LONG-TERM HYDROLOGIC RESPONSES TO SHRUB REMOVAL IN A SW TEXAS RANGELAND: USING SOIL CHLORIDE TO ESTIMATE DEEP DRAINAGE

A Thesis

by

DAVID ANTHONY BARRE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2009

Major Subject: Rangeland Ecology and Management

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Approved by:

Chair of Committee, Georgianne Moore
Committee Members, Tom Boutton
Charles T. Hallmark
Head of Department, Steve Whisenant

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ABSTRACT

Long-Term Hydrologic Responses to Shrub Removal in a SW Texas Rangeland: Using Soil Chloride to Estimate Deep Drainage. (August 2009)

David Anthony Barre, B.S., The University of Canberra

Chair of Advisory Committee: Dr. Georgianne Moore

The Carrizo-Wilcox aquifer is a valuable groundwater resource, situated in a semi-arid landscape of Southwest Texas, where over-use by dependent farming practices has lowered aquifer levels. In semi-arid regions, rates of groundwater recharge are predominantly low due to high potential evapotranspiration rates; however, least understood is the role that vegetation plays in soil-plant-water dynamics. Vegetation management potentially plays a major role in countering the loss to recharge because evapotranspiration (ET) varies with vegetation type and cover. The conversion from shrubland to grassland likely reduces rooting depths and total plant cover. Subsequently, deep drainage (percolation below the root zone) will likely increase and lead to groundwater recharge, at least temporarily. The primary aims of the study were to identify those biotic and abiotic factors facilitating deep drainage and to examine differences in recharge for the years following clearing of natural shrub vegetation. Soil chloride was examined to estimate long-term recharge rates, since its concentration in the soil is influenced by the movement of water. Short-term soil moisture trends were also monitored for any water movement deep in the soil profile in response to individual rain events. Rooting depths decreased following removal of vegetation; yet root biomass unexpectedly increased due to successful grass establishment during the first five years after treatment. Soil properties did not vary between treatments, indicating that the majority of chloride differences seen were a consequence of vegetation change. Peak and total soil chloride concentrations were expected to decrease and occur deeper in the soil profile 15-30 years following the clearing of woody vegetation. Total chloride decreased by up to 65% after 30 years and resulted in an estimated 14.9 mm/yr more recharge compared to adjacent untreated controls. Evidence in this study suggest that much of this chloride is leached during the first five years following treatment and that more leaching occurs in especially wet periods. During the wet 2007 growing season, soil moisture below the root zone increased by up to 17% after vegetation clearing. The results of this study indicate that hydrologic changes following brush removal were evident in this system and are likely to positively influence groundwater recharge in the long-term.

DEDICATION

To my inspirational wife,

Stephanie Barre

In memory of my mother,

Jacqueline Hall

ACKNOWLEDGMENTS

I would like to thank my committee chair, Dr. Moore, and my committee members, Dr. Boutton and Dr. Hallmark, for their continual guidance, advice and support through the course of this research. Also, thanks to Dr. Keith Owens who provided many ideas, field work and guidance.

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Finally and most importantly, I would like to thank my wife, Stephanie, for believing in me and for her continual support, encouragement, patience and love through the last three years.

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CHAPTER I

INTRODUCTION

In semi-arid regions of the world, aquifers are being depleted because the water withdrawn for human use exceeds the amount returning through irrigation or natural rainfall. Most commonly, over-use by dependent farming practices, especially irrigation, is the primary source of withdrawal. The economic vitality of farming regions around the world depend on sustaining aquifer water supplies. In these semi-arid regions, rates of recharge are quite variable depending on the landscape setting (Harrington et al., 2002; Petheram et al., 2002; Scanlon, 2000; Scanlon et al., 2006), annual rainfall patterns (Kennettsmith et al., 1994; Petheram et al., 2002; Scanlon et al., 2006) and soil characteristics (Cook and Robinson, 2002; Kennettsmith et al., 1994; Petheram et al., 2002; Scanlon, 1992; Scanlon et al., 2006; Scott et al., 2000). In semi-arid regions, deep drainage events, which refer to water that percolates below the root zone, are pulse-driven (McGrath et al., 2007), concentrated mainly during times when vegetation is senescent and/or where rainfall events are higher than average.

This thesis follows the style of Geoderma.

The area of interest for this study is located in the semi-arid region of SW Texas where the average yearly rainfall is about 600 mm (NOAA, 2002), much of which is thought to be intercepted by high potential evapotranspiration rather than allowed to percolate to groundwater (Green et al., 2008; Scanlon, 2000; Scanlon and Cook, 2002). Some studies have examined distributed recharge (Huxman et al., 2004; Jackson et al., 1996; Scanlon, 2000; Scanlon et al., 2002), water-balance (Carlson et al., 1990), groundwater chemistry and the age of aquifer water (Green, 2006) in this region, but until a recent study (Green et al., 2008) investigating groundwater systems, little is known about how land management in SW Texas affects actual recharge rates. The factor least understood is the role which vegetation plays in influencing deep drainage, and subsequent groundwater recharge, on both local and regional scales.

Some studies have examined how changes in vegetative cover effect recharge rates (Huxman et al., 2005; Petheram et al., 2002; Scanlon et al., 2006; Scanlon et al., 2005a). These studies found that vegetation was likely to impact groundwater recharge in semi-arid settings; however, the mechanisms are not well understood. There have been scientists that suggest a change in land-use from forest or shrubs to a grassland will increase the amount of water percolating past the root zone and therefore increase recharge rates (Jobbagy and Jackson, 2004; Kennettsmith et al., 1994; Leduc et al., 2001; Petheram et al., 2002; Poulton et al., 2005; Scanlon et al., 2005b; Tolmie et al., 2004; Walker et al., 1991; Walker et al., 2002).

This study stands apart from related studies of the past because it examines how vegetation affects recharge rates and how soil factors are interrelated with root characteristics to influence drainage dynamics in this system. Soils in the study area that occur within the Carrizo-Wilcox aquifer recharge zone are predominantly of sandy nature and inherently allow for the potential of recharge to occur in the 2,428 km^2 of land where the aquifer outcrops (Green et al., 2008). However, Green et al. (2008) points out that only about one sixth of the outcrop is on extremely sandy soils (Antosa/Bobillo series) with potential for significant recharge rates. Soil properties facilitate both the movement and retention of water. Research by Schenk and Jackson (2005) has shown how rooting depth and texture classes are correlated, which suggests that texture also has an indirect affect on groundwater recharge as it can shape the distribution roots.

Schenk and Jackson (2002a; 2002b; 2005) have also linked 50% and 95% rooting depth to climate and soil texture. Semi-arid shrubs have, on average, 95% of their root biomass in the first 1.3 meters of the soil. Generally grasses in both humid and semi-arid climates will have shallower rooting depths than shrubs. The difference between maximum rooting depth of grasses and shrubs increases with increasing aridity (Schenk and Jackson, 2002b).

A common and useful technique for estimating deep drainage rates is by using soil chloride as a natural tracer, which enters the soil from the atmosphere. 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, 2000; Scanlon, 1991; Scanlon, 1994; Scanlon, 2000; Scanlon et al., 2005b) have used the CMB approach, to varying degrees of precision, in order to identify the maximum extent of wetting fronts as well as recharge rates in semi-arid and arid areas. The CMB method balances chloride inputs via atmospheric deposition, both dry and in precipitation, with the chloride output lost by downward percolation through the soil.

Deep drainage is then estimated from the chloride accumulated in the soil as a result of evapotranspiration relative to the chloride concentration in precipitation (Scanlon, 2000). Accuracy in this method requires quality estimates of atmospheric chloride input, precipitation, and soil pore water chloride content. Recharge estimates are possible if dry and wet deposition from the atmosphere is assumed to be the only source of chloride input. An estimate of deep drainage is calculated by dividing the cumulative amount of chloride down to a depth of interest by the chloride input. Chloride concentrations in the soil profile are inversely proportional to recharge rates.

The aim of this research is to examine differences in deep drainage occurring in the years following the clearing of natural shrub vegetation in the semi-arid region of SW Texas. Firstly, we expect rooting depths to decrease following shrub clearing. Secondly, after examining correlations between soil and vegetation attributes, we will indicate the combined effects of soil and roots on the distribution of chloride in the soil. A predictive model for soil chloride will then be constructed based on the most influential abiotic and biotic variables that drive vertical fluxes of water in this system. We also expect to see an increase in deep drainage where land has been cleared of vegetation as indicated by expected reductions in total soil chloride. Further, in the vegetation chronosequence, local soil moisture trends below the root zone will be compared among treatments during wet and dry periods to determine whether short-term drainage dynamics are an important contributor to long-term cumulative deep drainage. Soil moisture is expected to respond positively to storm events where land has been cleared of shrub vegetation and during years of above average rainfall.

CHAPTER II

EXAMINING CHANGES IN SOIL CHLORIDE FOLLOWING SHRUB REMOVAL AND SUBSEQUENT REGROWTH

Overview

In semi-arid regions, rates of groundwater recharge are especially variable; however, least understood is the role that vegetation plays in soil-plant-water dynamics. Understanding how abiotic and biotic variables affect water movement and associated soil chloride distribution is essential to estimate recharge. The conversion from shrubland to grassland is likely to lead to a decrease in total chloride in the soil through increased leaching if evaporative water losses are less in the grassland than in the original shrubland. Any change that reduces rooting depth and plant cover should theoretically increase water availability, at least temporarily. Soil and root attributes were compared across a vegetation chronosequence at three sites, with each site including a control and two different successional stages of shrub regrowth; 5 and 15 years following removal. Peak soil chloride concentration was hypothesized to be deeper in the soil profile 15 years following shrub removal indicating an increase in deep drainage since treatment. Decreased maximum rooting depth was also hypothesized after conversion of shrubland to grassland. Shrub cover increased over time after clearing and grass cover was greatest in the 5-Year treatment plots, decreasing as shrub species regained dominance. Contrary to expectations, root biomass increased approximately five years following the clearing of shrubs but then subsequently decreased with time. Roots were distributed within shallower depths in earlier successional plots. Soil properties did not vary between treatments, indicating that the majority of chloride differences seen between treatments were due predominantly to changes in vegetation. There was an increasing trend in average depth to peak chloride, in the Control, 15-Year, and 5-Year plots, respectively. Most notably, there was reduced total chloride in both treatments compared to Control plots, suggesting chloride has been flushed from the profile following brush removal, after as little as five years. A step-wise multiple regression model was created based on key attributes and revealed that treatment alone accounted for 24% of the variation in the depth to maximum chloride concentration, whereas an additional 20% of the variation was explained by root depth. The results of this study indicate that hydrologic changes following brush removal were evident in this system within the first five years and this is likely to positively influence groundwater recharge.

Introduction

Vertical fluxes of water in the vadoze zone are driven by both abiotic and biotic processes. Estimating groundwater recharge requires a detailed understanding of how such processes affect deep drainage. Deep drainage refers to water that percolates past the rooting zone of vegetation and is subsequently unavailable for further plant uptake. This water potentially continues to recharge the groundwater or aquifer. In semi-arid regions, rates of recharge are especially variable depending on the landscape position (Harrington et al., 2002; Petheram et al., 2002; Scanlon, 2000; Scanlon et al., 2006), annual rainfall patterns (Kennettsmith et al., 1994; Petheram et al., 2002; Scanlon et al., 2006) and soil characteristics (Cook and Robinson, 2002; Kennettsmith et al., 1994; Petheram et al., 2002; Scanlon, 1992; Scanlon et al., 2006; Scott et al., 2000).

Biotic processes can also exert controls on deep drainage, particularly in semi-arid regions of the world where rainfall is limited and episodic. Least understood, however, is the role which vegetation type and abundance plays in influencing recharge on both local and regional scales. Some studies have examined how changes in vegetation cover effect recharge rates (Huxman et al., 2005; Petheram et al., 2002; Scanlon et al., 2006; Scanlon et al., 2005a). These studies indicate that vegetation is likely to impact groundwater recharge in arid and semi-arid settings; however, it is important to note that soil properties could offset vegetation affects. Both abiotic and biotic processes together impact recharge on the landscape.

Conservative chemical tracers, such as chloride, provide a long-term assessment of vertical fluxes of water in the root zone. Understanding all the parameters associated with deep drainage and how they interact with soil chloride is a key step toward estimating groundwater recharge. Once the influence of soil attributes on water movement and chloride distribution has been taken into account, the effects of a change in the vegetation become more apparent. Figure 1-1 is a theoretical schematic of the interrelationships between vegetation and soil that may influence long-term accumulated water movement. Climate dictates the total amount of water available, and the interaction between vegetation and soils affects how much water is further available for deep drainage. Chloride patterns indicate where water has been removed from the system by evapotranspiration (ET) and recharge can be estimated by the subsequent chloride concentration. The chloride mass balance (CMB) technique is applied to soil chloride concentrations to quantify and differentiate deep drainage and groundwater recharge (Allison and Hughes, 1983; de Vries and Simmers, 2002; Dyck et al., 2003; Edmunds et al., 2002; Gee et al., 2005; Harrington et al., 2002; Heagle et al., 2007; Kennettsmith et al., 1994; Petheram et al., 2002; Sandvig and Phillips, 2006; Scanlon, 2000; Scanlon et al., 2002; Scanlon et al., 2005b; Stephens, 1994; Sukhija et al., 2003; Walker et al., 1991; Walker et al., 2002).

Given that both vegetation and soil influence soil chloride patterns, the effects of one may be masked by variation in the other. Figure 1-1 indicates the direct effect of vegetation on chloride via differences in rooting depth and biomass. Soil characteristics may alter root patterns and cause indirect effects as well. For example, bulk density may limit rooting depth. These same soil characteristics also directly influence soil chloride patterns through their effect on, for example, hydraulic conductivity. It is critical to differentiate the relative impact of changes in vegetation cover on groundwater recharge under varying soil conditions.

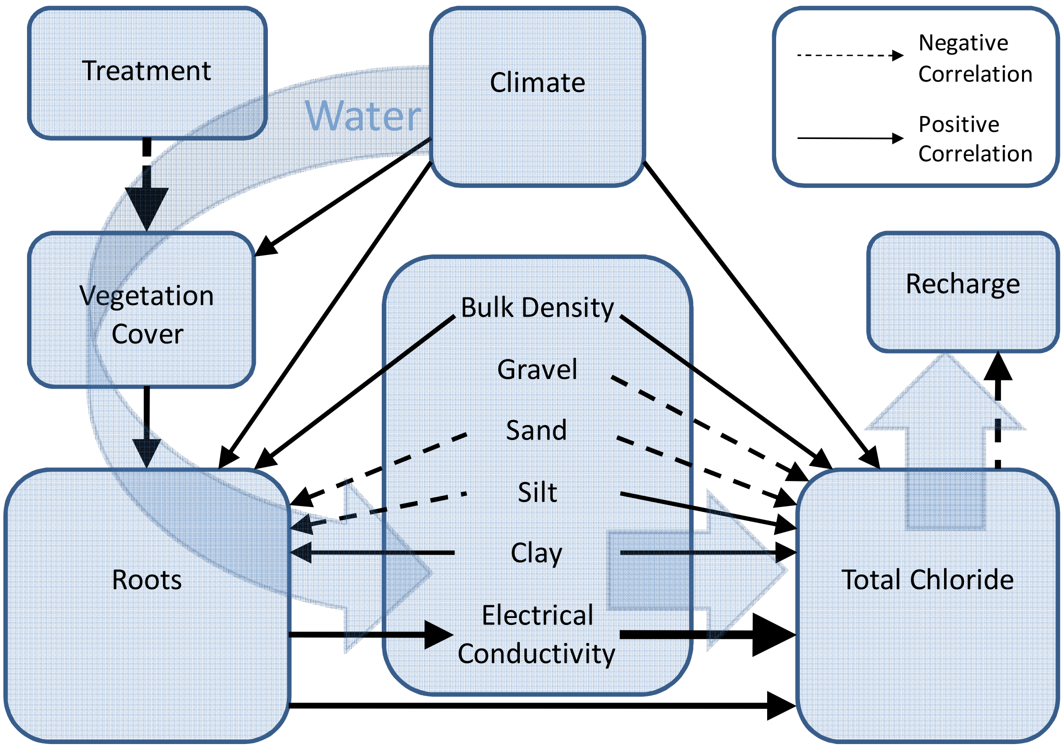


Figure 1-1. Theoretical schematic diagram showing *hypothesized* interrelationships between vegetation and soil attributes and their direct and indirect effects on soil chloride and water movement. Arrows denote the direction and magnitude (thickness) of predicted correlations, either positive (solid) or negative (dotted).

The conversion from one type of vegetation to another through changing land management practices, for example, shrubland to grassland, is likely to lead to an increase in deep drainage if evaporative water losses are less in the grassland than in the original shrubland. Some authors have suggested that a change in land-use from forest or shrubs to a grassland will increase the amount of water percolating past the root zone and therefore increase recharge rates (Jobbagy and Jackson, 2004; Kennettsmith et al., 1994; Leduc et al., 2001; Petheram et al., 2002; Poulton et al., 2005; Scanlon et al., 2005b; Tolmie et al., 2004; Walker et al., 1991; Walker et al., 2002). Any change to grassland from shrubland or forest should theoretically increase water availability, at least temporarily, since shrub clearing reduces rooting depth and plant cover. This negative impact of shrub clearing on rooting depths will provide a greater likelihood for water to percolate to depths beyond the reach of grass roots. The affect of shrub clearing on water use is likely countered, however, by colonizing grass species that could forage this water before it percolates to deeper depths. Without repeat follow-up management the magnitude of difference in deep drainage may diminish if woody plants re-invade the grassland via succession.

