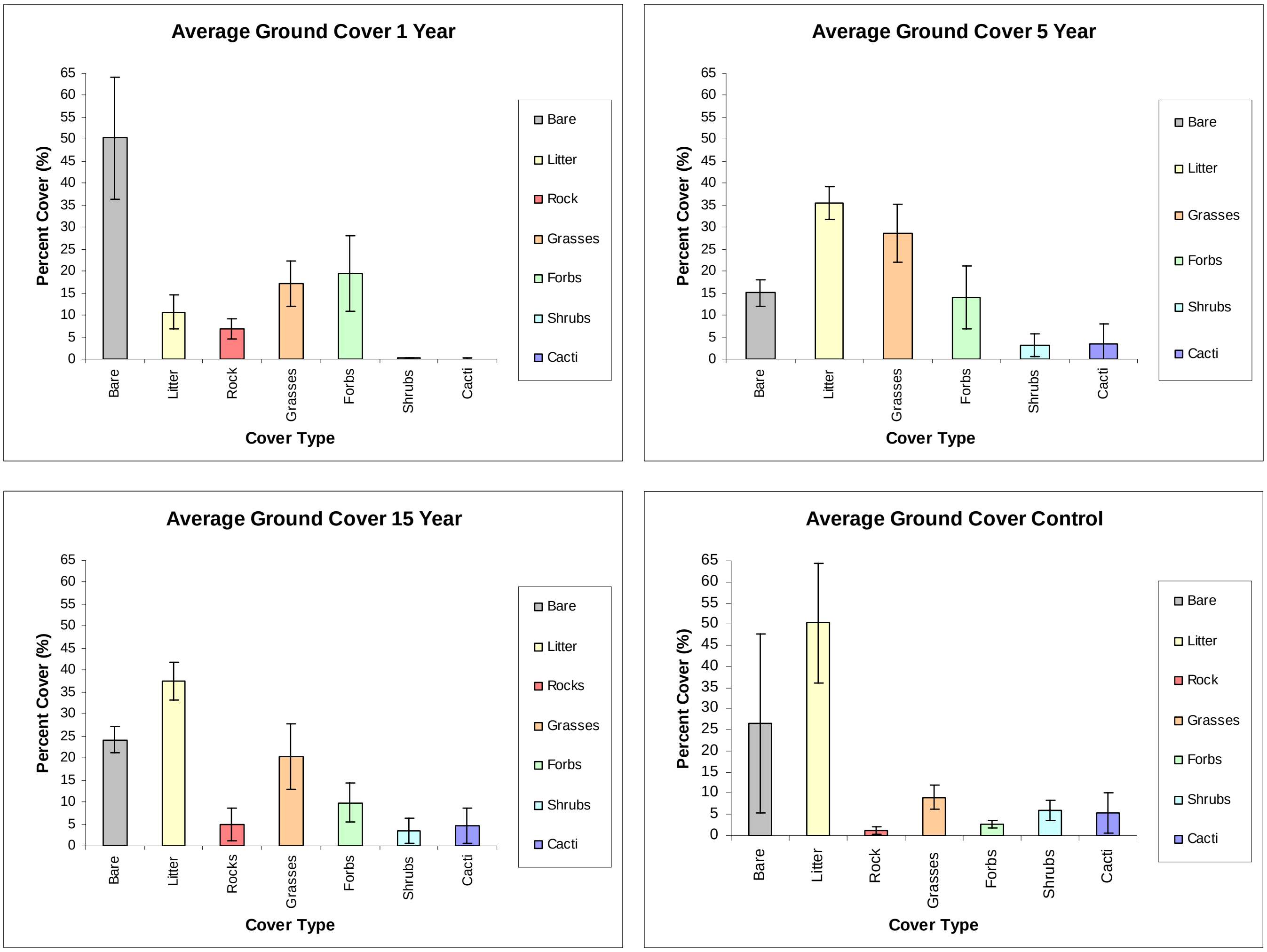
Soil Results

Preliminary investigations of soil properties show fairly uniform morphology within sites, however soil characteristics between Site 3 and the other two (Sites 1 and 2) seem markedly different (data not shown). Landscape position and differing parent material are thought to be responsible for Site 3 to have visibly sandier textures throughout. Further particle size analysis in the laboratory is hoped to support this explanation.

