5-2011

The Effects of Land-Use Change on the Hydrological Properties of Andisols in the Ecuadorian Paramo

James Joseph Hartsig
jhartsig@utk.edu

Recommended Citation

Hartsig, James Joseph, "The Effects of Land-Use Change on the Hydrological Properties of Andisols in the Ecuadorian Paramo. " Master's Thesis, University of Tennessee, 2011.
https://trace.tennessee.edu/utk_gradthes/978

To the Graduate Council:

I am submitting herewith a thesis written by James Joseph Hartsig entitled "The Effects of Land-Use Change on the Hydrological Properties of Andisols in the Ecuadorian Paramo." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

Carol P. Harden, Major Professor

We have read this thesis and recommend its acceptance:

Jaehoon Lee, Yingkui Li

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

The Effects of Land-Use Change on the Hydrological Properties of Andisols in the Ecuadorian Páramo

A Thesis Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

James Joseph Hartsig

August 2011

Acknowledgements

I would like to thank Dr. Carol Harden for her assistance in the understanding of the páramo processes as well as her guidance of this thesis. Her assistance and guidance in the field was immeasurable and greatly appreciated. I would like to thank Dr. Jaehoon Lee for his help in the Soil Physics lab as well as his help in interpreting and explaining the results. I would like to thank Dr. Yingkui Li for his contribution to this project and thesis. I would like to thank Hunter Terrell, Leah Bremer and Greg Metcalf for their outstanding assistance with the fieldwork. This research has been funded by NSF BCS-0852039. Mr. Metcalf's participation was supported by the NSF GK-12 Earth Project grant DGE-0538420. I would also like to thank Wesley Wright and Galina Melnichenko for their help with the sensors and bromide tracer study, and Will Fontanez and the Cartographic Services Laboratory of the University of Tennessee for drafting Figure 3. Stuart White and the Fundación Cordillera Tropical provided excellent resources and the opportunity to use the Mazar Wildlife Reserve. The Community of Zuleta was extraordinary in its help with field work on its property.

Abstract

The Ecuadorian páramo is characterized by unique soil properties that allow the ground to hold large amounts of water. These páramo grasslands support Andean cities and communities as a source of water for municipal, industrial, and agricultural use. Although recent research has suggested that changes in land use can decrease the amount of water and affect the water-holding capabilities of the soil, the hydrologic effects of different land uses, including burning for livestock grazing and pine planting for carbon credits, are currently under debate.

This research tested hypotheses about moisture-related properties of páramo soils under different land uses at two study areas in Ecuador. Bulk density, volumetric water content, water retention, and general physical properties were identified and compared between sites at those study areas. Soil structure differed between pine sites and other sites at both study areas, and moisture consistency differed between pine and other sites at the Mazar Wildlife Reserve. Volumetric water content values were high (mean of 86% at one Mazar site) but the pine sites contained less water by volume than the other sites. Water retention data showed that the surface horizons of all sites at both study areas require more pressure to release moisture than the subsurface horizons. Compared to other sites studied, the pine sites from both study areas have lower gravimetric water contents at saturation through -6.0 kPa. Different burning regimes do not appear to affect soil properties, in-situ moisture content, or water-retention capacity.

The introduction of pine plantations in the páramo at both study areas appears to have lowered soil moisture contents and reduced bulk density in the soil profile. This research adds to a growing group of studies that show that changes in land management can affect the hydrological properties of soils.

Table of Contents

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

Chapter 1

Introduction

One of the most important global issues is the diminishing availability of drinking water (Seckler et al., 1999). Water quality and water quantity problems affect numerous countries across six of the seven continents. With fluctuating climate patterns that result in heavier rainy seasons and prolonged droughts, many countries face shortages in water supply (Ragab and Prudhomme, 2000). While Africa and Asia are experiencing the most serious effects of droughts and floods (Rosegrant et al., 2002), South America is also experiencing shortages in available water. This is due to a number of factors, including a higher demand from an increased population and widespread water pollution (World Water Council, 2006). Ecuador is a country with water quantity concerns. The water supply for much of the country's population originates from high elevation páramo grasslands.

Páramos are high elevation grasslands located between 11˚ N and 8˚ S latitude and are known for the remarkable water-holding capabilities of their soil. These ecosystems are located at elevations of 3200 to 4700 meters in the upper mountain region of the Andes of Venezuela, Colombia, Ecuador, and northern Peru (Hofstede et al., 2003). Páramos are considered to be unique ecosystems and they provide important environmental services, including the storage of water. Since the Spanish arrived in the 1500s, páramos have been used for grazing cattle, sheep, and horses. The practice of burning grasslands to provide an available food source for livestock has been a part of Ecuadorian agriculture for centuries, at least (Balslev and Luteyn, 1992). However, the practice of afforestation in the páramos has just been promoted in the last few decades. The goal of afforestation projects is to provide economic viability by means of timber production, erosion control, and, more recently, carbon sequestration (Farley et al., 2004). The creation of the Clean Development Mechanism (CDM) as part of the Kyoto Protocol encouraged Kyoto-signing countries to meet their emission reductions by creating afforestation projects in developing countries. One of the ideas of the CDM is to use pine plantations (*Pinus radiata*) for CO_2 sequestration. Pine plantations are now scattered across the Ecuadorian highlands.

While it is generally understood that pine plantations consume more water than shrublands or grasslands (Hofstede et al., 2002), little is known about the long-term effect of pines on páramo soils. A major component of the increase in water consumption is the pine's deeper root system (Duncan, 1995). Other factors leading to decreases in soil moisture are interception and evapotranspiration from the trees' canopies (Farley et al., 2005). Very little attention has been given to the impact of pine plantations on the hydrological regime of the páramo (Buytaert et al., 2007). Since Andean cities and communities, such as Quito, the capital city of Ecuador, depend on the páramo as their source of water, the effects of afforestation projects on water resources should be carefully evaluated.

Water that originates in the páramo is essential to everyday life in the Andes. It is used for municipal, agricultural and industrial purposes. For example, 35% of the electricity consumed in the country of Ecuador's is supplied by the Paute-Molino Hydroelectric dam (Consejo Nacional de Electricidad, 2011). This study is designed to add to the ongoing research on the effects of land-use change, including the introduction of stands of pines and their impacts on water retention in the páramo.

Along with the unusual water-holding capabilities of the páramo, the soil also has the ability to capture and retain large amounts of organic carbon (Dahlgren et al., 1993). Organic carbon accumulates when below-ground and above-ground organic matter slowly breaks down into acids and plant-available nutrients (Schlesinger, 1997). Páramo vegetation typically consists of grasses and shrubs. The cool, humid conditions in the higher elevations of the Andes promote slow decomposition rates of páramo vegetation (Luteyn et al., 1992). When these slower decomposition rates occur on a regional scale, as in the northern Andes, the area becomes a carbon sink (Brown et al., 1986; Bashkin and Binkley, 1998).

Because such large stocks of soil carbon have become areas of interest for potential carbon sequestration projects for climate change mitigation, it is important to better understand these unusual soils.

In response to the environmental services associated with water and carbon storage provided by the Andean páramo, regional and international conservation groups have invested in Payment for Ecosystem Services (PES) programs (Wunder and Alban, 2008). These programs are intended to compensate parties who would otherwise unintentionally reduce the páramo's ability to store water and carbon. Originally, PES programs were intended to alleviate poverty and help poorer areas achieve environmental protection (Wunder, 2005). In this integration of conservation and development projects, the intention of PES programs was to increase incomes of poorer areas and remediate environmental concerns. These are the goals of PES programs in Ecuador (Espinosa, 2005). The capital city of Quito administers a water conservation fund, FONAG (*Fondo para la Conservacion del Agua*), to protect the hydrologic function of the páramos in its water source area. FONAG uses 1% of the water revenues and funds from voluntary contributions for watershed protection. While the intentions of FONAG are based on the premise that environmental services are correlated with land-use management, certain land-use practices are yet to be linked to higher or lower water yields (Espinosa, 2005). Determining the effects of these PES programs is the goal of a larger research project, directed by Carol Harden and Kathleen Farley, designed to provide a scientific foundation for understanding the effects of land-use change on water and carbon in the Ecuadorian páramo. This research contributes to that larger project.

The purpose of this study is to determine how different land uses affect the transmission of water and the water-holding capacities in selected Ecuadorian páramo soils. Land uses examined were (1) frequent burning for forage, (2) pine plantations, (3) *Polylepis* plantations, and (4) areas that had not been burned or grazed for more than 6 years. How these land uses affect the water storage of the páramos and the role of páramos in providing ecosystem services are currently topics of active debate. Two study areas in highland Ecuador were selected for this research, one in northern Ecuador, in the community of Zuleta, and one the Mazar Wildlife Reserve in the Nudo del Azuay area of southern Ecuador. The findings of this research will contribute to knowledge of the implications of different management strategies on the hydrology and water-holding capacity of páramo soil. Sites were selected on a space-for-time substitution basis that allowed us to sample areas of different land management practices that were representative of both previous and current practices.

Research Questions and Hypotheses

The objective of this research was to evaluate the impacts of different land uses and land management practices on the water storage and water transmission of Ecuadorian páramo soils. The research was designed to answer a set of questions and test four hypotheses that relate to soil-water relationships. The following questions address those relationships:

1. How do differences in land use affect the hydro-physical properties of the páramo soil?

Any changes in water movement and water retention can affect the structure, texture, and even color of the soil. If water flows through the profile of a pine plantation faster than through profiles of the grasslands typical of páramo, then this would be reflected in a drier, more friable structure. Identifying the soil properties associated with each land use will advance understanding of how to manage the different areas and add to knowledge of these soils. I hypothesize (H1) that differences in land use among sites will be associated with differences in the soil's physical properties.

2. Do differences in soil moisture content exist under different land uses in the páramo soil?

Soil moisture is dependent on the soil's physical and chemical properties in the páramo. This includes the abundance of organic matter in the soil profile. Any changes in the amount of organic matter and the change in the soil's physical properties will have the possibility to decrease the soil's ability to hold water. I hypothesize (H2) that soil moisture contents will differ between the pine plantation sites and the frequently and infrequently burned sites due to those changes in composition.

3. How do changes in land use affect the water-retention capacities of páramo soils?

While the effects of pine plantations on water retention in the páramo have received some prior study, little is known about the effects of frequent and infrequent burning on the water-retention capacities of grassland páramo soils. I hypothesize (H3) that the water retention curves associated with pine plantations will differ from those at grassy sites that are frequently or infrequently burned. I also hypothesize (H4) that the water retention curves associated with frequently burned (<6 years between burns) sites will differ from those that are infrequently burned.

4. How do changes in land use affect the movement of water in páramo soils?

The hydrologic characteristics of páramo soil are important because these soils feed and regulate flow to the fluvial system (Luteyn, 1999). Local differences in land use can substantially change the soil properties controlling the movement of water through the soil profile (soil structure, porosity, moisture content) in the páramo soil. Depending on the quantities, sizes, and connectivity of pore spaces, water will move down the soil profile more quickly in some soils than others. Other contributing factors, such as quantity and depth of roots, are likely to play a role in the transmission of water throughout the profile. I hypothesize (H5) that the water flux of the soil profile is more rapid in soils at the pine sites than in soils in grassy and recently burned grass-covered sites.

The next chapter describes the páramo ecosystem and how soil genesis occurs in the Ecuadorian highlands. The following chapter presents the research methods, including the research design, descriptions of both study areas (including a description of each site), and field and laboratory methods.

Results are presented and discussed in the fourth chapter, and conclusions are given in the final chapter.

Chapter 2

The Páramo Environment

Páramo

At high elevations in the northern region of South America, an ecosystem known as páramo stands out in the Andean landscape. A sharp contrast between shrubby and forested areas and grassland-dominated areas exists at the base of the páramo, which is considered to be at the forest border (about 3500 m.a.s.l.), although it is evident in the field and widely recognized that the lower boundary of páramo has been altered by forest clearance (Sarmiento, 2002). The upper limit is below the perennial snow limit (about 5000 m.a.s.l.) at a zone bare of vegetation. Páramos cover an estimated area of 77,000 km^2 throughout the northern Andes (Dinerstein et al., 1995; Figure 1). These grasslands consist mostly of tussock grass species (Luteyn et al., 1992). The turnover from regrowth and decayed tussock grasses accumulates in the soil as organic matter. Organic matter builds up in the soil, storing large amounts of soil organic carbon (Nanzyo et al., 1993). These values have been reported to be as high as 212 g kg^{-1} of organic carbon in páramo soil (Poulenard et al., 2001). The cool, moist climate of the páramo keeps the soil wet throughout the year. Cool temperatures, combined with high amounts of precipitation from rain, clouds, and fog, ensure a constantly high moisture content in the páramo soils. These conditions slow decomposition rates and allow for the accumulation of organic carbon. The combination of a cold, wet climate, volcanic ash soils, and slowly decomposing organic matter not only supports a diverse plant community, but also creates ideal conditions for water storage in páramo soils.

Figure 1 - Andean páramos (in yellow).

Soils

The dominant soil orders in the Ecuadorian páramos are Andisols, Inceptisols, Entisols and Histosols (Buytaert et al., 2006). The Andisols in the Ecuadorian páramo have been classified as having either a histic, fulvic, or melanic epipedon (Poulenard et al., 2001; Buytaert et al., 2005a). All of these epipedons represent wet soils with high organic matter contents. A histic epipedon is one in which the soils are saturated for 30 consecutive days or more during the growing season and have soil organic carbon contents of 16% or greater (Soil Survey Staff, 2003). A melanic epipedon is one in which the surface horizon is more than 30 cm thick, has a melanic index of 1.70 or less throughout the profile and has organic carbon contents greater than 6% (Soil Survey Staff, 2003). A fulvic epipedon is one in which the surface horizon has a melanic index of 1.70 or more throughout the profile, and is it used in describing soils according to the Food and Agricultural Organization or World Soil Classification. Melanic soils have humic type A organic acids, as opposed to humic acids type B and P, which are found in fulvic soils. Nierop et al. (2007) noted differences in the melanic indices of epipedons from soils under grass vegetation (melanic) and pine plantations (fulvic)(Figure 2). In U.S. Soil Taxonomy, Andisols with this type of aquic moisture regime are classified as either Epiaquands or Melanaquands. Andisols are formed in volcanic ash and are typically young soils, their age depending on the time of the most recent volcanic eruption. These soils contain large amounts of glass and colloidal materials, such as allophone and imogolite. Allophane is a weathered product of feldspars and ash and can further weather into halloysite (Parfitt et al., 1983). Andisols are usually easy to till and can be fertile depending on the chemistry of the volcanic ejecta (Buol, 2003a). Like Histosols, which are also known for their water-holding capacities, Andisols can store large amounts of organic carbon. This is credited to the ash composition and the high soil moisture contents (Shoji et al., 1993).

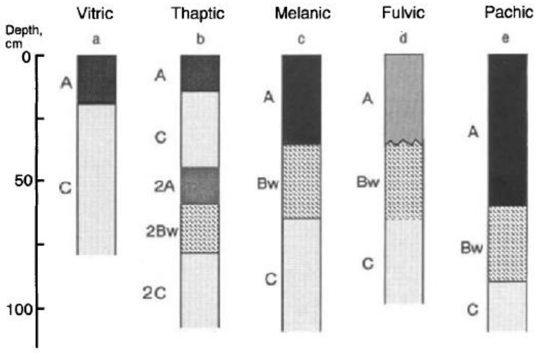


Figure 2 - Schematic representation of selected Andisol horizonations (from Shoji et al., 1993)

The physical composition of Andisols creates an ideal soil structure for water and carbon storage. Soils in the páramo typically have a very porous structure with an abundance of soil aggregates that are formed in the presence of high organic matter contents and weathered volcanic ash. This results in low bulk density values not typically seen in mineral soils. Bulk density values have been shown to reach as low as 0.13 g cm^{-3} (Buytaert et al., 2006).

The typical horizon sequence of an Andisol would be one with a (1) thick A surface horizon, or an A overlying up to multiple subsurface A horizons, followed by a (2) Bw horizon, if the soil has had time to develop, and then a (3) C or Cr horizon (Shoji et al., 1993). Factors controlling this sequence would include the five factors of soil formation identified by Hans Jenny (1941): climate, biota, relief, parent material, and time. Climate and parent material are the most prominent soil-forming features in the páramo. Relief and time are reflected in the thickness and ages of the volcanic ash soil layers. The thickness of the surface horizon depends on the slope where the wind-blown ash was deposited, with thicker layers on either backslopes or valley floors, or in other sites of aeolian deposits. Biota, especially vegetation, also plays a significant role in the páramo due to the rate and amount of decomposition of plant material in the surface horizons.

Globally, Andisols account for ~1% of the ice-free land area (Soil Survey Staff, 2003). They are the least extensive soil order and did not receive their own classification in the U.S. Soil Taxonomy until 1990 (Shoji et al., 1993). While the extent of worldwide Andisols has been mostly investigated in Japan and the Northwestern United States, any research conducted in South America, in particular in the páramo, could help improve the understanding of these soils. By identifying not only the water-holding properties of these soils, but also their structure, texture, color, and consistency, this research will help better understand the roles of Andisols in ecosystem services on a global scale. Along with other research from páramo studies, this project is intended to contribute to the understanding of the genesis and morphology of volcanic ash soils.

Parent Material

The parent material of soils at the areas studied in this project consists of large volumes of Holocene volcanic ash in thick deposits overlying andesitic and Tertiary bedrock. Layers of ash from the surrounding volcanoes blanket the páramos. Volcanic ash forms organometallic complexes that are resistant to microbial breakdown (Farley et al., 2004). Physical and chemical weathering breaks down the ash and supplies the profile with high amounts of iron and aluminum (Parfitt et al., 1983). As a result of the ash, moisture, cool temperatures, and vegetation, the páramo soils remain dark and humic. The high water storage in these soils is also attributed to the volcanic glass in the ash, combined with the cool, humid temperatures characteristic of those high elevations. This glass results from the rapid cooling of the molten materials that are ejected in a volcanic eruption (Buol, 2003a). Volcanic glass is more weatherable than crystalline materials and is usually broken down into secondary minerals.

The Ecuadorian Andes consist of two north-south oriented mountain chains known as the Western and Central Cordilleras. In between these cordilleras lies a tectonic depression in which the city of Quito is located. These cordilleras have distinctly different geologic formations. The Western Cordillera is made up of sedimentary and basic-to-intermediate volcanic deposits emplaced in a submarine environment (Barberi et al., 1988). This cordillera also has layers of lava and dacitic tuffs. In the Central Cordillera, the more recent volcanic materials overlie Precambrian and Paleozoic meta-volcanic with occasional granite and grandorite batholiths (Buytaert et al., 2005a). Further south in the Rio Paute basin, late Quaternary to Holocene aged deposits cover the area. This includes thin layers of fine-grained ash (Buytaert et al., 2005a).

Climate

The climate of the páramo is wet and cold and typical of tropical high mountains. Daily average temperatures can range between 0°C and 12°C (Poulenard et al., 2001). Temperatures can reach near-freezing at night and 20°C during the day (Buytaert et al., 2007). Precipitation can range from 700 mm to 3000 mm (Luteyn et al., 1992) during the year. This includes inputs from frequent fog, drizzle, and high- and low-intensity rainfall. Rainfall distribution throughout the páramo is generally characterized by a dry season from June to August and wet season that experiences 90% of the annual precipitation from

September to May (Zehetner et al., 2003). Solar radiation is constant throughout the year due to the close location of the Equator, resulting in a low variation of seasonal climate. The radiation is also intense due to the high elevations of the páramo. Snow does not accumulate in these areas due to the páramo's diurnal temperature cycle. This climatic environment is classified as a Tropical Summer High Mountain climate (HAw) in the Köppen reformed classification (van Veelen and de Vet, 2008).

Biota

The páramo supports about 5000 different plant species, and vegetation of the páramo is highly endemic (Buytaert et al., 2006). This vegetation includes tussock grasses, ground rosettes, dwarf shrubs, cushion plants and giant rosettes (Luteyn et al., 1992). When classifying and identifying vegetation zonation, authors have used three zones corresponding to elevation. These zones are the super páramo (4500–4800 m), grass páramo (3500–4100 m) and subpáramo (3000–3500 m). At both study areas used in this research, the observed vegetation consisted primarily of grasses, known locally as *paja*, short woody shrubs, and occasional stands of trees. Non-native pine plantations and stands of *Polylepis* can be found throughout the páramo. In one of the sites at the Zuleta study area, a ground cover plant was found in the *Polylepis* stand. This site was not typical of the páramo, as it had previously been a potato patch and had been fertilized during years of cultivation.

Macro-organisms living in the páramo include earthworms, several of which were observed to be 16 cm long. These were found in abundance in the Zuleta study area, but not seen in the Mazar Wildlife Reserve. However, the owner of the Mazar Wildlife Reserve has seen both smaller and large worms in the study area (Stuart White, personal communication, July 2009). When excavating soil pits at the Zuleta study area, worms were discovered, and their lengths were noted. Several worm castings were observed along site trails and paths at the Zuleta study area.

Hydrology

The hydrologic regime of the páramo is complicated and has not received the recognition it deserves. The water-regulating capacity of the páramo has been studied by only a handful of researchers (e.g., Podwojewski et al., 2002), and limited research exists on the effects of land use on soil-water relationships in the páramo. These limitations are due to difficult monitoring circumstances and the scarcity of long-term datasets (Buytaert et al., 2006). The soil's physical properties can have a direct impact on the hydrology of the páramos. The intensity and nature of human activities have increased in these areas, creating a reason for concern for water supply (Buytaert et al., 2006). Compaction of soils, which can occur when human activity increases, reduces the amount of available pore space and thus reduces the ability of the soil to store water (Harden, 2006). By identifying land uses that affect soil-water relationships in the páramo, management plans may be developed to help implement sustainable methods for protecting water yields.

Since most of the páramo consists of thick ash layers overlying bedrock, water moves predominately through the soil surface horizons. This hydrologic process, known as interflow, is the main path of water through the páramo (Ataroff and Rada, 2000). Interflow, which can occur above the water table, allows water to travel down a more direct path to the stream channel than groundwater typically does. Water can also move down the profile to where the A horizon meets the subsurface horizon. Buytaert et al. (2004) noted that "major subsurface flows were observed at the border between the H and A horizon and at depth between the A horizon and the bedrock" at a site in southern Ecuador just northwest of Cuenca.

The hydrologic soil properties of the páramo described in previous studies show that they are advantageous for storing water. These properties include low bulk density, high soil moisture contents, and porous, silt loam soil textures. These are considered part of the physical characteristics of the soil and were compared in this study on a site-to-site basis. Identifying these hydrologic properties, the rate of water movement, and water retention of these soils is expected to lead to a better understanding of their similarities to and differences from other soils. The organic matter in the soil helps create aggregates, which add to the porous structure. The physical composition of the porous soil aggregates allows water to move through the profile both laterally and vertically. In areas not disturbed by land management, infiltration capacity exceeds rainfall intensity (Harden, 1993).

Chapter 3

Methodology

Research Design

Northern and Southern Study Areas

Two study areas were selected for this research based on landowner permission and the availability of lands used for grazing, planted in pines, and burned at different frequencies. Páramo land uses vary among private properties. Both areas studied in this project were grazed by alpacas. To support grazing, land owners typically burn different sections of their property to remove old grass and allow the growth of fresh sprouts, which the livestock prefer for nutrition and taste (Schmidt and Verweij, 1992). Burning is often practiced in patches. Accidental burning also occurs. We were able to sample sites at both study areas with different burn histories. For this study, areas that had been burned in the previous 6 years were considered frequently burned. Areas that had not been burned for 6 years were considered infrequently burned.

Both study areas included pine plantations. The Zuleta study area is also undergoing experiments with the species *Polylepis racemosa*, a shrubby tree native to Peru. We were given the opportunity to sample soil under different aged stands of *Polylepis*, from a younger stage (1-2 years) to a more mature stage (8 years). The community of Zuleta has largely excluded burning of páramo grasses. Besides the burning of an 8-hectare area for alpaca grazing, the last burn at this study area was by accident and occurred in September 2007. Most of the areas have not been burned in the past 9–15 years. At the Mazar Wildlife Reserve study area, numerous land uses were available to study. One of these was land, now covered with shrubs and trees, that had previously been páramo 40–50 years ago. We sampled soils at this site to compare it with soil under nearby pine plantations and more recently burned páramo sites. Differences in topography, climate and parent material were minimized so that the different land covers appeared to be the only reasons for differences in soil properties.

Field work at Zuleta was conducted in June of 2009. Zuleta is located in the northern-central part of Ecuador (Figure 3). This area was of interest because it contained different land uses, including a recently burned site, a pine plantation, livestock grazing sites, a site that had been harvested for crops, and, more recently, sites with *Polylepis* cultivation. The study area is owned by the community of Zuleta and maintained by hired residents of Zuleta who manage the alpacas. They are paid by the city of Ibarra to protect these páramo headwaters for that city's water supply. The páramo study sites sampled at this area were at an elevation of around 3600 m (Figure 4). Research conducted at this site started on June 12 and lasted until June 17, 2009. Seven sites were selected for this analysis. Their physical descriptions can be found in Appendix A. Land-cover and land-use history at Zuleta were observed and interpreted with the help of a biologist from the Universidad Católica in Quito and the explanations of the president of the community and residents of the area.

Figure 3 - Study areas in relation to major cities. Nudo del Azuay is the site of the Mazar Wildlife Reserve.

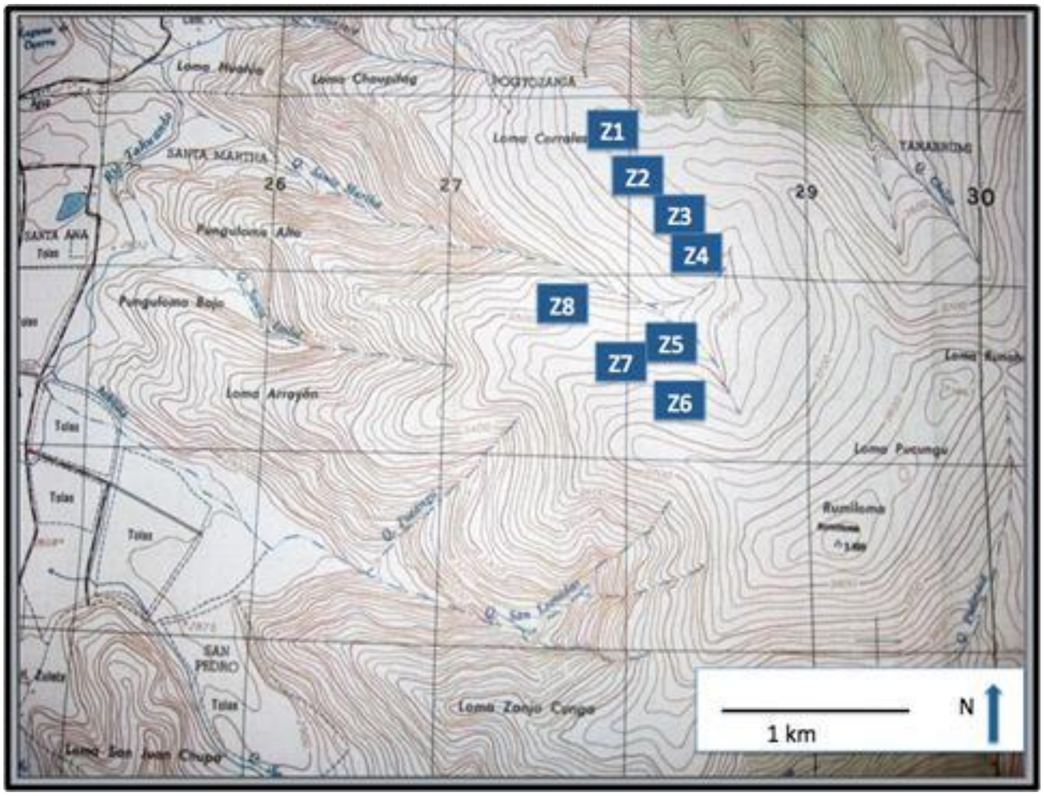


Figure 4 - Topographic map of the sites at the Zuleta study area.

The Mazar Wildlife Reserve was the focus of field work in the second year of this project. This reserve is located in the southern-central part of Ecuador (in Nudo del Azuay, Figure 3). The six sites investigated in this area were: recently burned, grazed grass, pine plantations, and an area that had not been burned for 40–50 years. Site descriptions can be found in Table 2, and physical descriptions can be found in Appendix A. As at the Zuleta study area, one of the management practices at the Mazar Wildlife Reserve is raising alpaca. Dr. Stuart White owns and manages the reserve, in conjunction with the Fundación Cordillera Tropical. Páramo sites in this area are at elevations of around 3400 m (Figure 5). Preliminary tests were done in July 2009, and research at all sites was conducted at the Mazar Wildlife Reserve from June 14 to June 23, 2010.

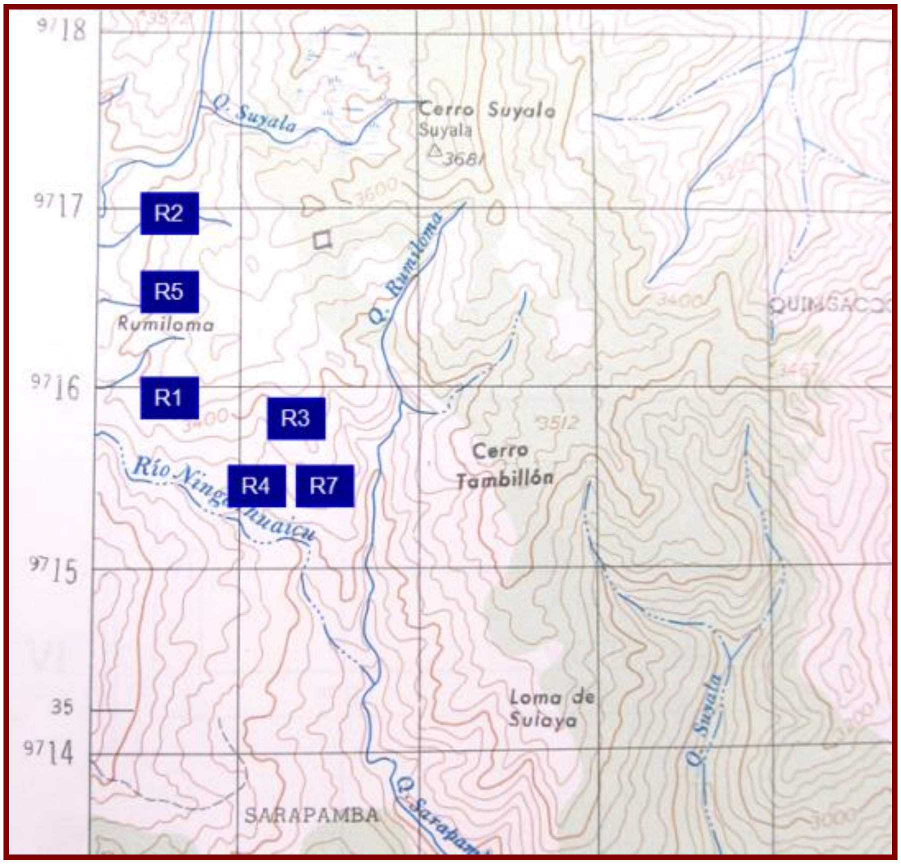


Figure 5 - Topographic map of site at the Mazar Wildlife Reserve study area.

Vegetative cover varied from site to site. Where burning was recent (within 1 year), small patches of bare soil were present. Sites that had not burned within recent years did not have bare patches, but still had shorter grasses than those with even older burns. The ground under pine plantations was covered in needle duff, which accumulated to an average depth of 7 cm. This duff was removed during sampling to reach the soil surface. We studied two pine plantations from this study area and found the R5 pine site to differ from R7 in the amount of surface vegetation and soil moisture.

Table 1 - Site data for the Zuleta study area

	ELEVATION (m)	SLOPE °	ASPECT	LAND COVER	LAND USE	TEMPERATURE
Z1	3623 - 3630	20	270	0-20% bare, 0-20% shrub, 80-100% herbs	Bunch grass burned 9 months earlier; *Polylepis* planted, but small and dispersed; no grazing	11.5° C
Z2	3636 - 3650	11.5	225	>80% paja, 0-10% tree (*Polylepis*)	Bunch grass; burned and grazed until 15 years ago; some small *Polylepis*	9° C
Z3	3642 - 3647	12.5		>80% herb, 0-10% shrub	Bunch grass; burned 15 (?) years ago, no trees	9° C
Z5	3598 - 3603	16	25	40-60% bare soil, 20-40% shrub, 60-80% tree canopy cover, variable understory	Pines (40 years old), previously grazed and burned	10° C
Z6	3649 - 3661	13	25	>80% herb (99% paja), 1-10% shrubs	Bunch grass; burned 9 (?) years ago; grazing, no trees	9° C
Z7	3608 - 3611	12	6	>80% herb, 0-10% shrub, 10-20% tree, 3m x 3m spacing of *Polylepis*	*Polylepis*; field was in potatoes until 12 years ago; then burned; alpaca grazing	9.5° C
Z8	3518	12	339	0-10% bare soil, 40-60% herbs, 10-20% shrubs, 20-40% trees	*Polylepis*; field was in potatoes for 10 yr with fertilizer; *Polylepis* for past 5 years; alpaca grazing	11° C

Table 2 - Site data for the Mazar Wildlife Reserve study area

	ELEVATION (m)	SLOPE °	ASPECT	LAND COVER	LAND USE	TEMPERATURE
R1	3449	21	192	50% shrub, 0-20% bare, 30-50% short paja	Bunch grass burned 7 months earlier, bare areas	12° C
R2	3428	20	248	>80% herb (99% paja), 1-10% shrubs	Bunch grass burned 6 years ago, some woody shrubs	14° C
R3	3453	13.5	149	75% shrub, 25% short paja	Burned 25 years ago; woody shrubs with some paja	11° C
R4	3351	22	204	75-80% montane forest, 20-25% shrub	40 - 50 year previously burned; montane forest	11° C
R5	3402	17.5	312	Evenly spaced pines (85-90%), 10-15% shrubs	Pines (20 years old)	11° C
R7	3249	20	190	Evenly spaced pines (75-80%), 20-25% shrubs	Pines (20 years old)	11° C

Experimental Design

At each research site, the first step was to establish three, parallel, 20-m horizontal transects. Aspect and slope were measured at the 0 and 20 m ends of each transect. A soil pit was excavated between transects. Each pit was excavated down to 100 cm or until the C horizon was exposed. Each horizon in the soil profile was described, including the C horizon, but only the A horizons were sampled. Observations from road cuts confirmed the typical order of horizons down to the bedrock. Soil temperature was measured at 50 cm below the surface in the pit wall. At this depth, variations in time of day or weather conditions are not expected to affect the temperature.

Soil Physical Properties

To test H1, that differences in the moisture content of soils would be associated with differences in soil properties, soil characteristics were determined for each site. Soil characteristics were determined by qualitatively describing the soil profiles from each pit. Soil pits were excavated at each site in both study areas, and the soil's physical properties were described for each horizon. Descriptions of these pits included the number of horizons, depth of each horizon, color (*in situ*), texture, structure, moisture consistency, root-limiting layer and percent coarse fragments. These dark, humic horizons were all designated as A horizons. Any notable change in texture, color, structure, or combination of the three was described as a change in horizonation. When a change occurred, as it did in the Mazar Wildlife Reserve site, it was noted as either a Bw, C, or Cr horizon. If an underlying B or C horizon was included in the 100-cm deep profile, it was also described.

Soil profiles were described in the following order: (1) The depth to the bottom of the horizon was recorded. (2) Colors were described using a Globe color chart. (3) Texture was determined using a step-by-step test that involves forming a soil aggregate into different shapes. Texture was also described using techniques from previous soil judging experience. (4) Soil structure was determined by observing the aggregates in the pit wall. Soil structure was described by chipping away soil aggregates from the pit wall and examining how those aggregates were bound together. (5) Moisture consistency was determined by wetting a soil aggregate and seeing how easily it crumbled under applied pressure. (6) Volumetric water content was recorded using the Campbell HydroSense meter horizontally in each horizon. (7) Root-limiting layers could be determined by measuring the depth, in the soil pit, at which roots ceased to extend, or by measuring the depth at which contact with a more compact horizon or a difference in lithology occurred. (8) Coarse fragments are rare in these soils, but when they were observed, their percentage in the horizon was recorded.

Particle size distribution of samples taken from each horizon was determined using a laser diffraction particle size analyzer (LS 13-320 Particle Size Analyzer with sonicator for additional dispersion activity). These soils are high in amorphous clay-sized materials that have great resistance to dispersion, particularly after oven drying (Kubota, 1972). Due to the difficulty in breaking down the aggregates of these soils, only portions of the American Society for Testing and Materials' test for dispersive characteristics of clay soil by double hydrometer (ASTM, 2000) were used. This included adding 5% concentrated hydrogen peroxide to each dried sample and heating it until frothing occurred. This process removed the organic matter and the free carbonates, if present, from the soil sample. A small amount (0.5 g) of sodium hexametaphosphate was added to the solution as a dispersing agent to help break apart soil aggregates. Samples were shaken for an hour before aliquots were taken. In addition to the dispersing agent, the laser diffractor was equipped with an ultrasonicator, which agitated the sample to further breakdown the soil aggregates.

Small changes in the properties of Andisols under different vegetation may lead to different classifications of these soils (Nierop et al., 2007). Depending on the amount of organic matter and organic acids added to the soil from the surface vegetation, the epipedons could be classified as either fulvic or melanic. Determining this classification aids in understanding the chemical composition of the soil. Since certain organic acids exist only when there has been an appreciable amount of weathering, it is possible to determine whether those acids are fulvic or humic. The procedure for testing the presence of organic acids in these soils was developed by Honna et al. (1988). It involves taking 0.5 gram of dried sample and mixing it with 25 mL of 0.5% NaOH for 60 minutes. One drop of a 0.1% Accofloc solution is added to the mixture, which is then centrifuged. One mL is pipetted out of that solution and put into a test tube. An additional 20 mL of 0.1% NaOH are added to the sample and mixed. A portion of this mixture is placed into a vial and inserted into a spectrophotometer. The measurements are read at wavelengths of 450 and 520 nm. The ratio of the resulting values is the melanic index (K_{450}/K_{520}). Soils having melanic index values less than 1.70 are classified as having a melanic epipedon, while soils with values greater than 1.70 are classified as having a fulvic epipedon. The different types of organic acids and their quantities are important factors when classifying these soils due to the expectation that the soils under pine plantations would be associated with fulvic epipedons and soils under grass vegetation would be associated with melanic epipedons. Understanding the humification of soil organic acids can help determine similarities or differences in soil properties under different vegetation covers, and between soils from the northern and southern parts of the country. This difference occurs mostly from the amount of allophane and weathered volcanic material in the soil (Buytaert, 2005b).

Soil Moisture

To test H2, that differences in soil moisture are expected in the pine plantation and grass páramo sites, volumetric moisture content was measured at 30 points across each transect using a Campbell HydroSense CS620. This instrument senses electrical conductance along two, parallel, 12-cm long probes and converts the signal to a volumetric moisture content (percentage). The results of these readings were analyzed statistically and used to help identify which sites had higher and lower moisture contents in the upper 12 cm of soil. Samples of known volume were also taken at five of the volumetric moisture content measuring points per transect for later determination of bulk density and gravimetric water content. In addition to the readings taken along each site's transects, percent volumetric water content was also measured at each horizon in the soil profiles by inserting the two probes into the pit wall at each horizon.

Water Retention

To test H3 and H4, that changes in land use affect the water retention of páramo soils, data were obtained in two sets of procedures. First, duplicate core samples were taken from each A horizon in the soil pits. These samples were extracted using a 200-A Soil Core Sampler designed for bulk density sampling. The auger used for this purpose contains a 6-cm long ring, designed to preserve the soil structure without allowing compression, which would give an inaccurate reading. Andisols with histic and melanic epipedons are typically characterized by multiple deep A horizons (Shoji et al., 1993). A total of six bulk density samples (three depths, all of which were different A horizons, two samples each) were taken at each pit. In the lab, these samples were analyzed for bulk density and mass water content. The moist samples were weighed, placed into an oven at 105˚ C for 24 hours, and reweighed. The following equation was used for bulk density determinations:

$$\rho_b = \frac{m_{dry}}{V_b}$$ (from Hillel, 1998a)

where V_b equals the volume of the soil sample. Volumetric water content (VWC) of samples taken from different depths in the soil pits was also calculated using the bulk density values and the mass of both the wet and dry soil samples. The following equation was used for VWC ( ) determinations:

$$\theta = \frac{m_{wet} - m_{dry}}{\rho_w \cdot V_b} \quad \text{(from Hillel, 1998a)}$$

where m_{wet} equals the mass of the wet soil sample, m_{dry} equals the mass of the dry soil sample, ρ_w equals the density of water at room temperature (1.00 g/cm^3) and V_b equals the volume of the soil sample.