A common management tool in rangelands to remove brush and encourage grass growth is “root plowing”. The practice of root plowing, usually adopted to increase pasture and grazing land for cattle, ultimately affects the way in which rainfall is utilized. Once a rangeland is removed of all shrub cover, there is a short period of time before grasses and forbs begin their successional colonization and spread into those areas cleared of woody species. The adaptations of semi-arid vegetation take advantage of any, and possibly all, seasonal rainfall, which in semi-arid environments is periodic and highly variable. Certain hydraulic characteristics of xeric deep-rooted soil-plant systems help assist soil water storage at depth for extended periods, ultimately buffering the vegetation from any harsh drought conditions that may persist at the surface (Seyfried et al., 2005).

Schenk and Jackson (2002a; 2002b; 2005) have established rooting depth distributions for varying biomes globally and have linked the depth which contains 50% and 95% of roots to climate and soil texture. Semi-arid shrubs have, on average, 95% of their root biomass in the first 1.3 meters of the soil profile. It is noted that with increasing aridity and length of the dry season, rooting depth generally increases (Schenk and Jackson, 2002a; Schenk and Jackson, 2005). In Mediterranean shrubland, where rainfall is out of phase (i.e. in Winter) with the summer growing season, 95% rooting depths average 1.7 meters (Schenk and Jackson, 2002a). Prairie and semi-arid steppe have 95% of their roots within the first 0.9 meters and 1.2 meters respectively. Generally grasses in both humid and semiarid climates will have shallower rooting depths than shrubs. The difference between maximum rooting depth of grasses and shrubs increases with increasing aridity (Schenk and Jackson, 2002b).

Soil properties facilitate movement and retention of water. Research by Schenk and Jackson (2005) shows how rooting depth is correlated with texture classes and provides evidence to suggest that texture also has an indirect affect on groundwater recharge as it can shape the distribution of roots (Figure 1-1).

Other factors expected to influence soil chloride, and thus groundwater recharge, include rainfall patterns as well as soil salinity related to marine deposits. In semi-arid regions, recharge events are pulse-driven (McGrath et al., 2007), concentrated mainly during times when vegetation is senescent and where rainfall events are higher than normal.

Increased rainfall, especially during winter months, will promote the flushing of chloride deeper through the soil. Soil salinity affects chloride concentrations in the soil, by contributing salts that will remain in the soil matrix, especially in soil layers where evapotranspiration leaves salts behind. Together observing rooting depths, soil texture and bulk density should be helpful in recognizing the relative importance of these variables on the distribution of chloride in the soil.

In order to predict deep drainage after changes in land management by using soil chloride as a natural tracer, it is important to know how rooting distributions and soil properties affect chloride build-up and removal in the soil. Increased root biomass, rooting depth, clay, silt and electrical conductivity should *positively* influence chloride build-up and concentration in the soil (Figure 1-1). Increased gravel, bulk density and sand should *negatively* influence chloride build-up and therefore be a catalyst for the downward movement of chloride (Figure 1-1). The most useful way to understand the interrelationships between these variables on the distribution of chloride is to examine their role collectively using a multivariate model.

The aim of this study is to identify, quantify, and inter-relate key abiotic and biotic factors that lead to differences in soil chloride, and thus influence deep drainage in a semiarid rangeland. Peak soil chloride concentration is expected to move lower in the soil profile by 15 years following shrub removal. Furthermore, maximum rooting depth is expected to be shallower after conversion of shrubland to grassland, which should be associated with less total chloride in the soil profile. Soil abiotic factors expected to affect soil chloride include bulk density, gravel, texture, and electrical conductivity. Root depth distribution and root biomass are the belowground biotic factors investigated. Abiotic and biotic attributes were compared across a vegetation chronosequence, including a mature shrub control plot and two different stages of shrub regrowth; five and 15 years following shrub removal. A predictive model for soil chloride will then be constructed based on the most influential abiotic and biotic variables that drive vertical fluxes in this system.

Methods

Site Description

The study area was located at the 162 hectare Northcut Ranch in La Salle County, Texas (coordinates 28° 27' 03" N, 99° 11' 02" W). Three treatment plots and a control were established at three separate sites on the ranch to represent a successional chronosequence, in which time is substituted for space, for a total of twelve experimental plots (each plot measured 15 x 15 meters). The control plots were a native, undisturbed stand of rangeland brush dominated by mature honey mesquite (*Prosopis glandulosa*) and C4 grasses. The three treatments were plowed of vegetation using a horizontal blade that cuts the roots 30 cm below ground level. Each were plowed at different times in the past (2005, 2001 and 1991) and subsequently allowed to re-grow. This root plowing process is a common management practice in this region to temporarily remove woody vegetation and increase grass production. Thus, the treatment plots represent vegetative regrowth after one, five and 15 years.

Vegetation

Two survey methods were adopted to describe the aboveground vegetation pattern represented in each of the twelve study plots: line transects and quadrats. Observations were made at all study plots between August 22-24, 2006 and so represent the relative growth distribution for that period. 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 cover for every species 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. Further ground cover classification was achieved using five 0.25m^2 quadrats spaced 3 m apart on alternating sides of each line transect. The center of the first quadrat was randomly selected within the first 3 m of the transect. Ground cover was sampled as a relative percentage of each quadrat and classified in terms of bare ground, litter and plant species. The species were further classed into four vegetation types: grasses, forbs, saplings and cacti. Saplings (woody species including trees and shrubs) and cacti were not sampled in the line transect if they were less than 30 cm high, instead were placed into the ground cover classification.

Soils

The majority of soils in the study area are moderately permeable, deep to very deep sandy loam soils in a gently undulating landscape. Soils in the local area belong predominantly to the Duval (Aridic Haplustalfs) and Webb (Aridic Paleustalfs) series, with a minor area of the Dilley (Ustic Haplargids) series. Over a period of one week in April 2006 and two weeks in July 2006, two soil cores were collected from each plot within each of the three sites, not including the three 1-Year sites, for a total of 18 replicate cores. A soil auger (Giddings Machine Company Inc., Windsor, CO), mounted on either the back of a tractor or trailer, was used to excavate 50-mm diameter cores from depths up to 4.2 m. The exact depth of each soil core was limited by the depth to rock or other impenetrable layer encountered, such as gravel or highly-compacted silt. The distance between the two cores within each plot was approximately 2 m.

Each soil core was sampled in 10-cm depth increments; however, not every increment of the core was analyzed. Since most of the chloride variability was expected to occur in the first 2 m, increments were spaced further apart with depth accordingly: 10, 20, 40, 60, 80, 100, 120, 140, 160, 180, 210, 240, 270 cm, etc. The number of samples per core ranged from nine to 18, depending on the total depth. If possible, the bottom 10-cm increment was sampled even if it fell outside the sampling protocol depths. Field soil morphology observations were also made, including any calcium carbonate, color, mottles and soil structure, in order to aid soil classification once laboratory data had been obtained. The 1-Year plots were not cored because it was unlikely adequate time had passed to alter the distribution of soil chloride.

Soil samples were used to characterize a variety of soil descriptive parameters including bulk density, gravel fraction, particle size, fine roots, pH, electrical conductivity (EC) and chloride content. 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 derived from auger tube dimensions. 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, 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. Subsamples for particle size were taken from depths 0-10, 10-20, 30-40, 50-60, 110-120, 150-160 and 200-210 cm. Root subsamples were analyzed for depths 0-10, 10-20, 30-40, 50-60, 70-80, 90-100, 110-120, 150-160, 200-210, 260-270, 320-330 and 380-390 cm. Subsamples for aqueous extract were ground on a custom roller grinder (Kansas State University, Department of Physics) for 4 hr prior to their further analysis. Particle size analysis on the 60 g subsamples was performed using the hydrometer method.

Eleven soil parameters were identified for each pedon that best describe the soil and which could be used as variables to compare between treatments in order to identify the affects of clearing woody vegetation. Bulk density, percent sand, percent silt and percent clay were averaged over all the sampled depths in each profile. A minimum and maximum value was also assigned to each profile for bulk density. Percent sand, percent silt and percent clay at 50 cm were used as an indicator of texture in the top of the B horizon. Two values for electrical conductivity were assigned for each profile; the actual maximum EC value in the profile and the depth (in centimeters) at which this maximum value occurs.

Root Analysis

Subsamples from the homogenized bulk soil sample allocated for fine roots (50 cm^3 equivalent) were wet-sieved using a 500-µm screen to remove any particulate matter, including clay, silt and fine sand. Roots were further isolated from coarse sand using flotation. These fine root subsamples (< 2 mm soil fraction) were oven-dried at 60° C to a constant mass, weighed, and then used to extrapolate a total root biomass for the entire sample.

Large roots isolated from the bulk samples, using the 2-mm sieve, were also washed using the same technique as above. Roots greater than 1 mm in diameter were dried and weighed separately and identified as the coarse root fraction of the sample. Coarse root biomass was added to the totals calculated for fine roots in the subsamples described above.

With root data measured at up to twelve discrete depths (according to the depth of the profile), root biomass for the remaining depths in each profile was interpolated using a fitted non-linear inverse curve; $M = a / D + b$, where M is the root biomass at depth (D) and both a and b are unique constants for each curve. Using the measured and interpolated biomass values a complete root distribution was projected for each of the pedons and subsequently eight root attributes assigned for analysis. Four attributes related to the biomass values: total root biomass, fine root biomass, total root biomass to the depth of maximum soil chloride and fine root biomass to the depth of maximum soil chloride. Four additional attributes were assigned according to cumulative root biomass values: these where depths within each profile above which 50% and 95% of fine roots and total roots occurred.

Aqueous Extract Analysis

The 50 g ground samples allocated for aqueous extracts were 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 100 ml of distilled water were added and noted. The 1:2 soil water slurry (similar to that used by Dyck et al., (2003)) was then left to settle for approximately 30 minutes and electrical conductivity measurements recorded (Model HI 98311, Hanna Instruments, Woonsocket, RI). pH readings were taken on a separate sub sample of this extract using a hand-held unit (Ecosense pH10, YSI Incorporated, Yellow Springs, OH), since the unit used KCl to measure pH and could subsequently alter chloride results. The soil slurry was then filtered through a Bachar Funnel with a #2 Whatman filter using a vacuum flask. The water extract was analyzed by the New Mexico Bureau of Geology and Mineral Resources for chloride using the ion chromatography method. Dilutions done in the lab to produce the water extracts for chloride were then calculated back to undiluted concentrations depending on the dilution used and then further converted to pore-water chloride concentrations using gravimetric water content at the time of sampling.

Statistical Analysis

An analysis of variance (ANOVA) and post-hoc multiple comparison analysis (Fisher's LSD) was performed, using SPSS v.14.0, to identify the direct effects of treatment on vegetation cover and ground cover. Treatment and control plots were pooled from all three sites in order to perform the comparison (n = 6 for each treatment). Indirect treatment effects on the 11 soil and eight root attributes stated above were also tested using ANOVA and Fisher's LSD post-hoc analysis.

The depths of maximum soil chloride between treatment profiles and control profiles for all sites were compared using ANOVA. Total chloride to a depth of 205 cm was compared between each treatment plot and the control plot for each site also using ANOVA. The depth of 205 cm was assigned since this represents the deepest depth shared by all profiles.

A correlation matrix, using Pearson's Correlation coefficient, was constructed of all possible bivariate comparisons between root and soil characteristics. This was done in order to help identify any direct or indirect relationships of vegetation management with water movement through the soil (see hypotheses in Figure 1-1). The strength of significance ($p < 0.01$, 0.01-0.05, 0.05-0.1) and the correlation coefficient (*R*) were noted. Those variables deemed significant in the bivariate comparisons were used to formulate a multiple regression model that could be used to predict chloride distribution in the soil, in particular the depth of maximum chloride concentration.

A multiple regression analysis was performed to indicate which soil and root attributes (dependent variables) account for variation in the depth of maximum soil chloride (independent variable). A step-wise procedure (sequential variable selection) was performed using specific variables related to chloride distribution in the soil based on bivariate comparisons. Specified parameters were selected for stepwise regression only if they met assumptions of normality, independence, and multicolinearity. The best model was selected using Mallow's Cp statistic and cross-validated using Baysian Information Criterion (Ramsey and Schafer 1997). An extra sum of squares F-test was then used to compare the best model with other potentially relevant models (Ramsey 1997). The percentage of response variation explained by the model (coefficient of determination) was reported as the adjusted R^2 to account for the number of parameters.

Results

It is evident from the vegetation chronosequence that root-plowing of native rangeland affected shrub cover and plant composition (P < 0.05) for 15 years at this study location. In the undisturbed control plots, shrub cover averaged 66%; whereas, in the plots that were root plowed 1, 5 and 15 years previously cover was 0%, 3% and 27% (Figure 1-2), respectively. Mesquite accounted for 0%, 2%, 19% and 41% of the total shrub cover in the 1, 5 and 15-Year plots, respectively. Cacti were not affected by treatment (P > 0.05), having cover of 7%, 7% and 8% in the 5-Year, 15-Year and Control plots, respectively (data not shown).

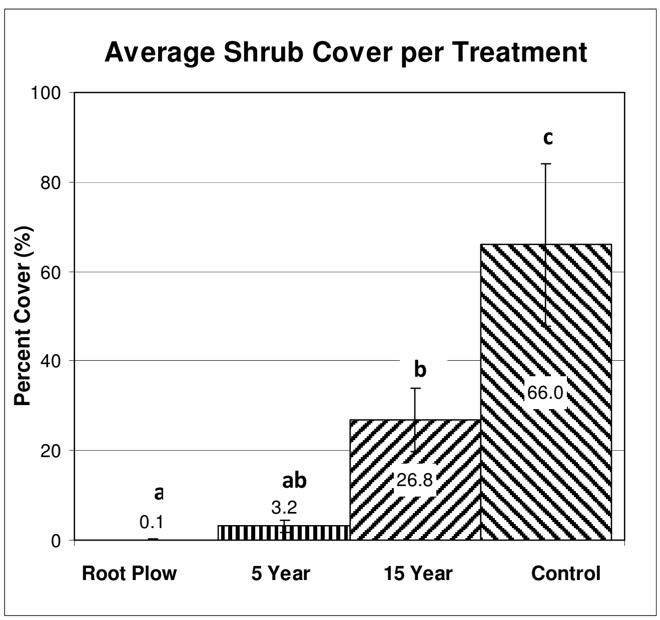


Figure 1-2. Percent shrub cover by treatment across all plots. Mean values are given for each, along with standard error bars. Letters above bars denote differences using multiple comparisons ANOVA (p < 0.05).

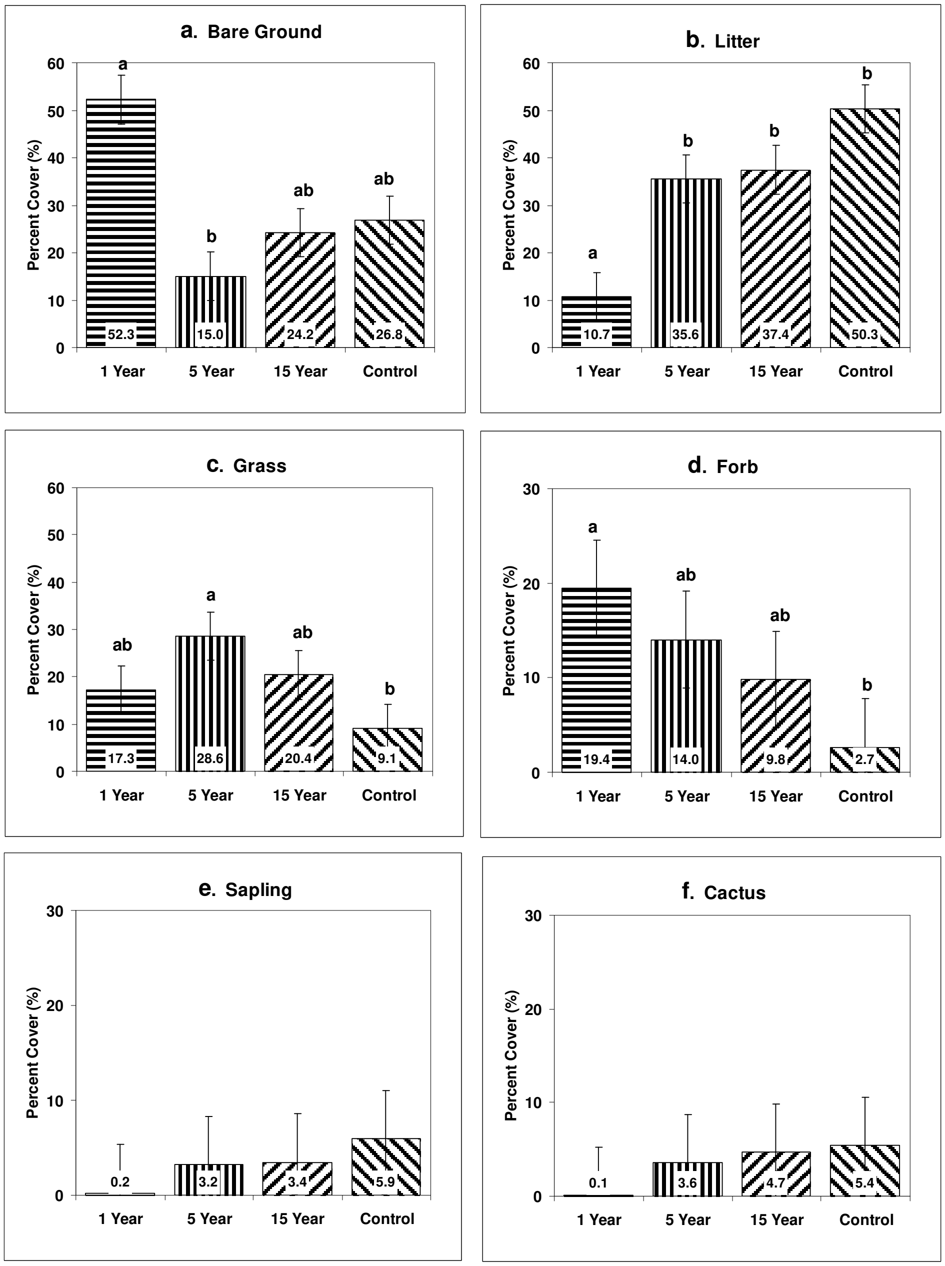


Figure 1-3. Percent ground cover, comparing treatments, for all six categories: bare ground (a); litter (b); grasses (c); forbs (d); saplings (e); and small cacti (f). Mean values are given for each, along with standard error bars. Letters above bars denote differences using multiple comparisons ANOVA ($p < 0.05$). There were no differences between treatments for saplings or cacti.