Vegetation

Average shrub cover for all sites between treatments is shown in Figure 2. The approximate ratio of shrub cover between treatments at each site are similar, however Site 1 supports considerably more cover than both Site 2 and 3, despite Site 1 and 2 being in a similar landscape position (data not shown). Inadequate sample size could be the reason why Site 2 is lower in shrub cover than Site 1. The five year plots have very little shrub re-growth, but by fifteen years after clearing, shrubs are again dominant and canopy cover has increased to around 27% (7.1 SE), with shrubs further increasing to around 66% (18.1 SE), observed in the control plot. There is an apparent threshold between five and fifteen years after clearing where shrubs replace grasses as the dominant vegetation type.

The herbaceous level ground cover observations reflect the change in grass to shrub dominance between five and fifteen years since clearing. Figure 3 (a-d) shows herbaceous cover estimates, which were largely influenced by the conditions at the time they were collected (July 2006). Prior to most summer rain, C4 gasses are still quite dormant; therefore, an under-estimation of grass cover is predicted compared to later in the growing season (e.g. September) when grasses are at their maximum extent. Once woody vegetation had been cleared there is a rapid increase in grass and forb cover (3a) and within five years grasses dominate the herbaceous layer, with 28.6% (6.6 SE) cover (3b). Percent bare ground reduces quite quickly after the first growing season. Five years after clearing, mesquite shrubs have yet to mature, with a canopy cover of only about 3.19% (Figure 2). After earlier periods of grass dominance, the shading/competitive effect of the shrub canopy and subsequent reduction in grass cover led to bare ground increases by fifteen years (3c) to the levels observed in the control plots (3d). However, variation in bare ground cover is substantially greater in the control plots, explained by the relatively bare soil in large inter-canopy spaces. Litter in the control plot is high because of the extensive shrub canopy cover of around 66%.


Average Ground Cover 1 Year

Average Ground Cover 5 Year

Average Ground Cover 15 Year

Average Ground Cover Control

Figure 3. Percent ground cover for all four treatments; 1 year since root plowing (a), 5 years since plowing (b), 15 years since plowing (c) and the control plot (d).

Chloride

Soil chloride concentrations, for those of the 18 profiles where analyses have been completed, are plotted with depth in Figure 4 (a-c). Results from the control plot(s) are consistent with the theory of an accumulation of chloride within the root zone for a significant period of time under a native, untreated stand of vegetation. Depth of the peak of maximum chloride concentration in the control plots are around 170, 240 and 260 cm for Sites 2, 3 and 1 respectively. This explains the build up of chloride over a long period of time in an un-cleared state. In those plots which had been cleared fifteen years ago, no chloride bulge is evident for four out of five of the plots. Chloride builds up where water has been removed through ET, and this is more evident for the control plots than the treatments. In the three treatment plots that were cleared 5 years ago, a chloride bulge is evident, however these chloride concentrations are lower in the profile, indicating that perhaps the chloride has been flushed to lower depths through increased deep drainage in these sites.