Second, soil samples were extracted from the soil pit wall for lab measurement of their water-retention capacity (Figure 6). These samples were taken in 5.08-cm (2-in) long PVC pipe tubes with a diameter of 5.08 cm (2 in) to preserve soil structure. Tube edges were beveled so that they would enter the soil with minimal disturbance. Back in the lab, they were placed on a tension table to measure water retention at pressures of 0, -0.5, -1.0, -2.0, -3.0, -4.0, -5.0 and -6.0 kPa to establish a water characteristic curve (Klute, 1986). Samples were first saturated and then placed onto the tension table at a stable matric potential. A drain attached to the tension table was then lowered to sequential depths to release water at a negative matric potential. Samples were reweighed after each depth and then placed back onto the tension table. After points along the drying curve had been measured, samples were allowed to rewet at the same pressures to establish a rewetted curve. Both the drying and rewetted curve were plotted to determine any rate of hysteresis. Results were plotted using the gravimetric water content.

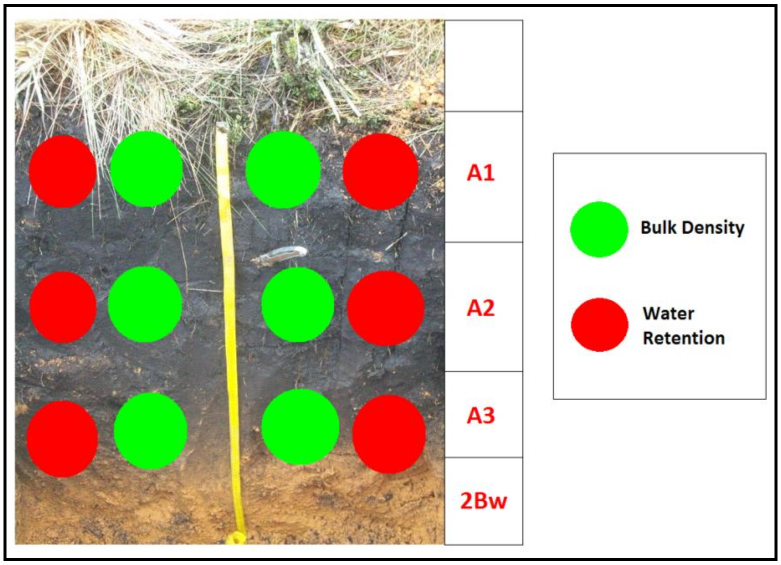


Figure 6 - Sampling design for bulk density and water retention samples extracted from pit wall.

Water Transmissivity

To observe water movement through the soil profile and test H5, that the movement of water in the soil profile is faster in the pine sites than in the infrequently and frequently burned sites, two field techniques were used to determine the rate of water movement down the soil profile. Laboratory methods for determining hydraulic conductivity were not expected to work well with the high moisture contents of the páramo soils due to possible edge effects and the fact that soil structure may have been disturbed when transporting samples. Therefore, two field-based techniques were used. The first field-based technique was an application of a potassium bromide (KBr) tracer to the surface of the recently burned, infrequently burned, and pine sites. This was performed using a liquid potassium bromide mixture of 500 parts per million in a 1-L application on a plot 76-cm wide (parallel to the contour) and 38-cm long (parallel to the slope). This mixture was evenly distributed using a watering can over the plot to apply the solution over one minute. This plot was then sampled in precise time intervals shortly after the application. Samples were taken with a soil auger, with a volume of 28.7 cm^3, at depths of 0–10, 10–20, and 20–30 cm at the Zuleta study area in 2009, and at depths of 0–20, 20–40, and 40–60 cm, with an auger volume of 57.3 cm^3 at the Mazar Wildlife Reserve study area in 2010. Samples were taken at different depths in the Mazar study area after results from samples taken at Zuleta in 2009 indicated rapid movement. It was assumed that, the more saturated the profile, the faster water would move down the soil profile. The abundance of fine, deep roots in each site was also a reason to sample further down the soil profile at these sites.

During the 2009 pilot study at Zuleta, tests with a liquid dye demonstrated that the liquid moved down the soil profile very quickly. Based on this, duplicate samples were taken according to the design shown in Figure 7, after 5, 13, 20, 60 and 120 minutes. They were sampled from the middle of the plot going downward towards the bottom of the plot. Samples were also taken below the plot.

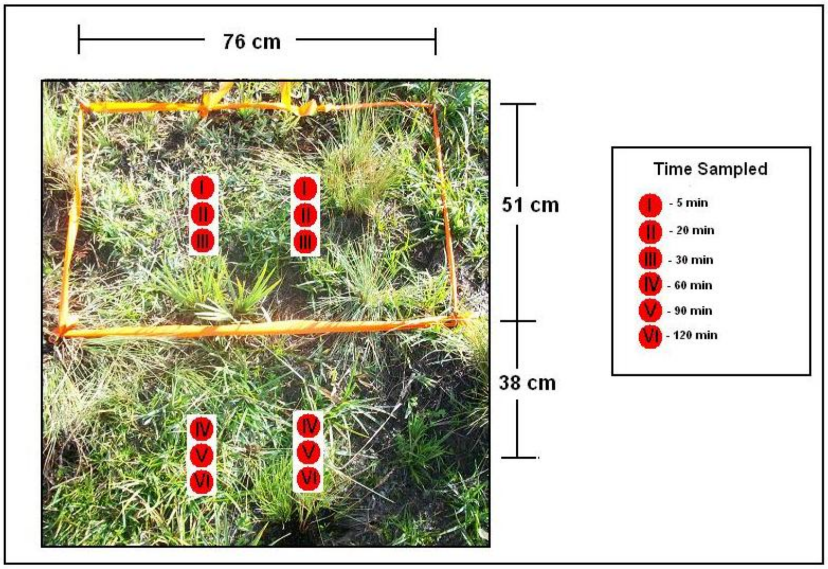


Figure 7 - Schematic representation of plot area for liquid bromide tracer test.

Samples were taken back to the University of Tennessee, where 25 mL of distilled water were added to each soil sample. The effluent was then tested for bromide concentrations using a mass spectrometer in the Water Quality Laboratory in the Biosystems Engineering and Soil Science Building.

In the second field-based technique, dry potassium bromide crystals were applied to the surface and allowed to infiltrate the surface over the course of a year (June 2009 to June 2010). The potassium bromide crystals (500 g) were sprinkled onto the soil surface of plots at the recently burned (Z1, R2) and pine plantation sites (Z5, R5) at both study areas in 2009. These plots were 1 m long by 2 m wide and were sampled one year later at depths of 0–30, 30–60 and 60–90 cm, in the same method as the liquid bromide test. Duplicate samples with a volume of 86.0 cm^3 were taken using a soil auger inside and outside (downslope) of the measured plot (Figure 8). Samples were brought back to the University of Tennessee and tested for bromide concentrations in the same manner as the first test. Concentrations were recorded, and potassium bromide concentrations were plotted with soil depth.

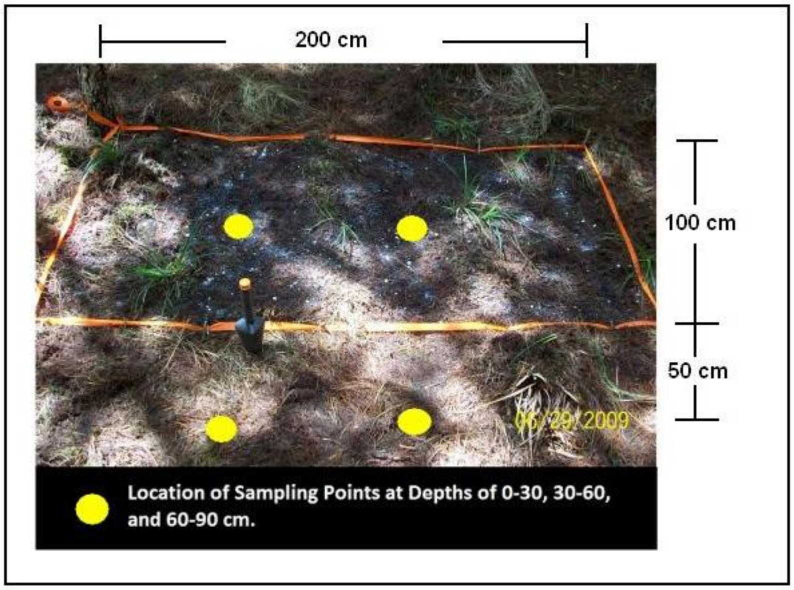


Figure 8 - Sampling plot for one-year bromide tests.

Soil moisture sensors were also put in place in the field to provide additional data for later analysis. At the Mazar Wildlife Reserve site, 24 Watermark sensors were placed in the ground to measure soil moisture at 25 and 50 cm depths. These sensors are set to record and log soil moisture data from June 2010 until June 2011 or longer. These data will show how water moves through the upper 50 cm of the surface horizons of the páramo under natural weather conditions. The sensors were placed in four representative sites, including a recently burned site, a pine plantation, a site burned 6-years earlier, and a shrubby site. Triplicate sensors were installed at each site for a better representation of the soil moisture regime. At the pine and 6-year burn sites, we installed rain gages. The 6-year burn site was also equipped with a relative humidity meter to represent the entire area’s local humidity.

Figure 9 - Datalogger with sensor placement (auger for scale)(photo by author).

Soil samples taken in the field were carefully placed in plastic wrap and then put in Ziploc bags to preserve moisture during transportation. These samples were then put into plastic bins and secured safely while packed tightly to preserve the soil structure. Once back at the University of Tennessee, soil samples were placed in quarantine and refrigerated. When samples were no longer needed, they were placed in an oven at 105˚ C for 24 hours and removed from quarantine.

Chapter 4

Results and Discussion

The goal of this project was to compare and evaluate the hydro-physical properties of the páramo soil in Ecuador under different land uses and land managements. The hydrologic properties of soil include any attribute of the water-holding capacity and the water transmission in that soil. I investigated the hydrologic properties by examining the soil's general physical properties, the water retention at low pressures, and the water flux, as determined using tracers. These tests made it possible to gain valuable insight into how water moved and how it was stored in these soils. In this chapter, I present and discuss results for each of the tests performed for this project.

Descriptions of Soils at the Two Study Areas

Zuleta Study Area

Soil profiles at the Zuleta study area contained A horizons that were very deep (>80–100 cm). The C horizon was not exposed when excavating the seven soil pits from these sites. The exposed soil profiles were all dark and humic, and careful observation was needed to distinguish the presence of multiple soil horizons. The horizonation sequence for these profiles was a series of A horizons that extended down past 100 cm. These were designated as A1, A2, and A3. In U.S. Soil Taxonomy, the only modifier for an A horizon is a "p," which denotes any anthropogenic disturbance such as grazing, plowing, or tilling. The surface horizon of the Z8 *Polylepis* site was classified as having an Ap horizon due to its history of crop harvesting and fertilizing. Horizon depths were determined by the increase in compaction down the soil profile. In grass sites, the structures of the surface horizons were strongly influenced by the presence of grass roots. These roots decreased in both size and quantity as they came into contact with the underlying horizons.

At all of the Zuleta sites, the depths of the surface (A1) horizons were similar, ranging from 19 to 26 cm deep. The next subsurface horizon (A2) ranged in depth from 42 to 56 cm. Below this horizon, differences in depths and designation of horizons varied. Surface (A1) horizon colors were very black and were either designated as 10 YR 1/0 (sites Z1, Z2, Z3), 10 YR 2/1 (sites Z5, Z8) or 7.5 YR 2.5/1 (sites Z6, Z7). Field textures for all A1 horizons were silt loams, except for those at Z5 (pine site), which had a sandy loam texture. Subsurface horizons also had a field texture of silt loam at the Zuleta sites, except at Z5 (pine site), which had a loamy texture. Below the A2 horizon, field textures varied from a silt loam to a loam. Soil structure for all surface horizons was strong, sub-angular blocky, except at Z5, where the soil had a granular structure. In general, this structure was maintained down the profile to the C horizon, which was determined to have a massive structure. The Z5 site did develop a more sturdy structure, as the three underlying subsurface horizons were all sub-angular blocky. Moisture consistency for all surface horizons was very friable. This term refers to the cohesion and adhesion of the soil particles to one another. Subsurface horizons were then found to be friable in any silt loam horizon and firm in any C horizon. Volumetric water contents in all A horizons ranged from 53–74% in sites Z1, Z2, Z3, Z6 and Z7. These values were substantially lower in the Z5 site (13–22%) and the Z8 site (45–52%). The laser diffractor used for determining particle sizes showed all Zuleta sites to have very high silt contents (51–78%). Data sheets for soil pits at the Zuleta sites are included in Appendix A.

Mazar Wildlife Reserve Study Area

Soil profiles at the Mazar Wildlife Reserve study area were shallow compared to those from the Zuleta study area. The top A horizons ranged from 43–57 cm deep. Surface horizons ranged from 18–25 cm deep. Depth to the Bw horizon ranged from 61–91 cm. The C horizon was exposed in all six soil pits. The horizonation sequence for these soil profiles was A1, A1, 2Bw, followed by either a 2C or 2Cr horizon. A distinctive contrast was observed between the Cr horizon and overlying A horizon. This horizon was designated as a 2Bw horizon that showed some soil development before reaching the Cr horizon. The B horizon is the product of soil development and is composed of highly weathered colluvium, alluvium or residuum. This horizon contains less organic matter than the A horizon and usually contains more clay. The "w" subordinate distinction stands for development of color and structure, but without apparent illuvial accumulations (Buol, 2003b). The "2" in front of the B signifies a lithologic discontinuity and is the result of the deposited ash on top of the developed B horizon. Not only was soil color a determining factor in this horizon, but there was also a noticeable change in the structure and texture. Surface (A1) horizons were all designated as having a color of 10 YR N/0. This color notation stands for a value of neutral over a chroma of zero and reflects a black color that is not found in any Munsell or Globe color charts. Soil horizons had similar colors in each horizon for every site from the surface down to the C horizon. The subsurface horizons were described as having a color sequence of 10 YR 2/1, 7.5 YR 2.5/2 in the A2 and A3 horizons, and either 7.5 YR 4/4, 4/6 or 5/6 in the Bw horizon.

Field textures for all A horizons were described as silt loams. Soil structure was described as moderate sub-angular blocky in all sites, except for R5 (pine) which had a moderate granular structure. Soil moisture consistency was friable in the surface (A1) horizon at sites R1, R2, R3, and R4. Sites R5 and R7, the two sites with pines, had very friable surface horizon moisture consistencies. Below the surface horizon, moisture consistency varied from site to site. Soil pits at this study area were noticeably wetter than those in the Zuleta study area, as was the weather during the period of field work. Sites had volumetric water content values of 66–89%, as measured in the soil pit walls in the A horizons of sites R1, R2, R3 and R4. The two pine sites, R5 and R7, had volumetric moisture readings of 63, 86, 82% and 76, 75, 75%, respectively.

The results from the melanic index test (Table 1) for the Zuleta and Mazar Wildlife Reserve study area sites were all under 1.70. These values were taken from the averages of three readings from the spectrophotometer, taken at both the 450 and 520 nm wavelength settings. Since the results for all sites were under the 1.70 index, the epipedons for all sites are classified as melanic. Most of the values were very close to 1.70, but, because none exceeded 1.70, none of the soils were classified as having fulvic epipedons.

Discussion of Soil Descriptions

Soil pit descriptions are a very important part of the evaluation of soil morphology. When examining physical and hydrological properties of the soil, it is necessary to describe the soil's texture, structure, color, moisture consistency, depth of each horizon, coarse fragments, and depth of the root-limiting layer. All of these factors are relevant to the ability of the soil to store and transport water. In this study, these properties were determined based on previous training and soil judging experience.

Soil texture relates to the proportions of different-sized particles in a soil. The soil separates in this project include sand, silt, and clay-sized fractions. When examining volcanic ejecta soils, volcanic glass can also be part of the soil texture. While the volcanic glass could be seen and felt when describing these soils, its presence was not enough to shift the texture to one textural class or another. Anything larger than a sand-sized particle was considered a coarse fragment in accordance with standard soil science descriptions. Since the A horizon soils under grass at Zuleta and in the Mazar Wildlife Reserve were dominated by silt-sized particles, the textural class in the grass páramo is considered silt loam.

Soil structures of surface horizons with andic properties are typically granular (spheroidal) or sub-angular blocky (block-like) (Shoji et al., 1993). Soil structure relates to the arrangement of the soil particles into separate aggregates or soil peds. When these aggregates are arranged in a similar pattern, they can influence the movement of water, aeration, and porosity. Granular soil structures are loosely arranged soil aggregates and are particularly porous. This was especially true in the páramo, where the granular and sub-angular blocky soil structures were observed to be very porous. A well-granulated soil has more total pore space and greater overall water-holding capacity than one with poor granulation or one that has been compacted.

Sub-angular soil structures are cube-like and are influenced by the compaction. They are typically found in subsurface horizons, usually B horizons. In all of the grass and shrubby sites, the surface structure had a sub-angular soil structure. This structure does not necessarily imply compaction as much as influence from the surface vegetation. The fine, fibrous roots from both the grass and the shrubs were adequate to aid in the aggregation of the surface soil. Every grass and shrubby site had either a strong or moderate sub-angular blocky soil structure. In contrast, both the Z5 and R5 pine sites had moderate granular soil structures.

The degree of development of the soil structure can also be identified and is used as a modifier in the field. In the presence of roots and high proportions of organic matter, this modifier is “strong.” A “moderate” grade was given to those in the absence of those vegetative influences. The strong grade can be attributed to the dominant influence of the grass and other vegetative root systems that helped hold the soil aggregates together. The presence of organic matter and high moisture contents, associated with melanic epipedons, adds to the structure and is likely to be the reason the Z5 and R5 pine sites had a moderate structure. The absence of an abundant fine root system was why the grade in the pine sites was not in the strong category.

Soil color is influenced by three major factors: organic matter, water content, and the presence of oxidized iron and manganese (Brady and Weil, 2002). In this project, color is most affected by water content and organic matter. A darker color would indicate higher moisture and organic matter contents. The colors of these soil horizons appear to be derived from the soil organic carbon that resides in the soil profile while it slowly decomposes in the limiting climate. The ability of the soil to remain wet throughout the year keeps these soils dark and humic. That soil colors were lighter in the pine site and *Polylepis* sites can be attributed to the lower moisture contents throughout the profile. Also, soluble organic carbon could have leached out of the profile, creating a lighter color than in the grass sites.

In some cases, the presence of mottles can indicate a well-drained soil. Redoximorphic concentrations include oxidized iron as well as manganese (Rabenhorst and Parikh, 2000). Upon close observation, mottles can be detected in these dark black soils. Mottles were observed in every site at both study areas. Gleyed soil mottles in the profile would indicate a poorly drained soil. None of the sites contained gleyed mottles or horizons. As wet as these soils get, the absence of any gleyed soil in the profile indicates that water moves freely through the profile and does not stand.

None of the soils in either study area contained a very firm moisture consistency. Moisture consistency of a soil refers to the cohesion and adhesion of the soil particles to one another. It also refers to the degree to which a soil resists deformation when a given force is applied at various moisture contents. Moisture consistency was described by saturating a soil ped and then applying a slight amount of pressure until that ped crumbled. It is used to indicate how water sticks to the particles as well as how it would move through the particles. Possible grades of moisture consistency in soils are very friable, friable, firm, and very firm. The higher the amount of clay in a soil, the more pressure it would take for the soil to maintain its resistance and hence have a firm or very firm moisture consistency. More silt and sand in the soil would result in lower pressures for the soil to resist and would be considered friable or very friable. Every site at the Zuleta study area had very friable moisture consistencies in the surface horizon. These were then described as friable in the underlying horizons before being described as firm in the lowest A horizons of some sites. The moisture consistencies at the

Mazar Wildlife Reserve study area were described as friable in the surface horizons of the grass and shrubby sites. They were described as very friable in the R5 and R7 pine sites

The root-limiting layer is a very important aspect of this project. Not only were the roots identified in the soil pits, they were also quantitatively measured and recorded by size and amount. The large quantity and deep presence (60+ cm under grass at both study areas) of the roots closely hold the soil in place, creating a sturdy foundation from the surface downwards. Although those data are not part of this thesis, the role of roots and in water movement is expected to become a crucial part of the understanding of the páramo hydrology.

Soils at grassy sites in the Zuleta study area were observed to have a strong, sub-angular structure, deep A horizons, very dark color (10 YR 1/0), friable moisture consistencies, and high volumetric moisture content readings from the Campbell HydroSense meter (uppermost 12 cm). Depending on the burn history, the surface was either sparse or completely covered with vegetation. These sites had dense stands of tall bunch grasses, some scattered shrubs were also observed. The strong structure of the grass site soils is most likely a result of the presence of abundant, fine, deep grass roots. Typically, surface horizons have a granular structure and a silt loam texture, which is likely to be the main reason for the friable moisture consistency.

Soil properties at the Zuleta pine (Z5) site were distinctly different from those of other Zuleta sites. The Z5 site had a granular, very friable surface horizon with a soil color of 10 YR 2/1. Volumetric moisture content readings were much lower at this site than at the other six sites in this study area. This site also had a deep soil profile, with visible pine roots observed in the lower subsurface horizons. The granular soil structure in the surface horizon of the pine site may result from a lack of surface vegetation due to pine needle litter and the absence of typical páramo vegetation. This duff layer covered the surface in thick deposits and most certainly inhibited the growth of any kind of ground cover. The granular structure of this site was underlain by a stronger structured horizon that appeared to maintain its structure by the compaction of the surface horizon. The very friable moisture consistency was a result of a drier surface horizon that lacked both moisture and organic matter. Due to the lack of a ground cover, there was no visible root structure in place at the surface horizon of the pine site, except the irregular, sparse, occurrence of pine roots. While the grass sites at Zuleta had an abundance of roots at the near surface, the pine sites had larger roots that were observed when excavating the soil pits. These root systems in both the grass and pine sites are expected to play an important role in the infiltration and movement of water down the profile.

Pine plantations were assumed to have been planted on land that had previously been grass páramo. Where possible, pine sites and grass páramo sites were established in adjacent positions, with the assumption that other factors were equal and observed differences could be attributed to the change in land use. For the Mazar Wildlife Reserve, the presence of páramo at what are currently pine sites is evident in a 1977 Landsat photo, and the history of pine plantation was recounted to us by the owner of the reserve (Stuart White, personal communication). The possibility that pines had been planted in an area where the land was degraded or severely eroded was of particular concern at Zuleta, where the soils under the pines differed so visibly from those under the present-day páramo. Only one small (<1 ha) pine plantation existed in the Zuleta study area, but its hydrological properties were so different from those of other sites that other research teams should be to study more pine plantations in the future. Buytaert et al. (2007) found significant differences in the water yield of a pine-planted catchment and a grassland catchment. The pattern in the páramo is that pine plantations do, in fact, lower the soil moisture levels, as well as the water yields. On another note, the pines in the Z5 site had been planted 30–40 years earlier. To understand how a land-use change could produce such significant differences in such a short amount of time would be another reason to further evaluate these sites.

Soil properties in the *Polylepis* sites at Zuleta were not very different from those at those sites with different burn histories. These sites had strong sub-angular soil structures with a very friable moisture consistency in the surface horizons. One noticeable difference was the color, which was 7.5 YR 2.5/1 at Z7 and 10 YR 2/1 at Z8 in the surface horizons. Both sites had soil colors in the 7.5 YR 2.5/1 range in the subsurface horizons. The Z8 site had lower volumetric moisture content readings for the upper 12 cm. This site was dominated by *Polylepis* trees, had a history of previous potato harvesting, and contained a ground cover that was not observed in any other site. At sites Z2, Z3, Z4, and Z7, the *Polylepis* trees were small and widely spaced among tall páramo grass. With grass dominant at these four sites, soil properties would be expected to not differ appreciably from those of sites without *Polylepis*.

Polylepis shrubs were planted in four sites of the Zuleta study area. The ages and spacing of these shrubs was highly variable, but the largest, densest stand appeared to have some impact on hydrology. The Z8 site had the most extensive and mature *Polylepis* stand (8 years) and *Polylepis* was the dominant vegetation of that site. *Polylepis* trees at Z8 were planted on a potato field, and the more compacted soil could be attributed to this factor. However, the stands were only 8 years old; thus, they could further impact the soil moisture regime in future years, and further drying could also affect the soil's physical properties. The R4 (40-50 year since previous burn) site in the Mazar Wildlife Reserve showed that the native, natural succession of vegetation in that area did not differ much in either the soil moisture regime or the soil's physical properties.

At the Mazar Wildlife Reserve, soils of the grassy sites selected for their burn histories (R1, R2) had moderate sub-angular blocky soil structures friable moisture consistencies, and very black soil colors of 10 YR 1/0 in the surface horizons. Only color changed in the subsurface horizons of these sites. Each horizon at both sites was very high in silt and was determined to have field textures of silt loams.

Volumetric moisture content readings were high (69–86%) in the horizons of both sites. The underlying C horizons in each site were also described and had very friable moisture consistencies, massive soil structures, and lighter soil colors. These were classified as having a loam field texture. As at the Zuleta grass sites, the structure of these soils was sub-angular blocky due to the high organic matter and water contents. Soil structures were designated as having moderate grade because the surface vegetation was not as extensive as at the Zuleta study area.

The soil of the two Mazar Wildlife Reserve pine sites (R5, R7) had both moderate granular and moderate sub-angular soil structures, with a very friable moisture consistency in the surface horizons. Each of these horizons was underlain by subsurface horizons with sub-angular soil structures and friable moisture consistencies. Soil colors in these horizons were very dark (10 YR 1/0) in the surface horizon and then were classified as having colors of 10 YR 2/1, 7.5 YR 2.5/1 and either a 7.5 YR 4/4 or 5 YR 5/6 in the subsurface horizons, moving downward. These two pine sites differed in the spacing between the trees as well as their location with respect to the topography. Site R5 was located on a more gently sloping ridge-crest position, while site R7 was located in more of a steep valley position closer to the river and was more likely to experience higher precipitation and more frequent fog. Site R7 is also farther from sites that have burned in the past 40 years and is near a montane forest. The wetter environment of this site, inferred from the damp vegetation and the presence of mosses and bryophytes, combined with a closer spacing of pine trees, resulted in more foliage, including understory vegetation that held the soil surface more tightly. The presence or absence of understory vegetation would be expected to influence the structure of the surface horizons. Surface vegetation was noticeably different between the two pine sites. The R5 pine site had wider spacing between trees and contained mostly needle duff on the surface. The R5 soil had a granular structure and did not have as much organic matter as the R7 pine site, which had a more sub-angular structure. Soil colors at both pine sites were not appreciably different from those at the other, non-pine sites, perhaps due to the fact that the pine sites in the Mazar Wildlife Reserve were just as wet as the other sites and had a similar long-term history.

The woody shrub sites in the Mazar Wildlife Reserve study area sites R3 and R4 had soil properties similar to those in the more recently burned, grassy, sites. The R3 site had not been burned for the past 25–30 years, and the last time the R4 site burned was 40 years ago. These different histories provided a good opportunity for our research team to consider the soil moisture implications of excluding burning in páramo sites. The structure was noted as being moderate sub-angular blocky, while the moisture consistencies were friable in each surface and subsurface A horizons. Soil colors were similar also, with surface horizons having a color of 10 YR N/0 and subsurface horizons having a color of 10 YR 2/1. As at the grass sites, the surface vegetation appears to play an important role in the structure of the soils through the presence of bunch grasses with long, fine roots. The high moisture and organic matter contents also lead to moderate sub-angular structures in the surface horizons. Without these components, sites would not be expected to have soil structures with this strong aggregation.

Soil profiles described at the Mazar Wildlife Reserve were much shallower than those at Zuleta. These profiles were described from the surface down as A1, A2, A3, Bw. The volcanic ash layer could be easily distinguished by its discontinuity from the underlying Bw horizon. All sites at this study area had very dark, wet surface horizons. This was due to the highly variable amount of precipitation in the southern and northern parts of Ecuador. The abundant precipitation in this area would be expected to lead to more extensive chemical weathering, which would break down the tephra deposits into secondary minerals. Redox concentrations were also observed in this study area’s soil pits. The presence of oxidized iron is indicative of a moving water table. Mottling in the soil profile confirms the fluctuating movement of water up and down the soil profile (Brady and Weil, 2002). The R5 pine site was observed to have a granular structure associated with the absence of a well-developed root system that was seen in the grass sites and the second pine site, R7. Surface horizons observed in all of the grass and shrubby sites were described as friable. This could have also been due to high volumetric moisture contents in these surface soils, which would result in more cohesion.

Particle Size and Soil Texture

Particle sizes were measured in the laboratory to accurately represent the amount of sand, silt, and clay-sized particles in the páramo soil samples. Results from the laser diffractor, are presented in Appendix B, indicate that all of the Zuleta study area sites had silt loam textures. This was different from the field textures described by the “feel” method. Field-described textures at Zuleta sites Z1, Z2, Z3, Z6, Z7 and Z8 were described as silt loam in the surface horizons and loam at some sites near the bottom of the A horizon. There was a noticeable increase in sand-sized particles in these lower horizons. If ash had been deposited from a single volcanic event, the heavier ejecta would have been deposited first, followed by the lighter ash. This would be represented in the soil profiles by the presence of more coarse fragments in the subsurface A horizons than in the surface horizons. Alternatively, it is possible that different volcanic events, or events from volcanoes at different distances, contributed ash of different sizes, with larger particles dropped by earlier eruptions. The Z5 site had field-described textures of sandy loam in the surface horizon and a loam texture in the subsurface horizons. This was most likely due to the granular structure, influenced by low moisture contents and its corresponding cohesion, and by the presence of different surface vegetation.

Particle sizes in the Mazar Wildlife Reserve study area were slightly coarser than those observed in the Zuleta study area. The laser diffractor results indicated sandy loam textures in five of the six Mazar Wildlife Reserve sites. Textural differences between the Zuleta and Mazar sites could be explained in two ways. One is that the volcanic ash present in their soils may represent different events and distances from volcanoes, and be of different composition. The other is that the Mazar soils, which were shown to be wetter, could have higher rates of chemical weathering, resulting in different amounts of allophane, imogolite, and other minerals. A complete chemical analysis of these soils would greatly benefit further research for this project, as well as other comparisons of soils between the northern and southern highlands of Ecuador.

Field textures and results from the laser diffractor differed for both study areas. Compared to the results of the laser diffractor, field-described textures from the Zuleta study area were more loam-like than the Laser Diffractor detected while those in the Mazar Wildlife Reserve were higher in silt. Textures described in the field were based on soil judging/texturing experience. These textures were confirmed by two other soil judges who described each horizon's soil sample from both study areas. While there was confidence in the textures described from these samples, it was instructive to also measure particle size distribution in the laboratory. The laser diffractor was calibrated before the soil samples were tested. One potential problem with this device is getting a representative sample after the addition of hydrogen peroxide and dispersant. For this reason, triplicate samples were taken for each horizon's sample. Differences in the readings from the laser diffractor and the field textures were most likely due to the composition of the páramo soil. When these soils start to break down, they exist as a gel-like texture that is often difficult to describe. Because of this gel-like texture, field estimates generally indicate more clay-size material than laboratory particle-size analyses do (Ping et al., 1989).

The results from the melanic index test showed that every site sampled had a melanic epipedon. This is an important test when examining volcanic ash soils because it allows one to determine the type and amount of organic acids present in the soil. The identification of humic acid type A at each site represents how much humification occurred in the soils. Humus is a byproduct of weathered plant remains and reflects how much chemical weathering is taking place in the soil. Neirop et al. (2007) noted that different organic acids formed in the presence of different vegetation in the páramo. In their sites, grass páramo had humic acid type A and melanic epipedons. Their forested sites contained humic acids type B and P and were thus classified as having fulvic epipedons. In the present study, one possible reason that pine and montane-forested sites from both study areas were also melanic could be that the stands are not very old (25–40 years old). This young age would not give the organic acids in the soil time to break down into further humified acids (types B and P). The results from this test also show that, not only do the forested and grass sites have similar epipedons, but so do soils from the northern and southern parts of the country.

The most notable differences in the soil's physical properties were in structure and moisture consistencies, which differed between surface horizons of the pine plantations and grass sites at both study areas. The grass sites had a strong, sub-angular soil structure, while the pine sites at Z5 and R5 had a granular structure at the surface. This difference is likely to be due to differences in the surface vegetation at these sites. Moisture consistencies within the Zuleta study area were very similar from site to site and classified as very friable at the surface horizon and friable at the subsurface horizons. The Mazar Wildlife Reserve had friable moisture consistencies at the surface horizons of the grass and shrubby sites, but very friable moisture consistencies in the same horizons at the pine plantation sites. This difference, too, may result from the scarcity of understory vegetation at the pine sites.

Table 3 – Spectrophotometer readings from 450 and 520 nm and results of the melanic index test results

	Zuleta Study Area							Mazar Wildlife Reserve Study Area					
	Z1	**Z2**	**Z3**	**Z5**	**Z6**	**Z7**	**Z8**	**R1**	**R2**	**R3**	**R4**	**R5**	**R7**
450 nm	0.89	1.01	0.88	1.15	0.82	0.68	1.03	0.91	0.50	0.48	0.77	0.69	0.80
	0.91	0.96	0.90	1.09	0.84	0.69	0.99	0.90	0.50	0.51	0.78	0.67	0.83
	0.87	1.00	0.89	1.12	0.81	0.68	1.04	0.93	0.49	0.54	0.77	0.66	0.85
Average	0.89	0.99	0.89	1.12	0.82	0.68	1.02	0.91	0.50	0.51	0.77	0.67	0.83
520 nm	0.56	0.64	0.60	0.70	0.55	0.49	0.64	0.55	0.34	0.32	0.50	0.45	0.63
	0.55	0.61	0.62	0.76	0.49	0.39	0.62	0.54	0.29	0.33	0.49	0.44	0.62
	0.54	0.60	0.57	0.75	0.51	0.43	0.66	0.58	0.29	0.31	0.41	0.42	0.48
Average	0.55	0.62	0.60	0.74	0.52	0.44	0.64	0.56	0.30	0.32	0.47	0.43	0.58
Melanic Index	1.62	1.61	1.49	1.52	1.59	1.56	1.59	1.63	1.63	1.60	1.65	1.55	1.43

Soil Temperature Regime

Soil temperature was measured at 50 cm depth in each soil pit at both study areas. Soil temperatures in the Zuleta study area ranged from 9–11˚ C, while temperatures from the Mazar Wildlife Reserve study area ranged from 11–14˚ C. These measurements can be assumed to reflect the mean annual temperature, since temperature at that depth is not affected by surface influences. This temperature range is considered to be in the mesic soil temperature regime (Soil Staff Survey, 2003).

Soil Moisture

The results from the Campbell HydroSense CS620 readings across transects at each site were plotted and used to compare the in-situ water contents among sites. These readings reflect the percent volumetric water content of the upper 12 cm of the soil surface. The graphs below show the results from those readings and illustrate how much more the soil water contents varied in the pine sites than in other sites of both study areas.

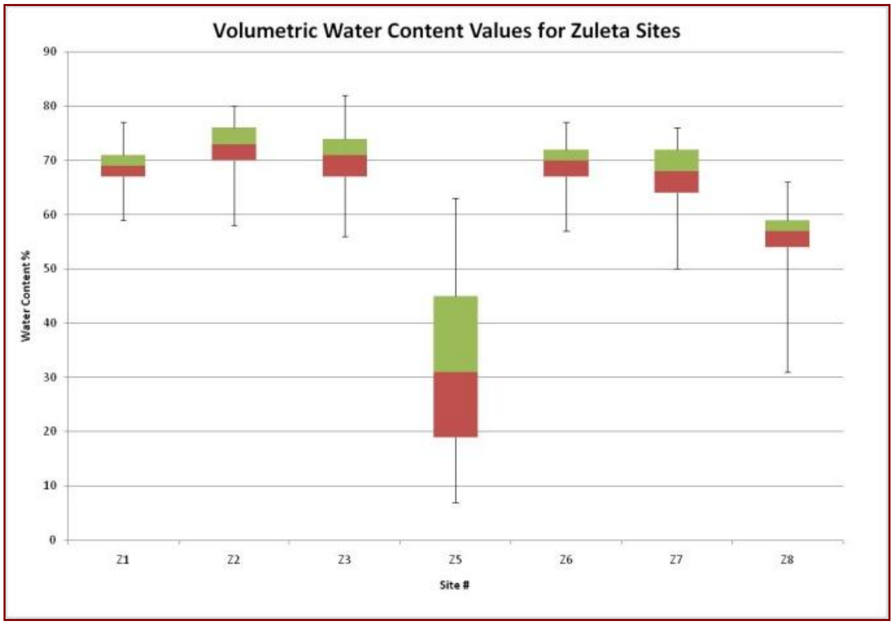


Figure 10 – In-situ volumetric water contents from the top 12 cm of the surface from the Zuleta study area. Values represent median, 1st and 3rd quartile ranges, and the minimum and maximum values. Site Z5 is the pine plantation.

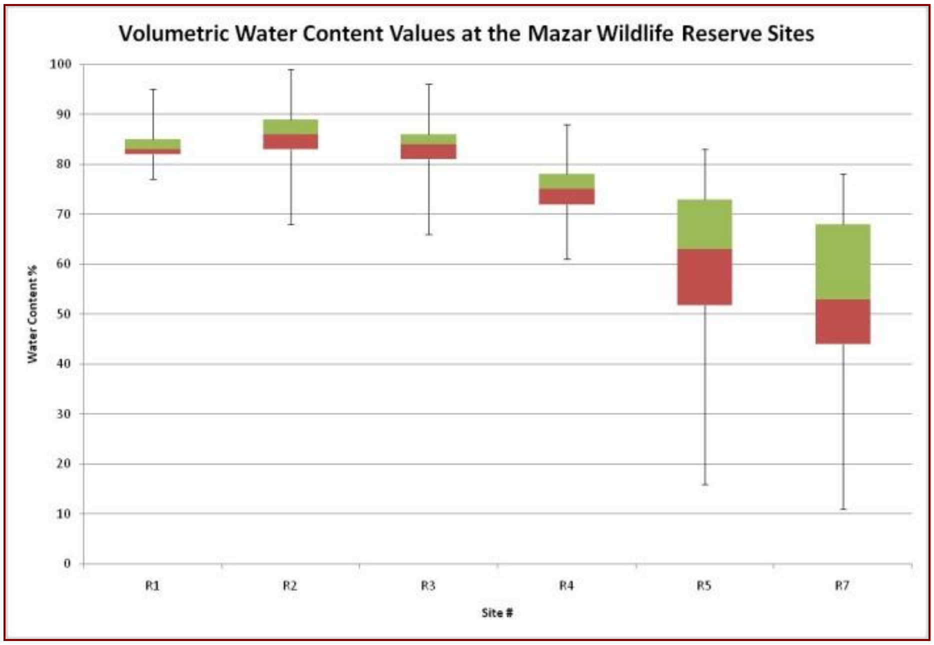


Figure 11 – In-situ volumetric water contents of the top 12 cm of the soil from the Mazar Wildlife Reserve study area. Sites R5 and R7 were in pines.

Figure 10 shows that five of the seven sites at the Zuleta study area have similar ranges of volumetric water contents. The Z5 pine site and the Z8 *Polylepis* site show lower percent volumetric moisture content values as well as a wider range of values. ANOVA showed the Z5 site to have significantly different volumetric content than the other six sites. Similarly, at the Mazar Wildlife Reserve, four sites, all under páramo, have a close range of values. The R5 and R7 pine sites show lower median volumetric moisture contents and a wider range of values.