Figure 1-3 shows the relative proportions of herbaceous cover, litter and bare ground for each of the three treatments and the control, averaged between sites. Bare ground decreased substantially from 52% to 15% ($P < 0.05$) in the first 5 years after root-plowing and then increased to 24% by 15 years, which is consistent with the control plot average of 27%. Litter increased significantly within 5 years since treatment from 11% at 1-Year to 36% in the 5-Year plots ($P < 0.05$) and ground cover of forbs decreased with time since treatment from 19% in the 1-Year plots down to 3% in the control ($P < 0.05$). Grass cover peaked 5 years after treatment at 29%, having increased from 17% the year following root-plowing, and then decreases to the cover seen in the control plots of 9%. Percentage of grass cover differs significantly between the 5-Year plots and the control plots ($P < 0.05$). Juvenile shrubs and cacti did not differ significantly between 5-Year and 15-Year treatments. They made up only about 4% each of the total ground cover at both 5 and 15 years since treatment compared to around 6% in the control plots.

Both total root biomass and fine root biomass increased after brush clearing (Figure 1-4a). Total root biomass to the total depth of the soil core in the control plots was significantly lower than that of 5-Year plots (543 g/m^2 and 1013 g/m^2 respectively; $P < 0.05$). Fine root biomass showed a similar pattern, decreasing with successional stage. Neither total root biomass nor fine root biomass differed significantly between 5-Year and 15-Year plots, or between 15-Year and Control plots, but a trend showed a decrease in biomass over time since treatment. Pooling root data from all 18 cores, fine root biomass on average made up 85.4% of total root biomass. Cumulative biomass to the depth of maximum chloride concentration for both total roots and fine roots followed a similar trend to total biomass since the majority of the root biomass was contained within the depth to maximum chloride. Root profile characteristics are given for all cores in Table 1-1.

Rooting depths in both total roots and fine roots were altered after brush clearing, but only for the 50% rooting depths (Figure 1-4b) and not for 95% rooting depths (Figure 1-4c). Although average rooting depth was deeper in control plots than 5-Year plots, 151.7 cm and 121.7 cm respectively, this difference was not significant ($P > 0.05$). The 50% rooting depth for total roots changed from 20 cm in the Control plots to 10 cm in the 5-Year plots ($P < 0.05$). For fine roots, the pattern was the same, with 50% rooting depths in the Control and 5-Year plots being 20 cm and 8.3 cm respectively ($P < 0.05$).

When looking at 95% rooting depths, the mean depth of fine roots for the 15-Year plots was about 83% of the mean depth for total roots. In the 5-Year plots this same depth ratio of fine roots to total roots was 96%. This suggests that by 15 years the coarse root fraction is rooting deeper, most likely from woody species in search of deeper sources of water. Surprisingly the two deepest rooting profiles were sampled from the 5-Year plot at Site T1 and the 15 Year plot at Site T2, where 95% of total roots extended to 265 cm. These two profiles provided much of the variability that can be seen for the 5 Year and 15 Year plots. Interestingly, the fine root fraction in the deeply rooting 15-Year core at

Site T2 only extended to 135 cm, and at the 5 Year plot at Site T1 fine roots were found down to 215 cm, leaving coarse roots to extend to deeper depths.

Table 1-1. List of root characteristics, sampling date, and total profile depth for all eighteen profiles by site, treatment, and profile replicate. Total roots and fine roots (<1 mm) are described by the depth to which 50% and 95% of the roots were found (cm), the total root biomass (g/m^2) to the Total Depth of the profile, and the total root biomass to the depth of peak chloride concentration (g/m^2).

Site	Treatment	Profile	Date	Total Depth	Total Roots				Fine Roots			
					Rooting Depth (cm)		Biomass (g/m^2)		Rooting Depth (cm)		Biomass (g/m^2)	
				cm	50%	95%	Total	To Peak Cl	50%	95%	Total	To Peak Cl
T1	Control	A	4/12/2006	330	25	175	346.2	340.3	15	115	289.7	289.7
T1	Control	B	7/13/2006	390	15	225	316.3	316.3	15	175	250.5	250.5
T1	15 Year	A	4/12/2006	240	15	105	376.1	376.1	15	105	367.4	367.4
T1	15 Year	B	7/14/2006	360	15	205	790.1	790.1	15	195	559.1	559.1
T1	5 Year	A	7/12/2006	420	15	175	1399.5	1399.5	15	175	1146.6	1146.6
T1	5 Year	B	7/12/2006	410	25	265	677.6	674.2	15	215	435.6	434.5
T2	Control	A	4/12/2006	295	15	85	348.2	347.6	15	85	329.2	328.6
T2	Control	B	7/17/2006	265	15	115	305.8	304.2	25	115	283.2	281.6
T2	15 Year	A	4/11/2006	260	15	125	1145.4	1145.4	5	125	1112.0	1112.0
T2	15 Year	B	7/14/2006	350	15	265	588.9	588.6	15	135	458.6	458.3
T2	5 Year	A	7/17/2006	420	5	105	1245.0	1245.0	5	105	1089.1	1089.1
T2	5 Year	B	7/17/2006	420	5	75	1020.0	1020.0	5	75	897.3	897.3
T3	Control	A	7/18/2006	225	25	155	974.1	952.7	25	155	815.6	796.3
T3	Control	B	7/19/2006	300	25	155	968.0	959.5	25	155	854.0	846.4
T3	15 Year	A	7/19/2006	260	15	45	884.1	467.8	15	45	546.7	445.2
T3	15 Year	B	7/19/2006	390	25	165	1198.4	1197.9	25	145	1121.3	1121.0
T3	5 Year	A	7/18/2006	330	5	65	818.7	818.7	5	65	781.7	781.7
T3	5 Year	B	7/18/2006	300	5	45	915.5	915.5	5	45	915.5	915.5

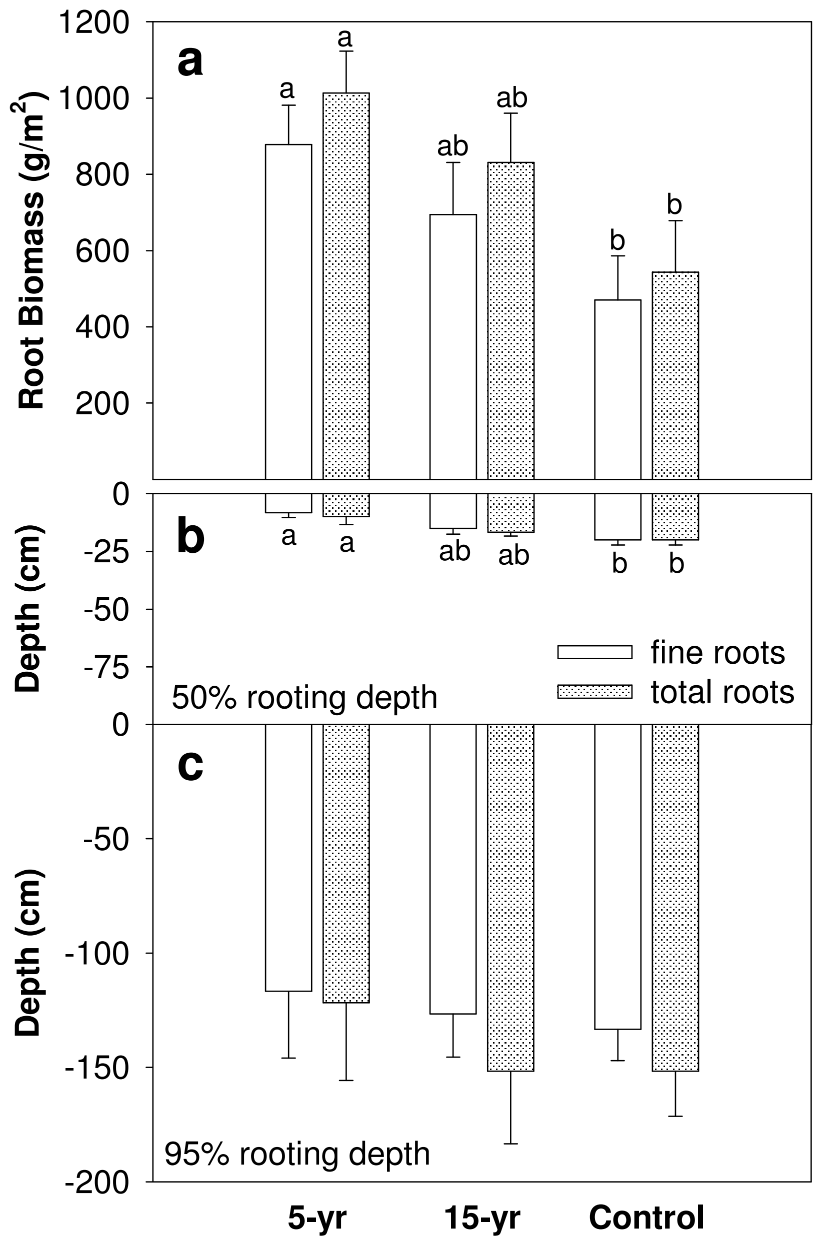


Figure 1-4. Differences between fine roots (<1 mm) and total root biomass for 5-Yr, 15-Yr and Control treatments in g/m^2 to the depth of soil core (a); 50% Rooting Depths (b); and 95% Rooting Depths. Mean values are given for each bar, along with standard errors. Letters above or below bars denote significant differences at $p < 0.05$ using multiple comparisons ANOVA.

Table 1-2. The range of observed soil properties for the eighteen individual cores, including bulk density, texture, and electrical conductivity. Both the total depth of each core and the observed depth to peak electrical conductivity are given.

Site	Treatment	Profile	Date	Total Depth	BD (g/cm^3)			Sand (%)		Silt (%)		Clay (%)		EC (µS/cm)	
				cm	min	mean	max	50cm	mean	50cm	mean	50cm	mean	max	depth (cm)
T1	Control	A	12/04/2006	330	1.2	1.7	2.0	62	63.8	12	13.8	26	22.4	665	325
T1	Control	B	13/07/2006	390	1.4	1.8	2.3	56	61.4	16	14.8	28	23.8	1269	325
T1	15 Year	A	12/04/2006	240	1.2	1.5	1.9	56	63.5	14	13.5	30	23.0	249	135
T1	15 Year	B	14/07/2006	360	1.3	1.8	2.3	49	60.5	15	16.2	36	23.3	413	265
T1	5 Year	A	12/07/2006	420	1.0	1.7	2.3	61	64.0	13	13.6	26	22.4	3582	415
T1	5 Year	B	12/07/2006	410	1.3	1.7	2.3	55	61.8	18	14.3	27	23.9	1215	405
T2	Control	A	12/04/2006	295	1.0	1.5	1.9	56	54.2	18	19.3	26	26.4	7980	175
T2	Control	B	17/07/2006	265	1.4	1.8	2.2	46	50.3	19	20.3	35	29.4	6660	205
T2	15 Year	A	11/04/2006	260	0.9	1.5	2.0	62	63.0	13	14.7	25	22.3	572	255
T2	15 Year	B	14/07/2006	350	1.2	1.7	2.3	65	66.4	9	10.0	26	23.6	260	345
T2	5 Year	A	17/07/2006	420	1.2	1.7	2.1	58	58.4	17	18.9	25	22.8	9105	325
T2	5 Year	B	17/07/2006	420	1.4	1.8	2.2	60	58.5	15	15.0	25	26.5	1864	385
T3	Control	A	18/07/2006	225	1.1	1.5	2.1	24	27.7	26	23.5	50	48.8	964	220
T3	Control	B	19/07/2006	300	1.0	1.5	2.1	22	20.3	21	25.1	57	54.6	1375	235
T3	15 Year	A	19/07/2006	260	1.3	1.7	2.4	53	62.9	14	9.0	33	28.1	159	5
T3	15 Year	B	19/07/2006	390	1.1	1.7	2.1	50	58.4	17	15.6	33	26.0	864	355
T3	5 Year	A	18/07/2006	330	0.9	1.5	2.2	8	18.8	31	36.4	61	44.8	1358	205
T3	5 Year	B	18/07/2006	300	0.8	1.4	2.3	29	24.7	12	27.4	59	48.0	669	205

Soil classification was variable between sites across the study area and was found to slightly vary morphologically between treatment plots, within each site (Appendix A). Table 1-2 summarizes soil characteristics for each core. Within-site variation in soil attributes was minor in most cases. The only differences observed within site T1 was that the depth to maximum EC was deeper in the 5-year plot than the 15-year ($P < 0.05$). Likewise, within site T2, the depth to max EC was deeper in the 5-year plot than the Control ($P < 0.05$). Mean sand percentage within site T2 was higher in the 15-Year plots than the Control plots ($P < 0.01$). Site T3 displayed the most variation, in mean bulk density, mean sand and mean clay between the 15-Year plot and the Control ($P < 0.01$) and between the 5-Year and Control plots ($P < 0.01$). In effect, the 15-Year plot at Site

T3 did not differ in average texture from the other two sites ($P > 0.05$), rather it was the Control and 5-Year plots at Site T3 that differed in texture from all other plots in the study. The average clay content for the Control and 5-Year plot at Site T3 was approximately double that of the average for all other plots in the study (see Table 1-2). When pooling soil data from all three sites, however, it was only average silt that varied between treatments ($P < 0.05$), and only between the 5-Year and the 15-Year.

Soil chloride profiles for each site are given in Figure 1-5 and show the chloride concentration in the soil with depth. The two cores within each plot are shown separately, for a total of six profiles at each site. Variation occurs between the paired chloride profiles within treatment plots, even though cores were taken only meters apart (e.g. Figure 1-5a, Site T1 Control). Differences in the depth of peak chloride concentration between plots for each site are of most interest; however, when sites are pooled, no differences were found between treatments despite the apparent differences in means. Overall, depth to peak chloride concentration was shallower in the Control (216 cm ± 23.2 cm) than the 5-Year plots (315 cm ± 33.5 cm) but at the <0.1 significance level. At Site T2, peak chloride concentration increased in depth following treatment (Figure 1-5c), between mean values in the 5-Year plot (325 cm) and the Control plot (165 cm). There was no difference in the depth of the peak chloride concentration between treatment plots at Sites T1 and T3 but with a greater number of profiles sampled, differences could possibly be detected. Maximum chloride concentration showed significant variation between the 5-Year plot and the Control plot at Site T2 (P <

0.05), but no significant could be detected between treatments at Sites T1 and T3. When treatments were pooled for all three sites, maximum chloride concentration was higher in 5-Year plots than in 15-Year plots (1057 ± 411 mg/L and 253 ± 113 mg/L respectively; $P < 0.05$). Interestingly, total soil chloride differed between treatment plots and the control when pooled for all three sites. Mean values for 5-Year plots (1078 ±615 kg/Ha) and 15-Year plots (1151 ± 547 kg/Ha) were similar in value, but the total chloride in the

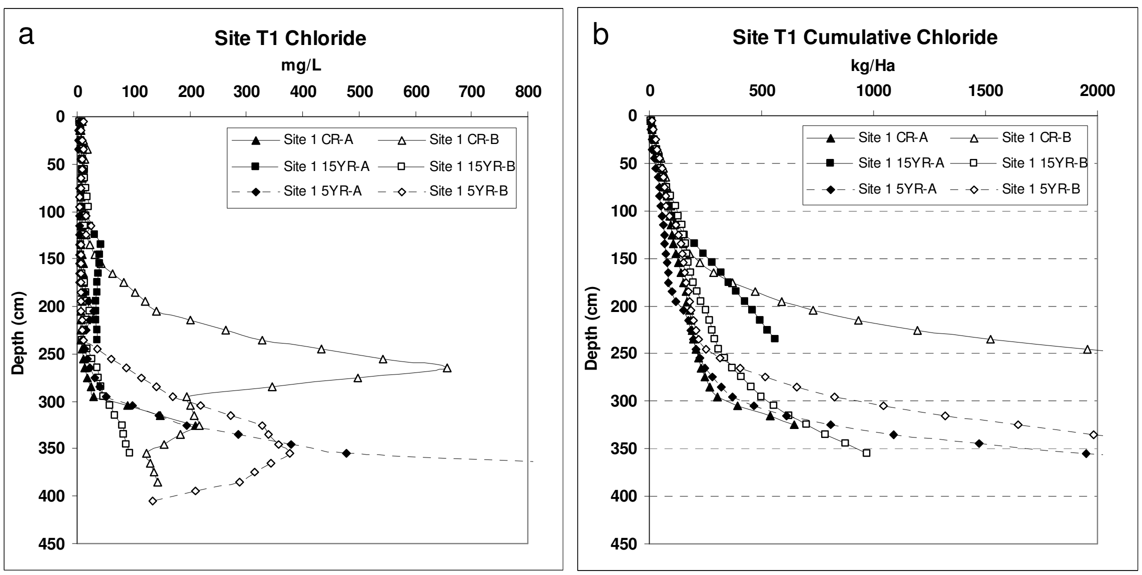


Figure 1-5. Chloride concentrations (in mg/L) and cumulative chloride (in kg/Ha) with depth at sites T1 (a, b) for 5-Year (dotted line), 15-Year (broken line) and control (solid line). Two separate profiles in each plot are denoted with closed symbol for A and open symbol for B profiles. The x-axis in each graph has been truncated in order to see differences in lower concentrations. Maximum chloride concentration for Site T1 was 1954.8 mg/L, which was at 415 cm in profile 5YR-A. Maximum chloride concentration for Site T2 (see page 32) was 2513.6 mg/L, which was at 385 cm in profile 5YR-A.