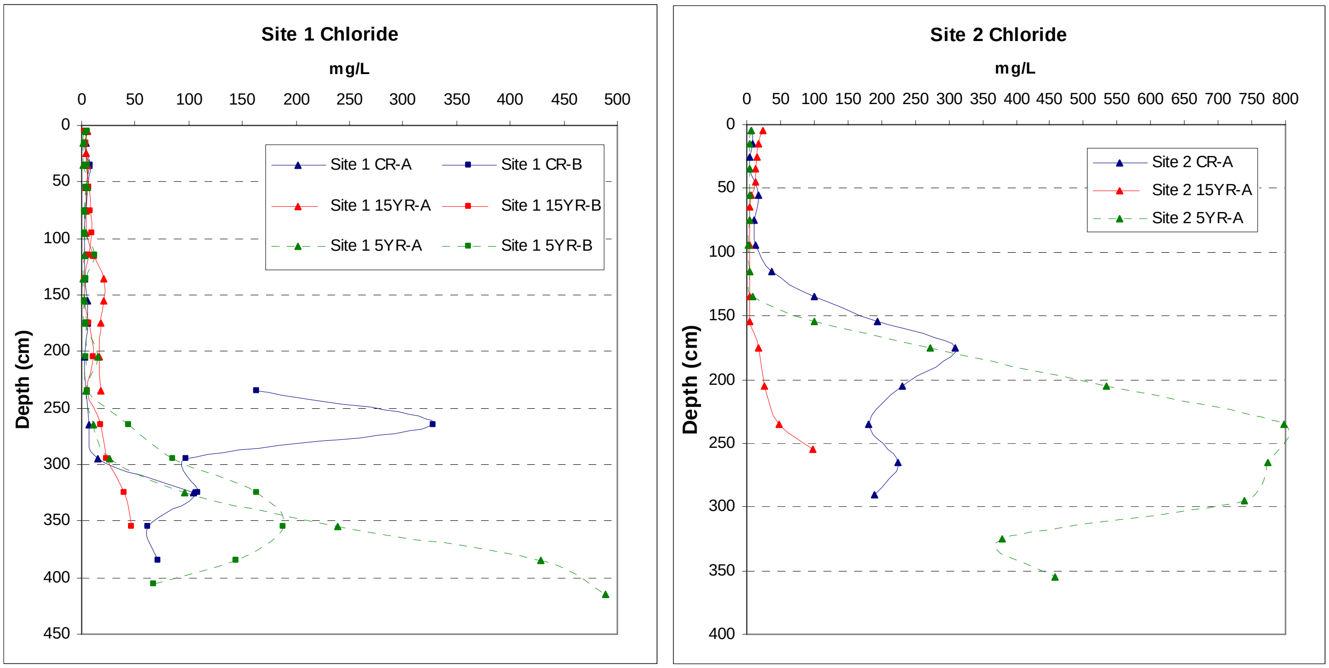


Figure 4. Chloride concentrations with depth for Site 1 (Figure a), Site 2 (Figure b) and Site 3 (Figure c). Treatments are 5 years since plowing (5YR), 15 years since plowing (15YR) and the control plots (CR). Different profiles within treatments are designated A (triangle symbols) and B (square symbols).

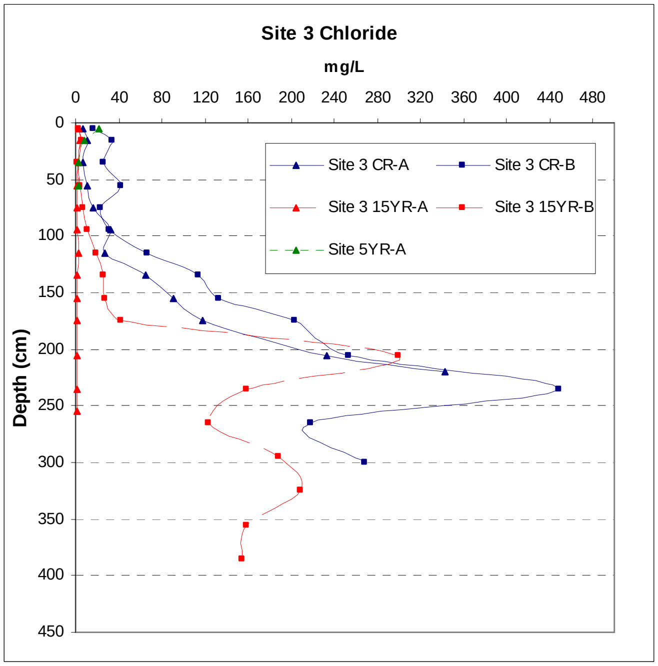


Figure 5 (a-c) represents the cumulative chloride in mg/L with depth and shows that substantially more total chloride is evident in the soil under the control plots compared to the plots that were treated fifteen years ago and allowed natural re-growth to occur. The steeper curves in Figure 5 indicate an absence of chloride with depth and represent flushing of chloride with increased deep drainage. Site 3 (Figure 5c) shows good evidence of reduced chloride due to the distinct difference in cumulative chloride curves between the control plot and the treatments. During the last fifteen years the chloride had flushed to lower parts of the soil profile and, in some cases (Site 2 15YR-A and Site 3 5YR-A), beyond the maximum depth sampled in this study. We attribute this chloride movement to the removal of vegetation, allowing water to penetrate through the shallower rooting zone of that of the grasses that colonized the area post-clearing.

These data suggest that root plowing, in most plots, allowed more water to penetrate to deeper depths over the 15 years since clearing and resulted in greater potential groundwater recharge.