Bulk Density

Bulk density determinations from both study areas resulted in very low values, ranging from 0.273 to 0.864 g/cm^3. These values typically increased when moving down the profile into the subsurface horizons. Tables 4 and 5 show bulk density values, gravimetric water contents, and calculated volumetric water contents from each site.

Table 4 - Bulk density, mass water content and volumetric water content (calculated) for the Zuleta sites.

Site # and Depth	BULK DENSITY (g/cm^3)	MASS WATER CONTENT (g/g)	VOLUMETRIC WATER CONTENT (cm^3/cm^3)
Z1 10-20	0.5502	0.971	0.534
Z1 30-40	0.5947	0.817	0.486
Z1 60-70	0.5406	0.699	0.378
Z2 5-10	0.5085	1.241	0.631
Z2 30-40	0.5970	0.979	0.584
Z2 50-60	0.7310	0.726	0.531
Z3 10-15	0.5947	1.042	0.620
Z3 30-40	0.6717	0.859	0.577
Z3 55-60	0.8263	0.656	0.542
Z5 10-15	0.7141	0.405	0.289
Z5 30-35	0.8175	0.348	0.285
Z5 50-55	0.8643	0.403	0.348
Z6 10-15	0.5998	1.016	0.609
Z6 30-35	0.6685	0.879	0.587
Z6 50-55	0.8084	0.638	0.516
Z7 10-15	0.5654	1.048	0.593
Z7 35-40	0.7766	0.708	0.550
Z7 65-70	0.8521	0.562	0.479
Z8 10-15	0.7895	0.687	0.543
Z8 35-40	0.7874	0.647	0.510
Z8 65-70	0.8362	0.570	0.477

Table 5 - Bulk density, mass water content and volumetric water content (calculated) for the Mazar Wildlife Reserve sites.

Site # and Depth	BULK DENSITY (g/cm^3)	MASS WATER CONTENT (g/g)	VOLUMETRIC WATER CONTENT (cm^3/cm^3)
R1 5-10	0.456	1.488	0.679
R1 25-30	0.539	1.211	0.652
R1 60-65	0.795	0.735	0.584
R2 5-10	0.310	2.324	0.720
R2 30-35	0.378	1.879	0.710
R2 60-65	0.507	1.312	0.657
R3 5-10	0.337	2.089	0.703
R3 30-35	0.475	1.350	0.642
R3 60-65	0.524	1.264	0.638
R4 5-10	0.366	1.833	0.670
R4 30-35	0.501	1.271	0.637
R4 50-55	0.651	0.926	0.603
R5 5-10	0.273	1.982	0.539
R5 40-45	0.318	2.338	0.744
R5 65-70	0.394	1.878	0.739
R7 5-10	0.422	1.390	0.586
R7 35-40	0.440	1.554	0.682
R7 60-65	0.478	1.268	0.605

At Zuleta the Z5 (pine) site had the highest overall bulk density (0.714–0.864 g/cm^3) of any site in this study area. This site also had the lowest (calculated) volumetric water contents (0.285–0.348 cm^3/cm^3). Bulk density increased from the surface horizon down to the C horizon at sites Z2, Z3, Z5, Z6, and Z7. At sites Z1 and Z8, bulk density values varied less among the horizons.

Calculated volumetric water contents decreased from the surface horizon down to the C horizon in all but one site, Z5. The Zuleta sites contained more soil moisture at the surface, with moisture decreasing down the profile as bulk density values increased. Volumetric water contents at Zuleta, ranging from 0.285 cm^3/cm^3 to 0.631 cm^3/cm^3, were lower than those at the Mazar Wildlife Reserve study area.

Results from the Mazar Wildlife Reserve show that site R1 (less than 1-year since previous burn) had the highest overall bulk density (0.456–0.795 g/cm^3). Bulk density increased from the surface horizon down to the C horizon in all of the Mazar Wildlife Reserve sites. Patterns of calculated volumetric water contents varied at the Mazar Wildlife Reserve, with values decreasing from surface horizons to C horizons in the grassy and shrubby sites, but increasing with depth in the pine sites. Compared to the Zuleta study area, the Mazar area had much higher calculated volumetric water contents, ranging from 0.539 cm^3/cm^3 to 0.744 cm^3/cm^3.

Results from the Zuleta study area showed that the lowest volumetric and gravimetric water contents were found at the pine site (Z5). The other sites had similar values and patterns for each horizon sampled. Low values of volumetric and gravimetric water content were associated with higher bulk density at the Z5 site. The mature *Polylepis* site (Z8) also had higher bulk density than the grassy sites, most likely as a result of previous farming practices used to cultivate, fertilize, and harvest crops at that site.

The Mazar Wildlife Reserve study area had higher soil moisture values than the Zuleta study area, but generally lower bulk densities. The R5 pine site had, not only the lowest bulk densities, but also the lowest volumetric and gravimetric water contents in the surface horizon.

Differences in soil moisture appear to be associated with either pine plantations or shrubby plants (Z5, pine plantation; Z8, *Polylepis* site; R5 and R7, pine plantations; and R4, 40–50 year since burn). Soil properties at these sites were shown to have either subangular or granular soil structures, or friable to very friable moisture consistencies in the surface horizons. These properties were associated with a drier soil and also a lack of diverse surface vegetation. Soil moisture contents of the infrequently burned and woody shrub sites did not differ significantly from those of more frequently burned sites (Z1, Z2, R1, R2).

Bulk Density and Volumetric Water Content Discussion

Bulk density is defined as the mass of a unit volume of dry soil and includes the solid and pore fractions. High water contents are possible in lower bulk density values because low bulk density soils have low dry mass and more void space. Since silt is organized in porous granules, a silt loam soil texture also tends to produce lower bulk density values. The aggregates in the silt loam páramo soil contain pores both between and within the granules. This texture, combined with the presence of organic matter, which can produce porous structures, can ensure high total pore space with low bulk density. This physical property of soil is relatively stable in that the volumetric water content of the soil may shift but the composition stays constant.

Values of bulk density at both study areas were very low in the surface horizon and, for the most part, increased down the soil profile. This is presumed to be due to a number of factors, including lower organic matter contents with depth, less aggregation, fewer roots, and the compaction caused by the weight of overlying layers. Andisols in the northern Andes and the páramo have remarkably low bulk density values. All of the samples taken for this study were found to have bulk densities lower than 1.0 g/cm^3. Theoretically speaking, these soils could float on water. These bulk densities are much lower than those associated with other soil orders, such as Ultisols and Alfisols, where they would be expected to range from 1.3–1.4 g/cm^3 (Rhoades et al., 1997).

The highest bulk density values for surface horizons at Zuleta were at the pine site (Z5) and the mature *Polylepis* site (Z8). The higher values at Z5 are likely due to the greater amount of sand-sized particles as well as a decrease in the amount of organic matter, while compacted soil horizons were observed at Z8. This site had relatively high bulk density values in each horizon and had previously been a potato field that had been fertilized and harvested. The previous agricultural practices at Z8 would have compacted the soil horizons and altered soil structure, leading to higher bulk density. The recently burned and *Polylepis* sites (Z1, Z2, Z3, Z6 and Z8) had low bulk density values in the surface (A1) horizon and values that increased down to the lowest A horizon. These sites all classified as silt loams, which are dominated by silt-sized particles that are already less dense than sand. Ash, being a lighter medium than most mineral fragments (Geist et al., 1989) could also be responsible for lower bulk density values in these soils.

Volumetric water contents (VWC) at the Zuleta study area decreased from the surface horizon down to the underlying horizons at all sites except Z5, where VWC values increased at the lower horizon (Appendix C). Measurements made with the Campbell HydroSense also showed increasing volumetric moisture at the lowest Z5 horizon. While the grass and *Polylepis* sites were, for the most part, nearly saturated, dry and moist pockets in the unsaturated pine sites resulted in highly varying VWC readings. Water contents may have been higher in surface horizons due to the higher amount of organic matter in the horizons of the grass and *Polylepis* sites. It is also possible that they were higher from recent rain events. Also, the A1 horizon is not affected by compaction, compared to the subsurface horizons. This would lead to more pore space as well as larger pore spaces. Soil pores are occupied by moisture and decrease in both abundance and size moving down the soil profile.

Bulk density values at the Mazar Wildlife Reserve were very similar from site to site. The highest values were at the R1 site in the bottom, A3, horizon. The pine sites had the lowest overall bulk densities. Neither of the pine site (R5, R7) bulk densities exceeded 0.50 g/cm^3, while every A3 horizon in the grass and woody sites had a bulk density greater than 0.50 g/cm^3. Given the light, very friable structures of these two sites, it is understandable that bulk densities would be so low.

Volumetric water contents of soil samples from the Mazar Wildlife Reserve study area, calculated from bulk density and gravimetric water contents in the laboratory, were similar in pattern to those at the Zuleta study area. One main difference between the two was that the Mazar Wildlife Reserve soil was wetter. While the volumetric water contents of soils from Zuleta ranged from 0.285–0.631cm^3/cm^3 they ranged from 0.539–0.744 cm^3/cm^3 at the Mazar Wildlife Reserve study area.

Bulk density values and volumetric water contents are often used to determine the amount of water a given soil can hold. While the resulting bulk density values from the Zuleta study area were similar from site to site, their low values express the great potential for water storage in these soils. At the Zuleta study area, higher measured volumetric moisture contents corresponded to textures higher in silt and structures with more aggregation. While the organic matter and surface vegetation would have had important effects on these soil properties, higher water content would also have been an important factor. For instance, one reason the organic matter is so high in those areas is that the soil moisture allows it to persist in the upper horizons. It should be noted that the volumetric water contents of these samples were “snapshots” of the soils in that state. Throughout the year, soil moisture contents would be expected to increase during rainy periods and decrease in periods without precipitation.

In the Zuleta study area, soil moisture was higher in the infrequently and frequently burned sites than under pine or *Polylepis* trees. The *Polylepis* sites were only slightly less moist than the burned sites. The pine site had much lower volumetric and gravimetric water contents all through the soil profile. There were distinct differences in the soil properties between the pine site and the other six sites. Less water in the surface horizon leads to lower organic matter, and vice versa. With less organic matter at the surface, the structure is unlikely to form aggregates. Also, a drier surface increases the amount of open pores in those soil structures. The moisture consistency was more friable because the lower soil moisture content caused a lack of cohesion and adhesion between the soil particles.

Soil moisture can act as a cohesive agent that helps hold soil aggregates together. This can be seen in the surface horizons of the grass and shrubby sites from both study areas, where soil structure was stronger, in part, due to greater soil moisture, but also due to the apparently higher organic matter content and more abundant root system. Soil texture in the grass and shrubby sites was observed to be different from the soil texture in the pine site at the Zuleta study area. This difference could be due to different weathering patterns in a drier soil environment or to the possibility that the pine site was planted on an area where the A horizons had been eroded away. A chemical analysis of these soils would help determine any differences in the soil's composition.

Water Retention at Different Matric Potentials

Relative values from the tension table analysis are presented in terms of gravimetric water content. The masses of the PVC ring and a 2'' x 2" piece of cheesecloth (8.61 g) were subtracted from the total mass to determine the mass of just the moist soil sample. Since all the PVC rings had the same dimensions, their masses can be assumed to be constant. Mass was recorded after each sequential increase in matric potential in the drying portion of the experiment. Water retention curves varied from site to site and replicate samples were shown to vary from each other. In each horizon, at every site, hysteresis was observed from the plotted drying and rewetting curves. Plotting these two curves together shows the rate of hysteresis for each horizon at each site. Figure 12 shows the water retention curves from the Z3 site, a site that had not been burned for 15 years. Each horizon's curves have separate gravimetric water contents and different shapes. Figure 13 shows the water retention curves for the Z1 recently burned site. The Z5 (pine) site had similar curves to those of Z3 in Figure 8, but the gravimetric water content was lower (Figure 14). Figure 15 shows how much the water retention curves can vary in the more disturbed Z8 *Polylepis* site. The gravimetric water contents and the shapes of the curves for each of the Z8 horizons differ from those of the Z3 site.

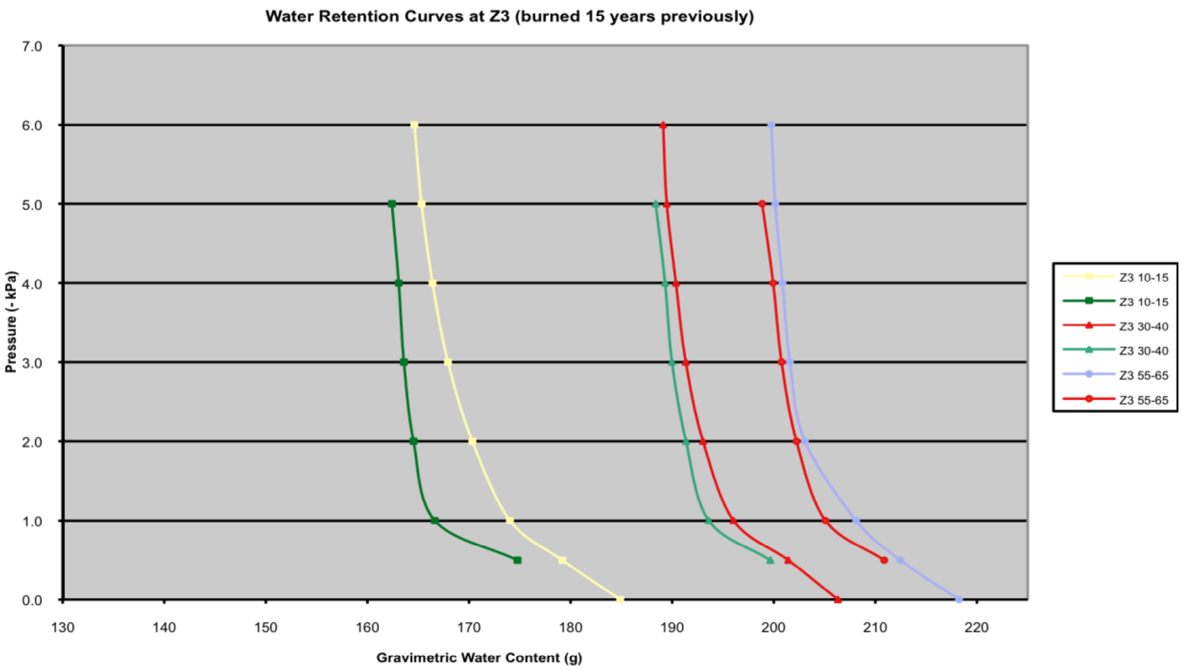


Figure 12 – Water-retention curves from Z3. Curves are separated into the three horizons sampled. Values in legend note the depth in cm where the sample was taken in the soil profile. The longer curve represents the drying curve while the shorter curve represents the rewetted curve.

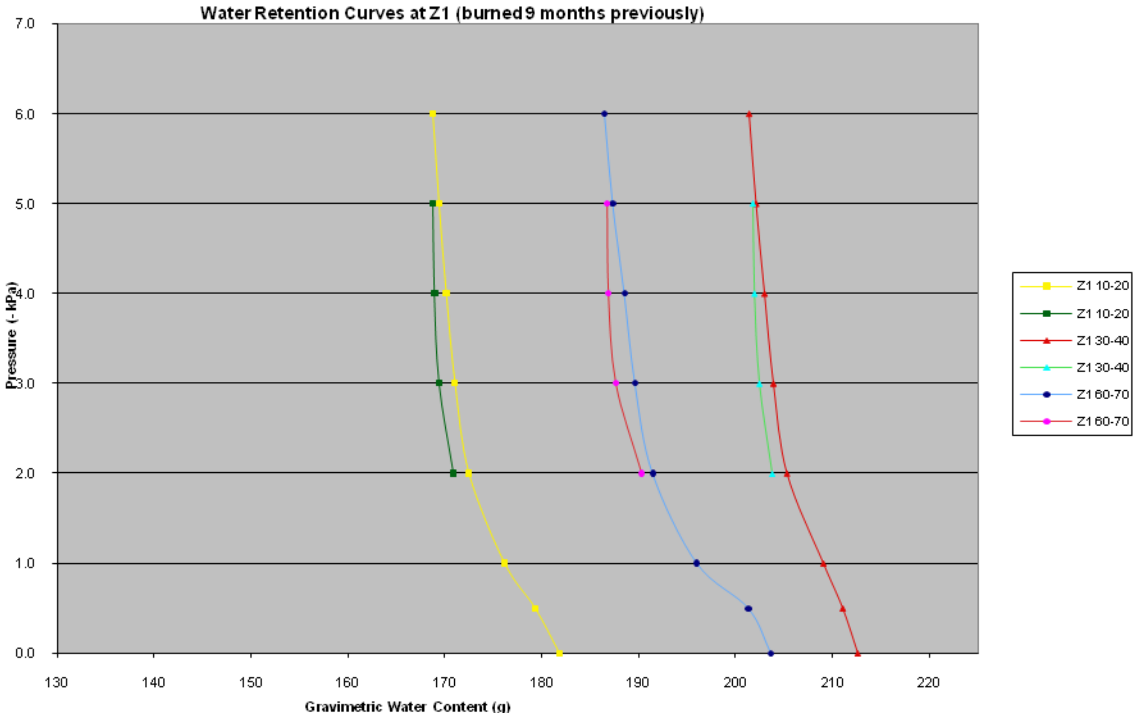


Figure 13 – Water-retention curves at Z1. Values in legend note the depth in cm where the sample was taken in the soil profile. The longer curve represents the drying curve while the shorter curve represents the rewetted curve.

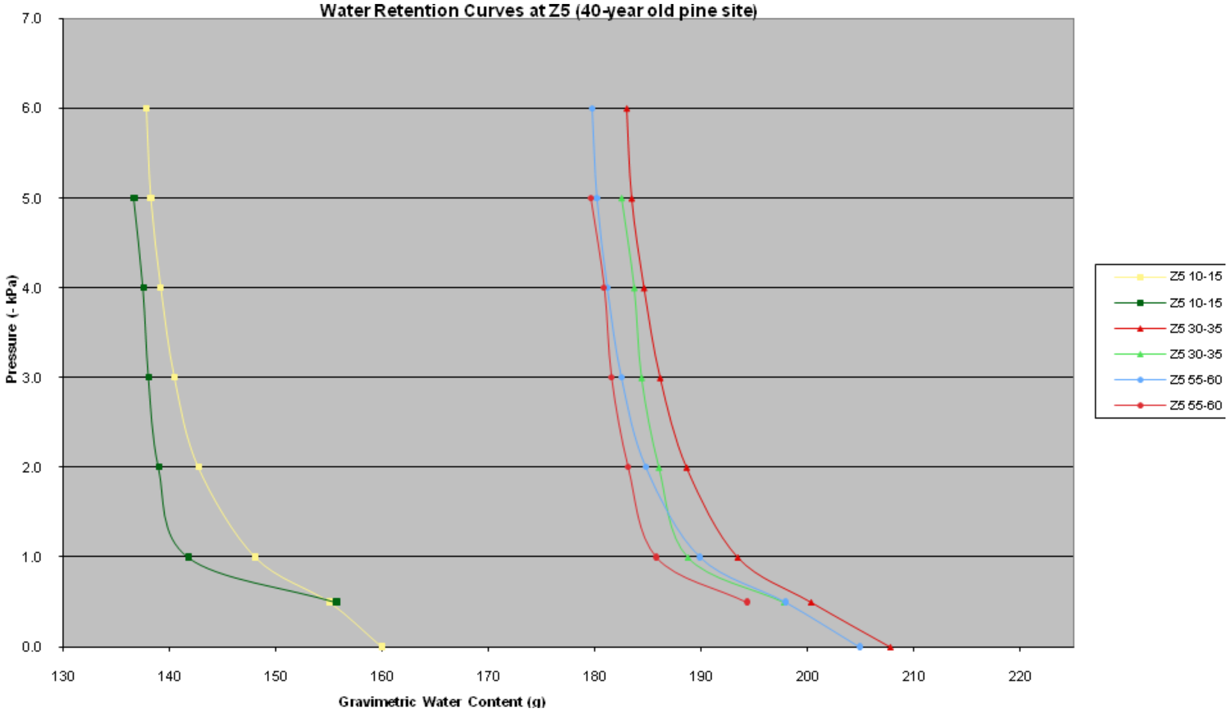


Figure 14 – Water-retention curves at Z5 (note lower water content values at surface horizon). Values in legend note the depth in cm where the sample was taken in the soil profile. The longer curve represents the drying curve while the shorter curve represents the rewetted curve.

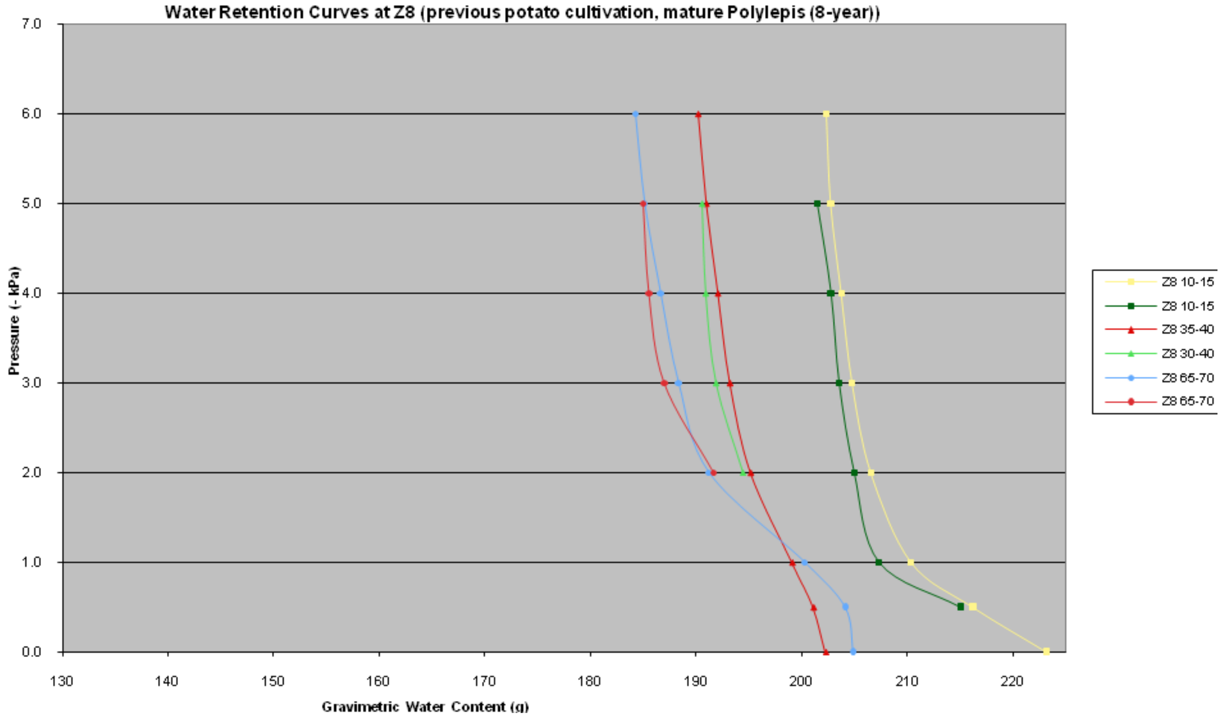


Figure 15 – Water-retention curves at Z8. Values in legend note the depth in cm where the sample was taken in the soil profile. The longer curve represents the drying curve while the shorter curve represents the rewetted curve.

Water retention curves for all sites were measured at tensions of 0–6.0 kPa. Infrequently burned sites had similar patterns in their curves, with surface horizons having the lowest relative gravimetric water contents. These sites had much higher water-holding capacities at lower matric potential than the frequently burned, shrubby, and pine plantation sites.

The frequently burned, shrubby, and pine plantation sites had highly variable curves which differed from each other. These curves were typically lower in gravimetric water contents in the surface horizon and varied with their subsurface horizons. Their water-holding capacities were lower than those under dense grass. Water-retention curves from the frequently burned sites had shapes and ranges of relative gravimetric water content similar to those from the infrequently burned and shrubby sites. However, the curves from the pine sites showed much different shapes and ranges of relative gravimetric water content than those from the frequently and infrequently burned grassy sites. As Figures 16 and 17 illustrate, the pine sites have lower relative gravimetric water contents as well as curves that represent a more rapid release of water under lower pressures.

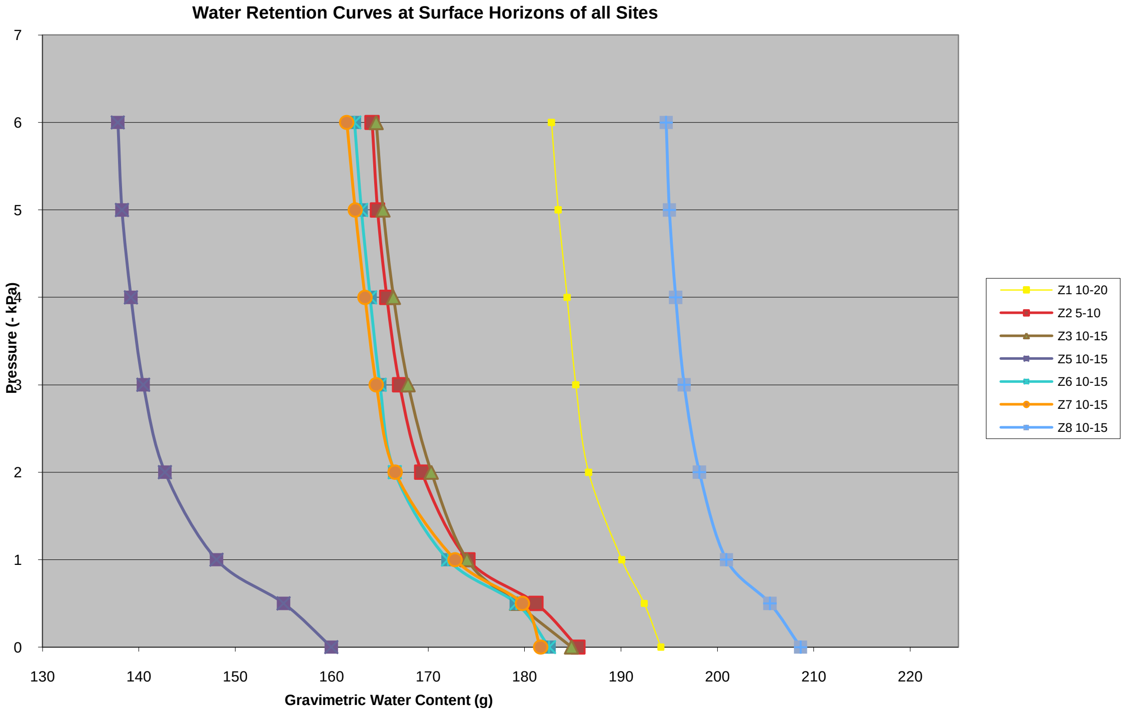


Figure 16 – Water-retention curves from all the surface horizons from the Zuleta sites. Values in legend note the depth in cm where the sample was taken in the soil profile.

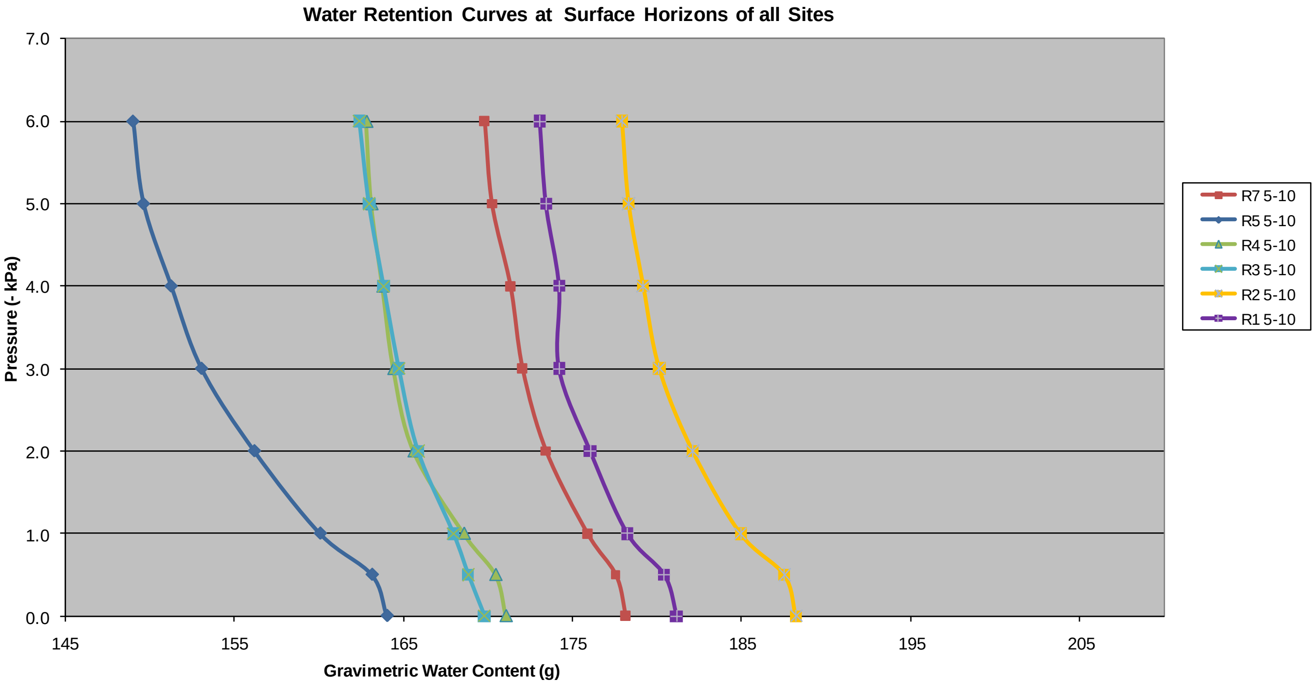


Figure 17 – Water-retention curves from all the surface horizons from the Mazar Wildlife Reserve sites. Values in legend note the depth in cm where the sample was taken in the soil profile.

Water Retention Capacity of Páramo Soil under Different Land Uses

Water retention is a very important property in páramo soils. Water retention refers to the amount of water a soil can hold or release based on a given pressure. This pressure, known as the matric potential, affects the movement of water and the availability of water to plants. Matric potential results from the adhesion and capillarity of water from moist zones to dry zones. By applying a negative pressure to these samples, one can determine how much water can be held and how much water is released from the soil. These pressures are negative because the water attracted by the soil matrix has an energy state lower than that of free water (Gardner and Widtsoe, 1921). These pressures are used to represent field conditions such as field capacity, permanent wilting point and any point in between. Pressures taken from 0 to -6.0 kPa reflect field conditions in which there has not been a recent rain event or when there has been an increase in evapotranspiration from the surface. Water retention tests in most studies take the soils to very high pressures (-33 and -1500 kPa) to see how much water the soil can hold at field capacity and permanent wilting point, respectively. This test was performed to examine how much water the soils could hold at low pressures because, in this environment, extreme drying events are rare. Water retention curves are used to determine how fast and how much pressure is needed to release water from a soil sample and then reach a steady-state. Soil structure predominately influences the shape of the water retention curve in the portion where the potentials are between 0 and about -100 kPa. The shape of the remainder of the curve generally reflects the influence of soil texture (Brady and Weil, 2002). Organic matter also affects the shape of the curve due to its ability to adsorb water (Dane and Klute, 1977). Due to the relationship between soil water and matric potential, drying curves will differ from rewetted curves. This phenomenon, known as hysteresis, is caused by factors such as a nonuniformity of soil pores. It is also an important feature when determining if the soil can recover from extreme drying events.

Tension table results from the Zuleta study area showed very different curves between the surface horizon and the underlying horizons. In sites Z2, Z3, Z6, Z7 and Z8, surface horizons had longer curves, meaning that it took more matric potential to draw water out of the sample. This is due to the higher amount of organic matter in the surface horizon. These soils contain a large volume of mesopores and micropores, which could cause that matric potential to take longer to draw water out of these pores. These curves also had corresponding rewetting curves that showed a hysteresis effect that took longer than the rewetting subsurface horizons. The irregularly shaped pores and the disconnection system of the pores could account for these wider hysteresis curves. In sites Z1 and Z5, surface and subsurface horizons had equally shaped curves for both the drying and rewetting tests. The Zuleta pine site (Z5) had much lower gravimetric water contents than the other sites.

Similar results appeared in the water-retention curves for the Mazar Wildlife Reserve sites (Appendix D). The surface horizons of all sites required a higher amount of matric potential to draw the water out of the pores of the soil. These horizons also showed wider rewetting curves, meaning that the hysteresis effect took longer in the surface horizons. Again, this could be due to the greater amount of organic matter at the surface from the turnover of surface vegetation. Subsurface horizons, especially those closest to the Bw horizon, had very similar drying and rewetting curves. Sites R1, R2, R3, R4 and R7 had the same relative gravimetric water content (170 g) for the surface horizon at the 0, 0.05 and 0.1 kPa ranges, while the pine site (R5) had a much lower gravimetric water content (155 g). Site R7 had the most within-site variation of results, with each horizon’s plotted water retention curve overlapping another. In the other Mazar Wildlife Reserve sites, horizons had distinctly different relative gravimetric water contents at the varying matric potential pressures. Pine site R7 did not have these distinct differences; all horizons had very similar mass contents.

Farley et al. (2004) showed that conversion of grasslands to pine plantations resulted in lower water retention rates. Lower water retention values also corresponded to the age of stands in her study. Her methods involved taking the sample to pressures of -33 and -1500 kPa for measurements at much higher pressures than this study. Poulenard et al. (2003) also showed the link between higher organic matter contents and higher water retention capacities in the Ecuadorian páramo. Both studies stressed the relationship of organic matter contents and soil moisture. Results from the present study show that water retention, expressed as relative gravimetric water content, is lower in the pine sites (Z5, R5).

Tracing Water Movement through Soil

Because a pilot dye test had demonstrated quick water movement down the soil profile, the water flux of these study areas was hypothesized to be high. In the first test for the bromide tracer, I sprinkled a liquid mixture over a predetermined plot, then sequentially sampled over known time intervals. In the second method, I sprinkled dry potassium bromide crystals over predetermined plots and allowed natural precipitation to move the tracer down the soil profile over a year. Both methods were used at both study areas.

Results from both study areas show that the liquid potassium bromide tracer did, in fact, move through the soil profile quickly (graphs showing these results are attached in Appendix E). The liquid tracer test was performed at the 9-month previous burn (Z1), 40-year old pine plantation (Z5), and the 12-year previous burn with *Polylepis* (Z7) sites in the Zuleta study area, and at the <1-year previous burn (R1) and 20-year old pine plantation (R5) sites at the Mazar Wildlife Reserve study area.

At the Zuleta study area, where soil samples for liquid bromide tracer analysis were taken at depths of 0–10, 10–20, and 20–30 cm, concentrations of bromide varied from site to site and over time, and ranged from 0 to 58.95 ppm. In most cases, the tracer concentration decreased from the surface horizon down to the bottom A horizon. A few time intervals showed sporadic concentrations at different depths. For instance, after 13 minutes at the Z1 site (9-month previous burn), no KBr concentration was detected at the 10–20 cm depth, but 58.95 ppm were detected at 20–30 cm depth.

Results of the liquid tracer tests at the Mazar Wildlife Reserve study area differed from those at the Zuleta study area. Depths sampled at these sites were deeper, at 0–20, 20–40, and 40–60 cm. The KBr concentrations recovered from these sites were much smaller, ranging from 0 to 1.89 ppm. Many of the samples, from both study areas, contained no detectable KBr, and when concentrations were detected, they were often miniscule. Very small concentrations were found in every horizon from the two sites, indicating that the tracer had moved through those horizons. The highest concentrations found at both study areas were of 120 ppm.

Results from the year-long crystal bromide test were from recently burned and pine sites at both the Zuleta and Mazar Wildlife Reserve study area. The Z1 site, which burned 9 months prior to sampling, had concentrations at the 0–30, 30–60, and 60–90 cm depths. Concentrations were relatively small in the 0–30 cm depth and then increased significantly in the 30–60 cm depth. Concentrations then decreased down to the 60–90 cm depth. Figure 17 shows how most of the tracer was detected at the 30–60 cm depth. Both replicate samples at Z1 show the same pattern, with higher concentrations at the 30–60 cm depth. The pattern of bromide concentrations outside of the plot test at Z1 was similar to the in-plot pattern, but the concentrations were smaller.

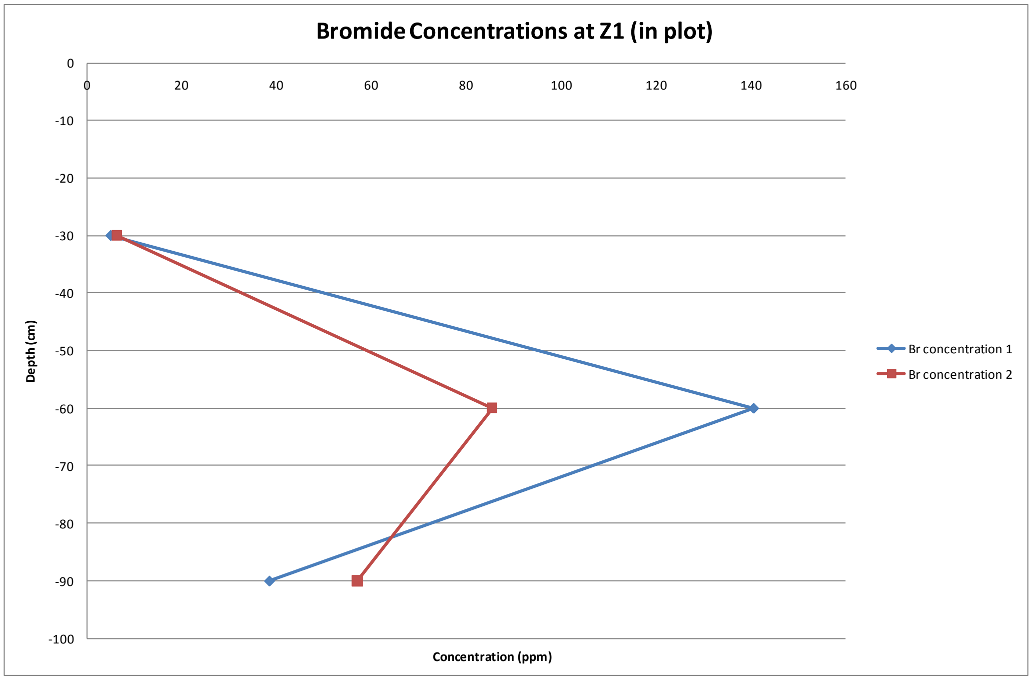


Figure 18 - Bromide concentrations (in ppm) of two replicate samples at selected depths for the Z1 (in plot) site after 1 year.

The R2 site, which had last burned 6 years prior to sampling, showed the same KBr pattern as the Z1 site. Concentrations were detected at every depth and were highest at 30–60 cm depth. Figure 16 shows how the concentrations increase at the 30–60 cm depth before decreasing at the 60–90 cm depth. The results from outside of the plot (Appendix E) were slightly different, with concentrations decreasing from 0–30 cm all the way down to 60–90 cm depth.

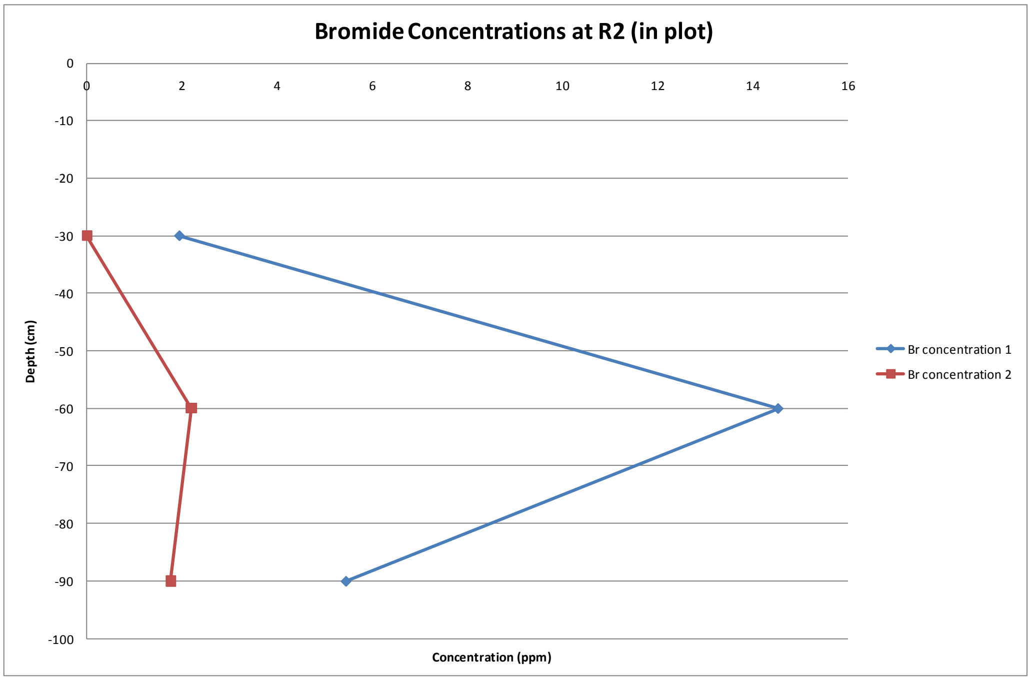


Figure 19 - Bromide concentrations (in ppm) of two samples at selected depths at the R2 (in plot) site after 1 year.