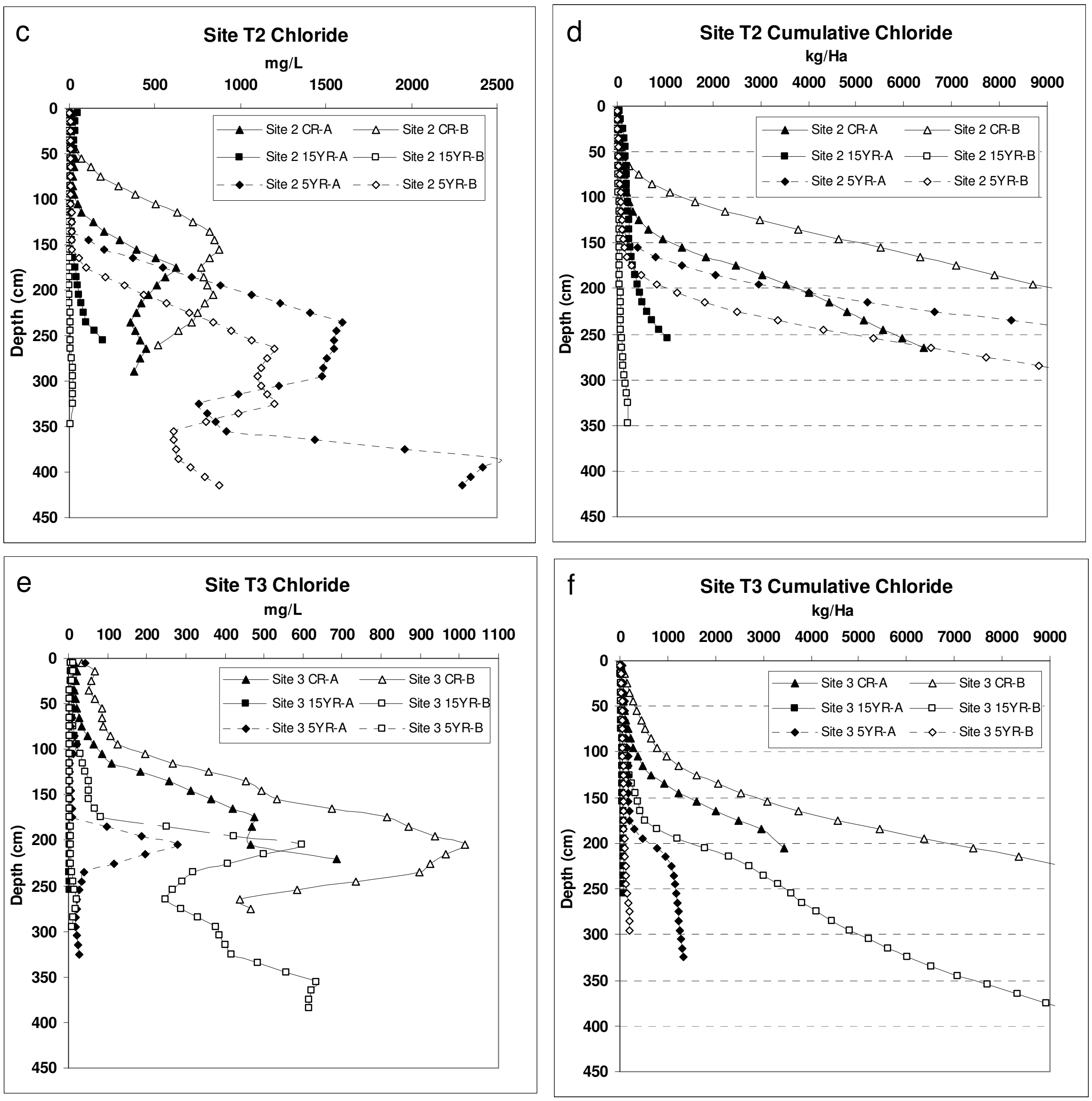


Figure 1-5 Continued.

Control plots (4201 ± 1499 kg/Ha) were higher than both the 5-Year and 15-Year treatment plots ($P < 0.05$).

Correlations between vegetation and soil attributes are given in a matrix (Table 1-3) and presented in Figure 1-6 as a modified version of Figure 1-1. Minimum and average BD was well correlated with particle size, primarily average sand, silt and clay percentages, as well as sand and clay percentages to 50 cm. Depths to maximum EC and maximum chloride were significantly correlated. Depths to both 95% fine and 95% total roots were correlated with depth to maximum EC and maximum chloride.

There was convincing evidence that depth to maximum Cl "bulge" was associated with both time since root plowing (treatment) and the maximum rooting depth (Total95). The bulge was significantly lower after 5 years (p=0.04) and marginally lower after 15 years (p=0.06). The bulge coincided with the root zone; whereby, for every 1 mm deeper the roots penetrate, the bulge lowered by about 0.9 mm (p=0.005). The final multiple regression model explained 44% of the variation in the depth to maximum chloride concentration. After accounting for differences due to rooting depth alone, brush clearing accounted for an additional 24% of the variation. The selected parameters and interaction terms for stepwise regression were: Av BD, Clay Av, treatment, Total95, Av BD:treatment, Av BD:Total95, Clay Av: treatment, Clay Av:Total95, and treatment:Total95 (see Table 1-3b for parameter descriptions). The final model took the general form of MaxClDepth ~ *f*(treatment + Total95).

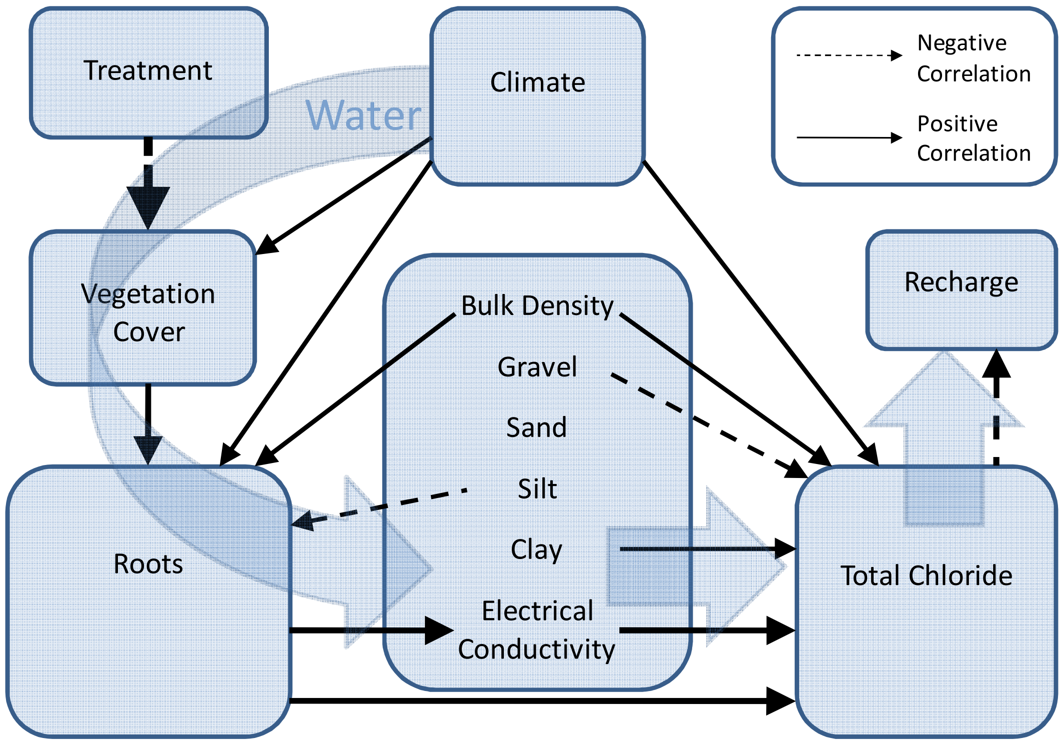


Figure 1-6. Schematic diagram, modified from Figure 1-1, to show the *observed* correlations and interrelationships between vegetation and soil attributes and their direct and indirect effects on soil chloride and water movement. Arrows denote the direction and magnitude (thickness) of predicted correlations, either positive (solid) or negative (dotted). As expected, vegetation treatments had a very strong negative impact on vegetation cover. There were strong positive relationships among vegetation cover, roots, and chloride. Electrical conductivity was also tightly coupled with roots and chloride. Contrary to expectations, sand and silt were not related to total chloride; sand and clay were not related to root distribution.

Table 1-3. Correlation matrix providing relationships between root and soil characteristics. R-coefficients are given for only those relationships that were significant at a p<0.1 level. Those correlations not significant are denoted "ns" and confounded correlations with inherent relationships denoted "x". Parameter explanations are detailed in Table 1-3b.

	Total50	Total95	Fine50	Fine95	Fine	Fine to Peak Cl	Total	Total to Peak Cl	Max EC Depth	Max EC	Min BD	Av BD	Max BD	Sand 50cm	Sand Av	Silt 50cm	Silt Av	Clay 50cm	Clay Av	Max Cl Depth	Max Cl	Cum. Cl to 205cm
Total50		x	x	x	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Total95			x	x	ns	ns	ns	ns	0.63	ns	ns	0.43	ns	ns	ns	ns	-0.41	ns	ns	0.50	ns	ns
Fine50				x	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.53
Fine95					ns	ns	ns	ns	0.58	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.51	ns	ns
Fine Root Biomass						x	x	x	ns	ns	-0.49	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Fine to Peak Cl							x	x	ns	ns	-0.50	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Total Root Biomass								x	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Total to Peak Cl									0.43	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.45	0.42	ns
Max EC Depth										ns	ns	0.44	ns	ns	ns	ns	ns	ns	ns	0.89	0.47	ns
Max EC											ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Min BD												x	x	0.42	0.49	ns	-0.53	-0.47	-0.42	ns	ns	ns
BD Av													x	0.51	0.60	ns	-0.53	-0.54	-0.59	ns	ns	ns
Max BD														ns	ns	ns	ns	ns	ns	ns	ns	ns
Sand 50cm															x	x	x	x	x	ns	ns	ns
Sand Av																x	x	x	x	ns	ns	ns
Silt 50cm																	x	x	x	ns	ns	ns
Silt Av																		x	x	ns	ns	ns
Clay 50cm																			x	ns	ns	ns
Clay Av																				ns	ns	ns
Max Cl Depth																					0.41	ns
Max Cl																						ns
Cum. Cl to 205cm																						

ns	not significant
x	confounding relationship

Table 1-3b. Description table for the parameters detailed in Table 1-3.

Parameter	Description
Total50	Depth above which contains 50% of total roots
Total95	Depth above which contains 95% of total roots
Fine50	Depth above which contains 50% of fine roots
Fine95	Depth above which contains 95% of fine roots
Fine Root Biomass	Fine root biomass in profile
Fine to Peak Cl	Fine root biomass contained above the depth of peak chloride concentration
Total Root Biomass	Total root biomass in profile
Total to Peak Cl	Total root biomass contained above the depth of peak chloride concentration
Max EC Depth	Depth of maximum electrical conductivity
Max EC	Maximum electrical conductivity in profile
Min BD	Minimum bulk density in profile
BD Av	Average bulk density of profile
Max BD	Maximum bulk density in profile
Sand 50cm	Percentage of sand in texture at 50 cm
Sand Av	Average of sand percentage for entire profile
Silt 50cm	Percentage of silt in texture at 50 cm
Silt Av	Average of silt percentage for entire profile
Clay 50cm	Percentage of clay in texture at 50 cm
Clay Av	Average of clay percentage for entire profile
Max Cl Depth	Depth of maximum chloride concentration
Max Cl	Maximum chloride concentration in profile
Cum. Cl to 205cm	Cumulative chloride concentration to a depth of 205 cm

Discussion

The effects of clearing woody shrubs on ground cover, rooting distributions and on the dynamics of deep drainage were evident in this study for the vegetation chronosequence investigated. The lasting effects of reduced aboveground cover and changes in belowground root distributions (Figure 1-4) were associated with long-term reductions in soil chloride, which indicate likely increases in deep drainage. Five years following treatment, 50% rooting depths were shallower and total chloride was much lower than in those plots not treated. Although some evidence suggests the differences remained for at least fifteen years, changes were most dramatic within five years of treatment.

We observed large differences in aboveground vegetation within the brush management chronosequence that correlated with observed differences in soil chloride profiles. By 15-Years post-treatment, grasses evidently were being replaced by woody species (Figure 1-2). The percent cover of shrub re-growth in our study of 27% (± 10%) after 15 years was also comparable to that observed by Grant and co-workers (1999), who established a timeline for re-growth following root-plowed shrubland in Southwest Texas and found the same level of cover reoccurs after approximately 14 years. Their model predicted the pre-treatment canopy cover of approximately 65% to return after around 25 years. The chronosequence year in which peak grass cover occurred was not determined in our study, but it was evident that the C4 grass species responded positively to above average yearly rainfall two years post treatment whereby grass cover greatly exceeded the measured values one year previously (D. Barre, personal observation). It is unknown to what extent shrub cover may have changed in the Control plots in the past 15 years; however, Control plots possibly experienced further woody plant encroachment, as is common throughout Texas rangelands (Asner et al., 2003).

Bare ground decreased significantly in the 5 years following treatment (Figure 1-3), since during the initial phase following the disturbance, the grasses were likely able to take advantage of the increased moisture availability in the absence of woody competition. We attribute decreased grass cover between 5 and 15 years to increasing competition with the emergent woody species. Whether the reduced grass cover is due to limited light or water resources, grass cover in the control plots averaged only 9%, illustrating the dominance of woody species in this region and the significance of woody encroachment on community structure.

With the evident change in plant community structure aboveground at different times after disturbance, there is an ensuing response of shrub clearing on belowground root morphology and distribution. Although both root biomass and 50% rooting depths differed between treatment plots and the control plots, the ratio of fine roots to total roots (about 0.85) remained consistent between treatments. As hypothesized, root profile patterns differed among treatments. Furthermore, the affect of roots distribution on depth to peak chloride depended upon treatment, as indicated by the multiple regression model. Note that the root processing procedure hindered the distinction between living and dead "relic" roots, which may have been more prevalent following treatment.

As reported earlier, fine roots extend deeper in the profile after five years than after fifteen years since clearing. An explanation for this could be that “relic” fine roots associated with the shrubs, which existed prior to removal, may not have had sufficient time to decompose. Whereas, after 15 years (e.g. The deeply rooting profile in the 15 Year plot at Site T2) the fine roots had ample time to decompose. Relic coarse roots could be a significant proportion of the rooting fractions five years post treatment, especially deeper in the profile and could result in an over-estimation in total rooting depths.

With reference to the global rooting depths established by Jackson et. al. (1997), 95% rooting depths in our 5-Year plots, which should reflect root morphology of a grassland, were equivalent to that of a semi-arid steppe. If “relic” roots were taken into account, however, the 95% rooting depths for the 5-Year plots may have averaged considerably shallower. The 95% rooting depth for both the 15-Year and Control plots were on average 30 cm deeper than that of semi-arid shrublands globally. These deeper rooting depths could be related to the timing of rainfall out-of-phase with the growing season, very similar to the deeper rooting depths of Mediterranean shrubland, where substantial rain falls during winter months. This causes wetting of deeper soil layers, while vegetation is senescent, and encourages deeper roots. A correlation has been found (Schenk and Jackson, 2005) where finer texture is responsible for more deeply rooted vegetation; however, there was no correlation found in this study between rooting depth and texture (Figure 1-6) except for a marginal negative correlation between average silt in the profile and the depth containing 95% of roots ($P < 0.1$). Usually, higher clay content is associated with greater water holding capacity and would account for root proliferation in these layers; however, this trend was not seen in this study.