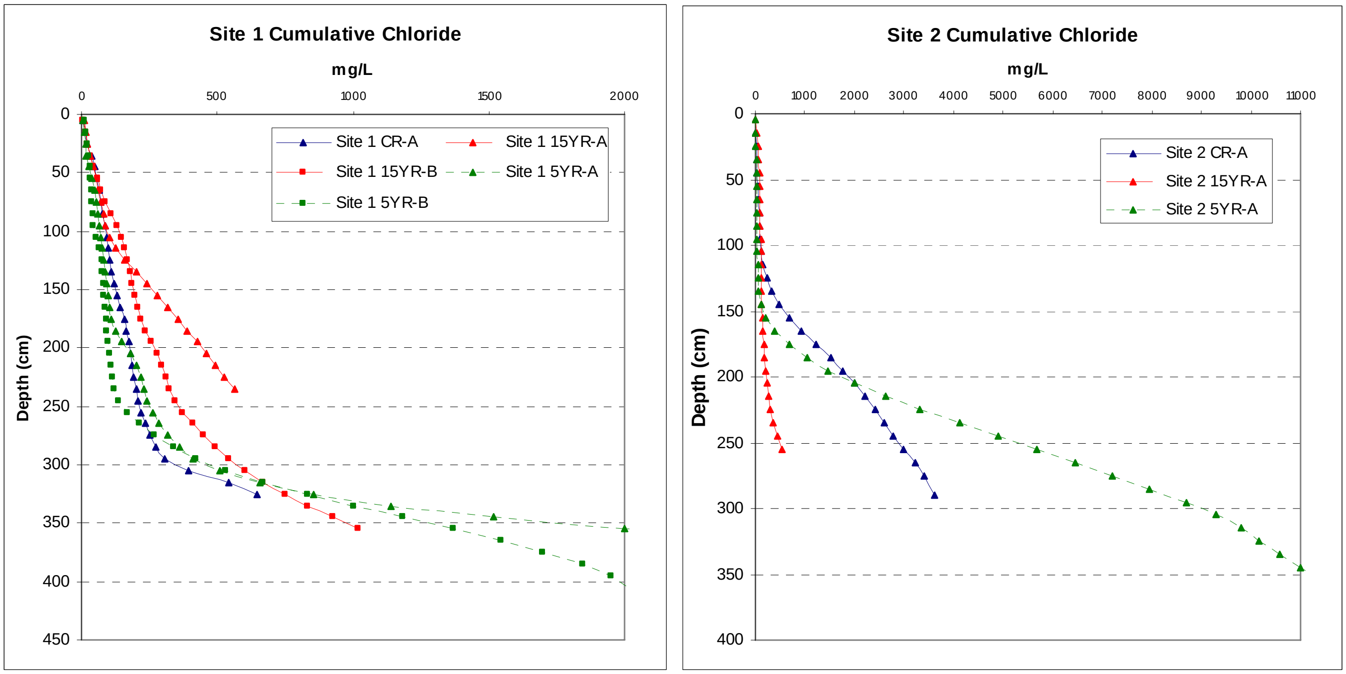
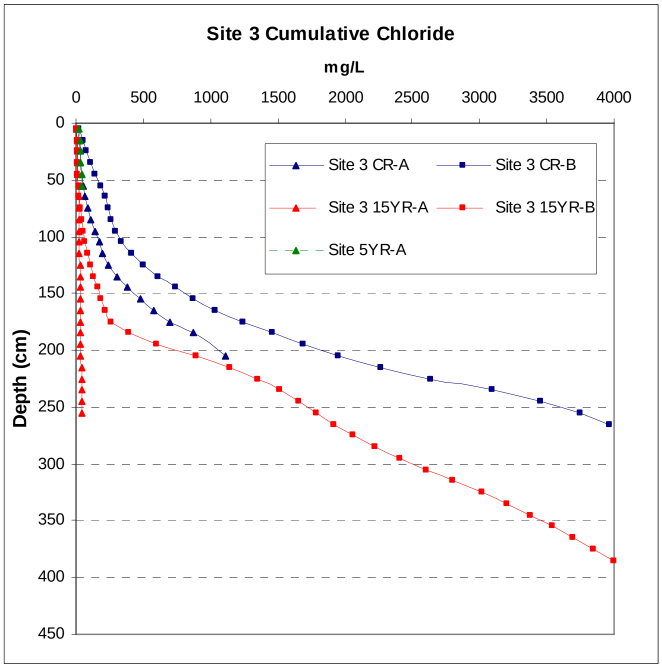


Figure 5. Cumulative chloride concentrations with depth for Site 1 (Figure a), Site 2 (Figure b) and Site 3 (Figure c).



Estimates of deep drainage have been calculated using Equation 2 and the results have been compiled for those profiles analyzed in Table 1. Depths are given that indicate where deep drainage is less than 1 mm per year. Some profiles show a greater than sign if the deep drainage result was estimated to be deeper than the maximum sampling depth. Deep drainage rates were also compared across profiles at a reference depth of 205 cm (Table 1). The results were consistent with our hypothesis, with control plots have less deep drainage rates than those plots that had been cleared of vegetation. Profiles that were inconsistent with expected results are assumed to have either chloride inputs from other sources (high chloride values) or coarse textures to facilitate water movement (low chloride values).