Results for the Z5 and R5 pine plantations sites were very different in the depths of the highest concentrations. The Z5 pine site had increasing bromide concentrations from the 0–30 cm depth to the 60–90 cm depth. As Figure 17 shows, bromide concentrations increase significantly from 0–30 cm to 30–60 cm and then are similar at 60–90 cm. Due to the presence of pine roots at the near surface, samples were unable to be replicated at this site. Samples taken outside of the plot at 0–30 cm depth came back without any detections of bromide.

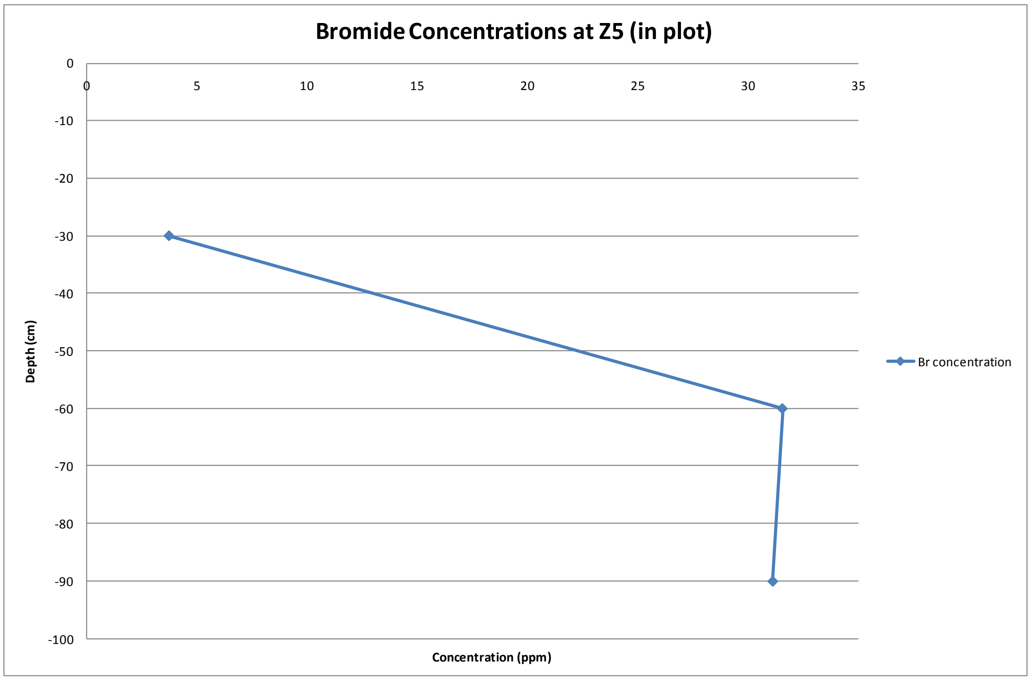


Figure 20 - Bromide concentrations (in ppm) at the Z5 pine plantation site. Replicate was not measured due to presence of larger roots at the surface.

The bromide concentrations at the R5 pine site were similar to those at the Z5 pine site. Concentrations were low at 0–30 cm and then increased at the 30–60 cm depth before, in this case, increasing again at the 60–90 cm depth. Figure 18 shows that both of the replicates had similar patterns of increasing concentrations down the soil profile. The outside-of-plot results for R5 also had this pattern.

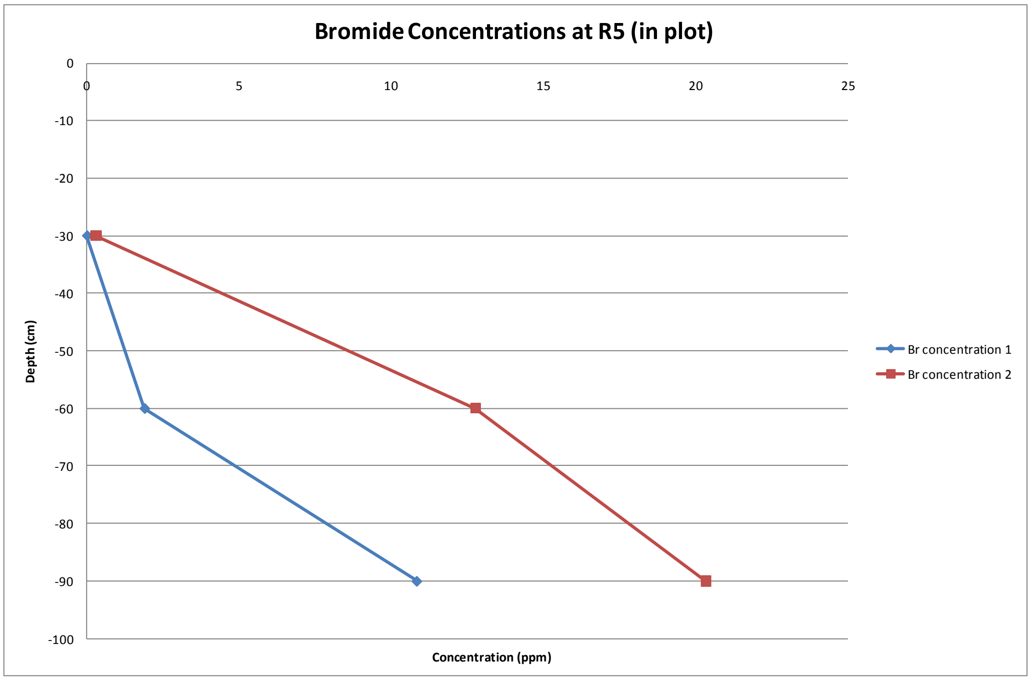


Figure 21 - Bromide concentrations (in ppm) of two samples from the R5 pine site.

Tracing Water Movement through Soil Discussion

Tracer studies were a very important part of this project because they help determine the rate and pathways of the movement of water in the páramo. The potassium bromide tracer test performed for this project was used to determine how quickly water moves through the soil profile. Bromide was used because it is both conservative in manner and is easily transported with water. It is also an inert substance that does not impose any harm on the local vegetation or wildlife. Pockets of completely saturated soil may exist in the surface horizon of the páramo. Water flow in unsaturated condition is very difficult to monitor and evaluate in the field because several factors influence the movement of water down the profile. Macro- and micropores can contain entrapped air, which may impede the downward movement of water. Matric potential also affects the movement of water and follows increasing matric potential gradients along areas of higher moisture contents. In-situ samples are preferred for hydraulic conductivity tests because they eliminate the problems experienced in a laboratory setting, including edge effects and the disruption of soil structure during transportation of samples. The presence of root channels, worm burrows or fractures in the soil can cause water to flow down through some areas of a soil profile more rapidly than others. Also, water travels down the profile in a three-dimensional pattern. To try to capture that movement using an auger is difficult, but was achieved for these study areas by placing the bromide plots on a slope and sampling within and downhill of the plot.

The liquid bromide tracer tests were performed at the Zuleta study area at three sites: the recent burn site (Z1), the pine site (Z5), and the 12-year previous burn site (Z7). At each time interval, the Z1 site had high concentrations of KBr at the surface that slowly diminished down into the subsurface horizons. Concentrations were detected at each depth sampled, with most of the sample remaining at or near (0–10 cm depth) the soil surface. One concentration at the 30-cm depth was much higher than any concentration from any other site. This could have been caused by preferential flow in a root channel. Results for the pine site (Z5) were very different from those at Z1. In one replicate at the Z5 sample site, KBr concentrations were detected in the 0–10 cm sample, not detected in the 10–20 cm sample, and then detected again at the lowest depth (30 cm). At the 120-minute time interval for each replicate, only one concentration was detected in the soil profile. This was a very small concentration (0.35 ppm) found at the 30-cm depth. Nonetheless, the presence of the tracer shows that the solution had moved to or past this point in 120 minutes. Results from Z7 were similar to those from Z1. Concentrations were higher in the top 10 cm and then diminished down the soil profile. For each time interval, concentrations at the 30-cm depth were very low to not detected. In the shorter time intervals, the tracer may not have had the chance to reach that point. In the later time intervals, the tracer may have somehow passed that depth without detection.

Bromide concentrations from the liquid bromide test at the Mazar Wildlife Reserve were very low at each site, and most samples resulted in no detection. Since this was a wetter study area, sampling depths were extended to capture any tracer concentrations that may have traveled deeper during the test run. Sites sampled for this analysis were the recent burn site (R1) and the ridge pine site (R5). For all but one sample in these sites, including replicates, concentrations were found at the 0–20-cm depth at each time interval. Concentrations reached a maximum of 1.49 ppm at this depth. However, concentrations were not found at any other depth during the analysis. Results from the R5 pine site were slightly different in that concentrations of KBr were found at each depth. The pattern of concentrations diminishing down the profile also occurred at site R5. On one plot for the R5 site, only one concentration was detected during the entire sampling period. That occurred at the 0–20-cm depth, with a concentration of 0.50 ppm. The fact that the replicates were different from one another suggests that the within-site variability of hydraulic conductivity is very high and helps show that measuring this property can be very difficult.

Results for the crystal bromide tracer test were remarkably similar between the recently burned (Z1 and R2) sites and between the pine (Z5 and R5) sites. Tracer concentrations were found to increase from the 0–30 cm depth to the 30-60 cm depth in both the Z1 and R2 sites. These results showed that the tracer was moved through the profiles by natural precipitation, but then collected in the middle of the profile. Since these sites contained a multitude of grass roots that dominated the upper A horizon and then decreased in size and quantity down into the underlying A horizons, it makes sense that the tracer would closely follow the channels of those roots. When these grass roots decreased in size and quantity, the tracer would not have been able to flow down the profile in those channels.

In contrast, the bromide concentrations detected at the Z5 and R5 pine sites increased all the way down the soil profiles. When comparing the pine sites results to the grass sites, it seems that the tracer moved through the pine site soils more easily. One of the reasons the tracer increased in every depth down the profile is the presence of the larger pine roots. While these roots were not observed at the surface or even the upper 20 cm of the soil profile, they were observed in the deeper parts of the profile. When trying to take samples for the Z5 site, the auger would keep hitting large roots that made taking samples at the 30–60 and 60–90 cm depths nearly impossible.

When attempting to measure the movement of water in the field or in the lab, many factors may affect the desired outcomes of the tests. The movement of water down a profile may be influenced by the hydraulic radii of preferential flow channels. These could be root channels, worm burrows, or fractures in the soil structure. Also, saturated and unsaturated flow was occurring at these sites. Both of these actions are affected by different factors. Unsaturated flow is influenced mostly by open pore spaces and gravity. Saturated flow is influenced mostly by gravity.

The results from the bromide solution test showed that water moves down the profile quickly at all the sites. In a 2-hour period, the tracer moved down to or past the lowest depth measured at all of the sites. While the bromide solution test did not really distinguish a land use with faster water movement, the crystal bromide test did. The higher bromide concentrations in the middle of the profile at the grass sites, compared to the higher concentrations at the lowest depths of the pine sites, represents how much faster the water moves at the pine sites. That water does, in fact, move through the soil faster in the pine plantations than in the infrequently and frequently burned sites, supports the fifth hypothesis.

One of the most striking features in our sites from both study areas were the root systems. Whether these were from the tall grass, the woody shrubs, or the pine trees, their sheer presence and abundance factors into the movement of water down the profile. In the recently and previously burned sites, where grass was the dominant surface vegetation, the surface soil horizon had an abundance of fine-sized roots. These roots were found in every soil pit and often reached down into the subsurface horizons. The woody shrub sites had larger roots that extended just as far as the grass roots and often contained grass roots cohabitually. The pine sites did not have any dominant root system from any surface vegetation but they did contain much larger roots scattered in the profile. These roots were observed when excavating the soil pits and were seen to extend far past the depth of the soil pits. Differences in the root systems of these different types of vegetation are important to note due to their role in the movement of water in the soil. Total flow rates in soil pores are proportional to the fourth power of the hydraulic radius (Beven and Germann, 1982). That water moved much faster than expected in these soils (e.g. 1200–1800 mm/hr in R5 at the 20-minute interval) can be attributed to several factors such as high moisture contents (which would fill more pores with water and thus increase flow), porous soil structure, and preferential flow channels along the roots. While results varied in the different sites, the larger pine roots in both study areas may have caused faster transmission of water down the soil profile.

Soil moisture and soil organic matter are closely related. Both of these components play an extremely important role in the storage and transmission of water on the soil surface as well as through the soil profile. The soil's physical properties, such as structure, texture and moisture consistency, are strongly influenced by the amount of organic matter and soil moisture. The lack of either soil moisture or organic matter can result in a drier soil that lacks a strong structure and moisture consistency. A soil structure that is moderate to weak in grade does not have as much ability to store and transmit water. Factors affecting the soil structure include the presence or absence of surface vegetation. In the grass páramo sites, the abundant root system, combined with higher amounts of soil moisture and organic matter, gives the soil a strong structure that tightly holds the soil aggregates together. In the absence of this surface vegetation, as seen in the pine sites, the soil lacks the root system or high soil moisture contents to hold the soil aggregates together. Furthermore, once these soils lose the ability to store water, the water has to go somewhere. Incoming precipitation entering the soil surface will either run off of the surface or quickly infiltrate and travel down the soil profile. Tracer data for the pine sites showed that water did, in fact, move down the profile quickly. This may also be attributed to the higher amount of available pore space in the less saturated soil profile. While tracer data were similar in the grass sites, the factor controlling the water flux was most likely the highly saturated soil that allowed the tracer to move freely without the influence of surface tension from open pore spaces.

Hysteresis

The hysteresis curves observed in the water-retention graphs are most pronounced in the pine plantation sites (Z5 and R5). These curves show the widest gaps between the drying and rewetting curves of any of the sites at both study areas. Several factors account for this wide gap, including a larger amount of non-uniform soil pores. This hysteretic effect is created because of irregularly shaped pores that drain and fill differently due to higher amounts of suction (Hillel, 1998b). The granular surface horizons in sites Z5 and R5 were described as having a granular soil structure, which was different from horizons in the other sites that were described as having sub-angular blocky surface soil structures.

Not only is there a hysteresis effect in the water-retention capabilities of these soils, it also occurs in the wetting fronts during infiltration. The initial wetness of the sublayers of a soil profile may affect the water-entry suction (Hillel, 1998c). This effect would create higher sorption than if the soil were initially dry. When this happens, infiltration into these sublayers occurs as “fingers” or “pipes” which act as preferential flow channels in subsurface horizons. This process has a hysteresis effect when the rewetting of a partially drained soil occurs at a higher suction than that of the entry of water into a completely dry soil. The results from the one-year-long bromide tracer tests show that the Z5 and R5 pine sites had higher bromide concentrations in the deeper horizons, suggesting that water moves faster through upper horizons in these sites. Coupled with the preferential flow channels from the pine roots, the antecedent moisture contents of subsurface horizons is another factor that could explain why water moves faster in these soils. The laser particle size analyzer showed that these sites had a silt loam soil texture in the surface horizons while the subsurface horizons in the R5 site had a sandy loam texture. While coarser soil textures were found in the subsurface horizons of most of the sites at both study areas, they were most pronounced in the pine sites, where other soil properties, e.g., soil structure and moisture consistency were different.

Chapter 5

Conclusion

In the highlands of the Ecuadorian Andes, which receive abundant precipitation during the year, any changes in land use occurring on the páramo have the possibility of altering the water-holding capacity of the hydro-physical properties of páramo soil. Andisols of the Ecuadorian Andes are truly remarkable for their wetness, low bulk densities, and high amounts of organic carbon. The movement and storage of water in soil is strongly influenced by the soil's physical properties, composition, and chemical make-up. Decomposing organic matter and volcanic glass, teamed with certain soil textures, increase the ability of páramo soils to absorb and store water.

The first hypothesis predicted that differences in land use would be associated with different soil physical properties. Of all the physical properties observed, the most striking differences were those in soil structure between the grass and pine plantation sites at both study areas. The grass sites had a stronger, sub-angular structure, while the pine sites had more of a granular structure. Moisture consistency was found to differ between pine and grass sites in the Mazar Wildlife Reserve, but not within the Zuleta sites. The relative dryness of surface horizons in the Mazar Wildlife Reserve's pine sites may be the reason for their very friable moisture consistencies. Soil textures were all very high in silt and did not seem to be influenced by soil moisture levels. Soil color did not differ as much as expected between sites. Color was most likely influenced by the parent material and presence of soil organic carbon rather than by the moisture content. Overall, the only differences in soil physical properties among sites with different land uses were differences in structure between pine and other sites at both study areas, and differences in moisture consistency between pine and other sites at the Mazar Wildlife Reserve. There were no notable differences in soil physical properties among the frequently burned sites at either study area.

The second hypothesis predicted that soil moisture contents would differ between pine sites and those that have been frequently and infrequently burned. During the periods of our relative measurements, the pine sites, Z5, R5, and R7, had much lower volumetric water contents than those in the grassy and shrubby sites. While the measured readings of the soil's volumetric water content were instantaneous and reflect the current state of the moisture in the soil, the values express just how variable the soil moisture levels can be. At the Mazar Wildlife Reserve study area, the lowest bulk density values and lowest volumetric water contents of soil surface horizons were at the R5 and R7 pine sites. In contrast, at the Zuleta study area, the highest bulk density values of surface horizons were at the Z5 pine site. This corresponds to the observed difference between the field texture, sandy loam, soil structure, granular, at Z5, both of which factors would cause the soil to not hold as much water as soils with a finer texture and more aggregation. These factors led to a drier soil surface at the pine site than those measured at the infrequently and frequently burned sites. Soil moisture decreased at all sites down the soil profile, presumably due to more compaction at depth, which would have limited the pore space in which water could be held.

Water retention was tested for the three A horizons at every site at both study areas. I hypothesized that the water-retention curves from the pine sites would differ from those of the infrequently and frequently burned sites and that curves from the frequently burned sites would differ from those of the infrequently burned sites. Water-retention curves, plotted after the completion of the tension table experiment, showed that the water-retention capacities differed in surface horizons but not in the lower horizons. While the subsurface horizon water-retention curves for all sites from both study areas had similar shapes and similar gravimetric water contents, water-retention curves for the surface horizons showed more variability. Most different were the lower gravimetric water contents of the pine sites (Z5, R5, R7), compared to those of the grassland, *Polylepis*, and woody shrub sites. Also, water-retention tests on samples from surface and subsurface horizons in the pine sites took longer to reach a steady state than those from other sites. The results of this experiment imply that planting pine trees in the páramo reduces the water-holding capacity of surface horizons at low tensions and reduces the ability of the soil to store water.

The last hypothesis of this thesis was that water would move through soil more rapidly in pine sites than in the grassland, *Polylepis*, and woody shrub sites. While this was tested using bromide tracers, results of all experiments were used to understand the water flux and hydrology of the páramo soils. Detectable bromide concentrations were sporadic following the bromide solution tests. The general pattern shown by all of the bromide tracer results was that water moved through the soil profile quickly regardless of land use. The crystal bromide tests, done over 1 year, showed that water did move faster in the pine plantations than in the grass sites. The pine roots are likely to exert a large influence on water flux in these sites. Therefore, based on the results from the bromide tracer tests, I conclude that pine plantations have the ability to increase water flux in the páramo.

One goal of afforestation projects in the páramo is to increase carbon storage. While the effects of pine trees on carbon storage in the páramo have been studied before, the effects on the hydro-physical properties of the soil have received little attention. The Zuleta study area offered a great opportunity for comparing the soil moisture storage and transmission properties between sites because it gave our research team the chance to evaluate differences between a pine plantation and the *Polylepis* sites. Since soil moisture contents at the pine site (Z5) were very low and soil moisture contents in the *Polylepis* (Z8) site were only slightly lower than those at the grass sites, the choice of a quasi-native shrub to collect carbon credits appears to merit further attention. While pine trees can grow in practically any environment, they have the capacity to use up more soil moisture and/or increase the water movement in the soils they grow in. Countries trying to earn carbon credits for afforestation projects should plant native shrubs or trees, such as *Polylepis*, to minimize the impact of trees on the ecosystem services of water production and storage.

The same can be said about the Mazar Wildlife Reserve study area, where the hydrophysical properties of soil at two pine plantations were compared to those at frequently and infrequently burned and woody shrub sites. The pine plantations have lower soil moisture contents and some differences in the soil's physical properties. Surface soil moisture levels were higher in the 40–50 year unburned montane forest site than at the pine plantation sites. The argument could be made that, left unburned, natural succession will allow the tree line of the páramo to migrate up to higher elevations. This vegetation is native to the Andes and would appear to sequester carbon without using the same amount of soil moisture that the pine plantations do.

Results for both study areas show that the practice of burning the páramo grass for livestock grazing does not have a negative impact on the soil's ability to store and transmit water. Although the lack of surface vegetation had been expected to increase evapotranspiration rates on bare surfaces following a burn, significant differences in the soil properties of the sites with different, recent burn histories were not observed. However, the lack of a surface vegetation or the patches of bare soil left from these burning events does create a concern for the susceptibility of those sites to soil erosion.

Further Research

This research project only scratched the surface of studying the implications of shifts in land management on the páramo. Andean páramos are tremendously important for their role as a reliable water source. In addition to further analyses from a chemical and biological standpoint, more research is needed on the hydrology of this ecosystem. This research adds to the growing group of studies that show that changes in land management affect the soil's hydrological properties.

Our research team placed sensors into the ground at four sites in the Mazar Wildlife Reserve to better compare water movement through soils under different land management. Readings of those sensors after a full year's worth of precipitation has fallen will be a valuable addition to our understanding of páramo soils. These results are expected to show what the moisture is doing in the soil and, in combination with the rain-gauge data, will also show how much precipitation is hitting the surfaces of the pine plantation and infrequently burned sites, allowing interception by the pine canopy to be evaluated.

Other potential future research could examine páramo stream networks and monitor how they regulate water flow. This would allow researchers to determine at what point the soil releases water into the stream after a storm event, how fast, and how much water the páramo soil could hold before and after a heavy rainfall. By installing a network of rain gauges and flow meters in the páramo and its nearby streams, one could better understand the hydrological processes, such as the hydraulic conductivity, at work in this ecosystem.

References

ASTM Standard D4221, 2000. Standard Test Method for Dispersive Characteristics of Clay Soil by Double Hydrometer. ASTM International, West Conshohocken, PA, 2000. DOI: 10.1520/D4221-11. www.astm.org.

Ataroff, M. and Rada, F., 2000. Deforestation impact on water dynamics in a Venezuelan Andean cloud forest. Ambio 29, 440-444.

Balslev, H. and Luteyn, J.L. (Eds.), Páramo: an Andean ecosystem under human influence. Academic Press, London, pp. 1-14.

Barberi, F., Cotelli, M., Ferrara, G., Innocenti, F., Navarro, J., and Santacroce, R., 1988. Plio-Quartenary volcanism in Ecuador. Geological Magazine 125, 1-14.

Bashkin, M. and Binkley, D., 1998. Changes in soil carbon following afforestation in Hawaii. Ecology 79 (3): 828-833.

Beven, K. and Germann, P., 1982. Macropores and Water Flow in Soils. Water Resources Research 18 (5): 1311-1325.

Brady, N. and Weil, R., 2002. Formation of soils from parent materials. *The Nature and Properties of Soils* 13th Edition. pp 77-79. Upper Saddle River, New Jersey: Prentice Hall.

Brown, S., Lugo, A., and Chapman, J., 1986. Biomass of tropical tree plantations and its implications for the global carbon budget. Canadian Journal of Forest Research 16, 390-394.

Buol, S., Southard, R., Graham, R., and McDaniel, P., (2003a). Andisols: Soils with Andic Soil Properties. In Soil Genesis and Classification. 5th Edition. Wiley-Blackwell, pp. 231-241.

Buol, S., Southard, R., Graham, R., and McDaniel, P., (2003b). Morphology and Composition of Soils. In Soil Genesis and Classification. 5th Edition. Wiley-Blackwell, pp. 44-60.

Buytaert, W., 2004. The properties of the soils of the south Ecuadorian páramo and the impact of land use changes on their hydrology. Unpublished Ph.D. Thesis, Katholieke Universiteit Leuven.

Buytaert, W., De Bievre, B., Wyseure, G., and Deckers, J., 2005a. The impact of land use changes on the hydrological behaviour of Histic Andosols in the south Ecuadorian páramo. Hydrological Processes 19, 3985-3997.

Buytaert, W., Sevnik, J., De Leeuw, B., and Deckers, J., 2005b. Clay mineralogy of the soils in the south Ecuadorian páramo region. Geoderma 127, 114-129.

Buytaert, W., Deckers, J., and Wyseure, G., 2006. Description and classification of highly weathered Andosols in south Ecuadorian alpine grasslands (páramo). Geomorphology 73, 207-221.

Buytaert, W., Iñiguez, V., and De Bièvre, B., 2007. The effects of afforestation and cultivation on water yield in the Andean páramo. Forest Ecology and Management 251, 22-30.

Consejo Nacional de Electricidad, 2011. Paute Molino Dam Profile. Dams in Amazonia. http://www.dams-info.org/en/dams/view/paute-molino/.

Dahlgren, R., Shoji, S., and Nanzyo, M., 1993. Mineralogical characteristics of volcanic ash soils. In: Shoji, S., Nanzyo, M., Dahlgren, R., editors. Volcanic ash soils: genesis, properties, and utilization. Amsterdam: Elsevier. p 101-143.

Dane, J. and Klute, A., 1977. Salt effects on the hydraulic properties of swelling soil, Soil Science Society of America Proc. 41, pp. 1043–1049.

Dinerstein, E., Olson, D.M., Graham, D.J., Webster, A.L., Primm, S.A., Bookbinder, M.P., and Ledec, G., 1995. A Conservation Assessment of the Terrestrial Ecoregions of Latin America and the Carribean. The World Bank, Washington. 174 pp.

Espinosa, C., 2005, Payment for Water-Based Environmental Services: Ecuador's Experiences, Lessons Learned and Ways Forward. IUCN Water, Nature and Economics Technical Paper No. 2, IUCN — The World Conservation Union, Ecosystems and Livelihoods Group Asia, Colombo.

Farley, K.A., Kelly, E.F., and Hofstede, R.G.M., 2004. Soil organic carbon and water retention after conversion of grasslands to Pine plantations in the Ecuadorian Andes. Ecosystems 7, 729-739.

Farley, K.A., Jobbagy, E.G., and Jackson, R.B., 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. Global Change Biology 11, 1565-1576.

Gardner, W. and Widtsoe, J., 1921. The movement of soil moisture. Soil Science 11, 230.

Geist, J., Hazard, J., and Seidel, K., 1989. Assessing Physical Conditions of Some Pacific Northwest Volcanic Ash Soils After Forest Harvest. Soil Science Society of America Journal 53, 946-950.

Harden, C.P., 1993. Land use, soil erosion, and reservoir sedimentation in an Andean drainage basin in Ecuador. Mountain Research and Development 13 (2), 177-184.

Harden, C.P., 2006. Human impacts on headwater fluvial systems in the northern and central Andes. Geomorphology 79, 249-263.

Hillel, D. (1998a). General Physical Characteristics. In Environmental Soil Physics. Academic Press, San Diego, pp. 11-15.

Hillel, D. (1998b). Hysteresis. In Environmental Soil Physics. Academic Press, San Diego, pp. 159-161.

Hillel, D. (1998c). Instability of Wetting Fronts During Infiltration. In Environmental Soil Physics. Academic Press, San Diego, pp. 411-415.

Hofstede, R., Groenendijk, J., Coppus, R., Fehse, J., and Sevink, J., 2002. Impact of pine plantations on soils and vegetation in the Ecuadorian High Andes. Mountain Res. Dev. 22, 159-167.

Hofstede, R., Segarra, P., and Mena, P.V., 2003. Los Páramos del Mundo. Global Peatland Initiative/NC-IUCN/EcoCiencia, Quito.

Honna, T., Yamamoto, S., and Matsui, K., 1988. A simple procedure to determine melanic index useful to separation of melanic and fulvic Andisols. Pedologist, 32, 69-78.

Jenny, H., 1941. Factors of soil formation: a system of quantitative pedology. New York: Dover Publications.

Klute, A., 1986. Water retention: Laboratory methods. In Methods of Soil Analysis. Part 1. Physical and mineralogical methods.

Kubota, T., 1972. Aggregate-formation of allophanic soils: Effect of drying on the dispersion of soils. Soil Science Plant Nutrition (Tokyo) 18, 79-87.

Luteyn, J.L., Cleef, A.M., and Rangel, O., 1992. Plant diversity in páramo: towards a checklist of páramo plants and generic flora. In: Balsev, H., Luteyn, J.L. (Eds.), Páramo: an Andean Ecosystem under Human Influence. Academic Press, London, pp. 71-84.

Luteyn, J. 1999. Introduction to the Páramo ecosystem. In Páramos: A checklist of plant diversity. New York: Geographical Distribution and Botanical Literature. Memoirs of the New York Botanical Garden 84, 1-278.

Nanzyo, M., Shoji, S., and Dahlgren, R., 1993. Volcanic Ash Soils: genesis, properties and utilisation. Developments in Soil Science, vol. 21. Elsevier, Amsterdam.

Nierop, K., Tonneijck, F., Jansen, B., and Verstraten, J., 2007. Organic Matter in Volcanic Ash Soils under Forest and Páramo along an Ecuadorian Altitudinal Transect. Soil Science Society of America Journal 71, 1119-1127.

Parfitt, R., Russell, M., and Orbell, G., 1983. Weathering sequence of soils from volcanic ash involving allophane and halloysite, New Zealand. Geoderma 29 (1), 41-57.

Parfitt, R., Percival, H., Dahlgren, R., and Hill, L., 1997. Soil and solution chemistry under pasture and radiata pine in New Zealand. Plant Soil 191, p. 279-290.

Ping, C., Shoji, S., Ito, T., Takahashi, T., and Moore, J., 1989. Characteristics and classification of volcanic-ash-derived soils in Alaska. Soil Science Society of America Journal 148, pp. 8–28.

Podwojewski, P., Poulenard, J., Zambrana, T., and Hofstede, R., 2002. Overgrazing effects on vegetation cover and properties of volcanic ash soil in the páramo of Llangahua and La Esperanza (Tungurahua, Ecuador). Soil Use and Management 18, 45-55.

Poulenard, J., Podwojewski, P., Janeau, J., and Collinet, J., 2001. Runoff and soil erosion under rainfall simulation of andisols from the Ecuadorian páramo; effect of tillage and burning. Catena 45, 185-207.

Poulenard, J., Podwojewski, P., and Herbillon, A., 2003. Characteristics of non-allophanic Andisols with hydric properties from the Ecuadorian páramo. Geoderma 117, 267-281.

Rabenhorst, M. and Parikh, S., 2000. Propensity of soils to develop redoximorphic colour changes. Soil Science Society of America Journal 64, 1904-1910.

Ragab, R. and Prudhomme, C., 2000. Climate Change and Water Management in Arid and Semi-arid Regions: Prospective and Challenges for the 21st Century. Biosystems Engineering 81 (1), 3-34.

Rhoades, C., Nissen, T., and Kettler, J., 1997. Soil nitrogen dynamics in alley cropping and no-till systems on ultisols of the Georgia Piedmont, USA. Agroforest Systems 39, 31-44.

Rosegrant, M., Cai, X., and Cline, S., 2002. Global Water Outlook to 2025: Averting an Impending Crisis. A 2020 Vision for Food, Agriculture, and the Environment Initiative. International Food Policy Research Institute. Washington, D. C.

Sarmiento, F., 2002. Anthropogenic Change in the Landscapes of Highland Ecuador. The Geographical Review 92 (2), 213-234.

Schlesinger, W., 1997. Biogeochemistry: An Analysis of Global Change. 2nd ed. San Diego: Academic Press. p. 588.

Schmidt, A. M. and Verweij, P. A., 1992: Forage intake and secondary production in extensive livestock systems in páramo. In Balslev, H. and Luteyn, J. L. (eds.), Páramo: An Andean Ecosystem under Human Influence. London: Academic Press. 197-210.

Seckler, D., Barker, R., and Amarasinghe, U. 1999. Water Scarcity in the Twenty-first Century. Water Resources Development 15, 29-42.

Shoji, S., Nanzyo, M., and Dahlgren, R., 1993. Volcanic Ash Soils: Genesis, Properties and Utilisation. Developments in Soil Science, vol. 21. Elsevier, Amsterdam.

Soil Survey Staff, 2003. Keys to Soil Taxonomy. United States Department of Agriculture, Washington, D.C.

van Veelen, M. and de Vet, S., 2008. Hydrological response of the North-Peruvian Páramo/Jalca to influences of land use and socio-economic practices. University of Amsterdam.

World Water Council, 2006. World Water Council 4th World Water Forum: Water Problems in Latin America. World Water Council and the Secretariat of the 4th World Water Forum.

Wunder, S., 2005. Payments for environmental services: some nuts and bolts. CIFOR Occasional Paper No. 42. Center for International Forestry Research, Bogor (Indonesia).

Wunder, S. and Alban, M., 2008. Decentralized payments for environmental services: The cases of Pimampiro and PROFAFOR in Ecuador. Ecological Economics 65, 685-698.

Zehetner, F., Miller, W., and West, L., 2003. Pedogenesis of volcanic ash soils in Andean Ecuador. Soil Science Society of America Journal 67, 1797-1809.