Contrary to expectations, as root depths decreased following shrub removal, total root biomass in the top 210 cm increased, for both total roots and fine roots (Figure 1-4a). Grasses are known to have dense root systems closer to the surface compared to shrubs, which tend to expend energy rooting deeper in search of further nutrients and water. Jackson and co-workers (1997) segregated vertical root distributions by vegetation biome and created their root biomass curves to estimate biomass with depth on the proportion of roots in proximity to the surface. In their equation, grasslands have a lower constant (0.954) than shrublands (0.975), corresponding to a larger proportion of roots closer to the surface in a grassland than a typical shrublands (Jackson et al., 1997). Using the Jackson et al. equation and the biomass results calculated in this study, the 5-Year plots have a constant of 0.974 and the Control plots have a constant of 0.980. From this, root distributions in the grass-dominated 5-Year plots are generally more deeply rooted than observed global grasslands; however, since relic roots have not been taken into account in this study it cannot be assumed that all roots quantified in the profile are alive. In fact, much of the deep root matter in the 5-Year plots could be those roots which remain of the shrubs prior to clearing and indeed $\delta^{13}C$ analysis could resolve whether the roots belong to C4 grasses or C3 shrubs.

Fine roots are generally responsible for more water and nutrient uptake than coarser roots due to their high surface area to volume ratio. The zone where the majority of fine roots are located is therefore where you would expect to see the biggest influence of roots on water uptake. It was found that chloride concentrations were generally greatest within the lower part of the total rooting zone and not necessarily in the fine rooting zone. Further, the indirect effects of fine roots on chloride concentrations, due to the build-up of chloride in the soil, were evident in the Control plots (Figure 1-5). Since evapotranspiration leaves chloride behind in the soil following water uptake, chloride accumulation in the root zone likely occurs over long periods (Reedy, 2000), especially if episodes of flushing due to deep drainage are rare.

With rooting depths reduced, and root biomass increasing following the removal of shrubs, the grass community is evidently utilizing available water to flourish, as seen by increased ground cover (Figure 1-3). However, with increased water availability during high rainfall years and times when vegetation is senescent, the possibility for deep drainage to occur is greater in those plots treated. Deeper chloride peaks were associated with shallower root depth profiles of 5-Year plots, even though these early successional plots may have the same or greater total root biomass. The most probable explanation is that increased deep drainage has moved chloride peaks further down. At Site T1, there is a strong positive correlation between total root biomass and depth to peak chloride ($P < 0.05$), and at site T2, fine root biomass was positively correlated with depth to peak chloride ($P < 0.01$). With sites pooled, root biomass, whether total roots or fine roots, was not significantly correlated with depth to peak chloride despite differences in root biomass between 5-Year and Control plots. With that in mind, depths containing 95% of both total roots and fine roots were positively correlated with depth to peak chloride. This seemed counter-intuitive from the hypothesis that in the control plots, with deeper rooting depths, chloride bulges should be higher in the profile. In fact, it is the total chloride in the profile that should be examined instead.

The total chloride in the control plots was higher than in both treatments. For all profiles, as the depth to 95% of roots increased, the total amount of chloride in the profile increased. With control plots having deeper 95% rooting depths, the soil chloride was able to be built up in the root zone of the profile. With the removal of brush and rooting depths becoming shallower, the peak chloride, or bulge in the chloride profile had a chance to move to a lower position, through deep drainage events. At the same time, the shallower rooting depths of the grasses could indeed be accumulating a secondary chloride bulge closer to the surface, but this effect was not evident. Total chloride did not seem to differ between the 5-Year and 15-Year plots (1078 ± 615 kg/Ha and 1151 ± 547 kg/Ha respectively), which would suggest that minimal deep drainage occurred beyond 5 years following shrub removal. Interestingly, one would also expect the chloride bulge to occur lower in the profile after 15 years than after five, but there was no evidence this happened. The position of the chloride bulge at site T3 is the same for all three plots, but the magnitude of this bulge decreases after clearing of vegetation, suggesting the flushing of chloride.

High correlations between the depth to maximum electrical conductivity and maximum chloride are suggestive that the dissolved solids and salts in the soil at these layers are having an influence on chloride concentrations. With high EC levels (Table 1-2) coinciding with high concentrations of chloride in deeper layers (Table 1-3), there is possibility for outside sources of chloride to exist in this system. Furthermore, the addition of other sources of chloride could underestimate deep drainage calculated below these depths. Deep drainage estimates in this study, however, were not affected by the high EC layers, since deep drainage was calculated to a standard depth of 205cm and high EC layers we found were deeper than this for all profiles except T2 Control.

With soil and root characteristics being closely inter-related (Figure 1-6), it is difficult to determine which attributes are responsible for the variation seen between sites. Fortunately the within-site correlations (Table 1-3) help indicate which attributes would most likely fit in a predictive model to explain the observed variation. Both bulk density and clay were incorporated into several iterations of the model, given their good correlation with chloride; however, they did not improve the model. Interactions between variables were considered for the model because there is an inherent complex relationship between abiotic and biotic variables and their effects on soil chloride distribution. However, given that bulk density and clay did not vary across either sites or treatments it follows that these variables would not effectively contribute to differing chloride concentrations between treatments. Due to its inherent correlation with chloride (i.e. violates assumption of independence), the depth of maximum electrical conductivity was removed from the list of variables for the model as it would have alone explained much of the variation in soil chloride.

Removal of shrub vegetation had a significant influence on root morphology and subsequent chloride concentrations in the soil profile. The data suggest that, on average, approximately 70% of the chloride in the top two meters of the soil profile is lost within the first five years after removal of shrubs and this could account for a considerable increase in deep drainage during this time. The correlations between chloride concentrations and root/soil morphology, outlined in our model above, help aid an interpretation of the relative importance of soil and root attributes in shaping chloride in the soil. The depth containing 50% of roots was significantly shallower five years following shrub removal and the depth containing 95% of roots was significantly correlated with the depth to peak chloride. Root biomass was greatest five years after the removal of shrubs, as grasses began to re-colonize, and after fifteen years root biomass had again decreased, despite deeper root penetration. With little variation between treatments in soil texture and bulk density, chloride concentration profiles differed significantly before and after treatment, indicating that vegetation affects chloride buildup/loss and therefore changes in deep drainage. Although the depth to maximum chloride in the soil deepened only marginally following treatment, total cumulative chloride in the soil was reduced a significant amount. Results from this work strengthen our understanding of how both biotic and abiotic factors together affects water resources.

CHAPTER III

SHRUB REMOVAL INCREASES GROUNDWATER RECHARGE IN SW TEXAS SEMI-ARID RANGELANDS: A SOIL CHLORIDE TRACER STUDY

Overview

An important aspect of quantifying groundwater recharge is the ability to estimate recharge inputs below the root zone and to identify those factors facilitating movement of water into aquifer storage. Although soil percolation, water potential and water holding capacity of the soil moderate rates of aquifer recharge, evapotranspiration (ET) by natural vegetation is a major limiting factor. Vegetation management potentially plays a major role in countering recharge gain because ET varies with vegetation type and cover. Clearing of vegetation on a natural landscape can influence the balance of water recharging aquifers; and, 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. The Carrizo-Wilcox aquifer is a valuable groundwater resource situated in a semi-arid landscape of Southwest Texas, where over-use by dependent farming practices has lowered aquifer levels significantly in the last 85 years. The aim of this research was to examine differences in deep drainage occurring in the years following the clearing of natural shrub vegetation in this semi-arid region of Southwest Texas. Combining short-term monitoring (monthly) of the changes in soil moisture and long-term (5-30 years) changes in total soil chloride, increases in deep drainage where land had been cleared of vegetation were observed. Annual recharge rates below rooting depths (standardized to 155 cm) averaged 12.7 ± 3.7 mm/yr, in areas not cleared of woody vegetation. Upon clearing, two thirds of the total chloride in the soil profile was flushed by increased deep drainage within 30 years. Observations made during the growing season of wet years (double the average rainfall) indicate deep soil moisture in recently cleared land increased by up to 17%, providing supporting evidence that more water penetrated below the roots. Consequently, if recharge occurs in the summer months, there is a good chance recharge would also occur during wet winter periods when vegetation is senescent. Indeed, mean annual recharge below rooting depths was 14.9 ± 4.6 mm/yr higher in areas cleared of vegetation than in areas left uncleared, as estimated by Chloride Mass Balance. These results provide evidence that brush management can increase recharge by modest, but measurable, amounts depending on site-specific soil characteristics and degree of reduction in vegetation.

Introduction

Deep percolation of distributed rainfall contributes positively to groundwater recharge in natural semi-arid landscapes at varying rates (Cook and Robinson, 2002; Harrington et al., 2002; Kennettsmith et al., 1994; Petheram et al., 2002; Scanlon, 1992; Scanlon, 2000; Scanlon et al., 2006; Scott et al., 2000). An important aspect of quantifying groundwater recharge is the ability to estimate recharge inputs below the root zone and to identify those factors facilitating movement of water into aquifer storage. Even though interactions between climate, soil, and vegetation influence the amount of recharge that penetrate into aquifers (Harrington et al., 2002; Kennettsmith et al., 1994; Petheram et al., 2002), vegetation factors, in particular, are the most dynamic and least understood. Although soil percolation, water potential and water holding capacity of the soil moderate rates of aquifer recharge, evapotranspiration (ET) by natural vegetation is a major limiting factor.

In semi-arid areas of the world, aquifers are being depleted because the water withdrawn for human use exceeds the amount returning through irrigation or natural rainfall. Most commonly, over-use by dependent farming practices, especially irrigation, is the primary source of withdrawal. The economic sustainability of farming regions around the world depends on maintaining aquifer water supplies. This study focuses on the Carrizo-Wilcox aquifer, a valuable groundwater resource situated in a semi-arid landscape of Southwest Texas. The sites included in this study are exclusively in an area where the Carrizo-Wilcox aquifer intersects the land surface and it is in this recharge zone where a large percentage of the aquifers recharge is likely to occur (Green, 2006). Some studies have examined recharge (Huxman et al., 2004; Jackson et al., 1996; Scanlon, 2000; Scanlon and Cook, 2002), water-balance (Carlson et al., 1990), groundwater chemistry and the age of aquifer water (Green, 2006) in this region, but until a recent study (Green et al., 2008) investigating groundwater systems, little is known about how land management in this region affects actual recharge rates. Scanlon (2003) has estimated stream-channel recharge into the Carrizo-Wilcox aquifer to be between 2.5-147 mm/yr, and state that little is known about inter-stream deep drainage inputs.

Groundwater levels of the Carrizo aquifer, located in a major agricultural region, have lowered around 30 m in the last 85 years (Texas Water Development Board, http://www.twdb.state.tx.us). It is assumed that irrigation has been the predominant cause of this depletion. It may be possible to manage the natural landscape in this region to counter rates of depletion in this and other parts of the world where aquifer levels have dropped significantly. If land management alters recharge, such information could prove useful to similar regions around the world where over-utilization of groundwater resources is threatening regional sustainability.

Vegetation in upland settings can influence recharge in semi-arid regions, but likely only accumulates over very long time scales. Rather, short-term recharge events may be possible under unusually wet periods and can be detected by monitoring soil moisture content in deep soil layers. Hydraulic characteristics of xeric, deep-rooted soil-plant systems help assist soil water storage at depth for extended periods (Seyfried et al., 2005). Any increase in this deeper soil moisture is likely to occur where rainfall is periodic and seasonal (as is the case in Southwest Texas), but will depend on antecedent moisture content. For the same size rain event, more water moves to deeper depths during late Fall and Winter dormancy than in the peak growing season.

Large precipitation events during the growing season are instead more likely to promote positive vegetation response, increased above- and belowground biomass production and deeper rooting depths. When rainfall is synchronous with high evapotranspiration, as it does in many semi-arid regions, possible soil water gains from rainfall are countered by losses due to high temperature and subsequent evaporation. Research shows (Allison et al., 1990; Seyfried et al., 2005) that it is possible for multi-year trends in increased annual precipitation to overwhelm the water capacity of the soil-plant system; however, it is excess rain during periods of winter dormancy that are the most likely contributor, e.g. over a decade of wetter than average winters.

Vegetation management potentially plays a major role in countering recharge gain because ET varies with vegetation type and cover. Management directly and indirectly alters in-situ factors that affect movement of water to groundwater (Chapter II). Supporting evidence is lacking, however, on how exactly management of vegetation on a natural landscape can influence the balance of water recharging our aquifers. Tolmie and co-workers (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.

Even small changes in groundwater percolation from minor shifts in natural vegetation may have substantial cumulative impacts if the spatial extent covers a large proportion of the aquifer recharge zone. Furthermore, if management practices maintain vegetation in an altered state for very long time periods, e.g. many years to decades, small changes in groundwater percolation accumulate over time. Long-term changes in deep percolation are evident by vertical patterns in evaporates such as chloride (Chapter II). For this reason, soil chloride serves as an excellent tracer to quantify cumulative deep drainage over long time scales.

To quantify the rate of water movement using soil chloride concentrations, 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 (Phillips, 1994; Reedy, 2000; Scanlon, 1991; Scanlon, 1994; Scanlon, 2000; Scanlon et al., 2005b) 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 via wet and dry atmospheric deposition, against the chloride output lost by downward percolation through the soil. Water flux is estimated from the degree of chloride enrichment in pore water as a result of evapotranspiration relative to the chloride concentration in precipitation (Scanlon, 2000). An estimate of deep drainage is calculated by dividing the cumulative amount of chloride down to a depth of interest by the chloride input. Chloride concentrations in the soil profile are inversely proportional to recharge rates.

In another part of this study, soil chloride profiles were examined in a vegetation management chronosequence to determine if brush clearing altered the vertical distribution of chloride five and 15 years later. The depth to the layer of soil with the highest chloride concentration (i.e. the "bulge") was marginally deeper five years after brush clearing (Chapter II). Most notably, cumulative chloride (or total chloride in the profile) was drastically lower five years following treatment. Lower total chloride was found to be a consequence of the change in vegetation type and subsequent shallower root distribution (Chapter II). These results are indicative of changes in deep drainage that can be quantified using the CMB technique. Although non-atmospheric sources of chloride were found in some plots, the close proximity of treatments to control locations led to nearly identical soil characteristics (Chapter II) for comparison.

The aim of this research is to examine differences in deep drainage occurring in the years following the clearing of natural shrub vegetation in the semi-arid region of Southwest Texas. We expect to see an increase in deep drainage where land has been cleared of woody vegetation as indicated by reductions in total soil chloride shown in Chapter II. Further, in the vegetation chronosequence, local soil moisture trends below the maximum root zone will be compared among treatments during wet and dry periods to determine whether short-term deep drainage pulses occur in this system, and how often. Deep percolation of soil wetting fronts are expected more frequently following storm events where land has been cleared of shrub vegetation and during years of above average rainfall. A valuable application of this research is to provide scientific input for effective land management strategies that increase recharge in the Carrizo Wilcox aquifer.

Methods

Site Description

This regional scale study encompassed data from twelve sites spread over four counties in the Wintergarden Groundwater Conservation District of Southwest Texas over a period of 30 months beginning in 2006. Soil chloride responses to brush removal were examined between soil samples taken from different stages of vegetation re-growth and compared with adjacent native vegetation stands. Nine of the twelve sites were distributed over the Carrizo-Wilcox aquifer recharge zone (hereafter labeled with “Z”). For these nine Z sites, a control plot was located in an area known to be contained within the recharge zone of the Carrizo-Wilcox aquifer, and which was also directly adjacent an area of rangeland cleared of brush at varying times in the past. Two of these nine Z sites were located in the Wilcox aquifer recharge zone (Sites Z2 and Z9) with the remaining seven sites paired in the Carrizo aquifer recharge zone. At each Z site the treatment plot was established as close as logistically possible to a natural control plot (within 50 m), for a total of 18 plots. In the remaining three of the twelve sites (hereafter labeled with “T”), two treatments and a control were studied, for a total of 9 experimental plots; the location and details of this part of the study, at the Northcut Ranch, Cotulla, Texas, are outlined in Chapter II. Individual land-owners provided information about the management history carried out, treatment dates, and the type of treatment utilized to control the brush (see Appendix A for details). Rainfall was gathered at two of the sites (Control plots of T1 and T2) and any gaps in the data collection were filled using available data online (NOAA, 2002) for either the Cotulla airport (for T sites) and Carrizo Springs airport (Z sites).

Soils and Vegetation

The majority of soils in the study area are moderately to highly permeable, moderate to deep sandy and sandy loam soils in a gently undulating landscape. Soils in the local area surrounding the study sites belong predominantly to the Antosa (Arenic Paleustalfs) and Bobillo (Grossarenic Paleustalfs) series with minor groups in Duval (Aridic Haplustalfs) and Webb (Aridic Paleustalfs) series. Control plots are native, undisturbed stands of rangeland brush dominated by mature honey mesquite (*Prosopis glandulosa*) and C4 grasses (Chapter II). The most common brush clearing method was to plow vegetation using a horizontal blade that cuts the roots 30 cm below ground level. Such root plowing usually results in bare ground. Typically, grasses are quickly re-established within the first year following brush removal; whereas, woody plants do not reach original densities until at least 15 years later (Chapter II).

Soil Samples

The details of sampling at the T sites are outlined in Chapter II. A very similar strategy was employed for the nine sites in the Carrizo-Wilcox area. Over a period of three months, between July and September 2007, two soil cores were collected from each of the two plots at all nine sites for a total of 34 cores (Note: Site Z9 had only one core taken in each plot). The distance between the two cores within each plot was approximately two meters. 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 2.7 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.