Conclusions

For each landscape the driving variables on potential recharge will be dependent on an interaction between soils, vegetation and climate. The transport of water through the landscape will be ultimately driven by multiple processes all interacting between and within different scales of focus. The relative magnitude or importance of these driving variables will be fundamental in determining the possibility for potential recharge in the landscape in question. To apply this theory to the research in this paper, and using the model by Huxman et. al. (2005), a setting can be hypothesized where recharge could potentially occur given certain scenarios. Further, a model can be designed in order to incorporate every variable that might facilitate water movement through the landscape and their relative effect on potential recharge. Conditions to favor recharge would be close proximity to riparian areas, ET and precipitation out of phase (i.e. winter-dominated rainfall), shallow soils, fractured bedrock, sandy or gravelly texture and a vegetation cover that minimizes water use. This model could be applied on a site by site basis.

Site	**Plot**	**Profile**	**$D_D < 1.0$ mm^{-1} yr^{-1} (cm)**	**D_D past 205 cm (mm^{-1} yr^{-1})**
1	C	4	>325 cm	25.78 mm^{-1} yr^{-1}
1	15	2	>235 cm	10.16 mm^{-1} yr^{-1}
1	15	9	>355 cm	16.67 mm^{-1} yr^{-1}
1	5	5	385 cm	26.08 mm^{-1} yr^{-1}
1	5	6	>405 cm	45.27 mm^{-1} yr^{-1}
2	C	3	215 cm	1.16 mm^{-1} yr^{-1}
2	15	1	>255 cm	9.91 mm^{-1} yr^{-1}
2	5	13	215 cm	1.15 mm^{-1} yr^{-1}
3	C	16	>205 cm	1.34 mm^{-1} yr^{-1}
3	C	17	185 cm	0.63 mm^{-1} yr^{-1}
3	15	18	>255 cm	47.90 mm^{-1} yr^{-1}
3	15	19	295 cm	2.56 mm^{-1} yr^{-1}

Table 1. Estimated deep drainage rates for treatment plots, expressed as the depth at which D_D rates are less than 1.0 mm per year and D_D rates past a reference depth of 205 cm for all profiles.

It is evident from the information discussed above that potential recharge might be possible to determine if the driving variables and their relative importance are identified, monitored and tested using a hypothesis similar to the objectives of this paper. Each driving variable can have a positive, negative or neutral effect on potential recharge depending on whether the movement of water is facilitated or not. With climate and landscape position variables held constant in this study, the predominant driving variables identified and tested were vegetation and soil texture. Clearing of woody vegetation increased deep drainage, as seen by reduced chloride concentrations with soil depth in treatment plots. Results of deep drainage rates were affected by texture (results not yet available) and in some profiles provided unexpected drainage rates. For example, the control plot at Site 1 (profile 4) had a deep drainage rate comparable to the five year plots and a rate greater than the fifteen year treatment plots. This would indicate that soil texture is facilitating water movement in this profile and also shows the inherent heterogeneity of soil properties at the plot scale.

Larger-scale processes, like climate (including rainfall and ET), will be more important at determining the possibility for recharge, because without precipitation no water will enter the system. More importantly, cool season rain will have a positive affect on potential recharge. Whether the site is in a riparian or upland position in the landscape will also affect the recharge potential, but in the case of this study, the site is in an upland position and will therefore be detrimental to potential recharge due to the vertical distance to the groundwater. At smaller scales, the texture and structure of the soil, as well as presence of impenetrable layers in the soil profile, will affect potential recharge.

The type of vegetation that exists and the community succession that propagates will have an affect on recharge, depending on the structure of the community and the way they forage for water resources below-ground. The scenario given in this paper hypothesizes that a change to grassland, by root-plowing of the woody shrubs will effectively increase the potential for recharge, since water is able to infiltrate past the majority of the roots and into the deeper subsoil during heavy rain, especially in cooler months of the year. If the soil texture is sandy, which is predominant in this landscape, and caliche horizons fragmented, the recharge has positive potential. When combined with a conversion of shrub to grass vegetation, given that grasses allow water to move deeper into the soil profile than shrubs, deep drainage and subsequent groundwater recharge is possible.

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