Appendices

Appendix A:

Soil Description Sheets and Photographs

Soil Description Sheets and Photographs from the Zuleta Study Area

Z1 – Burned 9 months previously

Name - Z1 - Burned 9 months previously				**Date** 6-12-2009		**Pit #** 1
Classification - Recent burn						
Location (Latitude and Longitude) N 0 13.887’ W 78 03.542’						
Weather Conditions - Sunny						
Vegetation - Short grass						
Grazing - No						
Elevation 3625 m			**Slope** 20˚	**Aspect** 270		
Root Limiting Layer N/A						
Landscape Position Backslope						
Horizon	**Depth (cm)**	**Color**	**Texture**	**Structure**	**Moisture Consistency**	**% VWC**
A1	23	10 YR N/0	SiL	ST SBK	Very Friable	71
A2	50	10 YR 2/1	SiL	ST SBK	Friable	60
A3	86+	10 yr 2/2	SiL	ST SBK	Friable	53

Z2 – Burned 15 years previously

Name - Z2 - Burned 15 years previously	**Date** 6-13-2009	**Pit #** 2
Classification - Infrequently burned		
Location (Latitude and Longitude) N 0 13.706’ W 78 03.457’		
Weather Conditions - Overcast		
Vegetation - Tall grass, some small Polylepis		
Grazing - No		
Elevation 3648 m	**Slope** 16.5˚	**Aspect** 225
Root Limiting Layer N/A		
Landscape Position Backslope		

Horizon	Depth (cm)	Color	Texture	Structure	Moisture Consistency	% VWC
A1	21	10 YR N/0	SiL	ST SBK	Very Friable	74
A2	43	10 YR 2/1	SiL	ST SBK	Friable	68
A3	76+	7.5 YR 2.5/1	SiL	ST SBK	Friable	62

Z3 – Burned 15 years previously

Name - Z3 - Burned 15 years previously	**Date** 6-14-2009	**Pit #** 2

Classification - Infrequently burned

Location (Latitude and Longitude) N 0 13.510’ W 78 03.167’

Weather Conditions - Sunny

Vegetation - Tall grass

Grazing - No

Elevation 3643 m	**Slope** 10.5˚	**Aspect**

Root Limiting Layer N/A

Landscape Position Backslope

Horizon	Depth (cm)	Color	Texture	Structure	Moisture Consistency	% VWC
A1	24	10 YR N/0	SiL	ST SBK	Very Friable	68
A2	49	10 YR 2/1	SiL	ST SBK	Friable	62
A3	72+	7.5 YR 2.5/1	SiL	ST SBK	Friable	56

Z5 – 40-year pine plantation

Name - Z5 - 40 year pine site				**Date** 6-15-2009		**Pit #** 5
Classification - Pine plantation						
Location (Latitude and Longitude) N 0 13.158’ W 78 03.201’						
Weather Conditions - Overcast						
Vegetation - Pine trees with thick needle duff						
Grazing - Yes						
Elevation 3598 m			**Slope** 16˚	**Aspect** 25		
Root Limiting Layer N/A						
Landscape Position Backslope						
Horizon	**Depth (cm)**	**Color**	**Texture**	**Structure**	**Moisture Consistency**	**% VWC**
A1	24	10 YR 2/1	SL	MO Gr	Very Friable	22
A2	42	10 YR 2/1	L	MO SBK	Friable	20
A3	65	10 YR 2/1	L	MO SBK	Friable	13
AC	96+	10 YR 2/2	L	MO SBK	Friable	-

Z6 – Burned 9 years previously

Name - Z6 - Burned 9 years previously				**Date** 6-15-2009		**Pit #** 6
Classification - Infrequently burned						
Location (Latitude and Longitude) N 0 12.987' W 78 03.210'						
Weather Conditions - Sunny						
Vegetation - Tall grass						
Grazing - Yes						
Elevation 3656 m		**Slope** 12.5˚		**Aspect** 25		
Root Limiting Layer N/A						
Landscape Position Backslope						
Horizon	**Depth (cm)**	**Color**	**Texture**	**Structure**	**Moisture Consistency**	**% VWC**
A1	25	7.5 YR 2.5/1	SiL	ST SBK	Very Friable	71
A2	43	10 YR 2/1	SiL	ST SBK	Friable	66
A3	65	10 YR 2/1	SiL	ST SBK	Friable	58
AC	105+	7.5 YR 2.5/2	L	MA	-	50

Z7 – 12-year previous burn, Polylepis, alpaca grazing

Name - Z7 - Polylepis, 12 years previous burn				**Date** 6-16-2009		**Pit #** 7
Classification - Polylepis plantation						
Location (Latitude and Longitude) N 0 13.116' W 78 03.262'						
Weather Conditions - Overcast						
Vegetation - Mature Polylepis (8 years)						
Grazing - Yes						
Elevation 3608 m		**Slope** 12˚		**Aspect** 6		
Root Limiting Layer N/A						
Landscape Position Backslope						
Horizon	**Depth (cm)**	**Color**	**Texture**	**Structure**	**Moisture Consistency**	**% VWC**
Ap	26	7.5 YR 2.5/1	SiL	ST SBK	Very Friable	70
A1	58	7.5 YR 3/1	SiL	ST SBK	Friable	59
AC	115+	7.5 YR 2.5/2	L	MA	-	56

Z8 – Previous potato cultivation with fertilizer, mature Polylepis (8-year)

Name - Z8 - Polylepis, potato cultivation with fertilizer	**Date** 6-17-2009	**Pit #** 8
Classification - Polylepis plantation		
Location (Latitude and Longitude) N 0 13.118’ W 78 03.777’		
Weather Conditions - Sunny		
Vegetation - Mature Polylepis (8 years)		
Grazing - Yes		
Elevation 3518 m	**Slope** 12.5˚	**Aspect** 339
Root Limiting Layer N/A		
Landscape Position Backslope		

Horizon	Depth (cm)	Color	Texture	Structure	Moisture Consistency	% VWC
Ap	19	10 YR 2/1	SiL	ST SBK	Very Friable	52
A1	56	7.5 YR 2.5/1	SiL	ST SBK	Friable	53
AC	94+	7.5 YR 2.5/1	L	MA	-	45

Soil Description Sheets and Photographs from the Mazar Wildlife Reserve Study Area

R1 – Less than 1 year previous burn

Name - R1 Less than 1 year burn				**Date** 6-14-2010		**Pit #** 1
Classification - Recent Burn						
Location (Latitude and Longitude) S 02.34286˚ W 078.44870˚						
Weather Conditions - Overcast						
Vegetation - Bunch grass, bare areas						
Grazing - Yes						
Elevation 3449 m			**Slope** 21˚	**Aspect** 192		
Root Limiting Layer N/A						
Landscape Position Backslope						
Horizon	**Depth (cm)**	**Color**	**Texture**	**Structure**	**Moisture Consistency**	**% VWC**
A1	18	10 YR 2/1	SiL	MO SBK	Friable	79
A2	45	10 YR 2/1	SiL	MO SBK	Friable	73
2Bw	79	7.5 YR 2.5/2	SiL	MO SBK	Friable	66
2C	120+	7.5 YR 5/6	L	MA	-	49

R2 – Burned 6 years previously

Name - R2 - 6 year burn	**Date** 6-15-2010	**Pit #** 2
Classification - Recent Burn		
Location (Latitude and Longitude) S 02.56224˚ W 078.74703˚		
Weather Conditions - Overcast		
Vegetation - Bunch grass, woody shrubs		
Grazing - Yes		
Elevation 3428 m	**Slope** 20˚	**Aspect** 248
Root Limiting Layer N/A		
Landscape Position Backslope		

Horizon	Depth (cm)	Color	Texture	Structure	Moisture Consistency	% VWC
A1	24	10 YR 2/1	SiL	MO SBK	Friable	86
A2	45	10 YR 2/1	SiL	MO SBK	Friable	84
2Bw	75	7.5 YR 2.5/2	SiL	MO SBK	Friable	79
2C	110+	5 YR 4/6	L	MA	-	66

R3 – Woody shrub

Name - R3 - Woody shrubs					**Date** 6-17-2010	**Pit #** 3
Classification - Infrequently burned, shrubby						
Location (Latitude and Longitude) S 02.56753˚ W 078.74351˚						
Weather Conditions - Overcast						
Vegetation - Woody shrubs with some tall grass						
Grazing - Yes						
Elevation 3453 m		**Slope** 13.5˚		**Aspect** 149		
Root Limiting Layer N/A						
Landscape Position Backslope						
Horizon	**Depth (cm)**	**Color**	**Texture**	**Structure**	**Moisture Consistency**	**% VWC**
A1	22	10 YR 2/1	SiL	MO SBK	Friable	89
A2	53	10 YR 2/1	SiL	MO SBK	Friable	81
2Bw	76	7.5 YR 2.5/2	SiL	MO SBK	Friable	73
2C	98+	7.5 YR 5/6	L	MA	-	60

R4 – Burned 40-50 years previously

Name - R4 - 40-50 year burn			**Date** 6-23-2010		**Pit #** 6	
Classification - Infrequently burned, shrubby						
Location (Latitude and Longitude) S 02.57086˚ W 078.74458˚						
Weather Conditions - Rainy						
Vegetation - Montane forest						
Grazing - Yes						
Elevation 3351 m		**Slope** 22˚	**Aspect** 204			
Root Limiting Layer N/A						
Landscape Position Backslope						
Horizon	**Depth (cm)**	**Color**	**Texture**	**Structure**	**Moisture Consistency**	**% VWC**
A1	22	10 YR 2/1	SiL	MO SBK	Friable	-
A2	43	10 YR 2/1	SiL	MO SBK	Friable	-
2Bw	61	7.5 YR 2.5/2	L	MO SBK	Friable	-
2Cr	77+	-	-	-	-	-

R5 – 20-year pine plantation

Name - R5 - 20 year pine site					**Date** 6-16-2010	**Pit #** 3
Classification - Pine plantation						
Location (Latitude and Longitude) S 02.56542˚ W 078.74841˚						
Weather Conditions - Overcast						
Vegetation - Pine trees with thick needle duff (7 cm)						
Grazing - Yes						
Elevation 3402 m			**Slope** 17.5˚		**Aspect** 312	
Root Limiting Layer N/A - Coarse fragments found at 83 cm (5-10%)						
Landscape Position Backslope						
Horizon	**Depth (cm)**	**Color**	**Texture**	**Structure**	**Moisture Consistency**	**% VWC**
A1	26	10 YR 2/1	SiL	MO Gr	Very Friable	63
A2	57	10 YR2/1	SiL	MO SBK	Friable	86
2Bw	83	7.5 YR 2.5/1	SiL	MO SBK	Very Friable	82
2C	124+	5 YR 5/6	L	MA	-	72

R7 – 2nd 20-year pine plantation

Name - R7 - 20 year pine site **Date** 6-22-2010 **Pit #** 5

Classification - Pine plantation

Location (Latitude and Longitude) S 02.57016˚ W 078.74301˚

Weather Conditions - Sunny, shady in pines

Vegetation - Pine trees with thick pine needle duff (7 cm), mosses and byrophytes

Grazing - Yes

Elevation 3249 m **Slope** 20˚ **Aspect** 190

Root Limiting Layer N/A

Landscape Position Backslope

Horizon	Depth (cm)	Color	Texture	Structure	Moisture Consistency	% VWC
A1	25	10 YR 2/1	SiL	MO SBK	Very Friable	76
A2	52	10 YR 2/1	SiL	MO SBK	Friable	75
2Bw	91	7.5 YR 2.5/1	SiL	MO SBK	Very Friable	76
2C	100+	7.5 YR 4/4	L	MA	-	65

Appendix B

Laser Particle–Size Analysis Results

Zuleta Study Area Results

Particle Size Analysis from the Zuleta Study Area					
Sample	**Clay %**	**Sand %**	**Silt %**	**Total %**	**Texture**
Z1 10-20	11.7	68.0	20.3	100	
	10.7	66.8	22.5	100	
	11.0	69.8	19.2	100	
Average	11.1	68.2	20.7	100	SiL
Z1 30-40	11.3	72.6	16.2	100	
	11.8	74.5	13.7	100	
	11.2	69.8	19.0	100	
Average	11.4	72.3	16.3	100	SiL
Z1 60-70	5.6	50.6	43.8	100	
	7.0	65.2	27.8	100	
	7.3	70.3	22.5	100	
Average	6.6	62.0	31.4	100	SiL
Z2 5-10	11.8	77.5	10.7	100	
	8.3	63.5	28.2	100	
	9.9	73.6	16.5	100	
Average	10.0	71.5	18.5	100	SiL
Z2 30-40	10.3	72.7	17.0	100	
	11.0	74.8	14.3	100	
	11.4	72.5	16.1	100	
Average	10.9	73.3	15.8	100	SiL
Z2 50-60	5.9	58.0	36.2	100	
	6.3	60.3	33.4	100	
	8.5	61.5	30.0	100	
Average	6.9	59.9	33.2	100	SiL
Z3 10-15	8.2	58.4	33.4	100	
	11.9	74.0	14.1	100	
	11.2	70.2	18.5	100	
Average	10.4	67.6	22.0	100	SiL
Z3 30-40	11.8	76.8	11.4	100	
	11.4	75.3	13.3	100	
	11.7	73.2	15.2	100	
Average	11.6	75.1	13.3	100	SiL
Z3 55-65	7.4	65.1	27.5	100	
	6.7	60.5	32.8	100	
	6.8	61.6	31.6	100	

Average	7.0	62.4	30.6	100	SiL
Z5 10-15	8.4	67.8	23.9	100	
	8.7	69.4	21.9	100	
	17.2	76.6	6.3	100	
Average	11.4	71.2	17.3	100	SiL
Z5 30-35	10.9	70.4	18.7	100	
	11.5	75.7	12.8	100	
	10.9	72.2	16.9	100	
Average	11.1	72.8	16.1	100	SiL
Z5 55-60	6.9	62.1	31.0	100	
	6.5	60.2	33.3	100	
	6.9	60.8	32.3	100	
Average	6.8	61.0	32.2	100	SiL
Z6 10-15	10.9	86.5	2.5	100	
	10.1	71.4	18.4	100	
	10.6	76.6	12.8	100	
Average	10.6	78.2	11.3	100	SiL
Z6 30-35	8.6	61.6	29.8	100	
	9.9	68.4	21.7	100	
	10.0	71.2	18.8	100	
Average	9.5	67.1	23.4	100	SiL
Z6 50-55	10.4	56.3	33.3	100	
	12.1	67.4	20.5	100	
	12.9	69.4	17.7	100	
Average	11.8	64.4	23.9	100	SiL
Z7 10-15	11.6	66.8	21.7	100	
	11.7	68.9	19.4	100	
	10.3	60.3	29.5	100	
Average	11.2	65.3	23.5	100	SiL
Z7 35-40	7.7	70.9	21.4	100	
	7.9	62.1	30.0	100	
	10.4	79.8	9.8	100	
Average	8.7	70.9	20.4	100	SiL
Z7 65-70	8.5	74.8	16.6	100	
	7.3	65.4	27.3	100	
	7.9	70.1	22.0	100	
Average	7.9	70.1	22.0	100	SiL
Z8 10-15	10.2	71.2	18.6	100	
	10.7	70.5	18.8	100	
	10.4	69.6	20.0	100	
Average	10.4	70.4	19.1	100	SiL
Z8 35-40	8.4	66.4	25.2	100	

	8.8	71.6	19.6	100	
	7.9	61.9	30.2	100	
Average	8.4	66.6	25.0	100	SiL
Z8 65-70	4.5	49.2	46.3	100	
	4.5	52.5	43.0	100	
	4.6	53.0	42.5	100	
Average	4.5	51.6	43.9	100	SiL

Mazar Wildlife Reserve Study Area Results

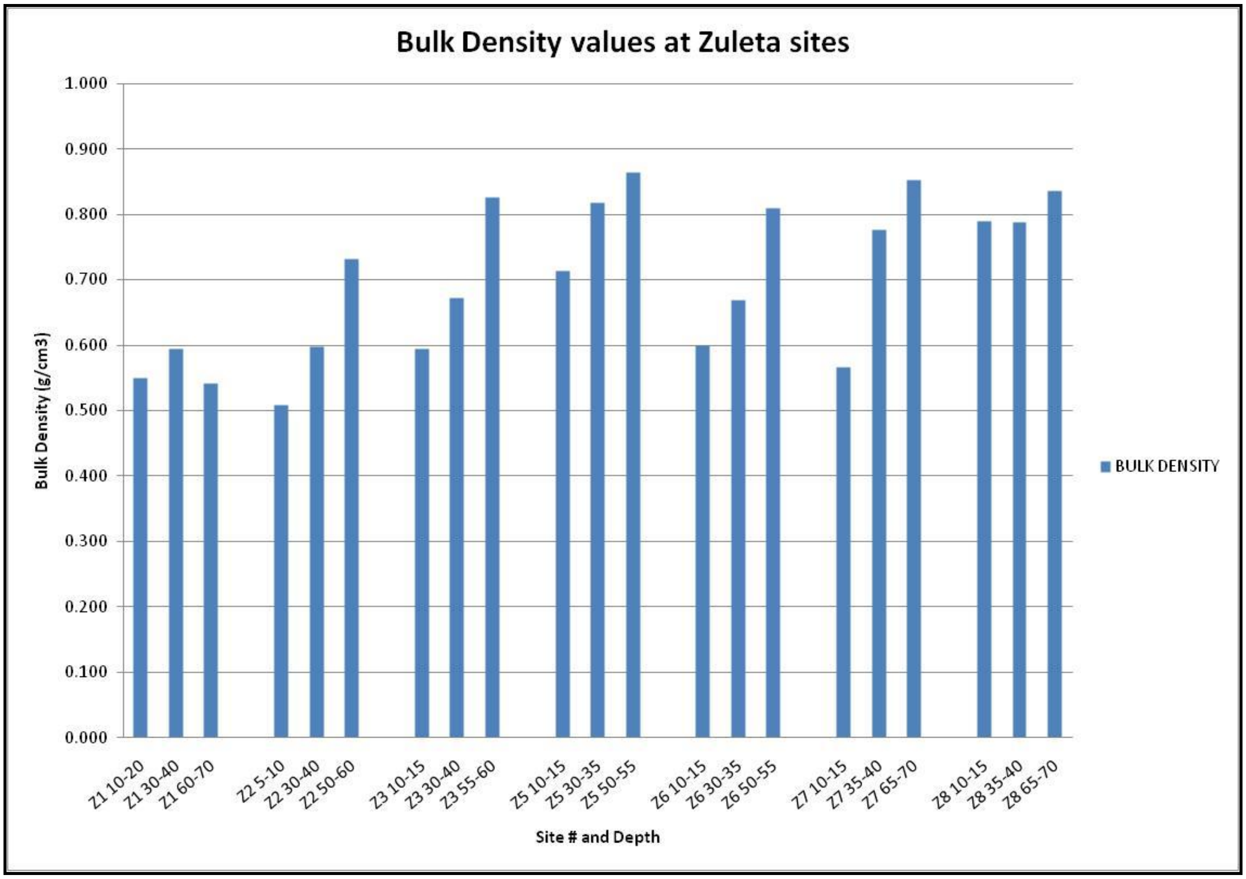
Particle Size Analysis from the Mazar Wildlife Reserve Study Area

Sample	Clay %	Sand %	Silt %	Total %	Texture
R1 5-10	6.4	72.0	21.6	100	
	9.3	83.1	7.7	100	
	14.0	84.8	1.2	100	
Average	9.9	79.9	10.2	100	SiL
R1 25-30	4.6	38.2	57.2	100	
	4.7	62.2	33.2	100	
	8.8	70.2	21.0	100	
Average	6.0	56.9	37.1	100	SiL
R1 60-65	7.3	38.8	53.9	100	
	8.3	63.7	28.0	100	
	4.4	31.6	64.0	100	
Average	6.7	44.7	48.6	100	LS
R2 5-10	11.7	77.0	11.3	100	
	7.6	74.0	18.4	100	
	13.2	80.5	6.3	100	
Average	10.8	77.2	12.0	100	SiL
R2 30-35	3.7	47.7	48.6	100	
	2.6	41.0	56.4	100	
	5.4	70.4	24.2	100	
Average	3.9	53.0	43.1	100	SiL
R2 60-65	1.8	19.7	78.6	100	
	2.3	22.5	75.1	100	
	2.0	20.7	77.2	100	
Average	2.1	21.0	77.0	100	SL
R3 5-10	7.5	77.7	14.9	100	
	6.8	74.4	18.8	100	
	7.9	79.1	13.1	100	
Average	7.4	77.0	15.6	100	SiL
R3 30-35	3.5	47.1	49.4	100	
	3.3	48.1	48.5	100	
	3.1	44.9	52.0	100	
Average	3.3	46.7	50.0	100	SL
R3 60-65	1.7	12.8	85.5	100	
	1.6	12.5	85.9	100	
	1.9	11.2	87.0	100	
Average	1.7	12.1	86.1	100	LS
R4 5-10	5.8	77.9	16.3	100	

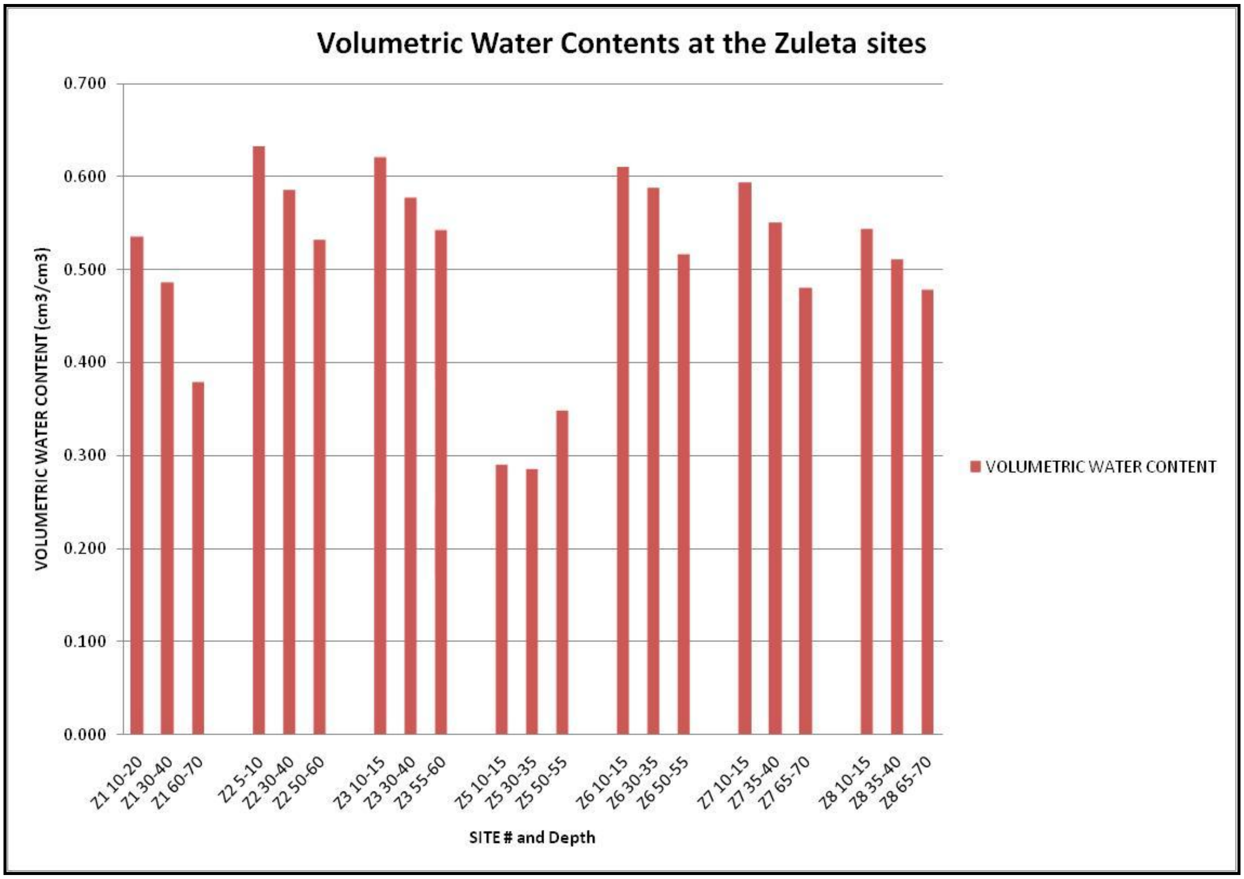
	8.3	89.1	2.6	100	
	7.9	81.3	10.7	100	
Average	7.3	82.8	9.9	100	SiL
R4 30-35	3.6	40.1	56.3	100	
	3.0	32.8	64.3	100	
	3.2	29.6	67.2	100	
Average	3.2	34.2	62.6	100	
R4 50-55	1.9	19.7	78.4	100	SL
	2.3	22.3	75.4	100	
	2.1	25.7	72.2	100	
Average	2.1	22.5	75.4	100	SL
R5 5-10	4.1	81.1	14.8	100	
	4.0	77.5	18.4	100	
	4.6	82.6	12.8	100	
Average	4.3	80.4	15.4	100	SiL
R5 40-45	2.4	34.6	62.9	100	
	3.0	42.8	54.2	100	
	3.1	40.2	56.7	100	
Average	2.8	39.2	57.9	100	SiL
R5 60-65	2.1	20.4	77.5	100	
	3.8	42.5	53.7	100	
	2.5	24.1	73.4	100	
Average	2.8	29.0	68.2	100	SL
R7 5-10	3.6	83.6	12.8	100	
	3.3	77.4	19.3	100	
	3.4	76.2	20.4	100	
Average	3.5	79.0	17.5	100	Sil
R7 35-40	2.7	35.1	62.1	100	
	3.3	39.4	57.3	100	
	3.2	38.0	58.8	100	
Average	3.1	37.5	59.4	100	SL
R7 60-65	2.5	19.3	78.2	100	
	2.2	20.4	77.4	100	
	2.9	23.3	73.8	100	
Average	2.6	21.0	76.4	100	LS

Appendix C: Bulk Density and Volumetric Moisture Content (calculated)

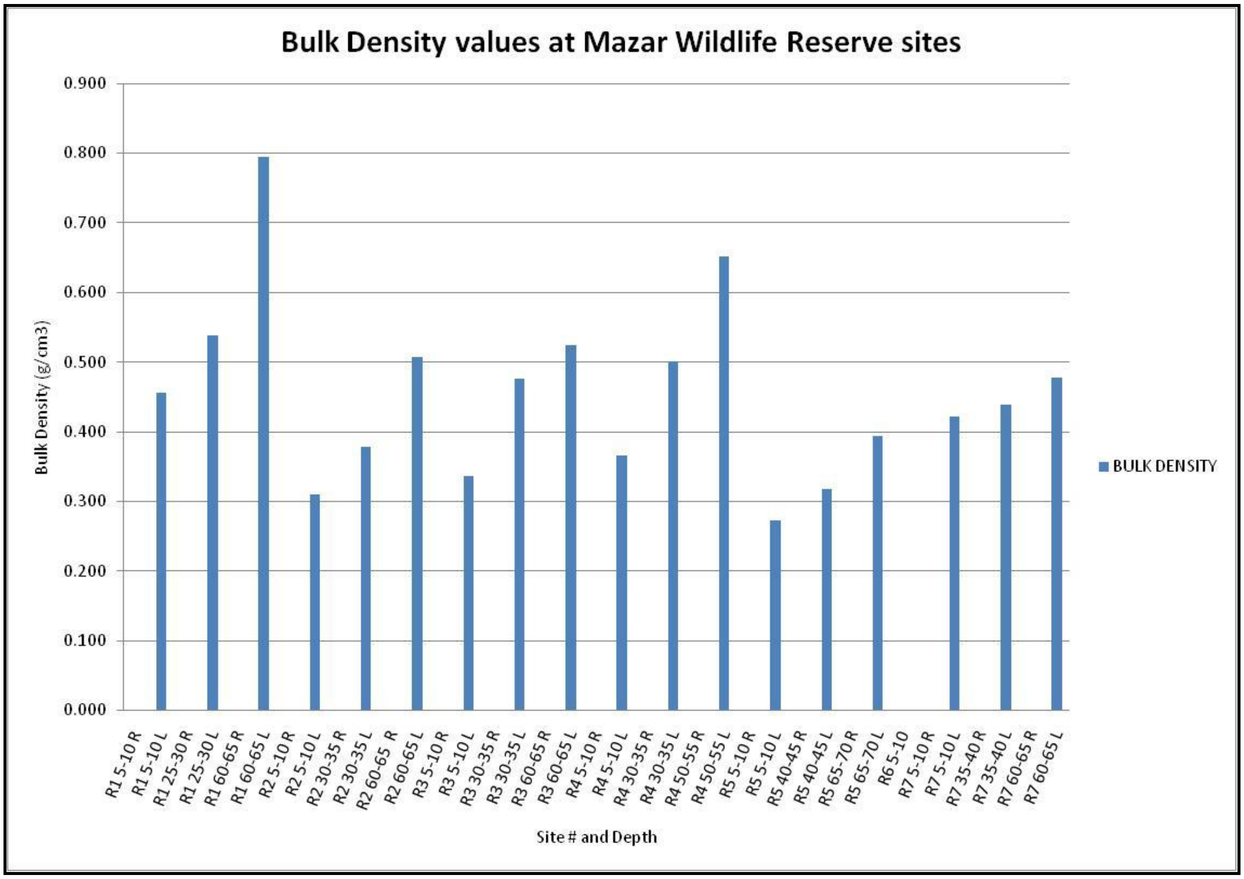
Zuleta Bulk Density Values



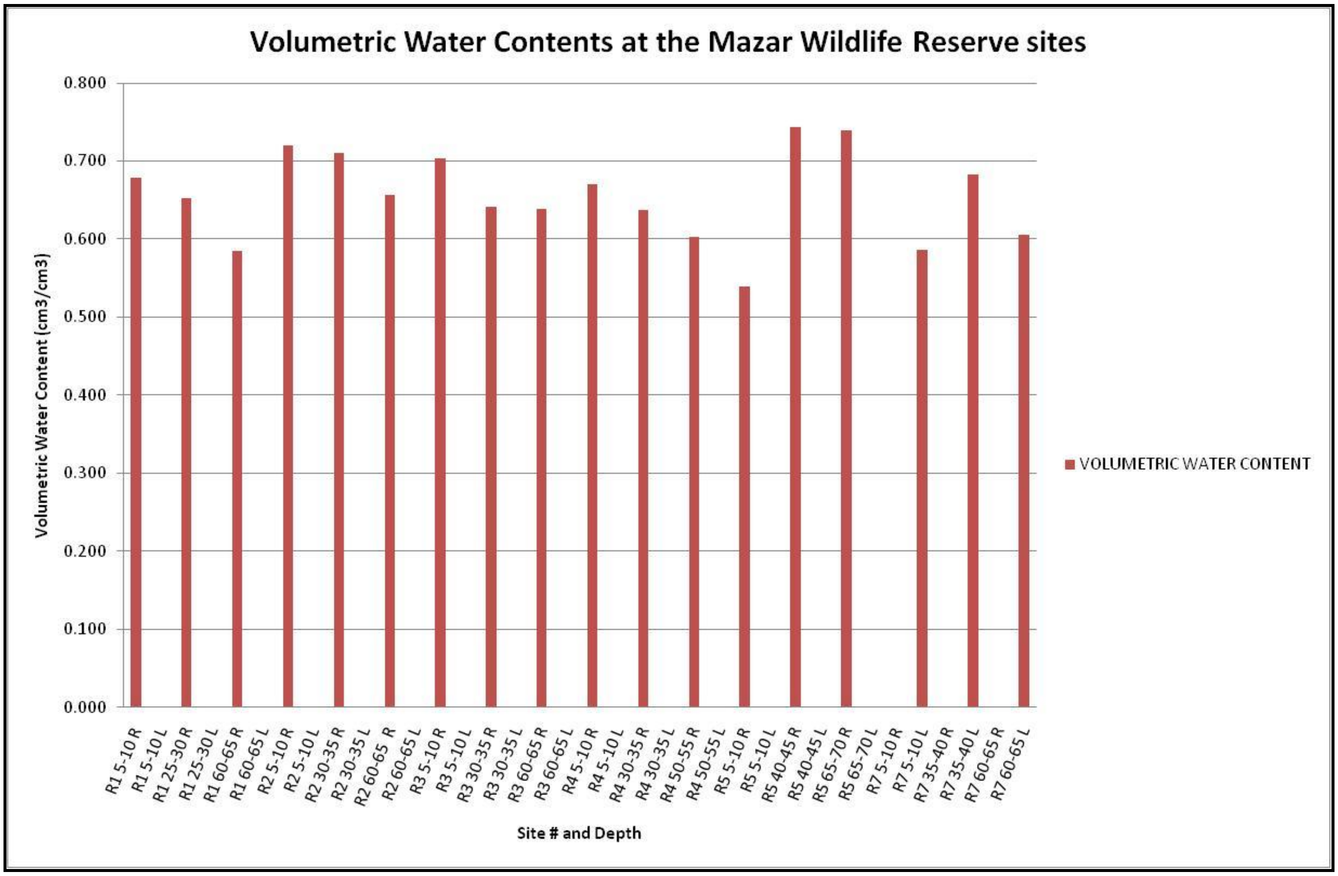
Zuleta Volumetric Water Contents



Mazar Wildlife Reserve Bulk Density Values

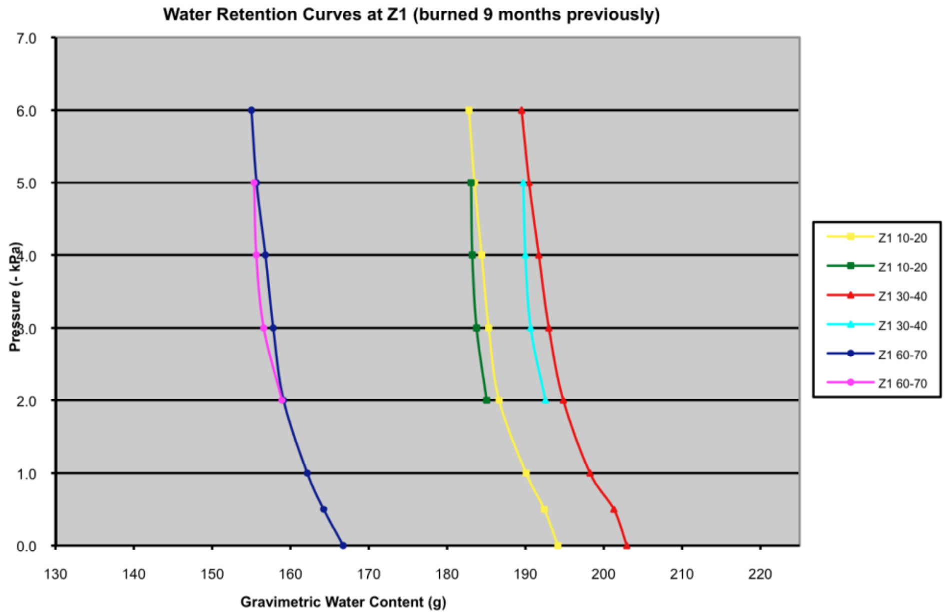


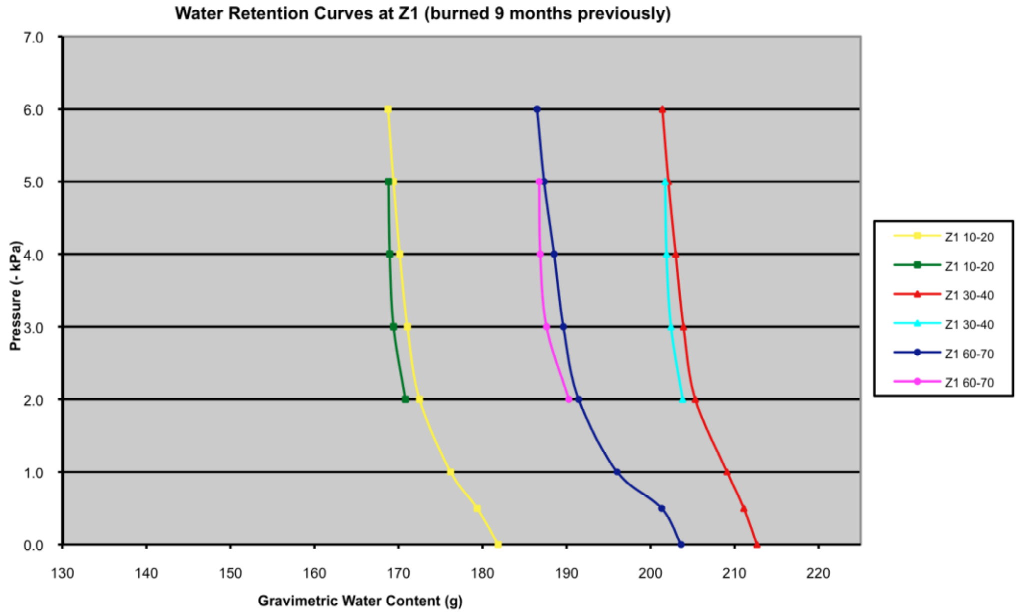
Mazar Wildlife Reserve Volumetric Water Contents



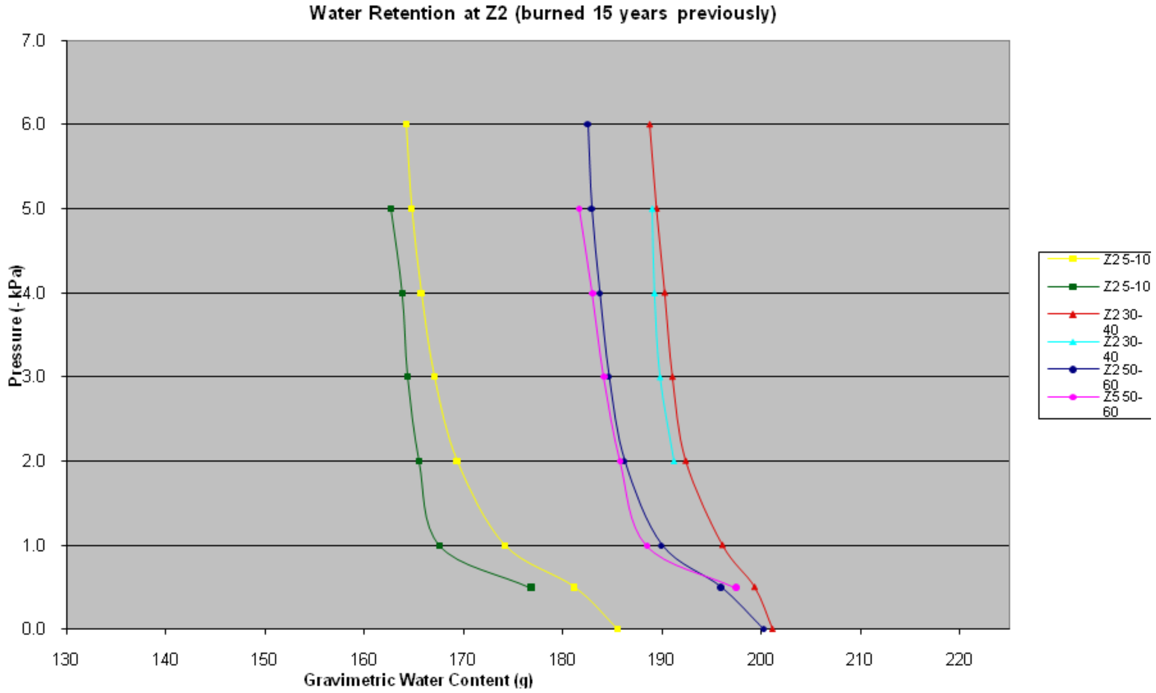
Appendix D: Water–Retention Drying and Rewetting Curves

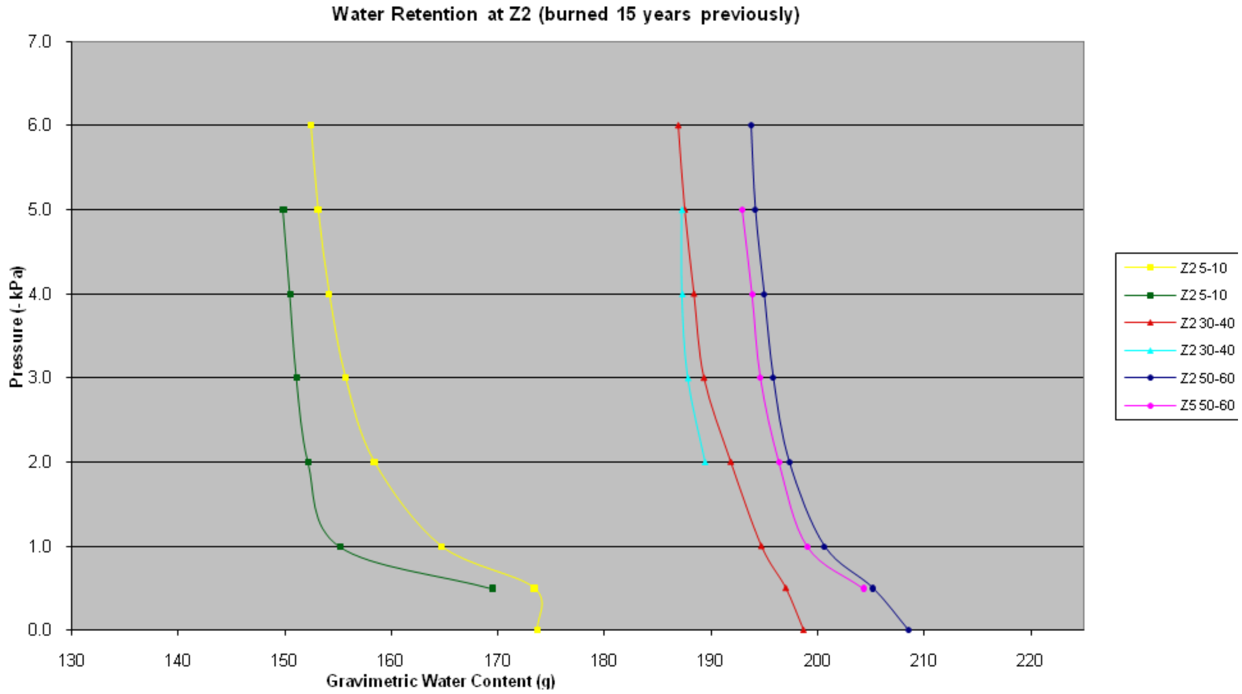
Zuleta Study Area site Z1 (including replicate)



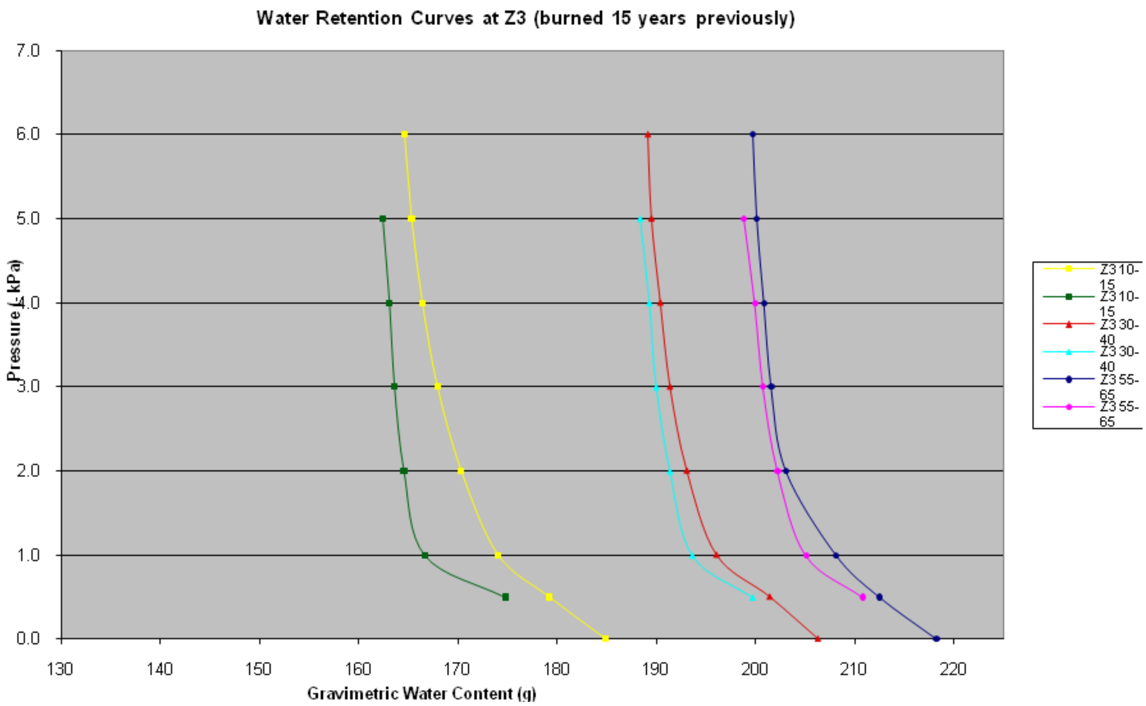


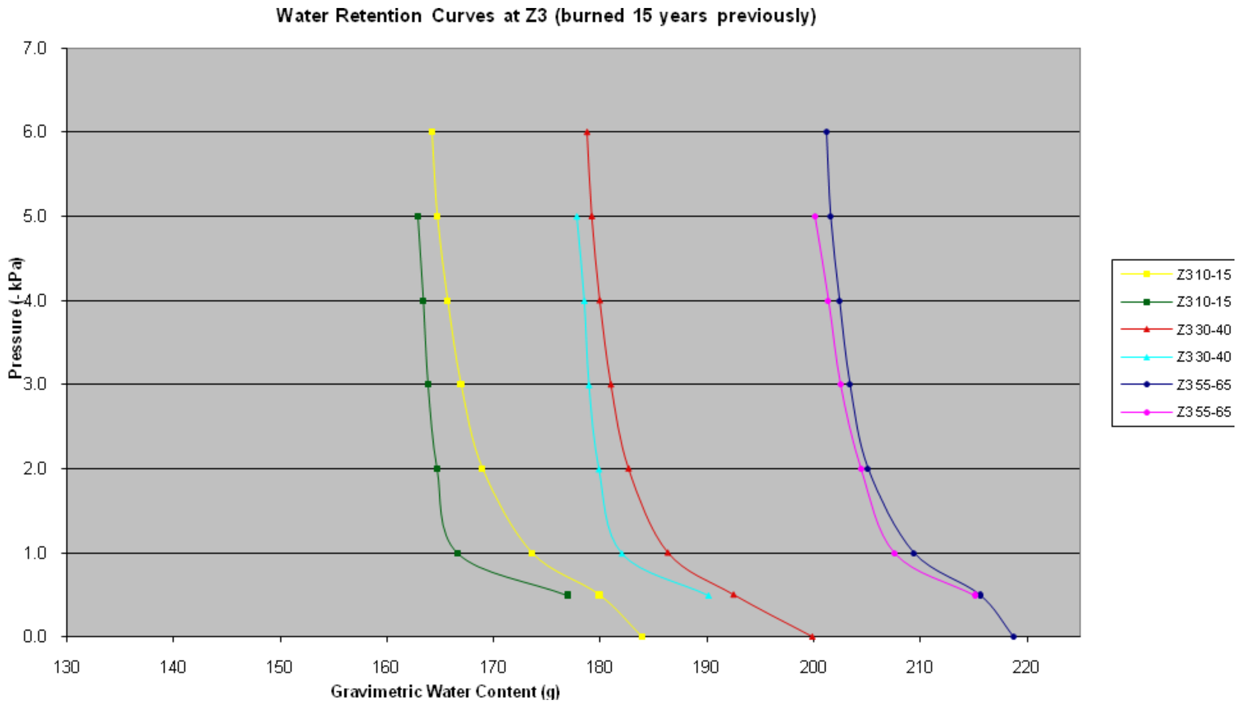
Zuleta Study Area site Z2 (including replicate)