A detailed description of soil sampling protocols is given in Chapter II. Briefly, each soil core was sampled in 10 cm increments; however, not every increment of the core was sampled. Since most of the chloride variability is expected to occur in the first two meters, increments were spaced 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, and so forth. The number of samples per core ranged from nine to 18, depending on the total depth. If possible, the bottom 10 cm increment was sampled even if it fell outside the sampling protocol depths.

Soil profile samples were used to characterize a variety of soil descriptive parameters including volumetric soil moisture, bulk density, gravel fraction, pH, electrical conductivity and chloride concentration. Samples taken at the three T sites were also analyzed for particle size and root biomass (see Chapter II). As described, aqueous extracts were taken from the soil samples at each sampling depth. The water extract was analyzed by the New Mexico Bureau of Geology and Mineral Resources for chloride using the ion chromatography method. Dilutions done in the lab to produce the water extracts for chloride were then calculated back to undiluted concentrations depending on the dilution used and then further converted to pore-water chloride concentrations using gravimetric water content at the time of sampling.

Soil Moisture

In the short-term, investigation was undertaken of daily, weekly and monthly changes in soil moisture following storm events. We monitored and measured soil moisture at the three T sites, with two different instruments over the 30 month period of the study. One instrument recorded soil moisture data continuously (Decagon Ech20 probe), while one instrument (Sentek Diviner 2000) monitored soil moisture instantaneously, with periodic measurements throughout the year. The Decagon Ech20 probes were installed in all four plots at two of the three sites (T1 and T2) and yielded moisture data at 15 and 30 minute intervals and at four depths (20, 40, 70 and 200 cm). The Sentek Diviner 2000 is a 1.7 m probe, which is inserted into pre-established PVC access tubes to record soil moisture instantaneously. A total of 64 access tubes were installed in the 12 study plots, with between 5 and 10 access tubes in each plot. Soil moisture was recorded for each manual sampling time instantaneously at 16 depths (every 10 cm down to 160 cm). To compare the same period in all three years, the following Diviner measurements are presented in this paper: May 25th and July 7th, 2005, on May 2nd and July 12th, 2006, and on April 12th and July 9th, 2007. Exact dates vary from year-to-year depending on field sampling dates. Between the two types of instruments, a good representation of fluctuations in soil moisture was attained, which would aid in interpreting any effects of vegetation change in soil moisture with season and depth.

Chloride Deposition

Chloride deposition data were obtained for a twenty three year period (1984-2006), from the National Atmospheric Deposition Program (http://nadp.sws.uiuc.edu), and collated to provide average chloride depositions for the two closest known observation points to the study area, Beeville, approximately 130 km away, and Sonora, approximately 260 km away. A linear distance-weighted interpolation of monthly chloride deposition values was made from those values obtained for each of the two observation stations. The interpolated rate of monthly chloride wet and dry deposition for Cotulla was 0.59 mg L^{-1} yr^{-1}. For simplicity, all sites were assigned the same chloride deposition rate, given that exact deposition rates *in situ* were not measured, and because all sites were within 50 km.

Chloride Mass Balance

Chloride Mass Balance can be expressed as:

$PC_P = D_DC_S$ (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 chloride concentration in the soil pore water at a depth of interest (mg/L). Rearranging for D_D gives:

$D_D = PC_P / C_S$ (2)

An estimate of deep drainage is calculated by dividing the amount of chloride at a depth of interest by the chloride input.

Equation 2 was used to calculate recharge draining below the bottom depth attained in each profile. To standardize all profiles, recharge estimates were calculated below 155 cm in the Carrizo sites and 205 cm in the Cotulla sites; the depths common to all profiles in each part of the study. Standardization was necessary to avoid overestimation of recharge rates within deeper profiles. The difference in cumulative chloride between each treatment and associated control plot was then calculated and Equation 2 used to estimate the additional yearly recharge for the time since vegetation was cleared. Accuracy in this method requires quality estimates of atmospheric chloride input, precipitation, and soil pore water chloride content. We assume dry and wet deposition from the atmosphere is the only source of chloride input to subsurface layers.

Statistical Analysis

Analysis of variance (ANOVA, SPSS Inc.) was used to test for differences between treatments in a series of key variables of interest. Only replicates from six out of the nine sites were used in this analysis because these sites had been treated at approximately the same time, 30 years ago. The five soil variables tested were: depth to maximum EC, maximum EC, and minimum, average and maximum bulk density. The three chloride variables tested were: depth to maximum chloride concentration, maximum chloride concentration, and total chloride.

Diviner data were evaluated for each of the twelve Cotulla plots for both May and July in each of the three years of the study. This period during the year is of most interest as it is known to be a time of high evapotranspiration and when vegetation is most influential on soil moisture. The average soil moisture was totaled between 120 cm and 160 cm for each profile and expressed as the difference in percent soil moisture between the two dates. Each treatment plot was then averaged for all three sites and compared using ANOVA between years.

Results

Rainfall

During the study period two useful periods of yearly rainfall distribution were captured; a period of drought and a period of unusually high rainfall. Data from the past 30 years showed that mean annual rainfall at the T sites is 604 mm and for Z sites is 526 mm. The long-term total precipitation during the months of May, June, and July is 248 mm. The year 2005 was dry during that period, with only 97 mm precipitation. That same period between May and July of 2006 was more normal, with 241 mm precipitation. May through July 2007, however, was considerably wetter, having nearly twice the normal precipitation, 480 mm. Monthly rainfall for the duration of this study are given in Figure 2-1 and monthly totals for the May-July period in each year is given in Figure 2-2.

Soil Moisture

Three distinct years of rainfall resulted in highly contrasting soil moisture in deeper layers (120-160 cm) among the same periods spanning three years. Volumetric water content either decreased or remained unchanged for deep soil layers in the period between May and July 2005, despite almost 50 mm of rain during May (Figure 2-3a). In the relatively dry 2005 year, 5-Year plots at all three sites showed consistent decline in deep soil moisture between May and July; whereas, 15-Year and Control plots illustrate

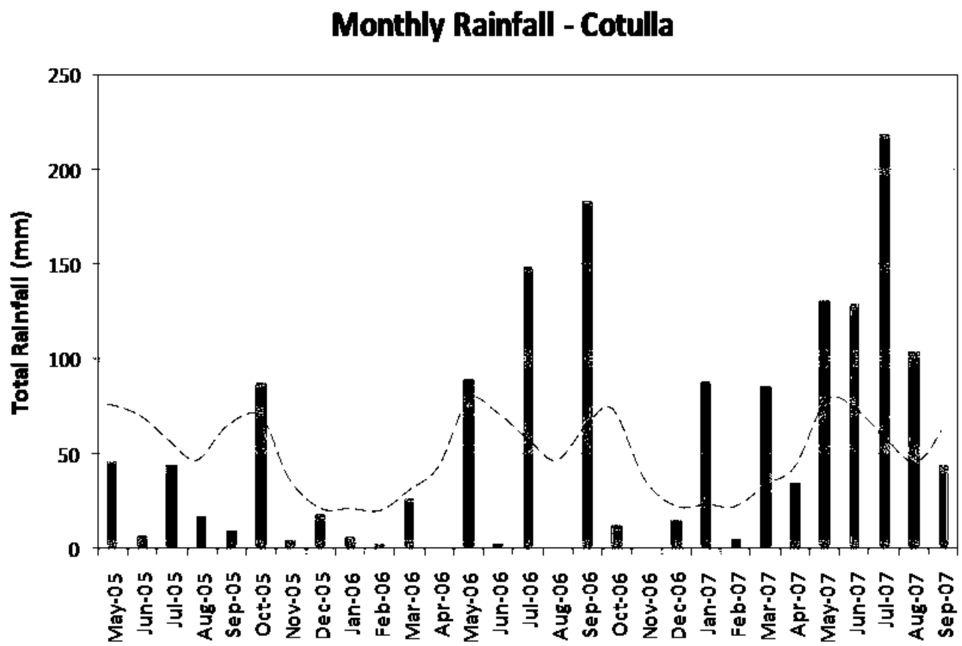


Figure 2-1. Monthly rainfall in millimeters for the duration of the study in the proximity of T sites near Cotulla. The 30-Year average is shown as a dotted line.

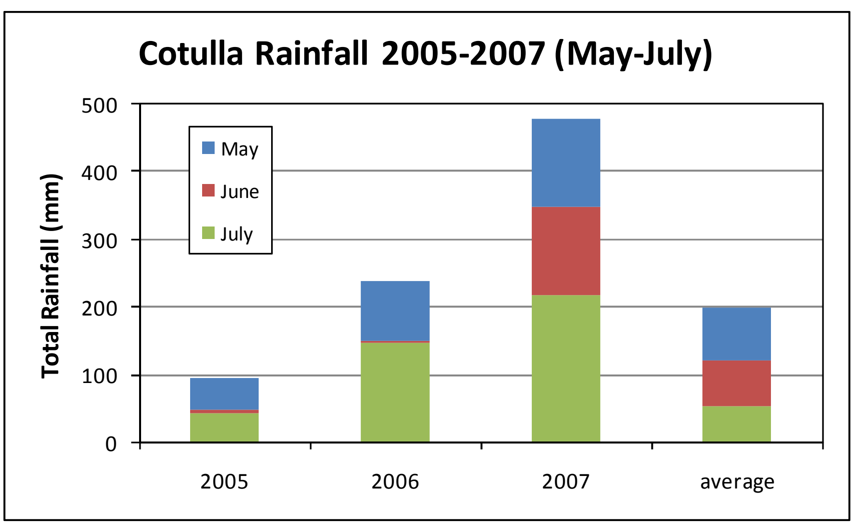


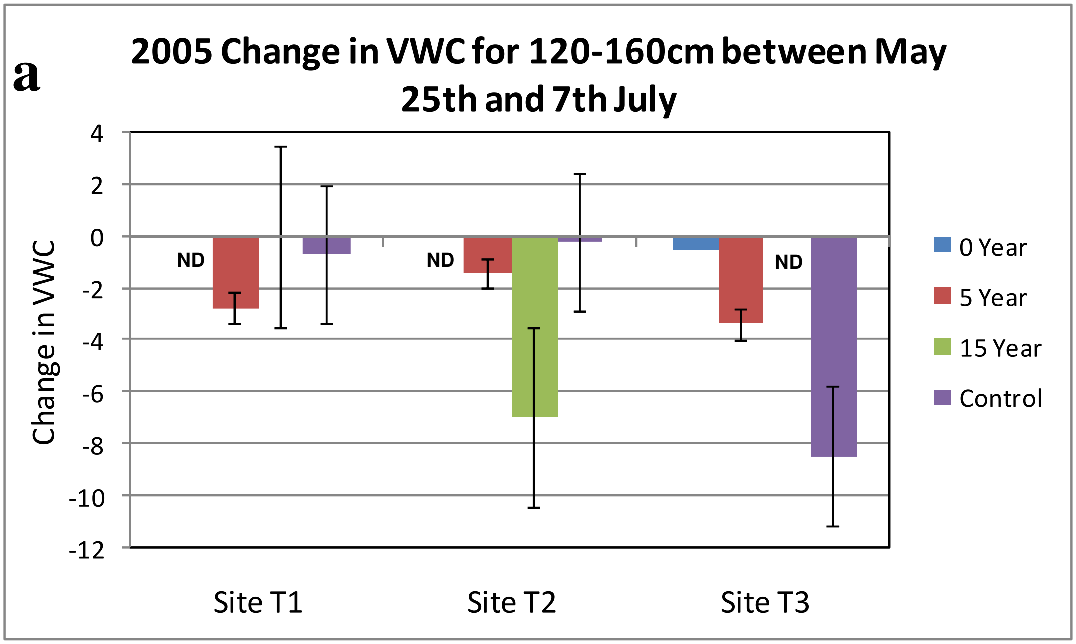
Figure 2-2. Cumulative rainfall for the months of May, June and July showing contrasting precipitation for the three years of the study and climatic averages.

variation between sites. There was only one recently plowed site established in 2005 and this plot showed no change in soil moisture at 120-160 cm (Figure 2-3a).

For the same period in 2006 (Figure 2-3b), with yearly rainfall comparable to the climatic average, volumetric soil moisture at depth increased between 1.2% and 2.5% in the 15-Year plots. Both 5-Year and Control plots also had an equivalent increase in soil moisture for two of the three sites. Again, like in 2005, 0-Year plots either decreased by 1% in volumetric soil moisture or stayed constant (Figure 2-3b).

A relatively wet year in 2007, with double the average rainfall for the same May-July period, produced soil moisture increases of up to 17% (Figure 2-3c). Site 3 showed the least change with 0-4% increases between treatments. Treatment plots showed more response to the increased rainfall than control plots.

Soil moisture deep in the profile (200 cm) at Site T2, as measured by Echo probes, is shown in Figure 2-4. Moisture levels increase in both 5-Year and 15-Year treatment plots during the two month period of 2007 shown in the graph. No moisture change is apparent for either Control plot or the 0-Year plot in 2007. Saturated water content is approximately 20% in these soils (Dunne and Leopold 1978), which was suddenly and synchronously exceeded in the 5-Year and 15-Year plots following a large rain event in late May (Figure 2-4). With already high moisture levels in the 0-Year plot (31-33%),



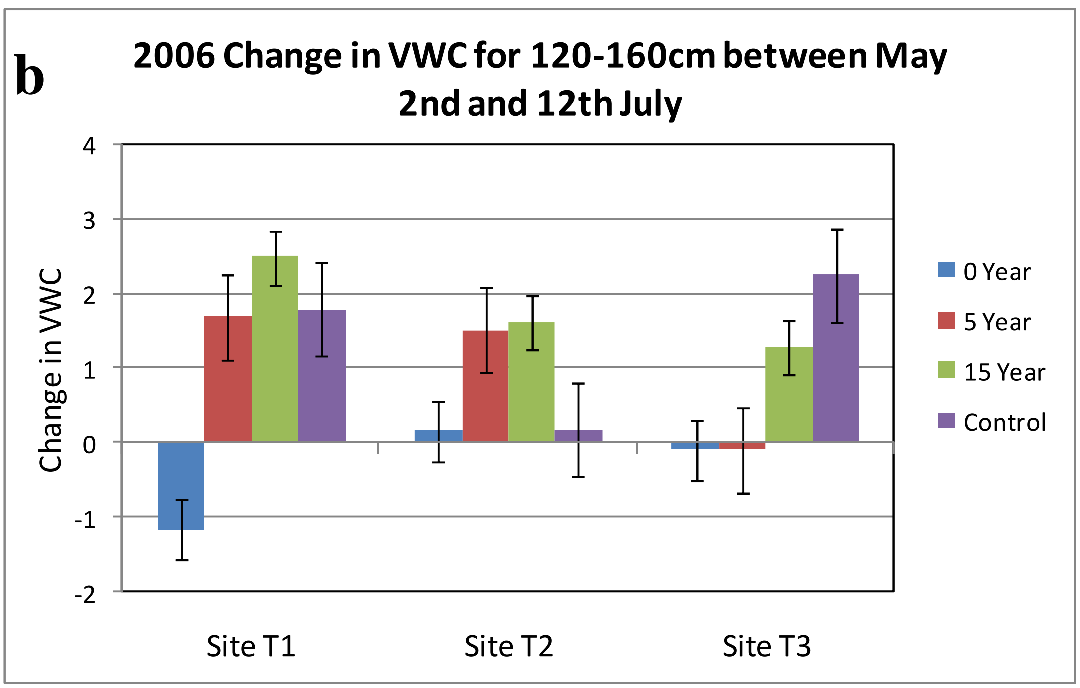


Figure 2-3. Change in average soil volumetric water content (VWC), for the depths 120-160 cm, between root plow treatments at each T site for 2005 (a), 2006 (b) and 2007 (c). Plots without data for these dates are denoted "ND".

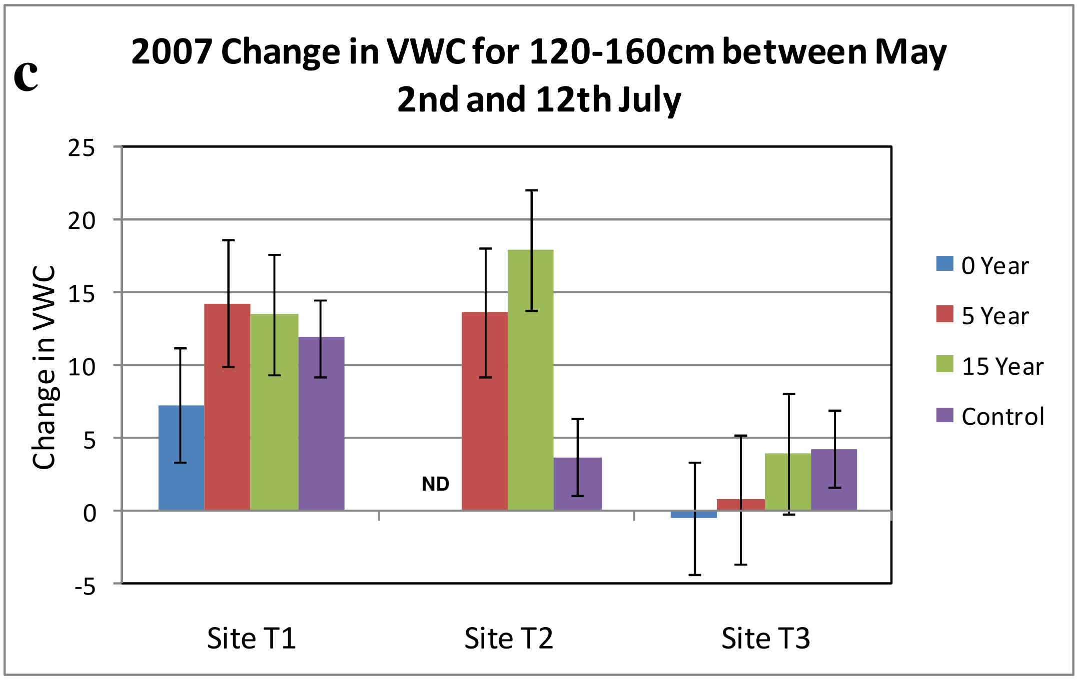


Figure 2-3 Continued.

saturation levels in these soils were exceeded since approximately early February 2007 (data not shown). Note in the 0-year plot, however, that 2% fluctuations in moisture are occurring over a matter of days (Figure 2-4), most likely indicative of downwards movement of water rather than uptake by plants, as this plot is devoid of shrub vegetation. A slight 2-3% rise in soil moisture in the Control plot over the two month period in 2007 suggests water is penetrating to depth but given that moisture did not reach 20% suggests the Control plot was never saturated in either year.

Soils

Bulk density did not differ between 30-Year and Control plots ($p < 0.05$). Depth to maximum EC was deeper for plots treated 30 years ago than those plots never treated (221 ± 13 cm and 103 ± 22 cm respectively). Maximum EC was lower in 30-Year plots than in the Control plots (264 ± 19 µS/cm and 349 ± 45 µS/cm) but this difference was only marginal ($p < 0.1$).

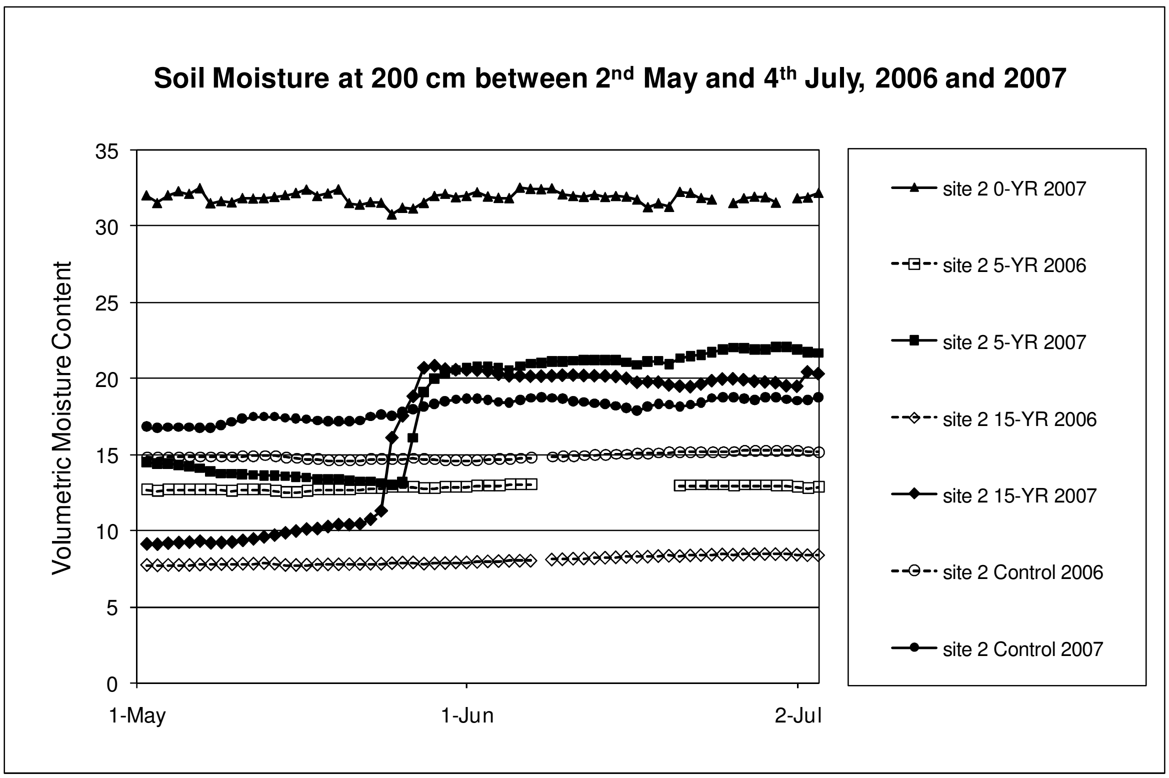


Figure 2-4. Site T2 volumetric soil moisture at 200 cm for Control (circle), 15-Year (diamond), 5-Year (square) and 0-Year (triangle) between 2nd May and 4th of July in 2006 (open symbols) and 2007 (closed symbols). There is no data for 0-Year in 2006.

Chloride

Chloride concentrations with depth for each profile are shown in Figure 1-5 (Chapter II) for the T sites and in Figure 2-5 for all Z sites. Those Z plots cleared 30 Years ago had almost one third of the total chloride stored in the soil profiles down to 155 cm compared to that in the untreated control plots (339.19 ± 68 kg/Ha and 954.99 ± 208 kg/Ha respectively). In fact, treatment plots were significantly lower in total chloride than control plots at all depths lower than 95 cm (Data not shown). Peak chloride concentrations were more than 50% lower in the 30-Year plots, 67 ± 12 mg/L, compared to values of 150 ± 25 mg/L in the untreated plots. Furthermore, the depth to peak chloride was, on average, deeper in the profile for plots treated 30 years ago compared to the control (175 ± 15 cm and 133 ± 23 cm respectively); however, these differences were not significant to the 0.05 level.

Recharge rates below 155 cm in those plots cleared of vegetation (all twelve sites combined) were more than double the recharge rates in control plots (27.7 ± 6.1 mm/yr and 12.7 ± 3.7 mm/yr respectively; $p < 0.05$). The same trend was observed for recharge rates calculated below the bottom depth of all profiles, as opposed to the standardized depth of 155 cm. This more conservative calculation resulted in lower recharge estimates that averaged 12.5 ± 4.0 mm/yr in treatment plots and 5.8 ± 2.2 mm/yr in control plots;

however, this difference was not significant ($p = 0.15$). On average, a reduction in recharge of 50% was accounted for in the soil layers between 155 cm and the bottom of all profiles. Recharge below 155 cm in the unmanaged sites ranged from 2.4 – 46.3 mm/yr, and in treated sites from 6.8 – 72.6 mm/yr. Figure 2-6 illustrates the difference in recharge between control and treatment plots for each site in the study, which represents the *additional* yearly recharge that land cleared of vegetation has over those plots left unmanaged, derived from both the standardized and conservative calculations. Below 155 cm, root plowing increased recharge, on average, by 14.9 ± 4.6 mm/yr, and below the bottom of all profiles, root plowing increased recharge by 6.7 ± 2.1 mm/yr. Site Z5 is the only site among twelve where the treatment plot has greater chloride concentrations than the control plot and therefore is shown to have 11.3 mm/yr more recharge when unmanaged.

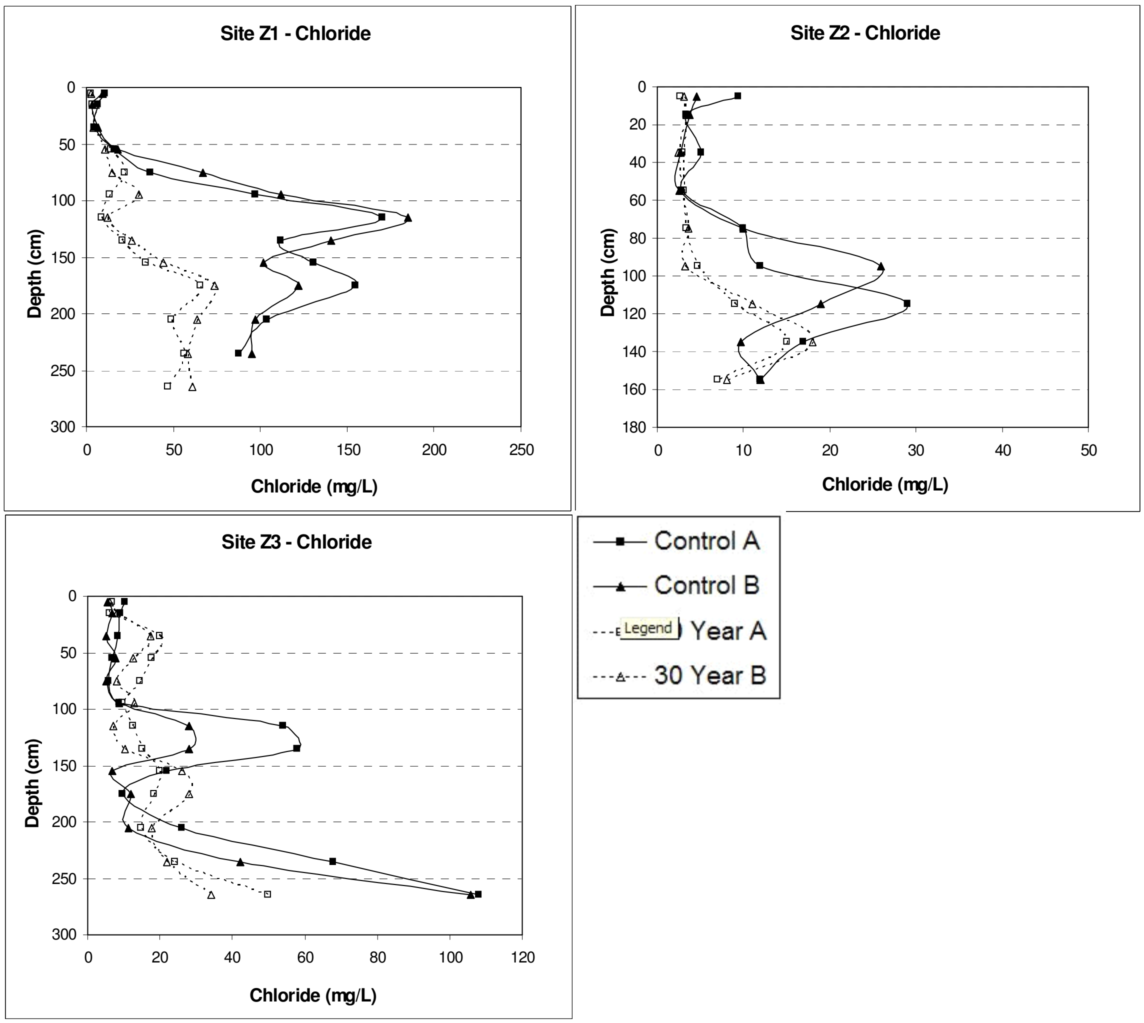


Figure 2-5. Chloride concentration with depth for each of the nine Carrizo sites. Solid lines indicate control plots and dotted lines indicate treatment plots.

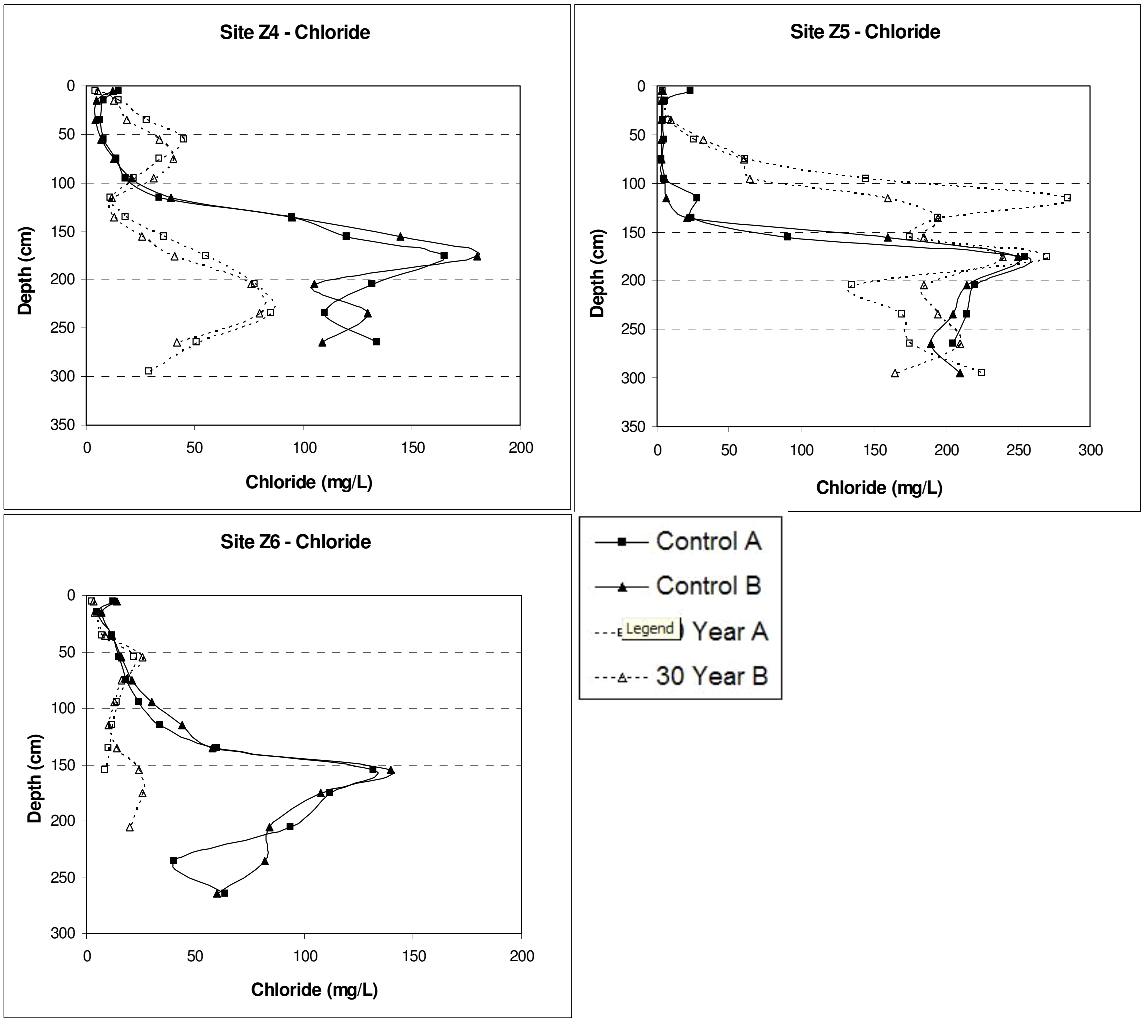


Figure 2-5 Continued.

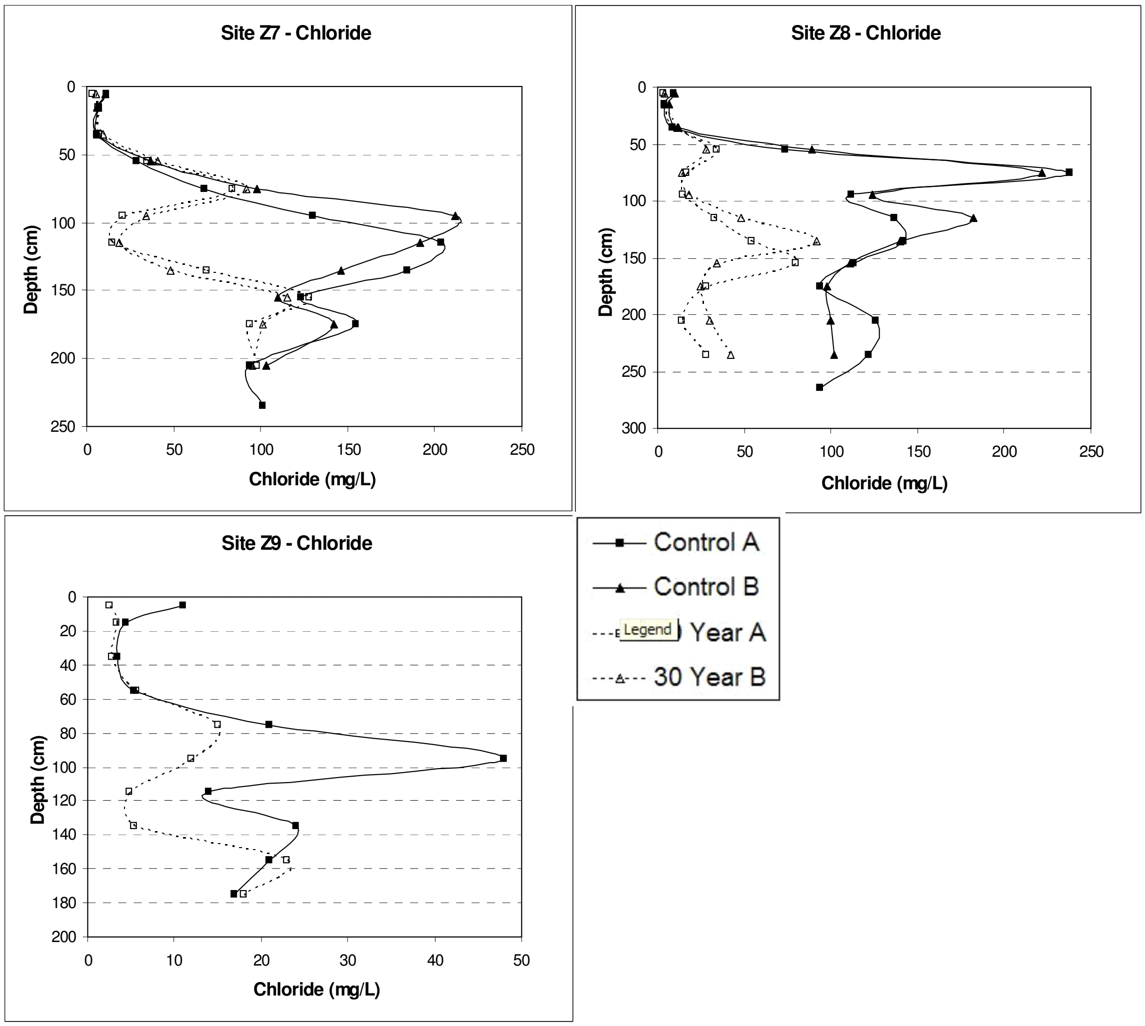


Figure 2-5 Continued.