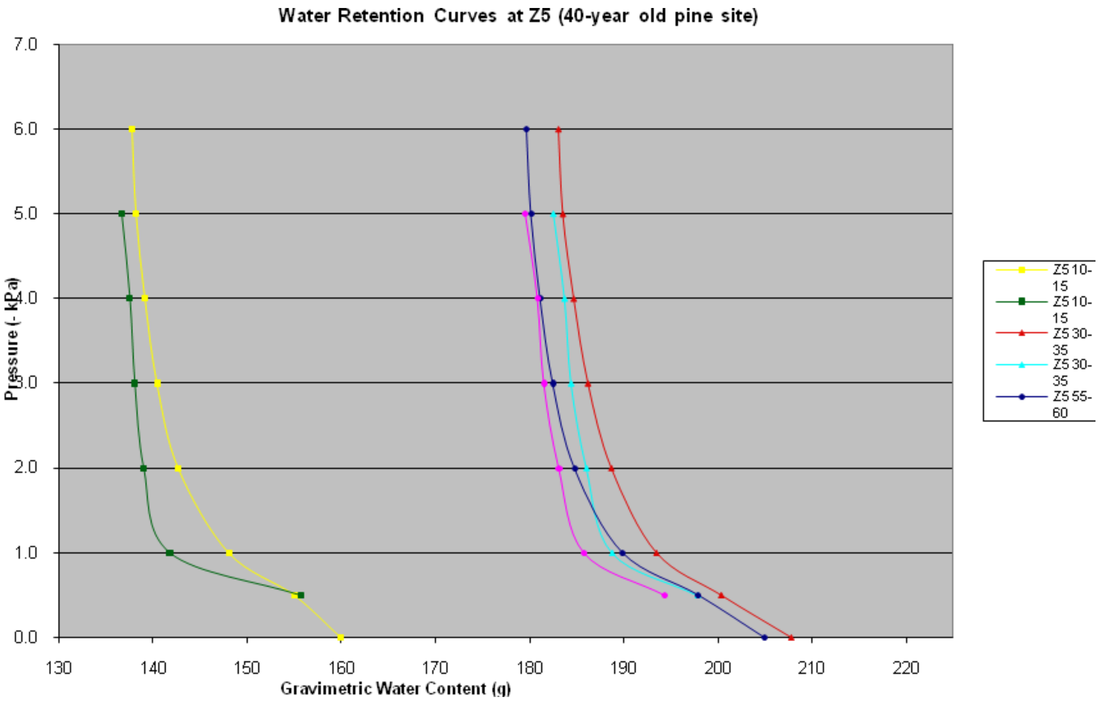


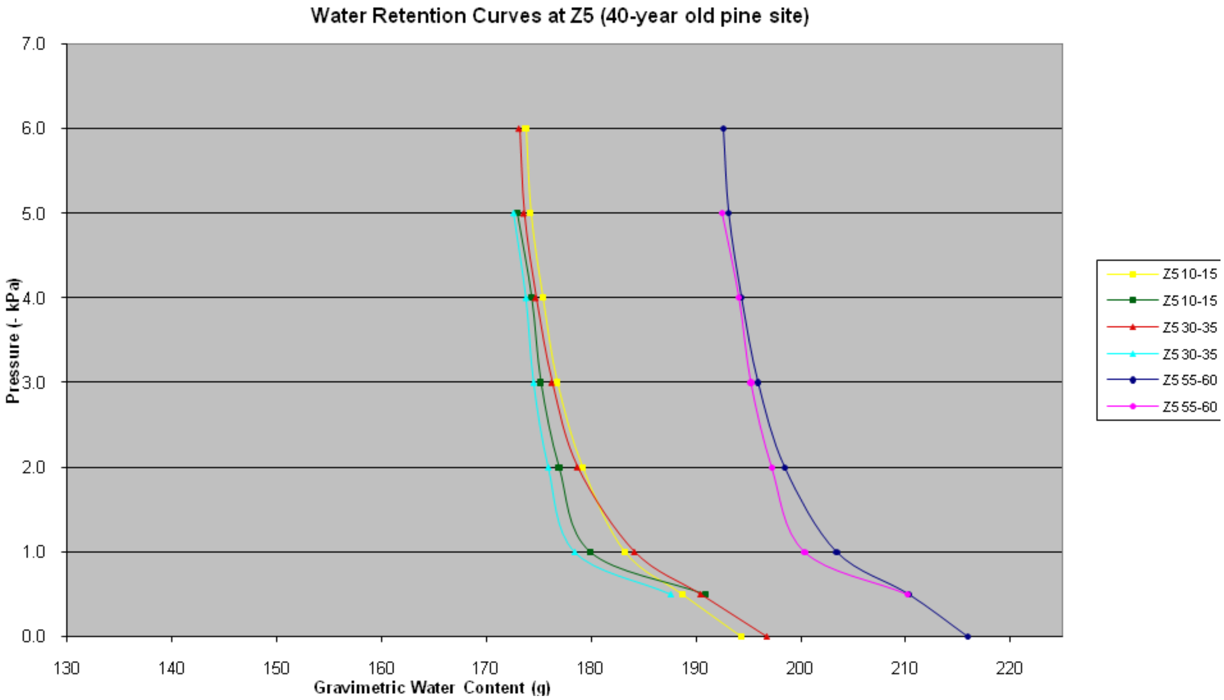
Zuleta Study Area site Z3(including replicate)



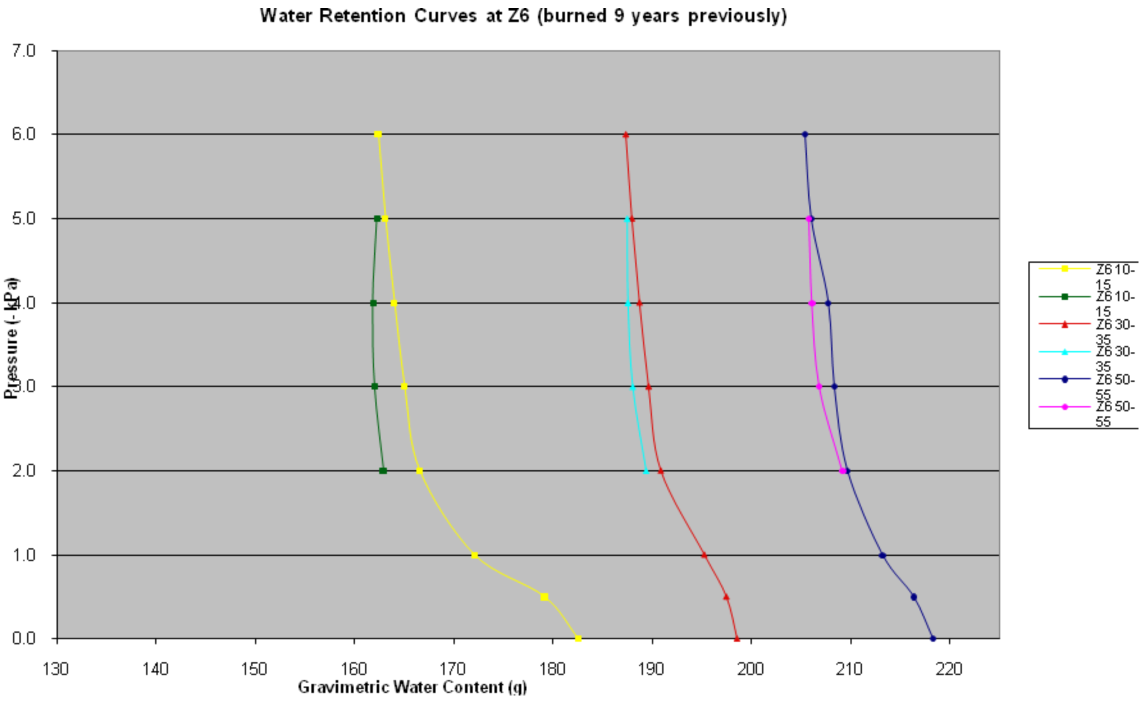


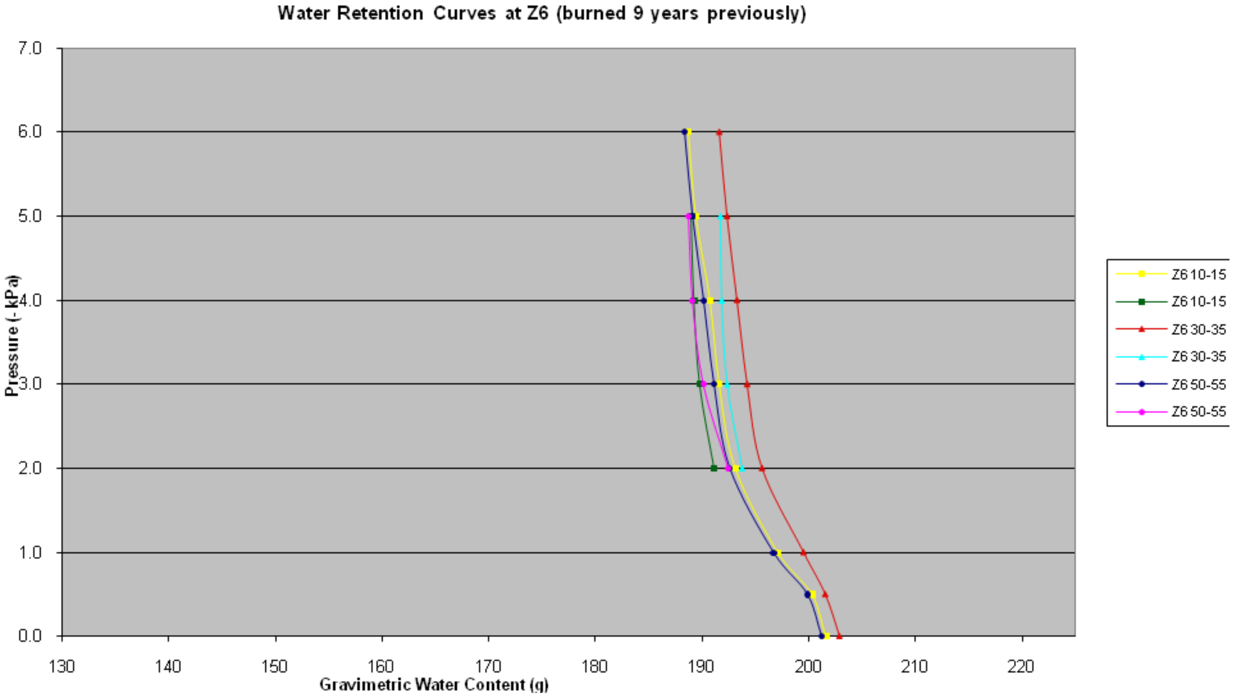
Zuleta Study Area site Z5 (including replicate)



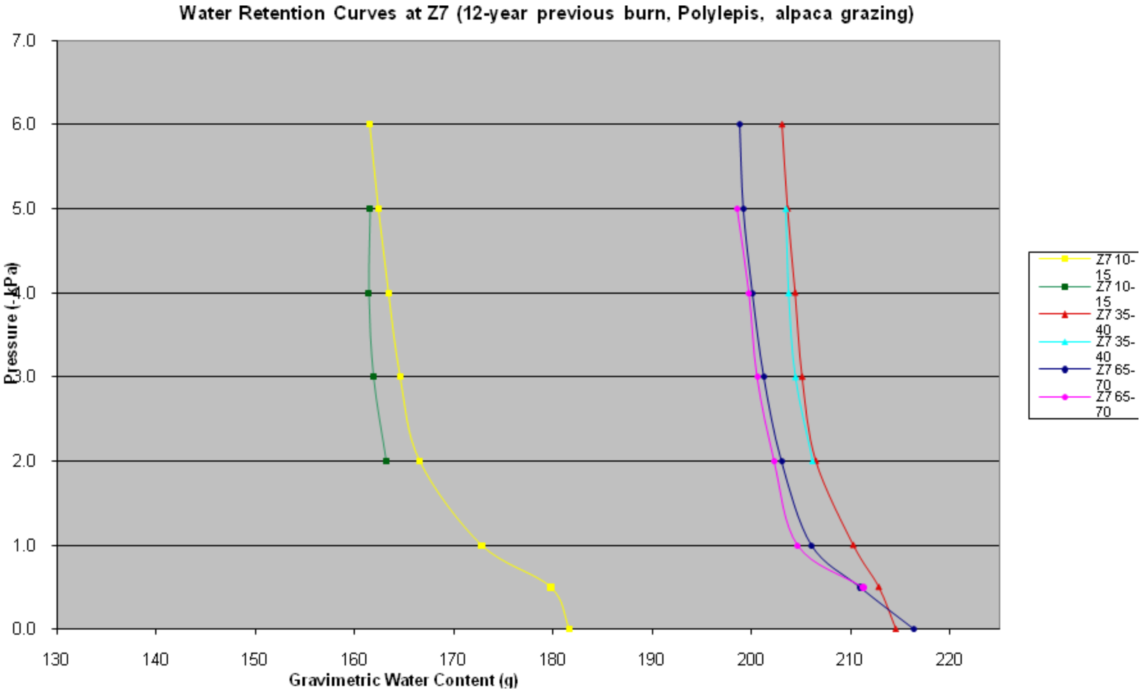


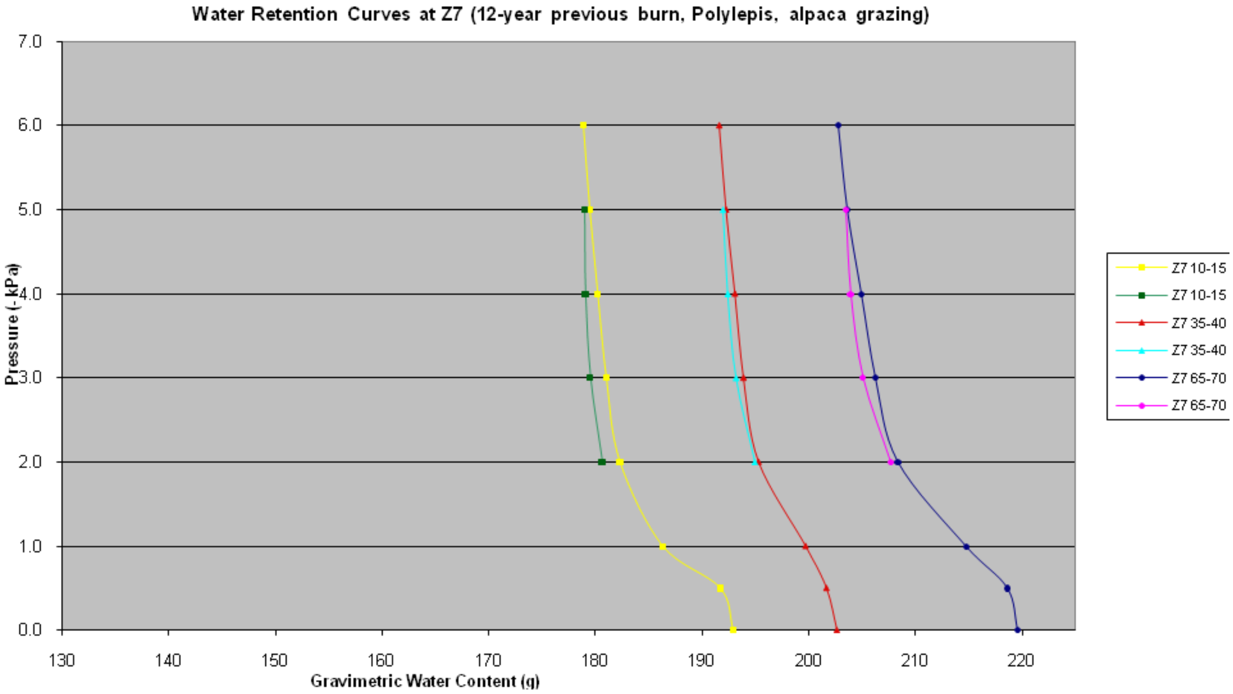
Zuleta Study Area site Z6 (including replicate)



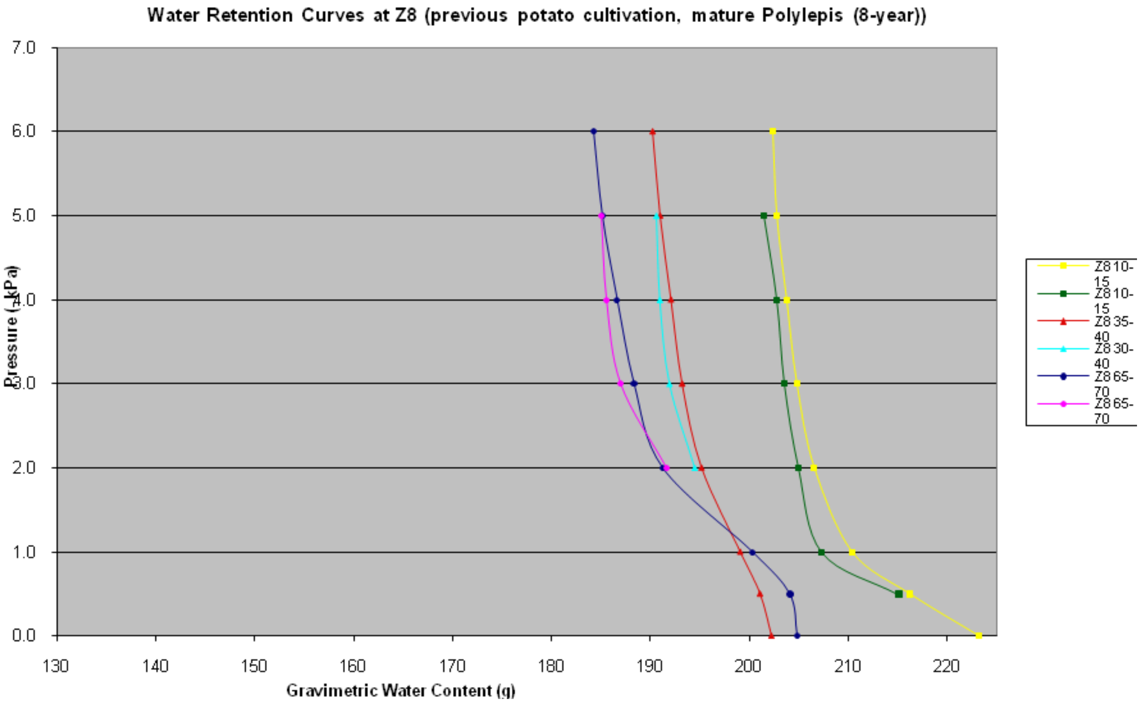


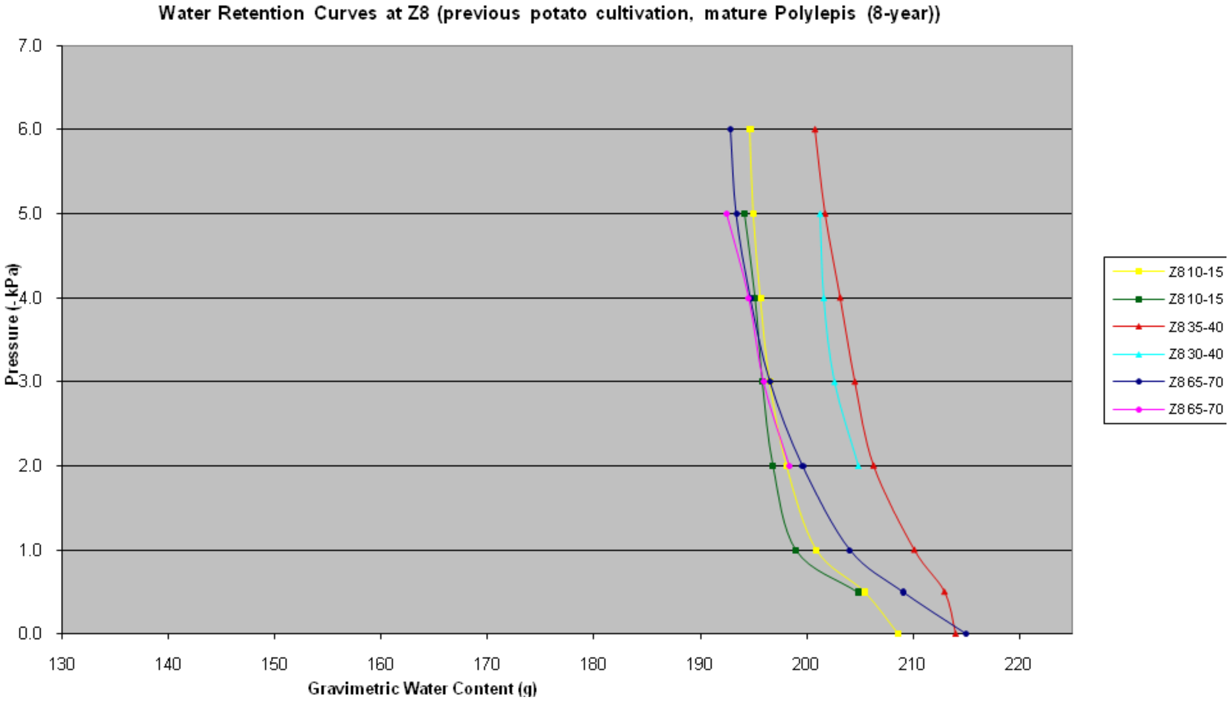
Zuleta Study Area site Z7 (including replicate)



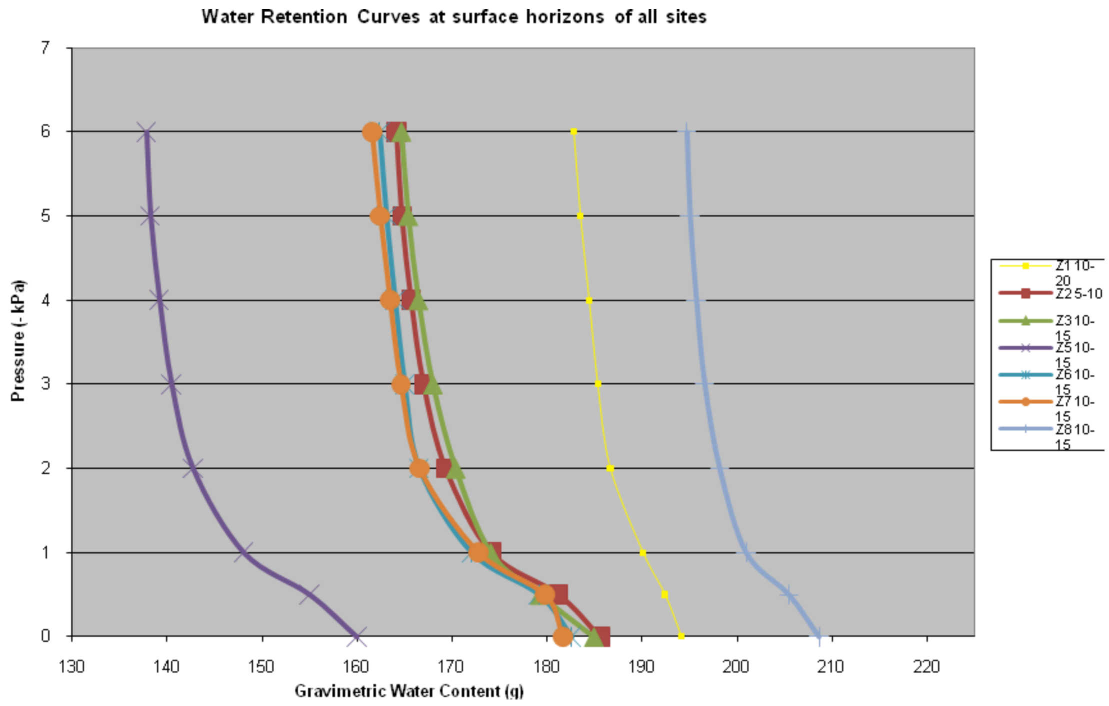


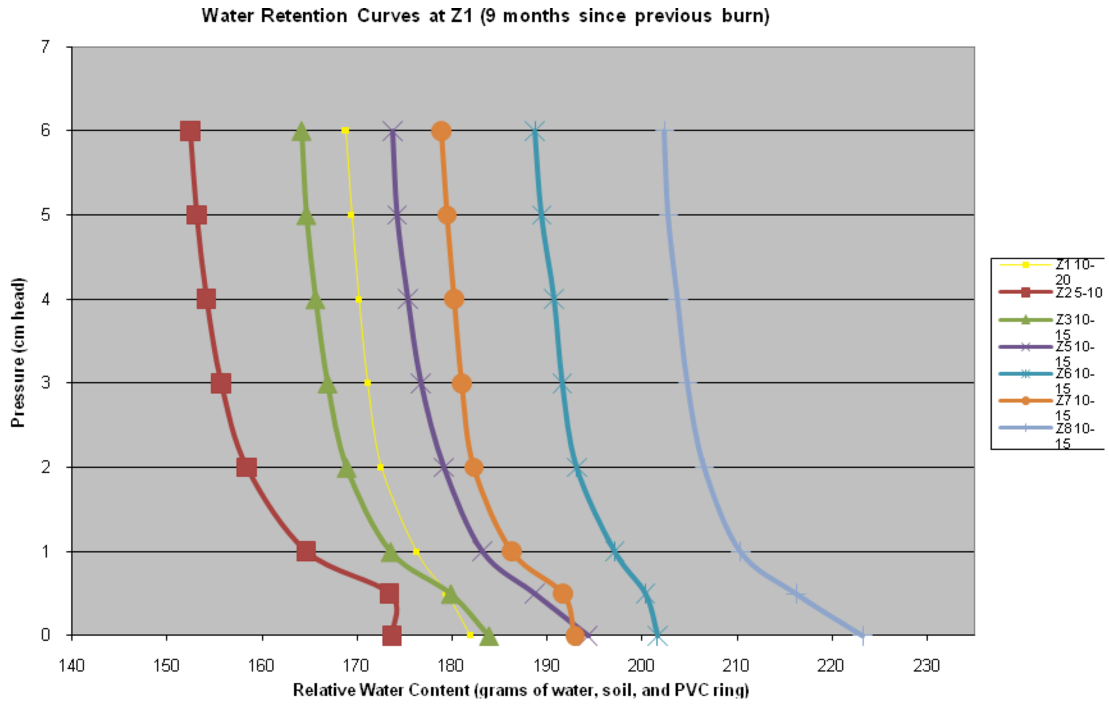
Zuleta Study Area site Z8 (including replicate)



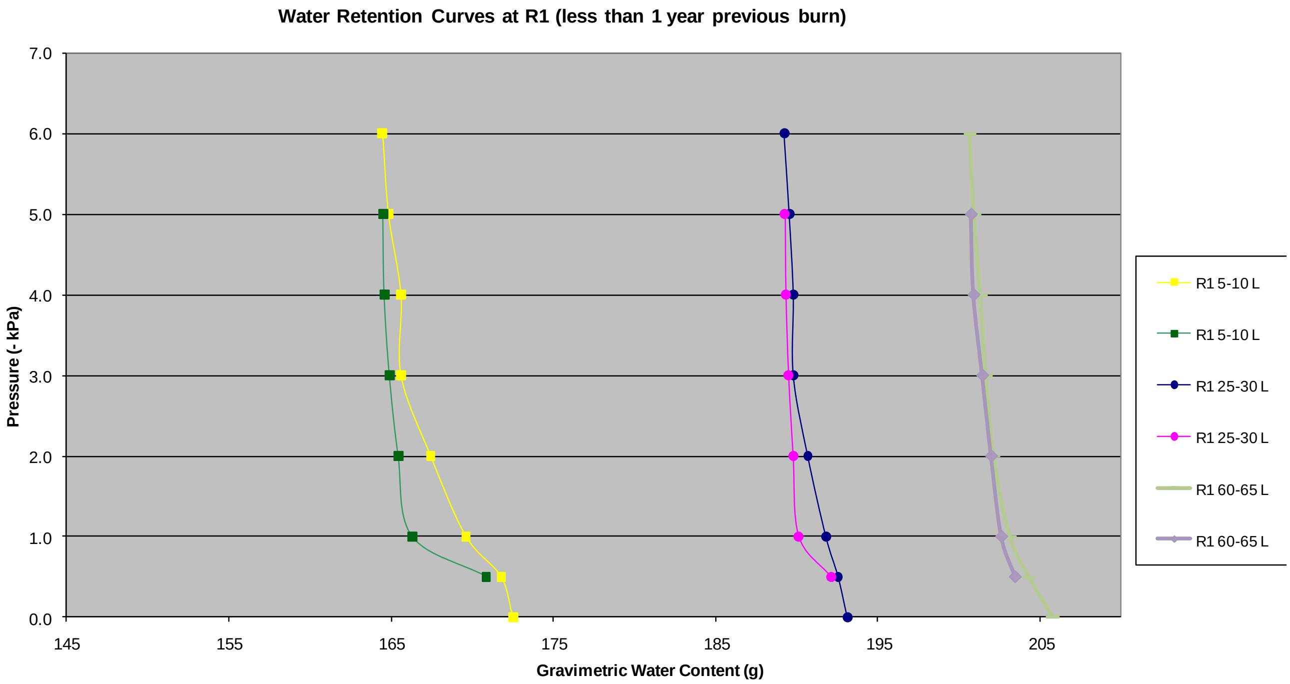


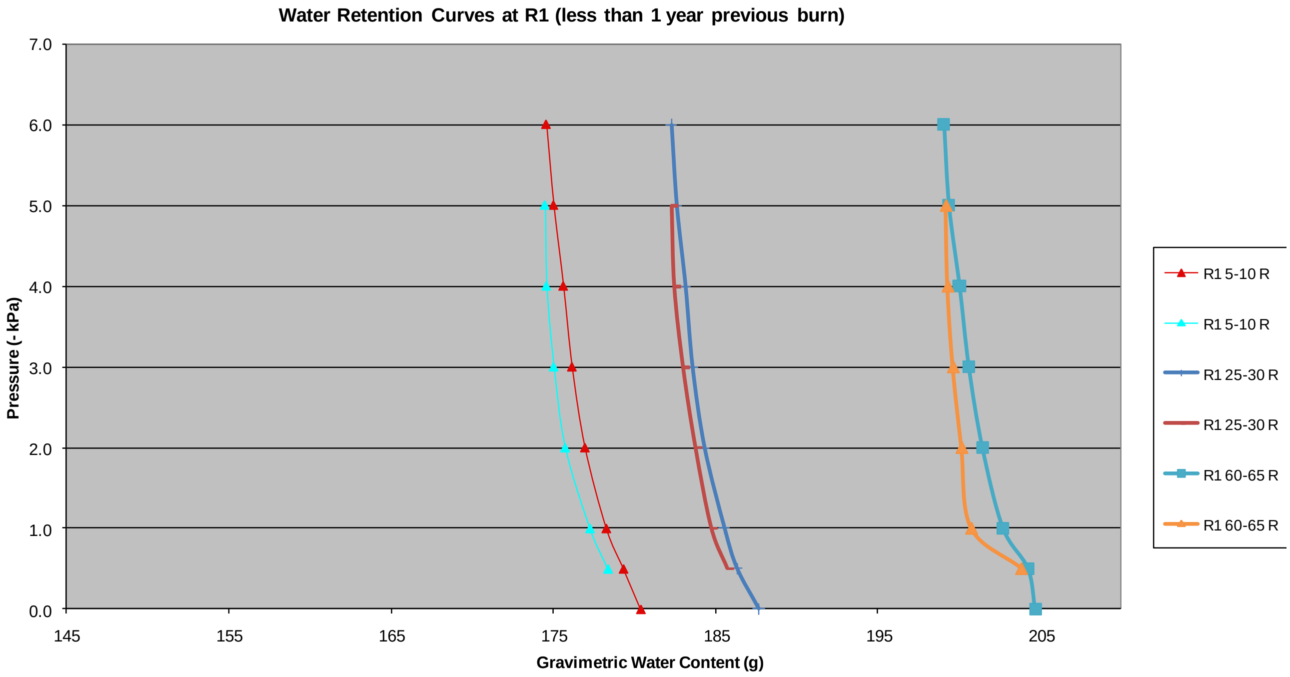
Zuleta Study Area surface horizon WRC from all sites (including replicate)



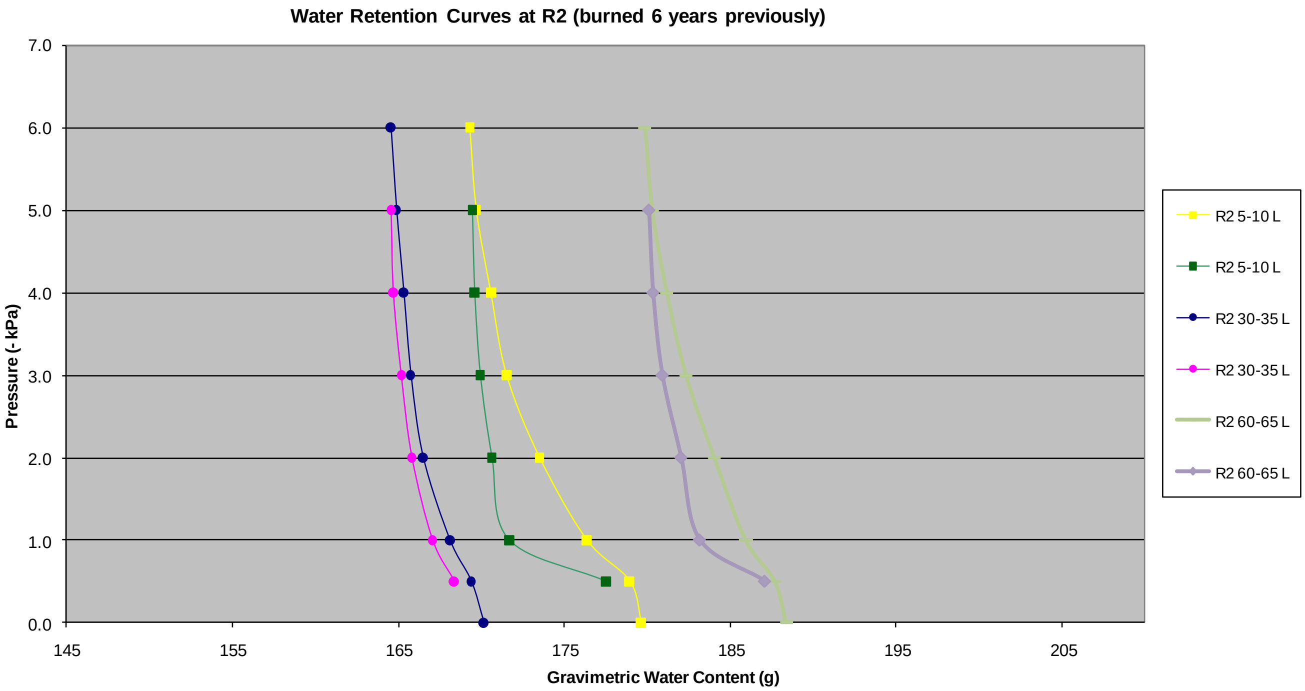


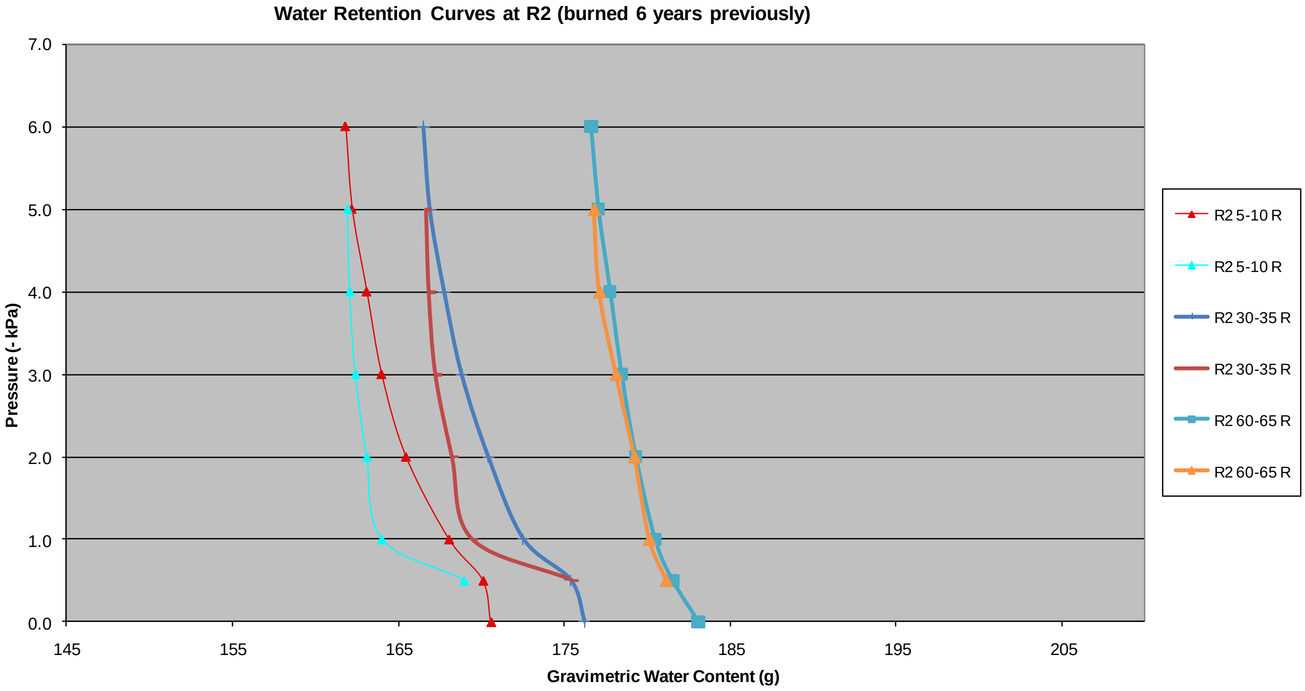
Mazar Wildlife Reserve Study Area site R1 (including replicate)