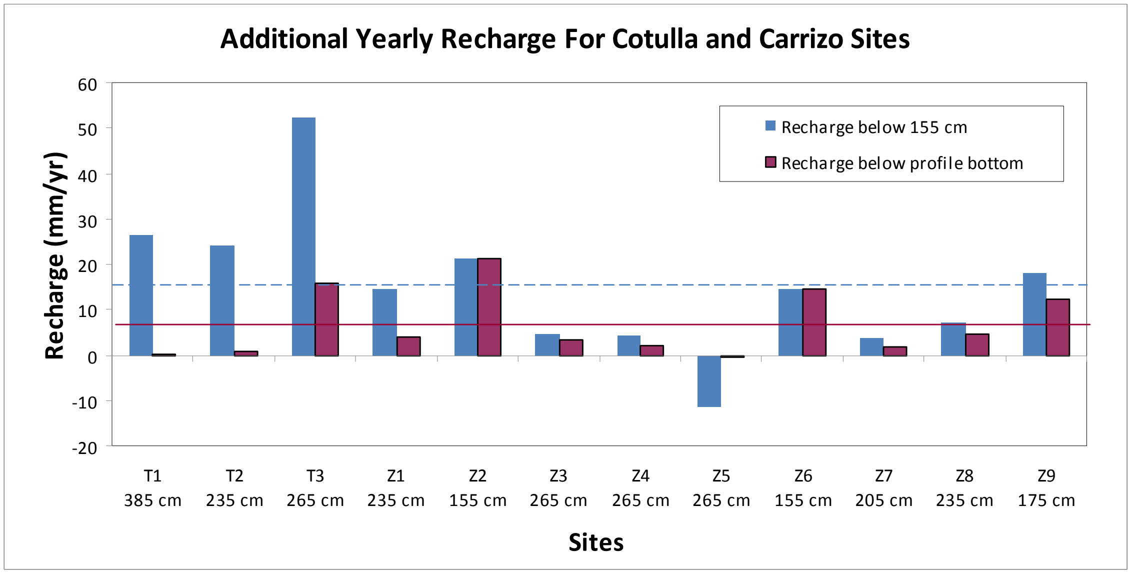


Figure 2-6. Additional yearly recharge estimates for all Cotulla (T) and Carrizo (Z) sites below 155 cm (standardized) and the total depth of each profile (conservative), representing the affect of root plow treatments on deep drainage. Average yearly recharge below 155 cm (dotted line) and below bottom of profile (solid line).

Discussion

Monitoring soil moisture with high temporal resolution and spatial replication within a focused area provided detailed information on the dynamics of water movement and more importantly, emphasized any gains and losses as a consequence of infiltration, percolation and root uptake. Deep drainage calculated from CMB was contrasted between adjacent areas of cleared and uncleared vegetation replicated across a range of spatial and temporal conditions. Short-term soil moisture trends combined with long-term soil chloride distributions observed on rangelands in different stages of re-growth clearly indicated that brush clearing facilitated deep drainage below the root zone.

Our results indicate that between-year variability in soil moisture at depths of 120-160 cm is highly dependent on soil and vegetation characteristics, as suggested by others (Allison et al., 1990; Huxman et al., 2004; Seyfried et al., 2005); however, during years with above-normal rainfall, even during the growing season, water is able to penetrate to these depths. Soil moisture at the bottom of the root zone remains low (below the estimated saturated water content of 20%) and stable during below-normal rainfall years indicating very little potential for deep drainage. For example, between May 2nd and July 12th, 2006, soil moisture trends in the 5-Year, 15-Year, and control sites were not consistent across the three sites (Figure 2-3b), suggesting that differences in soil characteristics and vegetation combined control deep drainage responses. The data shown for 2006 also suggest that deep drainage is possible during the growing season of a moderate rainfall year but was small in volume as seen by the increase of only 0-2% (Figure 2-3b).

Soil moisture increases were much more pronounced during the same period between April 12th and July 9th, 2007 (an above normal rainfall year), with increases of 15-18% (Figure 2-3c), which is equal to about 15-18 mm of water penetrating to the depth of these measurements (120-160 cm). When above normal precipitation occurs, as during May 2007, deep soil moisture increased rapidly in 5-Year and 15-Year plots (Figure 2-4), signifying that water is most likely moving to deeper layers through saturated flow. Such patterns may be the result of roots unable to transpire all available water, which would contribute to potentially higher recharge rates in wet years. However, the most compelling evidence of saturated flow occurred in spring of 2007 at Site T3, where deep soil moisture remained well above saturation for the duration of the period indicated (Figure 2-4).

During the same relatively wet period at the beginning of the growing season of 2007, Figure 2-4 shows that, the Control plot did not reach saturation point. It is noteworthy that in 2006 (a normal year of rainfall), no change was observed in soil moisture at 200 cm in any plot at the same time of year, despite having a month with greater than 80 mm of rainfall. Deep soil moisture in the most recently plowed 0-yr plots (T1, T2, and T3) did not alter significantly (Note the high moisture content for the 0-Year plot in Figure 2-4 and the little or no differences shown in Figure 2-3). It is critical to point out that these soil moisture increases were at times when plant water use was quite high. Such deep drainage events are even more likely during late Fall, when rainfall is high and vegetation is senescing; however, insufficient data and the fact the study ended in September of 2007 precluded data availability that following winter.

The expected trend is for water to drain from upper soil layers downward, but with less and less drainage deeper in the profile because of plant uptake. The zone with most influence on water uptake is that occupied by roots and is within the top 1.5 m, as shown in Chapter II, similar to results by Schenk and Jackson (2002a). Due to evapotranspiration losses primarily caused by plant uptake, those materials not absorbed by the plant tend to accumulate in layers occupied by the majority of roots. Calcium carbonate accumulates in the root zone and provides evidence of the depth to which water can penetrate before it is moved up and out of the soil through evapotranspiration. Usually, in semi arid (and more prominently in arid regions) there exists a layer of calcium carbonate which will indicate the common depth of seasonal wetting fronts. If deep drainage is able to increase in areas removed of vegetation, and subsequent reductions in rooting depths (as seen in Chapter II), then there could be evidence of the flushing of calcium carbonate.

Soil chloride is flushed deeper into the profile in the same manner. Total soil chloride was reduced by approximately 75% by five years following treatment, as seen in the three T sites (Chapter II); after a period of 30 years since brush clearing, in the nine Z sites, approximately 65% of the original chloride was flushed downwards below the root zone. This reduction in chloride concentrations resulted in at least 6.7 mm/year of recharge potentially contributed to the aquifer in the 30 years since initial brush removal. Data from the T sites suggest this recharge could indeed be occurring in as little as the first five years following treatment, underestimating the yearly recharge that actually occurs just after removal of brush.

Despite strong evidence that chloride is leaching downward, the possibility remains that it may be re-deposited at deeper depths. It appeared that there was more drainage from the upper layers after 15-years at site T3, but less at sites T1 and T2. As with the 5-yr plots the effect largely disappeared by the deepest depths in the profile. At two of the sites (T1 and T3) the additional recharge within the first five years diminished by fifteen years. We are confident that our measurements were able to capture cases of re-deposition. Scanlon (1991) suggests that the pattern of chloride concentrations with depth indicate a history of deep drainage events or a lack of, allowing chloride to build up, but this study refers to chloride concentrations that have been accumulated in an arid environment, devoid of flushing events. The majority of roots should be above the deepest point measured in the soil core, as such deep drainage estimated at the bottom sampling points represents water available to recharge the aquifer.

Especially evident in the time since clearing, chloride is newly accumulating in surface layers even though the layer of maximum chloride has lowered, and in most cases diminished. This double “bulge” is evident in six of the nine Z treatment plots (Figure 2-5). It is important to note that atmospheric deposition of chloride is a continual process, as a part of rainfall or through the dry deposition of dust. Each time rainfall occurs, the chloride infiltrates into the soil with the precipitation and continues to depth until the pore water transporting it either evaporates or is taken up by plants. When the removal of water occurs chloride is left behind. A secondary bulge of chloride concentration close to the surface was apparent in the treatment plots that developed in the 20-30 years since clearing, due to a shallow root zone (post clearing pasture) that makes use of available rainfall during dry to normal years. During wet years there is potential for a portion of this upper-profile chloride to leach downwards by increased deep drainage.

The greatest contrast between control and treatment plots was found at site Z2 where soils were sandiest (Appendix A). Root plowing resulted in 21 mm/year more deep drainage in the Z2 treatment compared to the Z2 control. This again provides evidence that both soil and vegetation exert strong controls on deep drainage (Chapter II). Substantial increases in deep drainage were also found at sites Z6 and Z9, with 14 and 12 mm more deep drainage, respectively. These results contrast those by Carlson et. al. (1990) who suggest that little or no additional recharge occurs when vegetation is cleared of brush in a Texas rangeland. Their lysimeter data at 3.0 m showed an increase in deep drainage in bare ground plots compared to vegetated plots, but his result was not significant. The soils studied, however, had higher silt and clay content which could have impeded water penetration, thus accounting for the high water loss measured by evapotranspiration.

Overall, this study successfully applied the CMB method to estimate recharge in semiarid rangelands of SW Texas. We found a small amount of recharge was occurring even on unmanaged rangelands (mean of 12.7 ± 3.7 mm/yr). Recharge from unmanaged natural rangelands was less than half that from land cleared of brush, such that annual recharge below rooting depths was 14.9 ± 4.6 mm/yr higher. We present evidence that brush management can increase recharge by modest, but measurable, amounts depending on site-specific soil characteristics and degree of reduction in vegetation. Based on our deep drainage estimations, for every 56 acres of unmanaged natural rangeland an average of one acre-foot of groundwater recharge per year is yielded. If that same 56 acres is managed via root plow, yield may increase to as much as five acre-feet, but may not increase at all, depending on soil conditions.

CHAPTER IV

CONCLUSION

This research is influential towards a better understanding of water resources in the Carrizo-Wilcox aquifer by directly providing recharge estimates. The Chloride Mass Balance method was able to distinguish small differences in recharge for areas cleared of shrub vegetation. The removal of shrub vegetation has a significant influence on root morphology and subsequent chloride concentrations in the soil profile. Our results estimate that, on average, approximately 70% of the chloride in the top 2 m of the soil is lost within the first five years after the removal of shrubs and this could account for a considerable increase in deep drainage during this time. The correlations between chloride concentrations and root/soil morphology, outlined in the model in Chapter II, help aid an interpretation of the relative importance of soil and root attributes in shaping chloride in the soil.

The depth containing 50% of roots was significantly shallower five years following shrub removal and the depth containing 95% of roots was significantly correlated with the depth to maximum chloride. Root biomass was greatest five years after the removal of shrubs, which was contrary to what was expected, as grasses began to re-colonize. After fifteen years, root biomass had again decreased, despite deeper root penetration. Despite little variation among plots in soil texture and bulk density, chloride concentrations were significantly lower after treatment, indicating that vegetation affects chloride buildup/loss and therefore changes in deep drainage. Although the depth to maximum chloride in the soil deepened only marginally following treatment, total cumulative chloride in the soil was reduced by about 65% in some profiles and resulted in an estimated 14.9 mm/yr *more* recharge compared to adjacent untreated controls.

Short-term soil moisture trends enhanced our understanding of deep drainage dynamics. This information supported findings that water is penetrating to 2.0 m and therefore moving below the root zone, which is predominantly in the soil layers above 1.5 m. Areas removed of vegetation both five years and 15 years prior facilitate deep drainage, as seen during years of above-normal rainfall and even in the growing season. Within a year immediately following shrub removal, evidence suggests that soils approach saturation quite rapidly and remain so continually during high rainfall years. Furthermore, recharge is deemed possible during the growing season despite the literature agreeing that recharge occurs only during dormant winter months.

Results reinforce understanding of how biotic and abiotic factors together affect the processes in which aquifers recharge. Land managers can utilize the knowledge gained to better manage rangelands to enhance water resources, based on critical soil and vegetation factors presented in this work. We provide evidence here that significant amounts of chloride are leached during the first five years following treatment and that more leaching occurs in especially wet periods. Greater leaching led to greater estimates of additional deep drainage. The results of this study indicate that hydrologic changes following brush removal were evident in this system and are likely to positively influence groundwater recharge in the long-term. Importantly, much of the deep drainage that occurred following treatment happens in the first five years, with evidence showing that soil chloride is in similar concentrations after fifteen years if left untreated. The effects of chloride flushing can also be seen thirty years following treatment. Nonetheless, most changes occur soon after vegetation is cleared and so, in a management perspective, shrub clearing would be most beneficial if re-implemented within fifteen years after clearing, and best soon after five years.

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APPENDIX A

Study Site Description Narrative

Site T1

Landscape position: On a gently sloping (<2%) low backslope.

Management: Three separate root-plowed areas: 2005, 2001, 1991.

Field Soil Texture: Sandy clay loam A horizon, Sandy clay B horizon.

Soil Classification: Webb series.

Site T2

Landscape position: On a very slight lower slope (<2%).

Management: Three separate root-plowed areas: 2005, 2001, 1991.

Field Soil Texture: Sandy clay loam A horizon, Sandy clay B horizon.

Soil Classification: Duval series.

Site T3

Landscape position: A slight upper slope (<2%).

Management: Three separate root-plowed areas: 2005, 2001, 1991.

Field Soil Texture: Sandy loam A horizon, Sandy clay loam B horizon. 15-Year and Control a bit sandier.

Soil Classification: Webb and Duval series.

Site Z1

Landscape position: On a very slight convex slope (<1%) halfway from the drainage line to the ridge.

Management: Originally cleared approximately 30 years ago. Maintained as pasture with fire every 5 years.

Field Soil Texture: Sandy loam A horizon, Sandy clay loam B horizon.

Soil Classification: Antosa series.

Site Z2

Landscape position: On a ridgeline that has a very slight slope (<2%) on the eastern portion of the Wilcox aquifer recharge zone.

Management: Strip plowed 30 years ago and allowed to regrow. No treatment since. Originally cattle but now maintained for only deer.

Field Soil Texture: Sandy clay loam A horizon, Sandy clay B horizon.

Soil Classification: Webb series.

Site Z3

Landscape position: A slight upper slope (<2%) near the Neueces River.

Management: Originally cleared 30 years ago and plowed every 5 years to remove regrowth. Pasture for cattle.

Field Soil Texture: Sandy loam A horizon, Sandy clay loam B horizon.

Soil Classification: Bobillo series.

Site Z4

Landscape position: Slight midslope (<2%) in the heart of the Carrizo aquifer recharge zone.

Management: Maintained as pasture for the last 20 years since clearing. Cattle grazing and feed grown.

Field Soil Texture: Sandy loam A horizon, Sandy clay loam B horizon.

Soil Classification: Bobillo series.

Site Z5

Landscape position: Low angle lower slope (2%) near drainage line in the heart of the Carrizo aquifer recharge zone.

Management: Cleared approximately 20 years ago and maintained as pasture by plowing every 5 years. Occational crop grown and possible irrigation applied.

Field Soil Texture: Sandy clay loam A horizon, Clay loam B horizon.

Soil Classification: Webb series.

Site Z6

Landscape position: Slight upper slope (<1%) near ridgeline in the eastern portion of the Wilcox aquifer recharge zone.

Management: Cleared approximately 20 years ago, this land has been left to regrow and is used for cattle grazing.

Field Soil Texture: Loamy sand or sandy loam A horizon, Sandy loam B horizon.

Soil Classification: Antosa series.

Site Z7

Landscape position: On a convex upper slope (<1%) near a ridgeline. This site is in the heart of the Carrizo recharge area.

Management: Cleared approximately 30 years ago and maintained as pasture by plowing and fire every five years or as needed.

Field Soil Texture: Sandy loam A horizon, Sandy clay loam B horizon.

Soil Classification: Bobillo series.

Site Z8

Landscape position: On relatively flat ground in the heart of the Carrizo recharge zone.

Management: Cleared approximately 30 years ago for grazing and maintained every five years with plowing.

Field Soil Texture: Sandy clay loam A horizon, Sandy clay B horizon.

Soil Classification: Webb series.

Site Z9

Landscape position: On a very slight (<1%) lower slope on the Western edge of the Carrizo recharge zone.

Management: Cleared approximately 30 years ago and left to regrow, this land is used for cattle grazing.

Field Soil Texture: Loamy sand or sandy loam A horizon, Sandy loam B horizon.

Soil Classification: Antosa series.

VITA

Name:	David Anthony Barre
Address:	Texas A&M Agricultural and Research Extension Center 7887 U.S. Hwy 87 North San Angelo, Texas, 76901
Email Address:	kachoong@tamu.edu

Education:	B.A., Earth and Land Resources, Canberra University, 2002.
	M.S., Rangeland Ecology and Management, Texas A&M University, 2009.