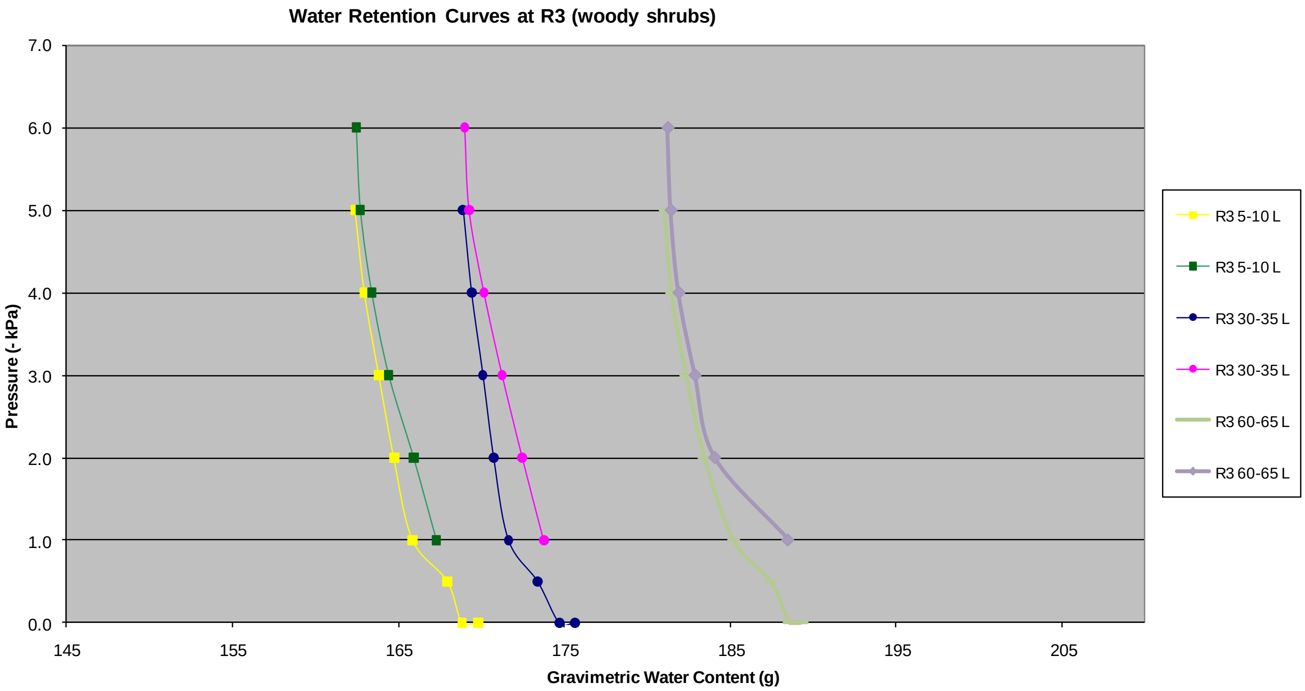


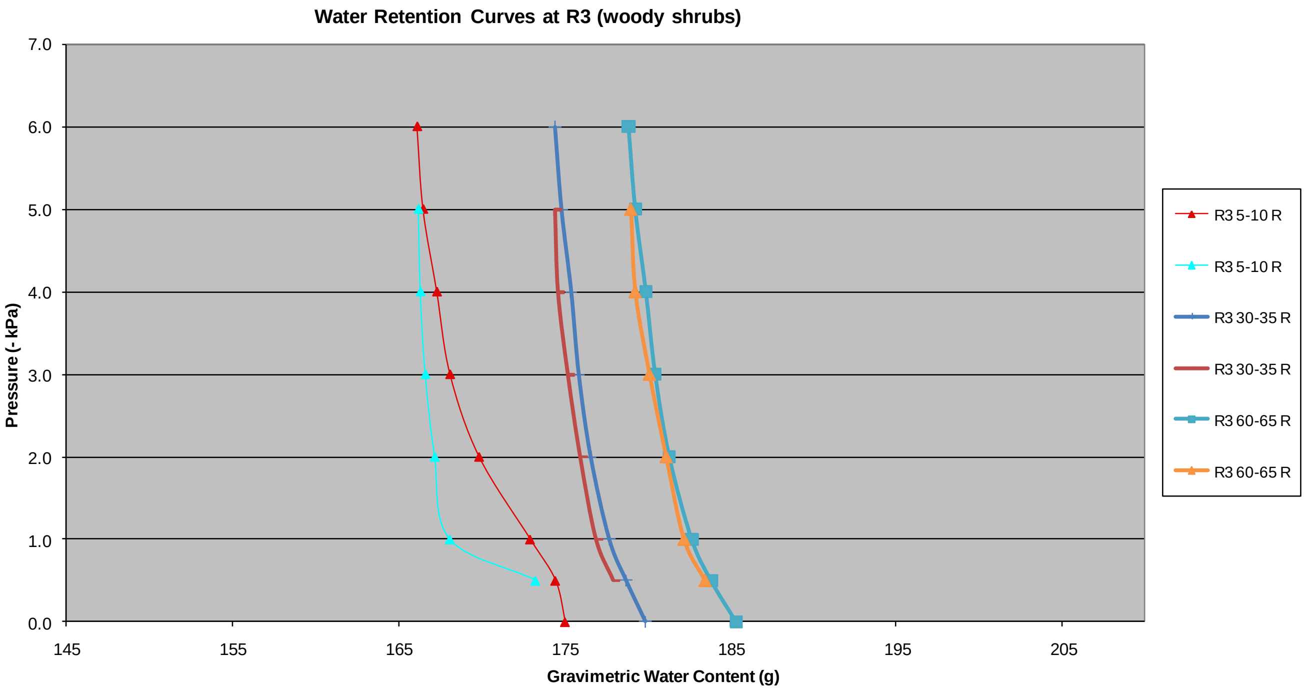
Mazar Wildlife Reserve Study Area site R2 (including replicate)



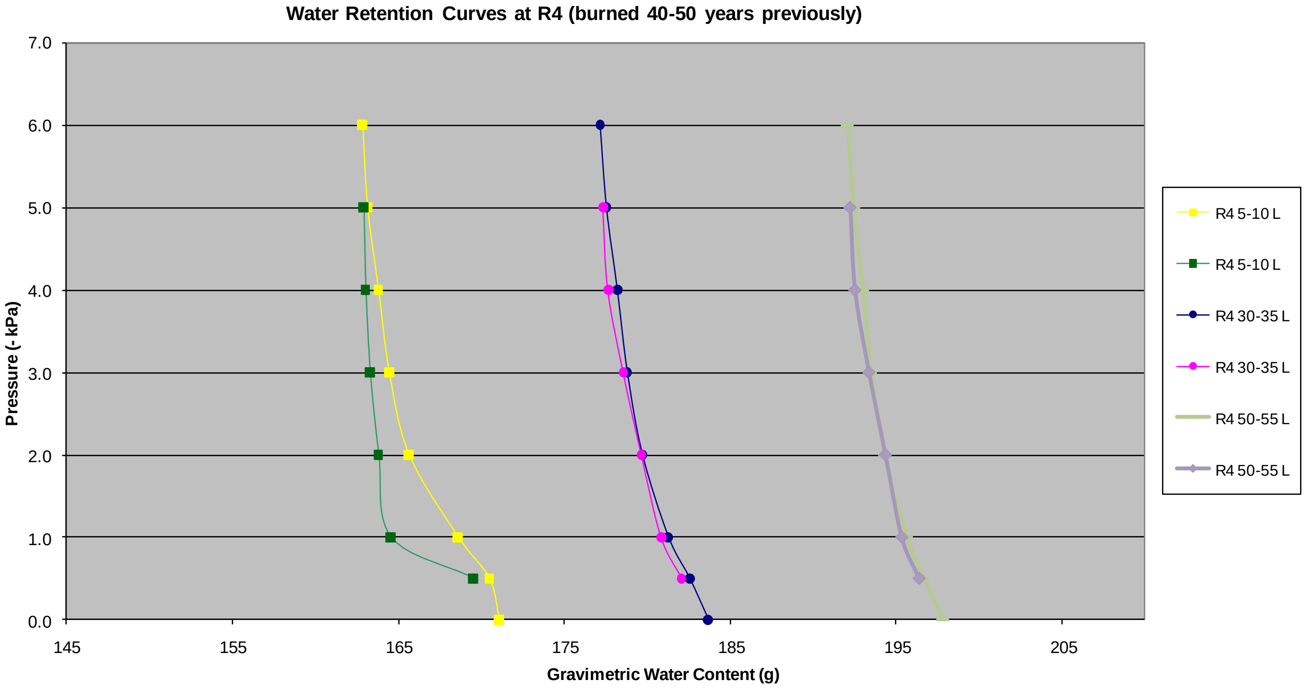


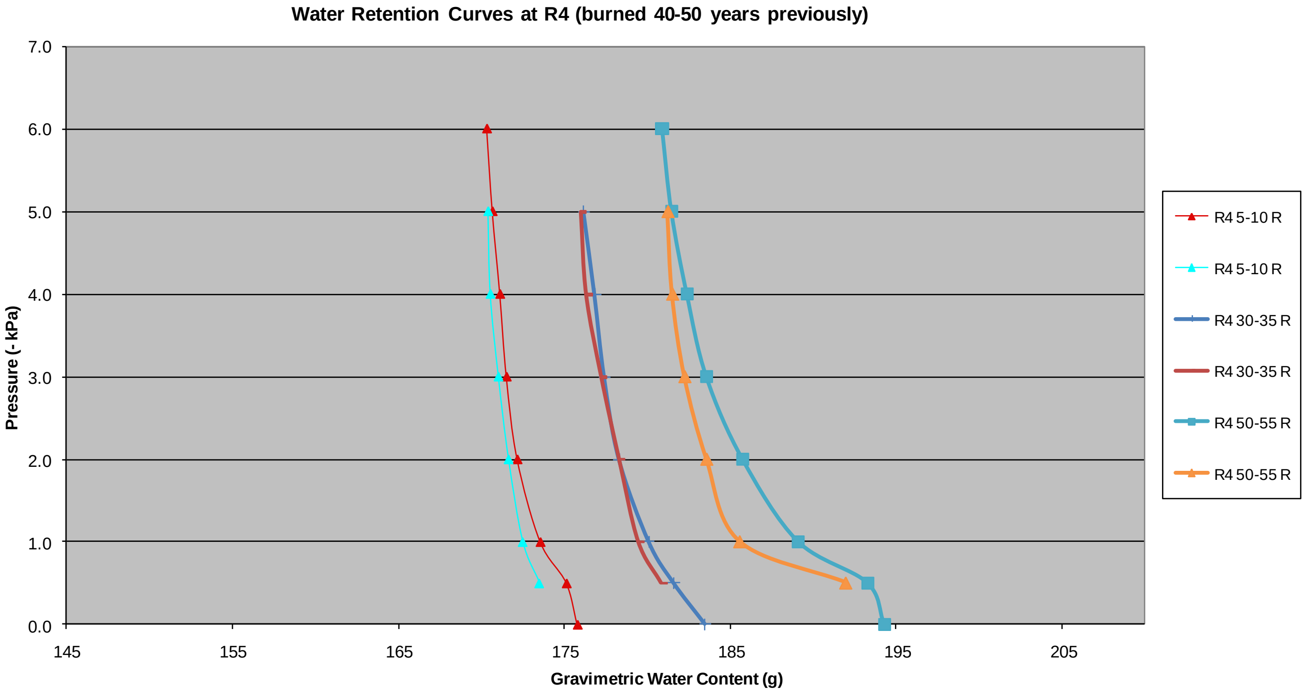
Mazar Wildlife Reserve Study Area site R3 (including replicate)



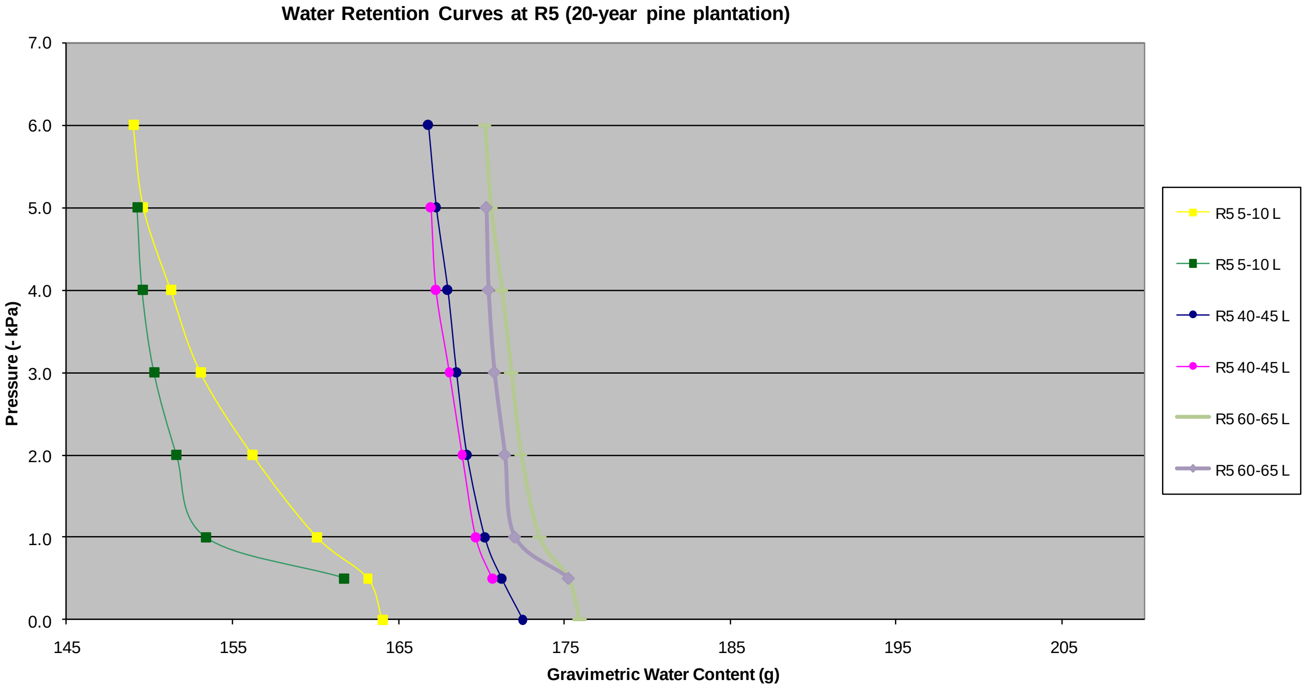


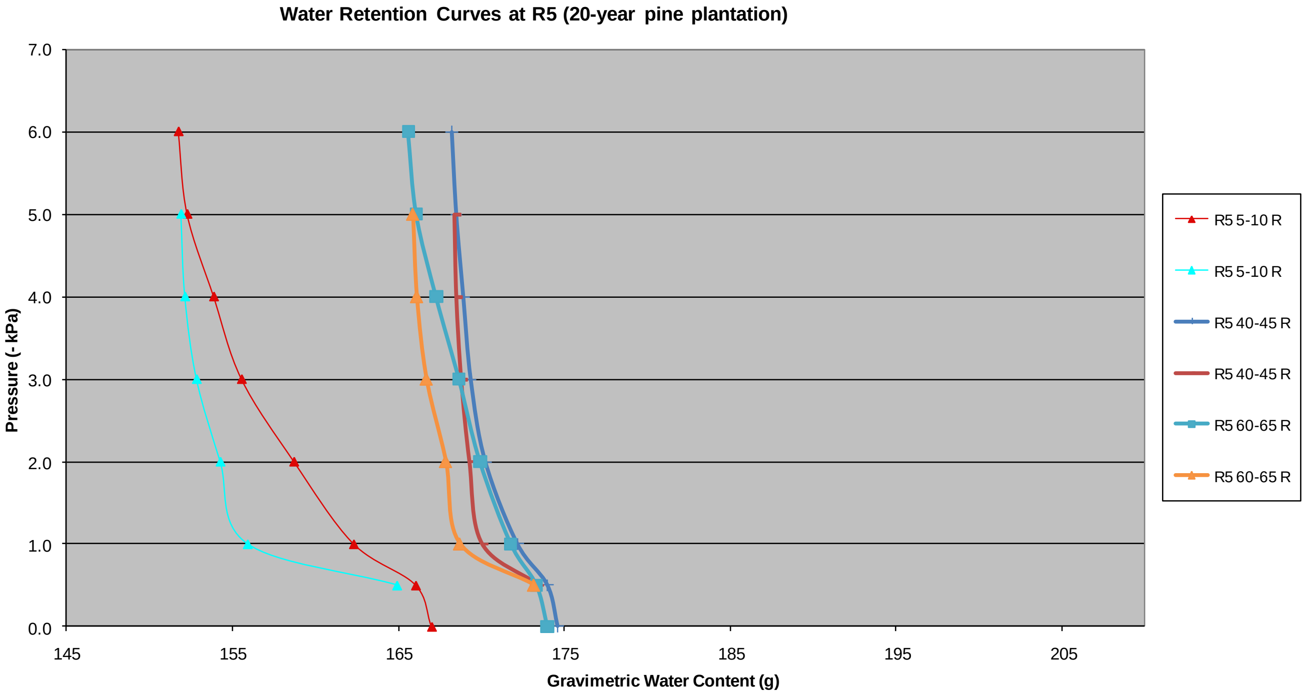
Mazar Wildlife Reserve Study Area site R4 (including replicate)



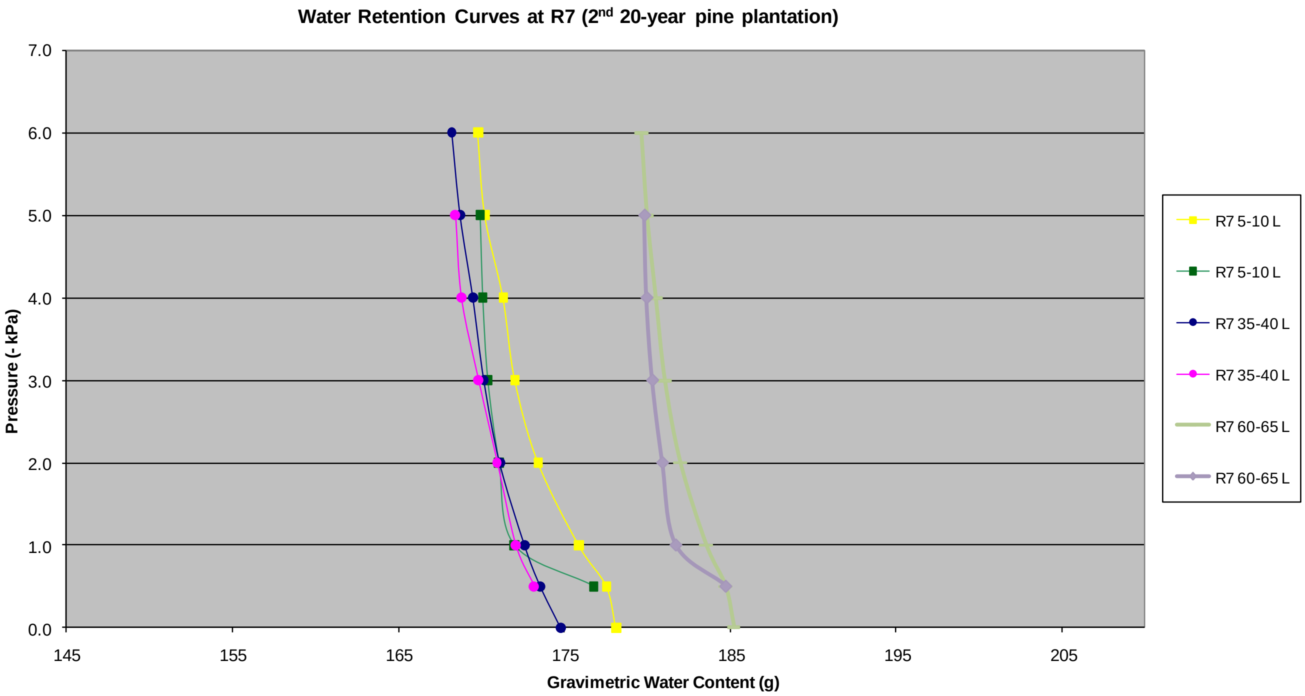


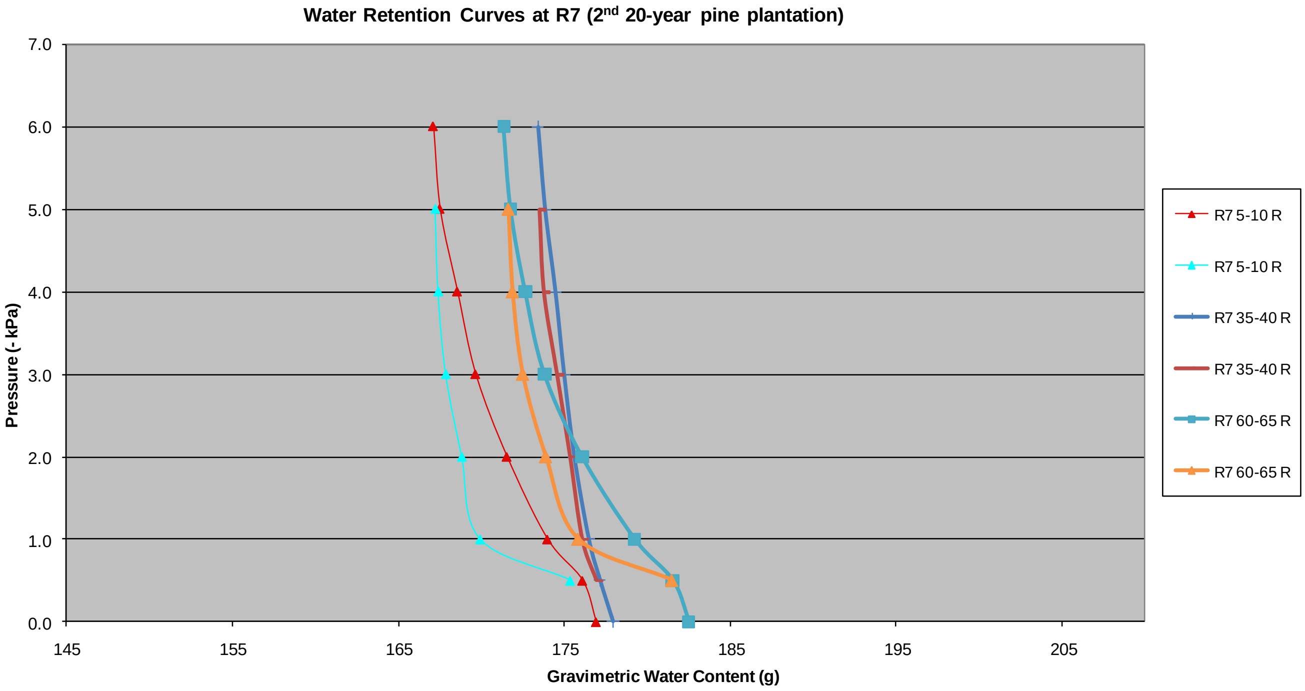
Mazar Wildlife Reserve Study Area site R5 (including replicate)



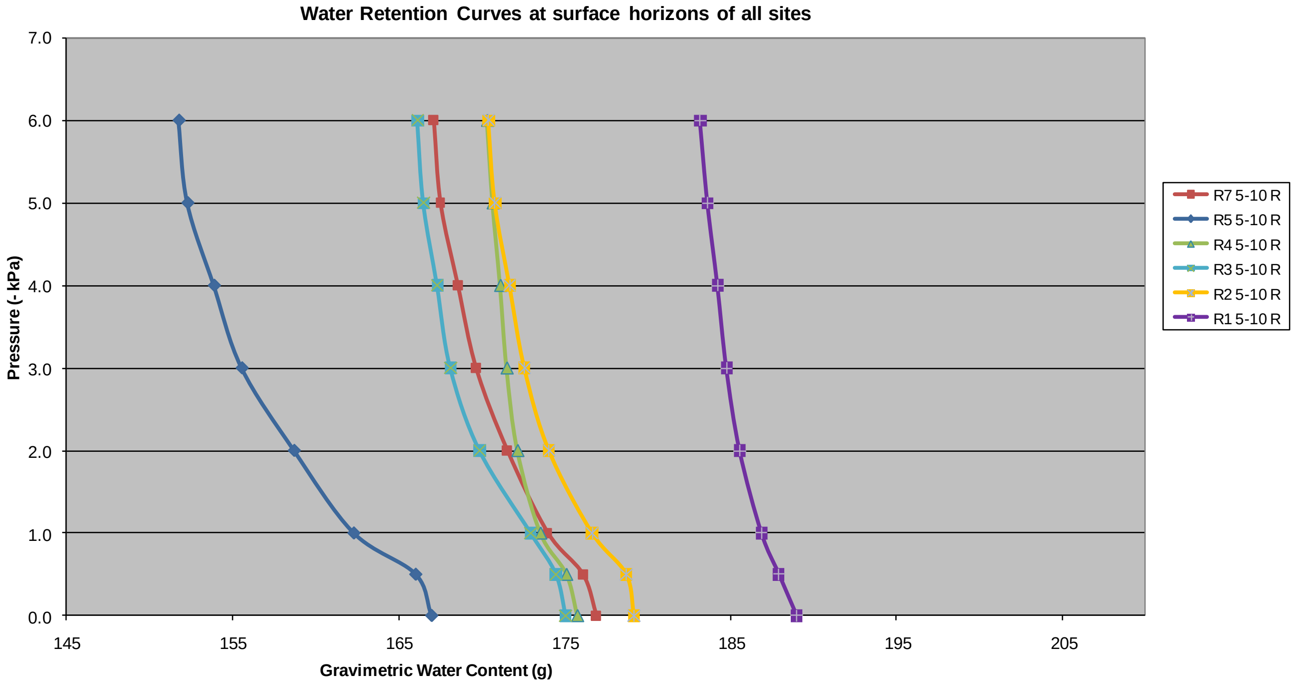


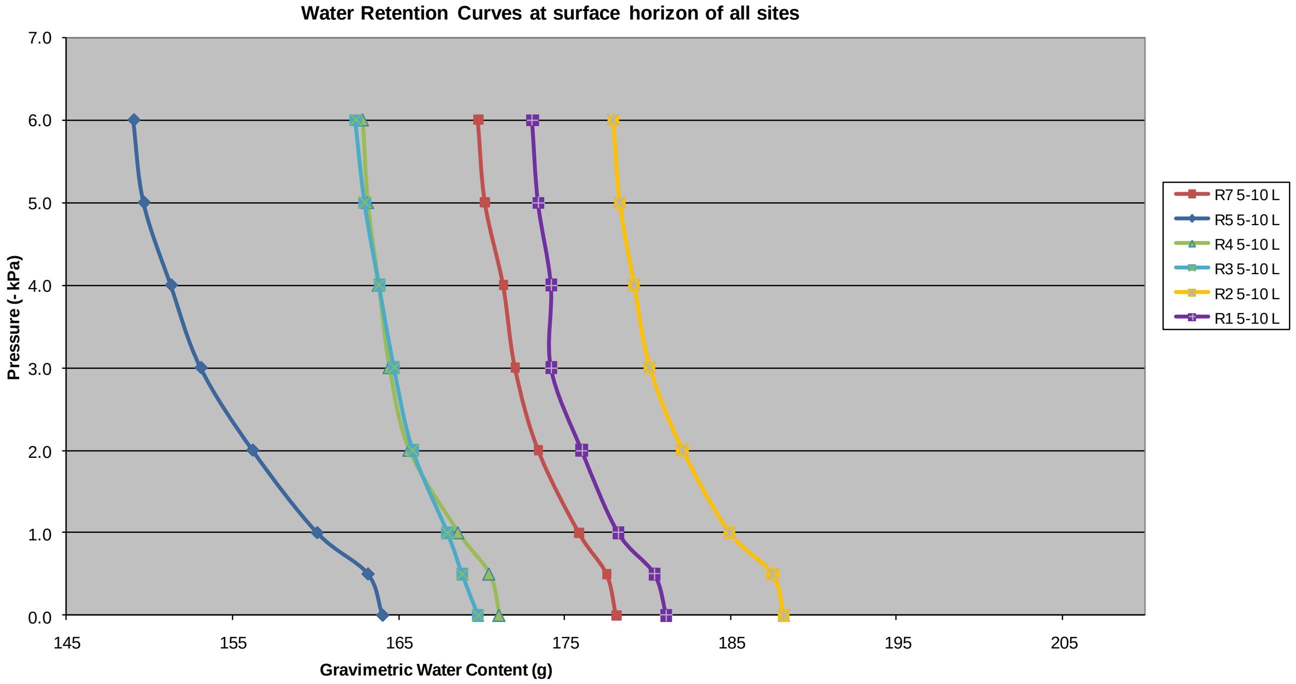
Mazar Wildlife Reserve Study Area site R7 (including replicate)



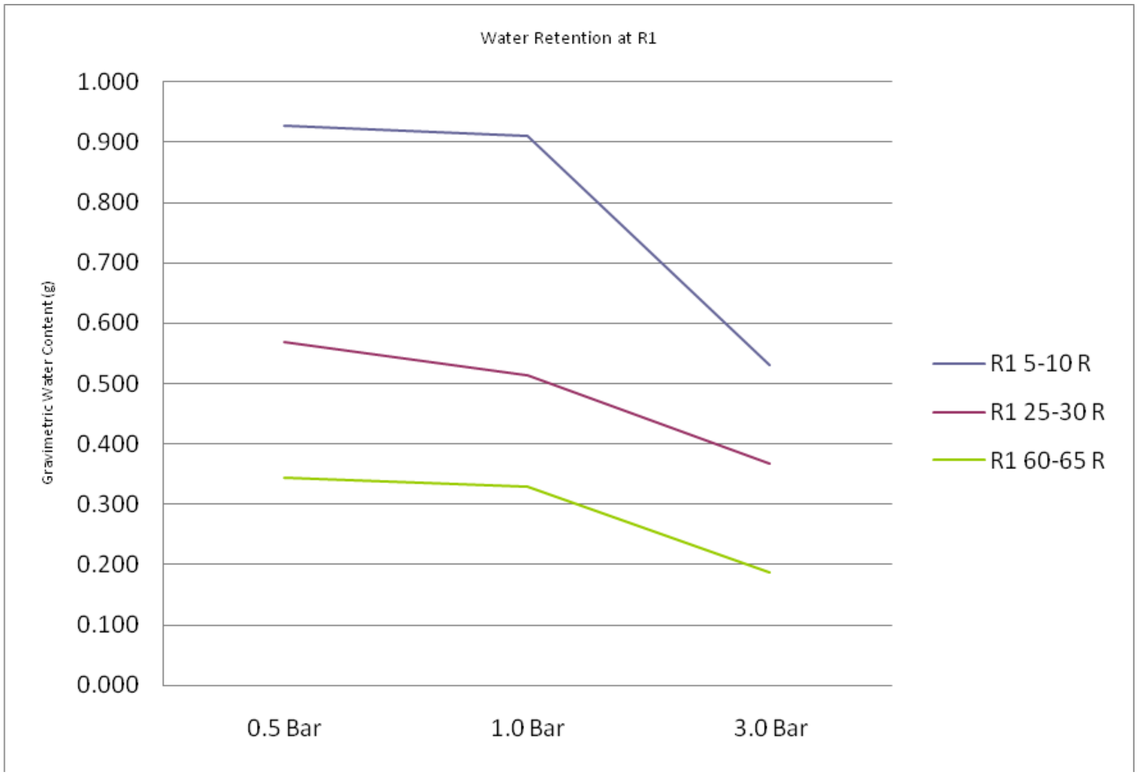


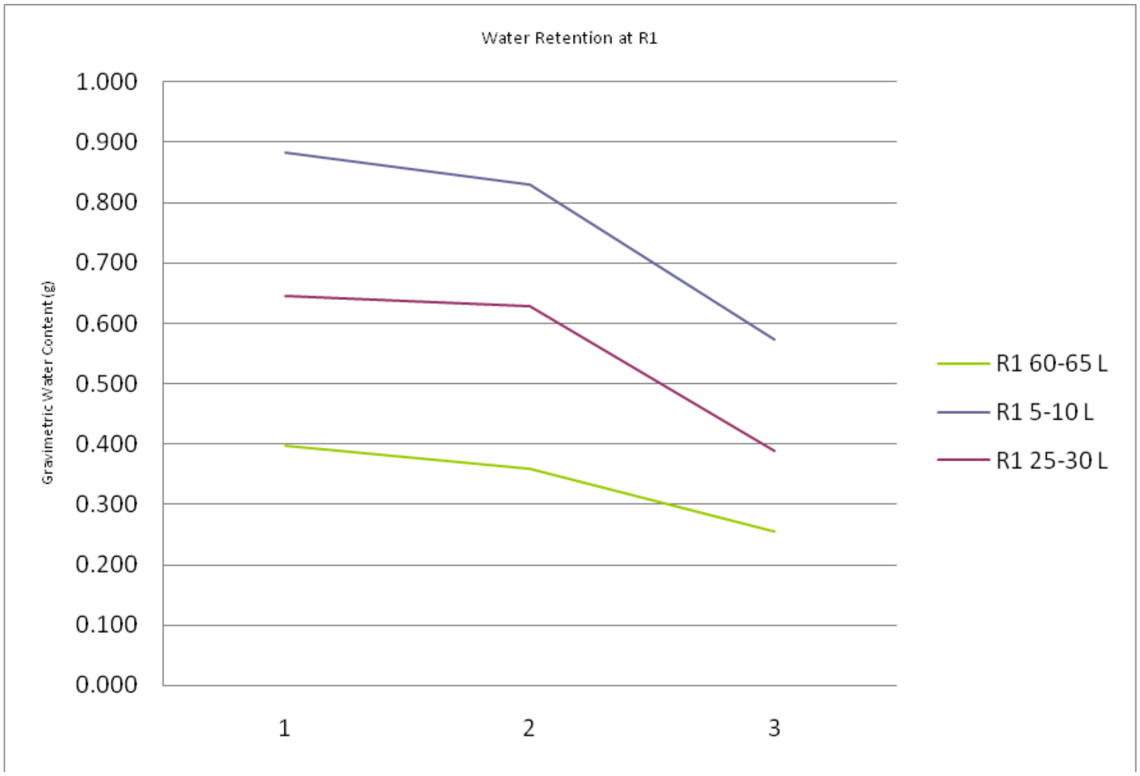
Mazar Wildlife Reserve Study Area surface horizon WRC from all sites (including replicate)



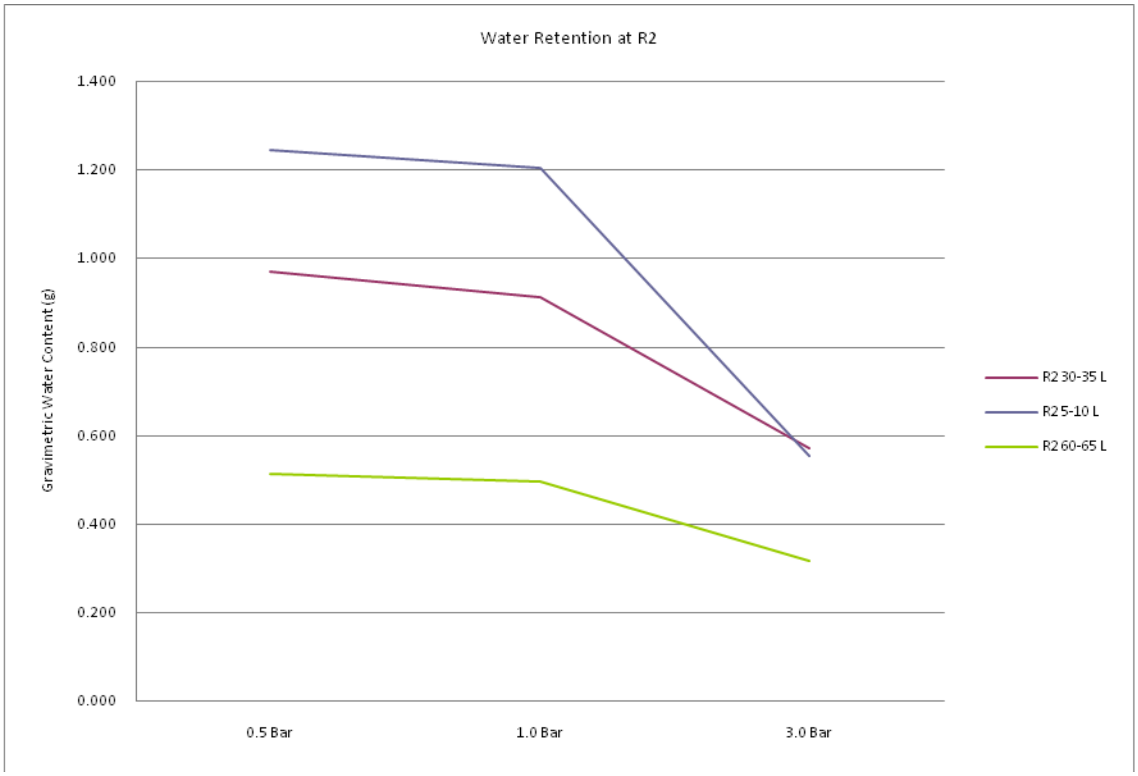


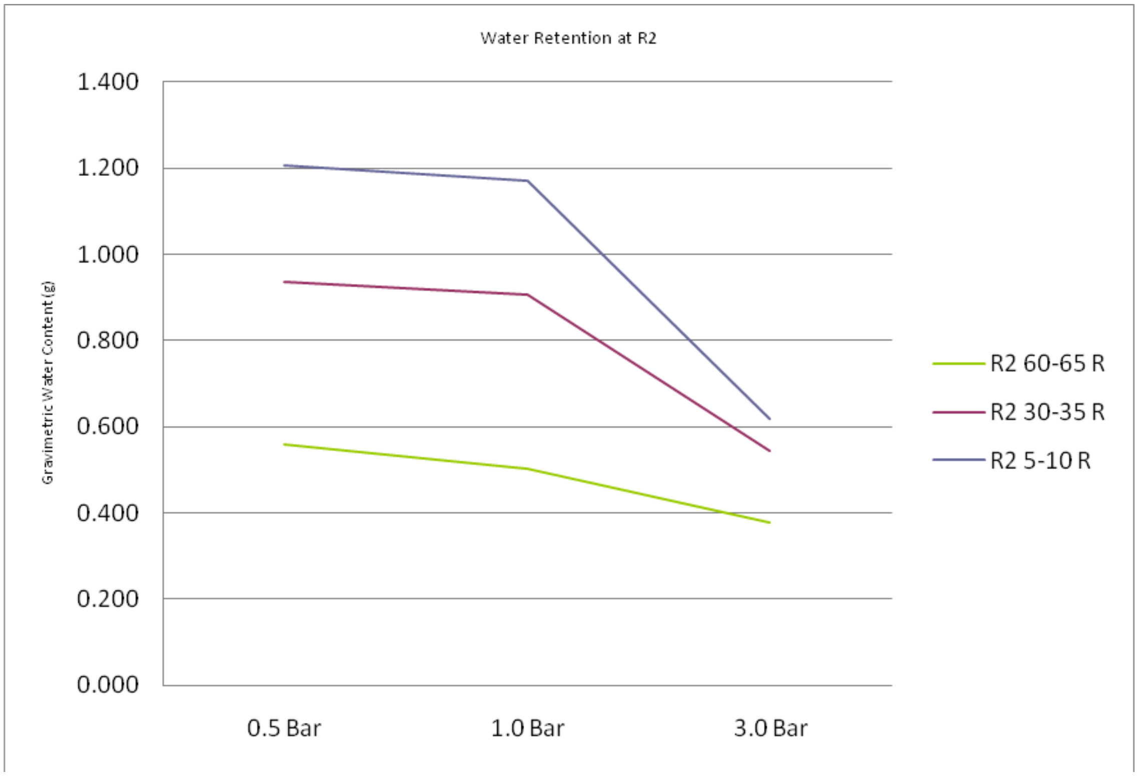
Water Retention at Lower Tensions for the Mazar Wildlife Reserve study area (in bars) (including replicate)



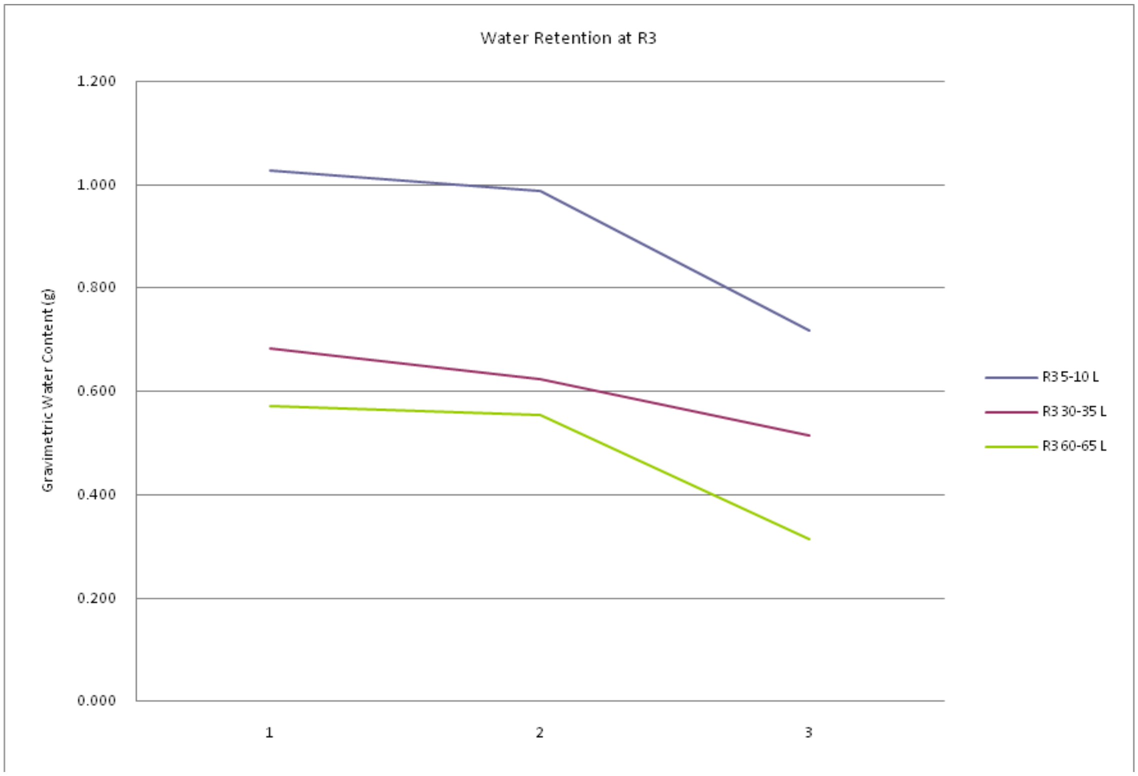


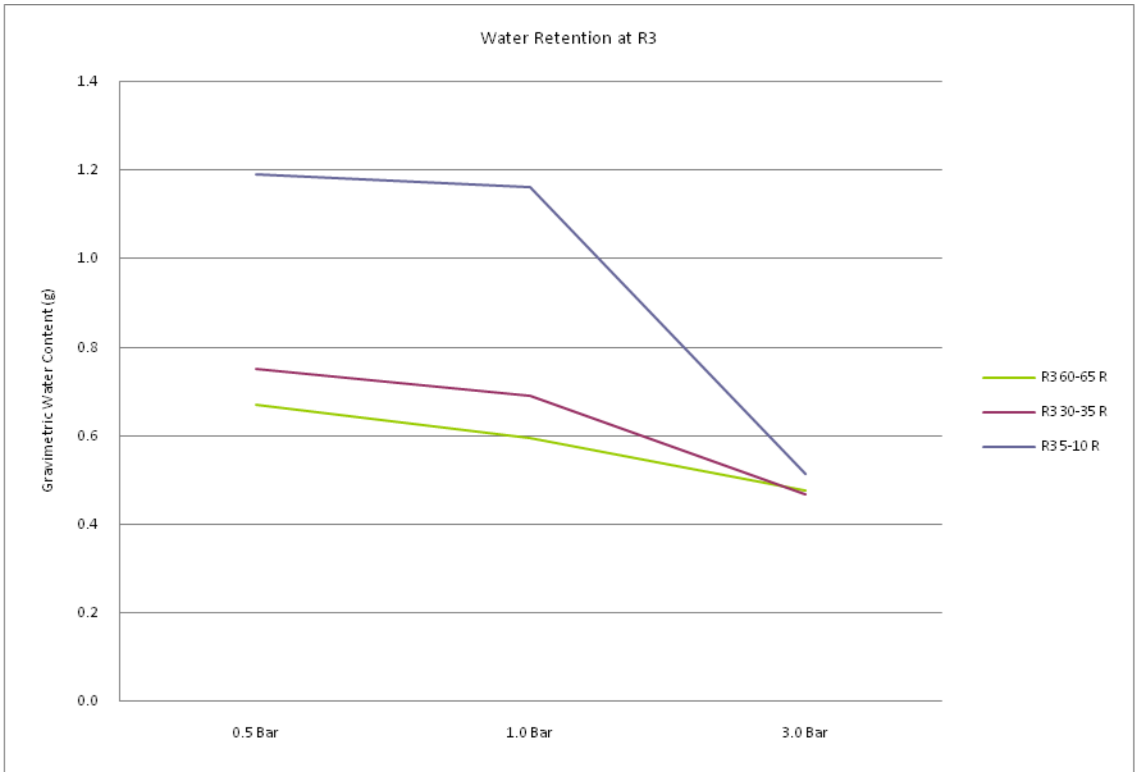
Water Retention at Lower Tensions for the Mazar Wildlife Reserve study area (in bars) (including replicate)



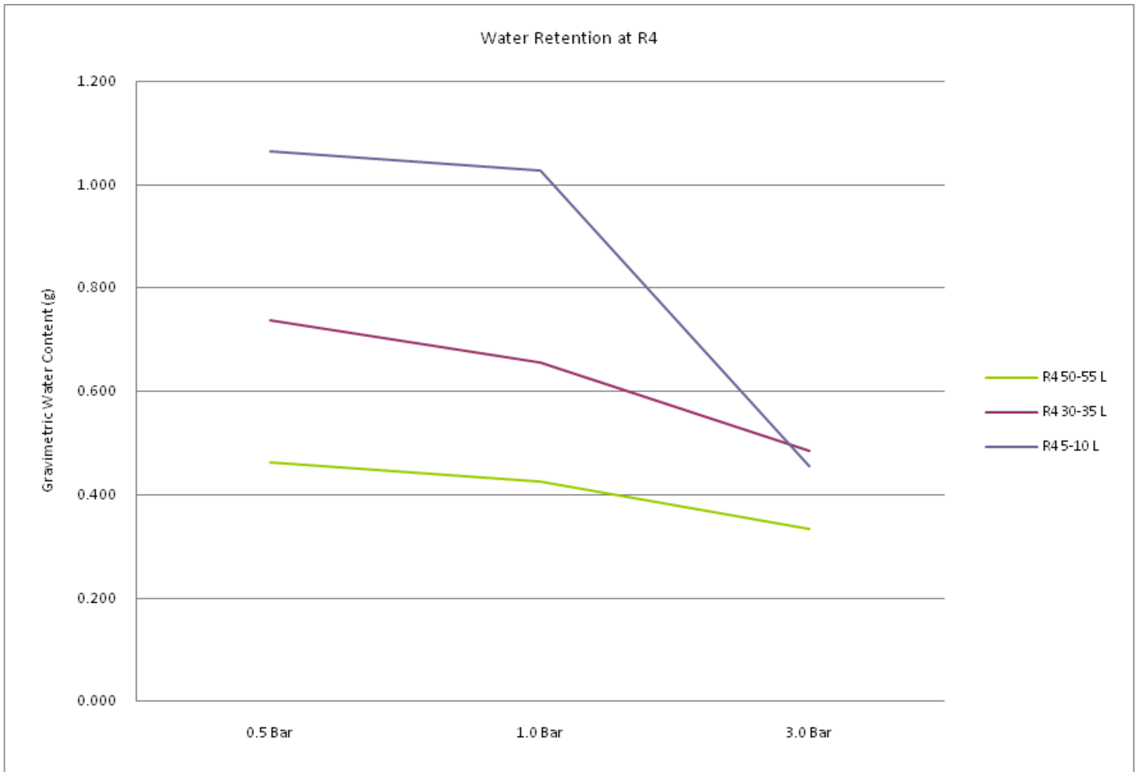


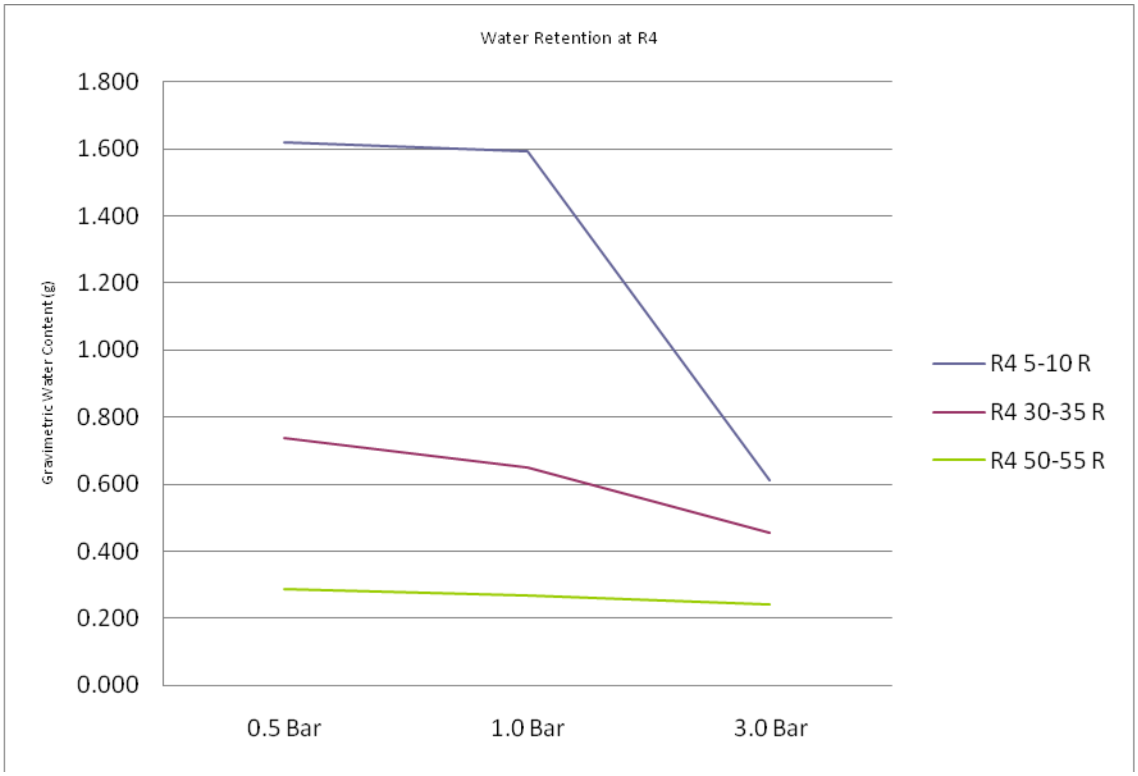
Water Retention at Lower Tensions for the Mazar Wildlife Reserve study area (in bars) (including replicate)



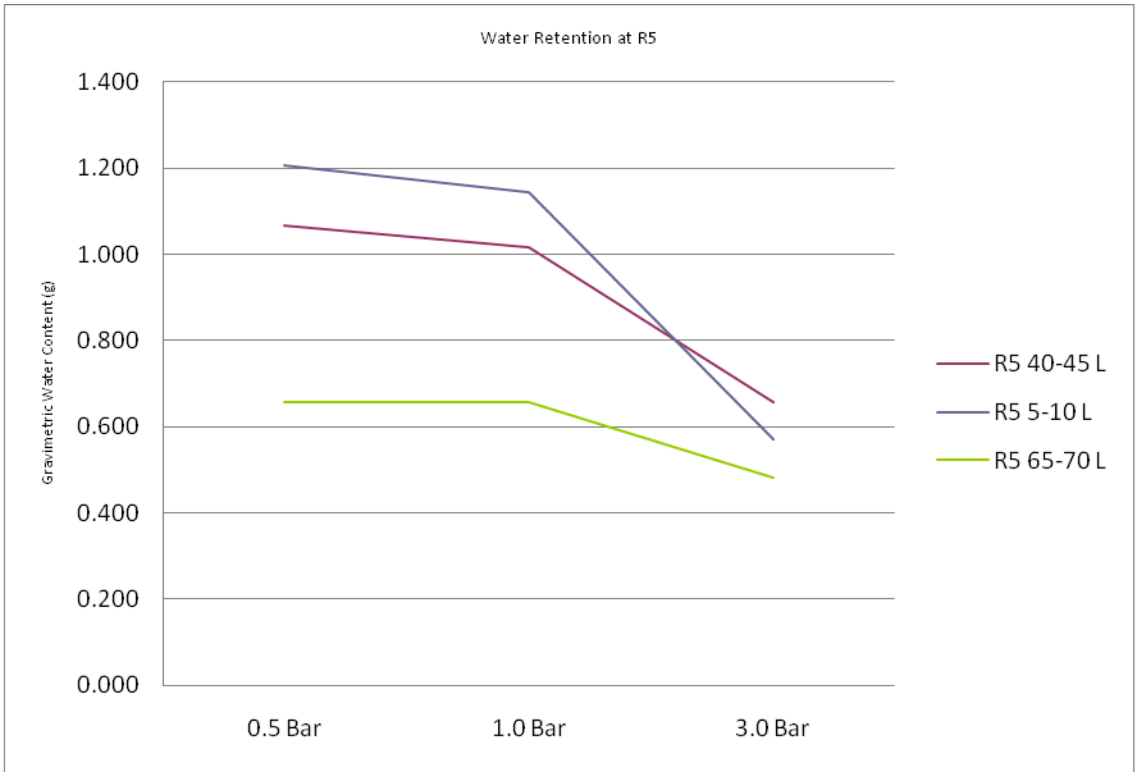


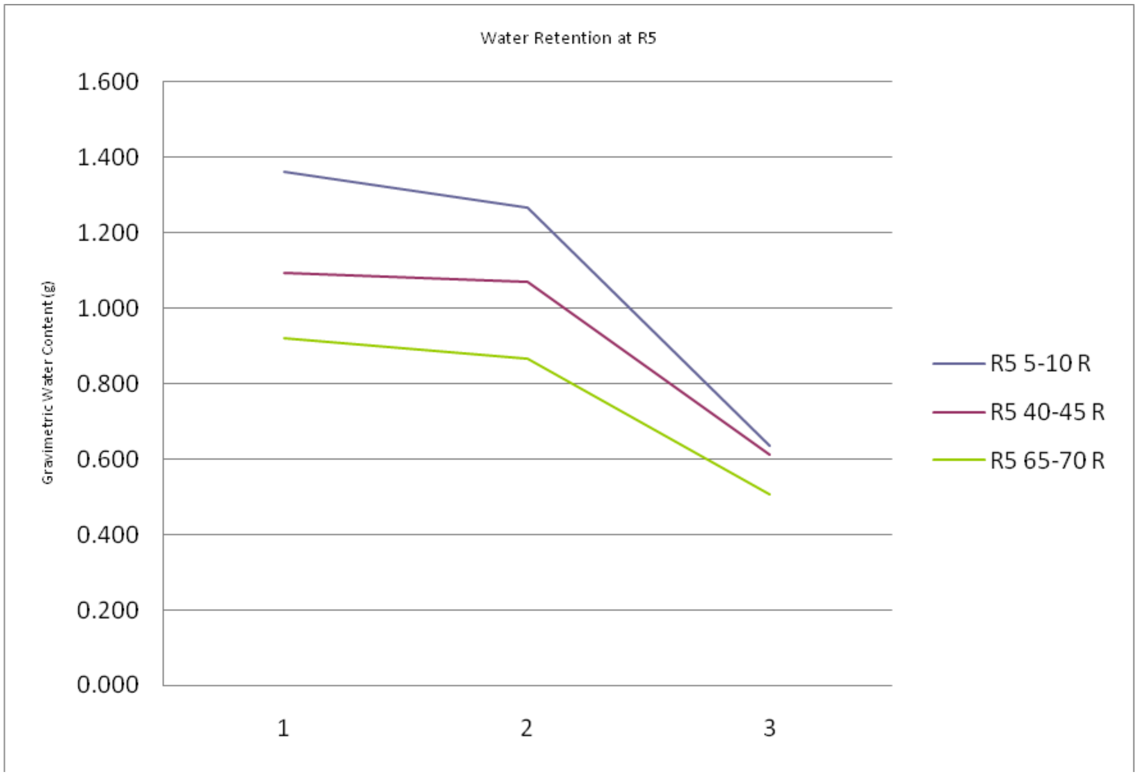
Water Retention at Lower Tensions for the Mazar Wildlife Reserve study area (in bars) (including replicate)



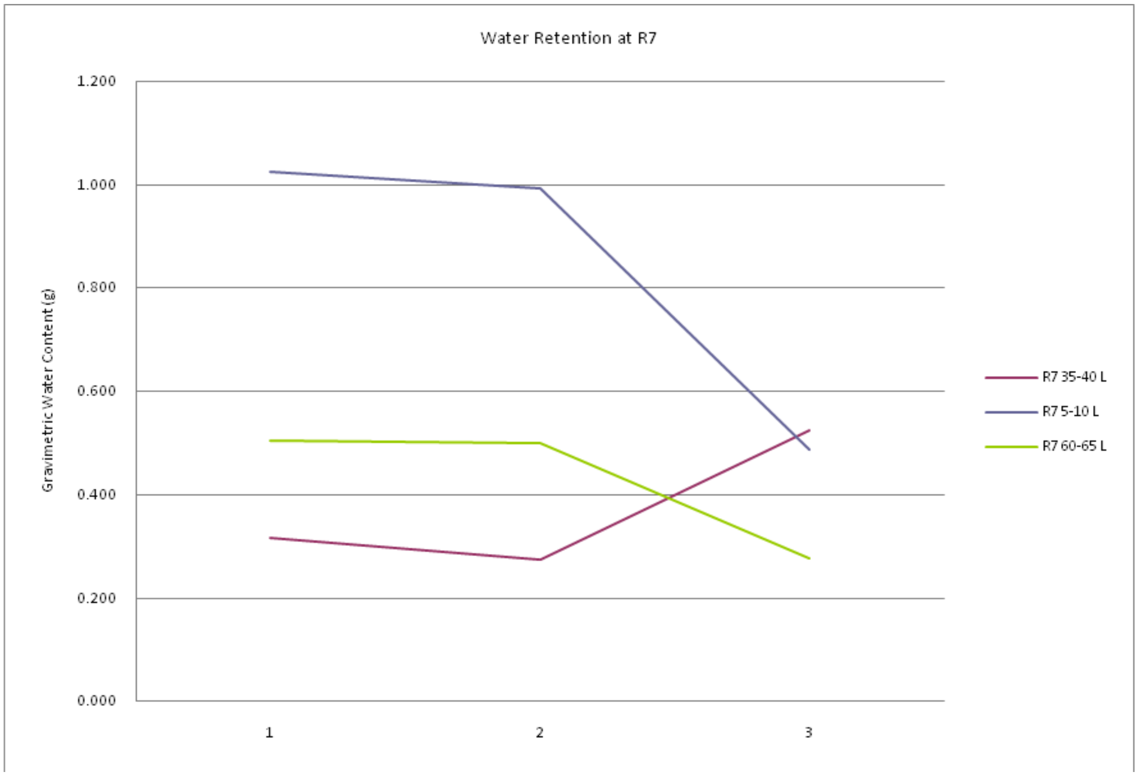


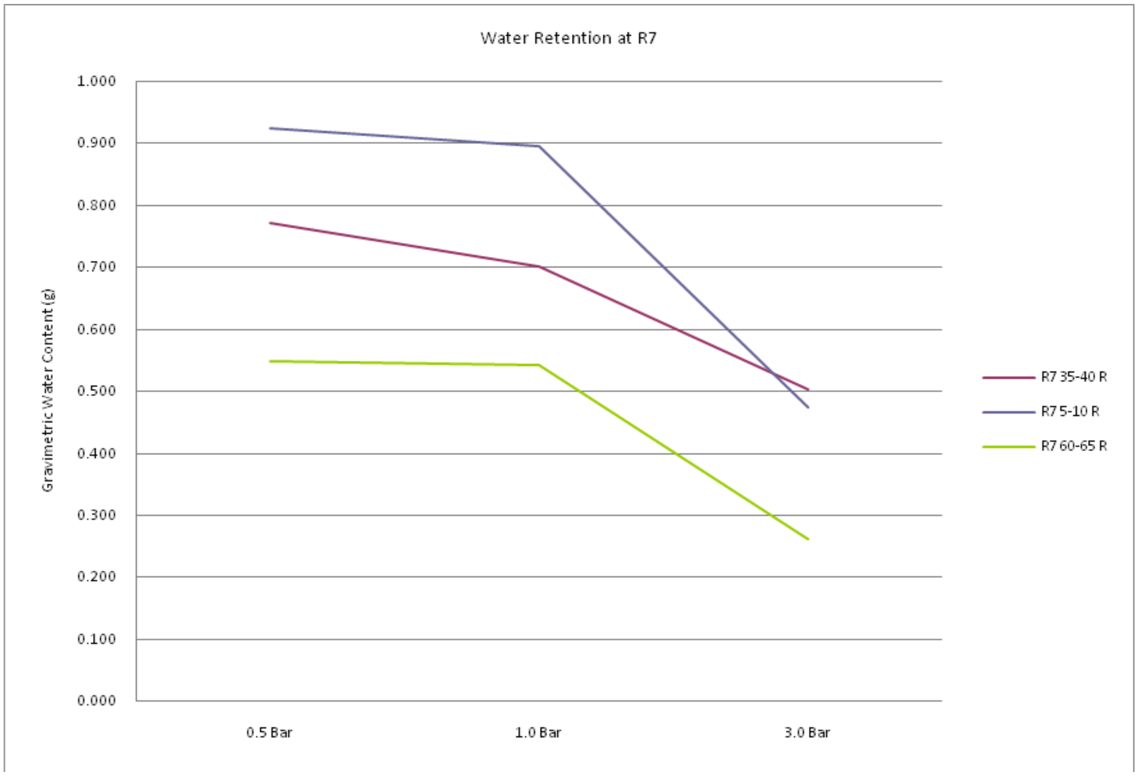
Water Retention at Lower Tensions for the Mazar Wildlife Reserve study area (in bars) (including replicate)





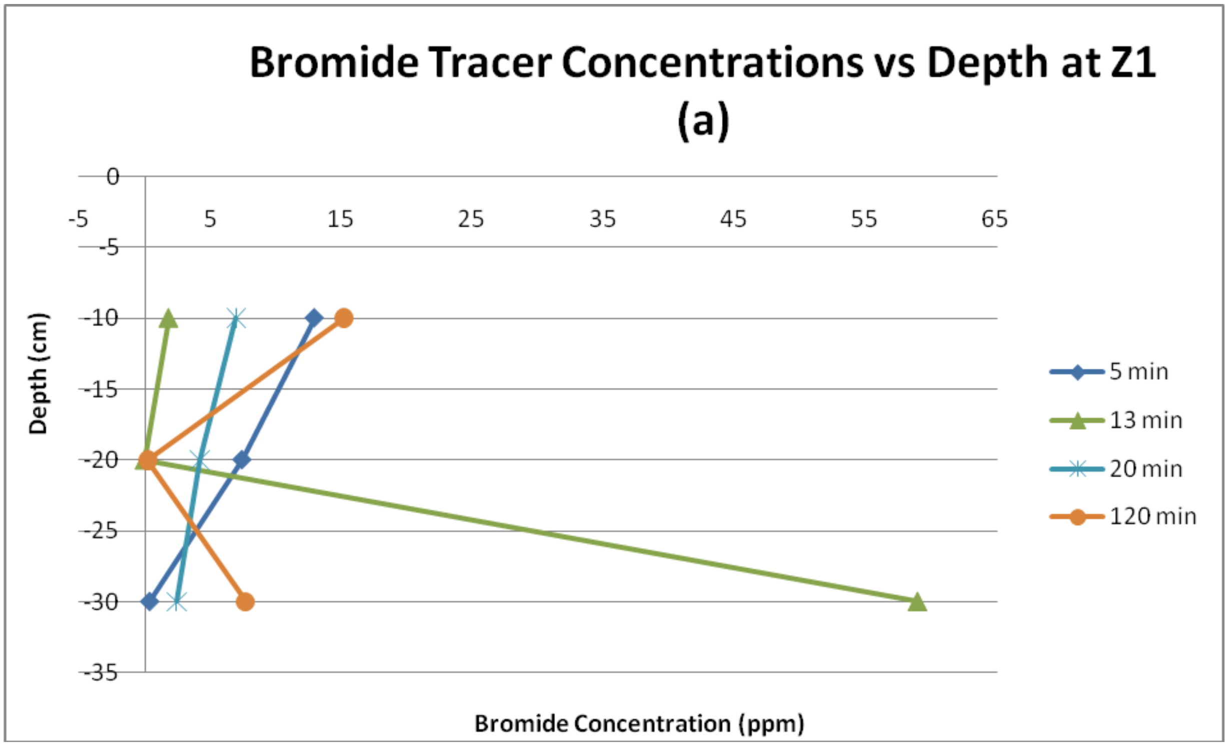
Water Retention at Lower Tensions for the Mazar Wildlife Reserve study area (in bars) (including replicate)

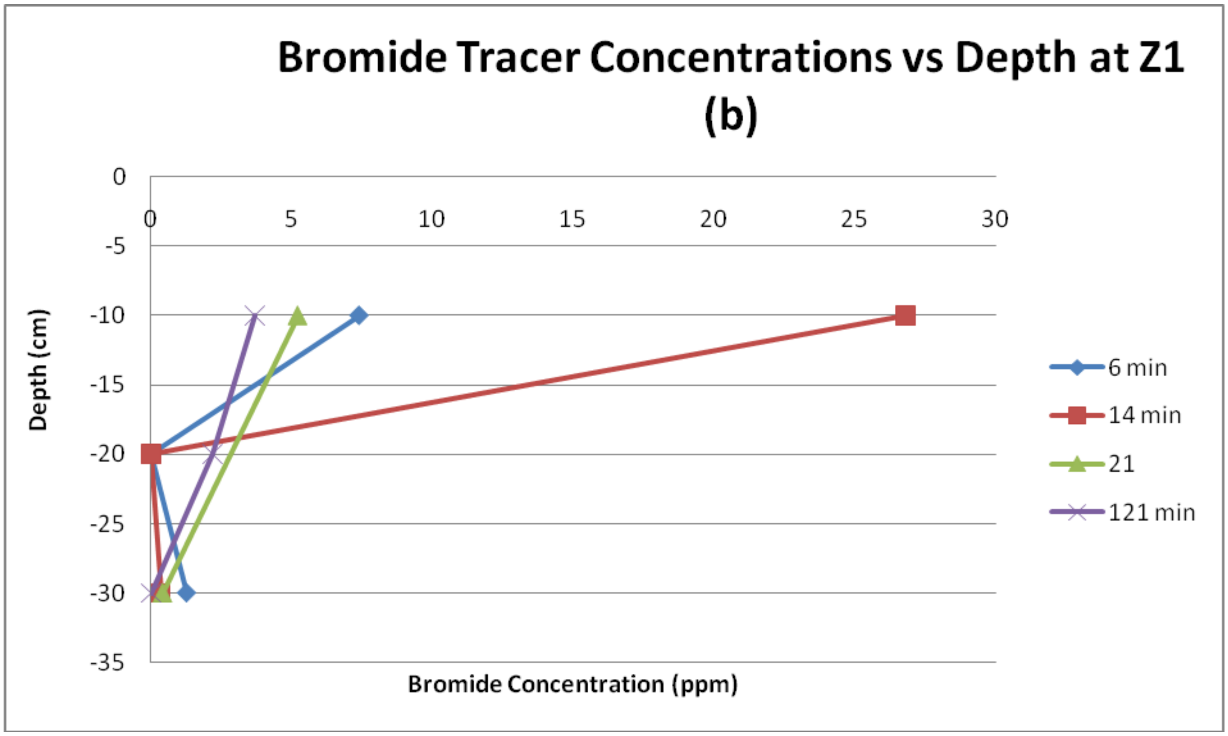




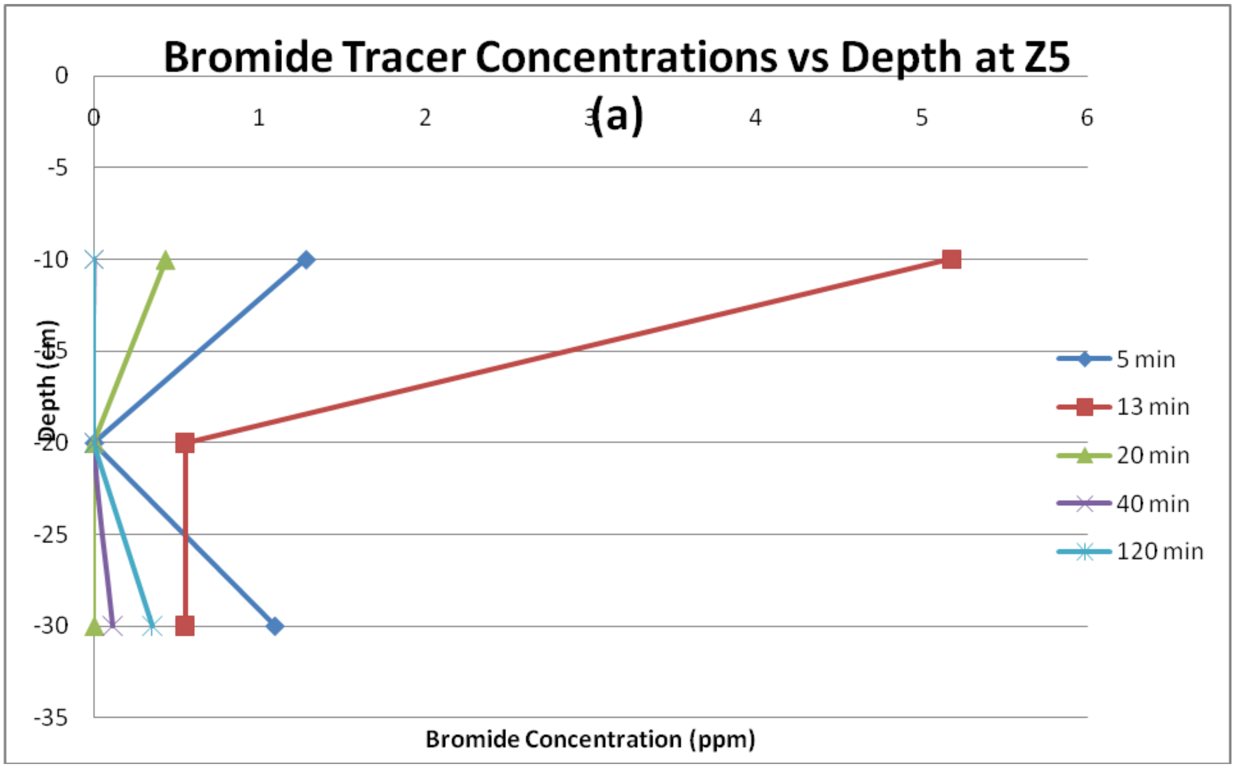
Appendix E: Bromide Ttracer Solution Plots

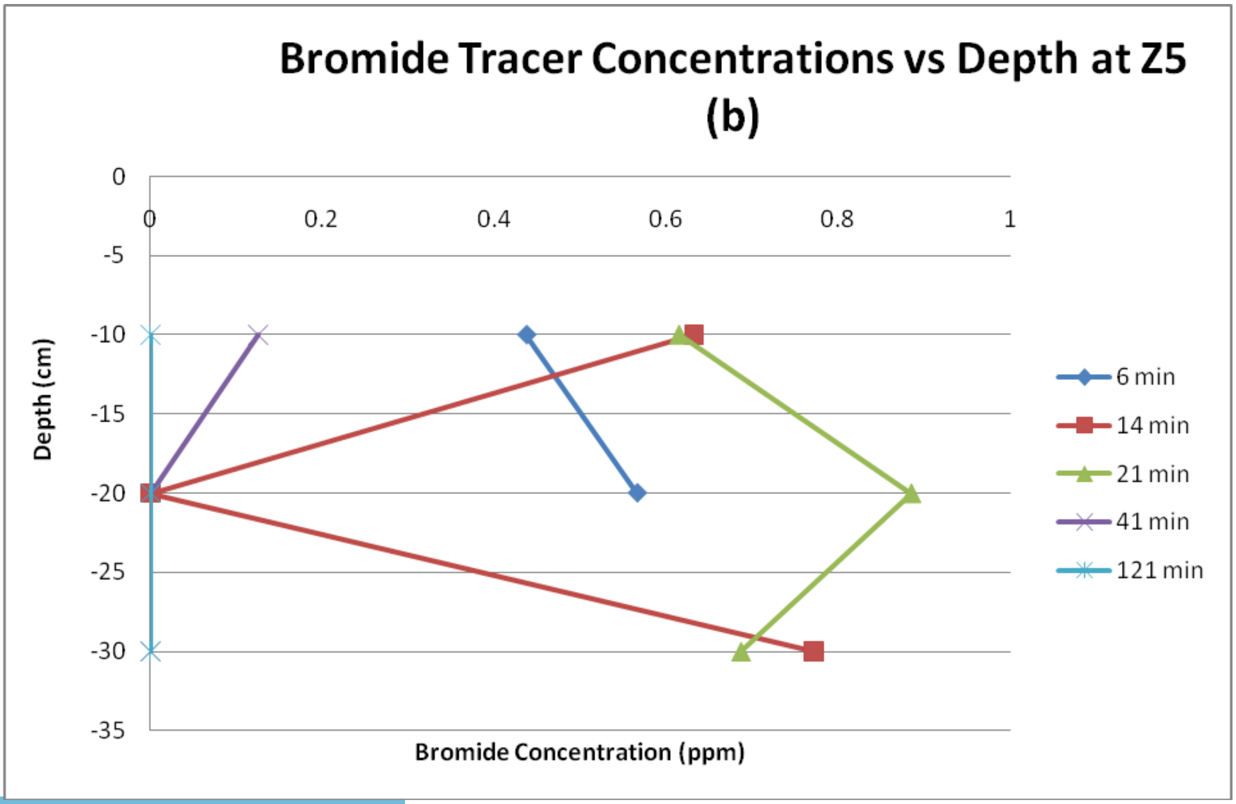
Bromide Tracer Solution Plots at the Zuleta Study Area



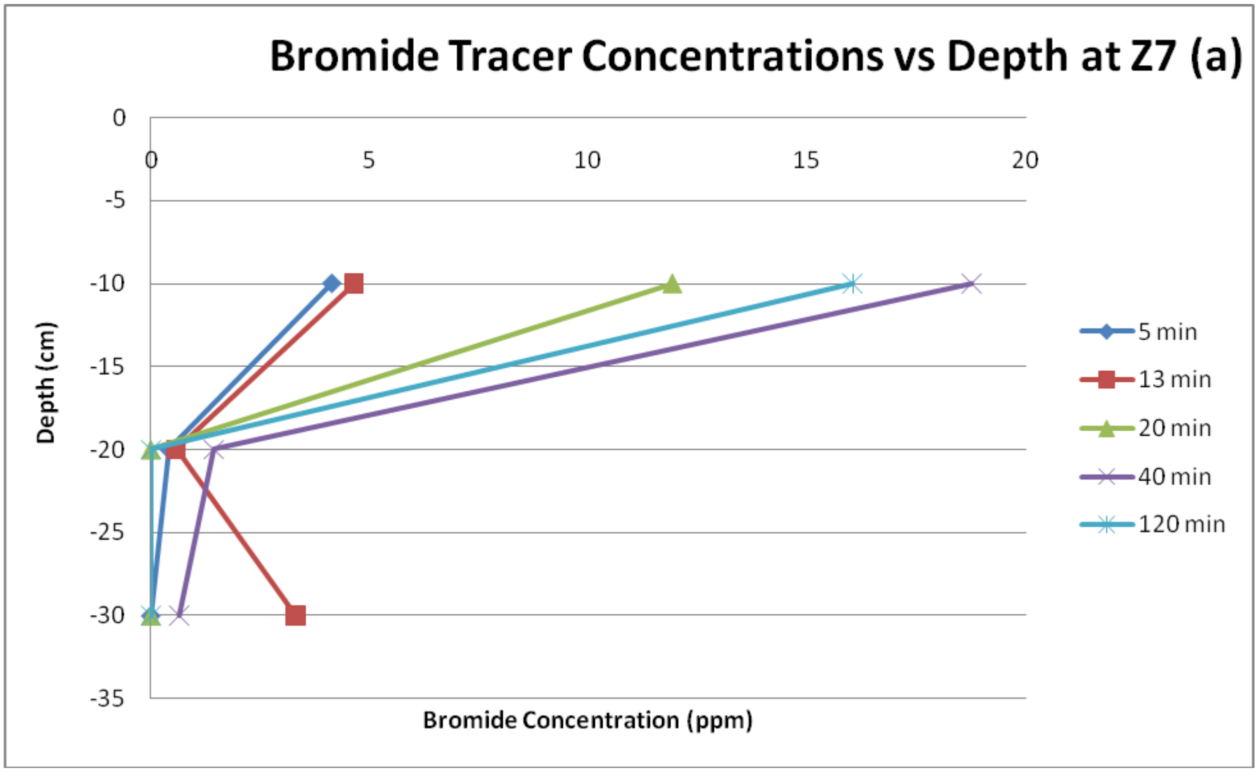


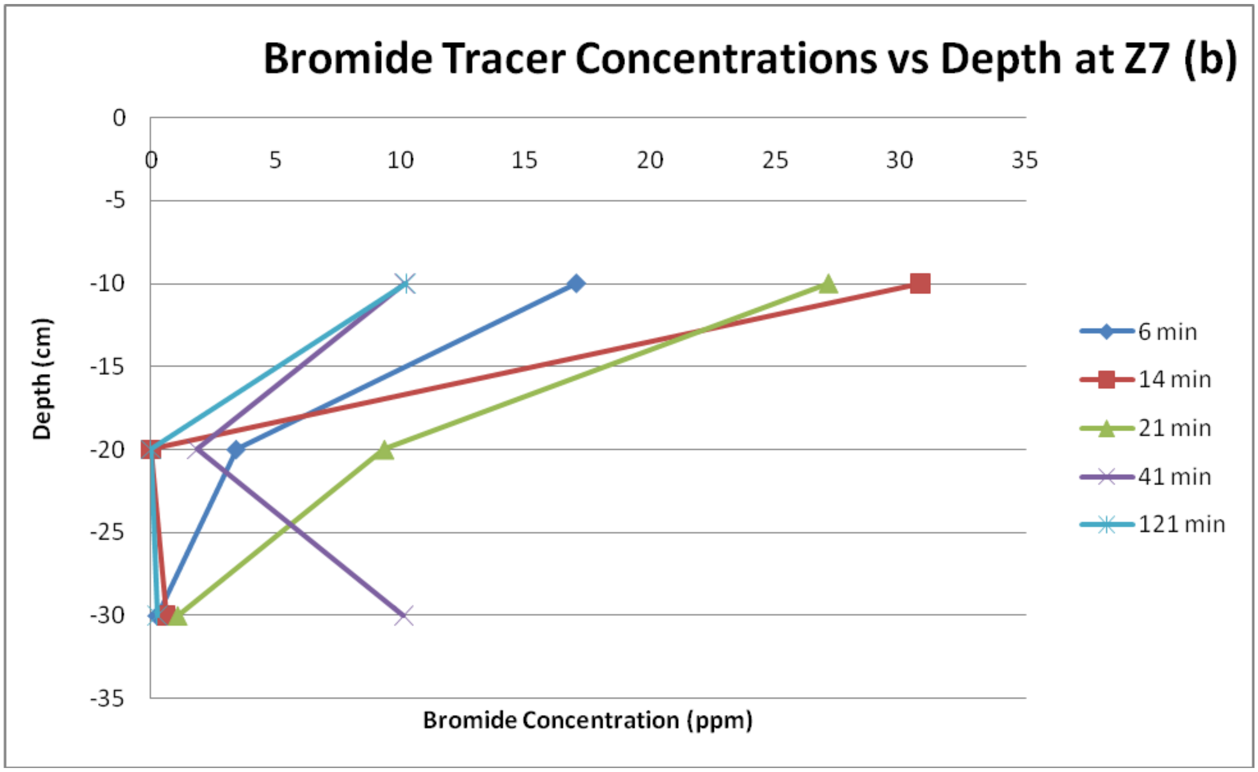
Bromide Tracer Solution Plots at the Zuleta Study Area



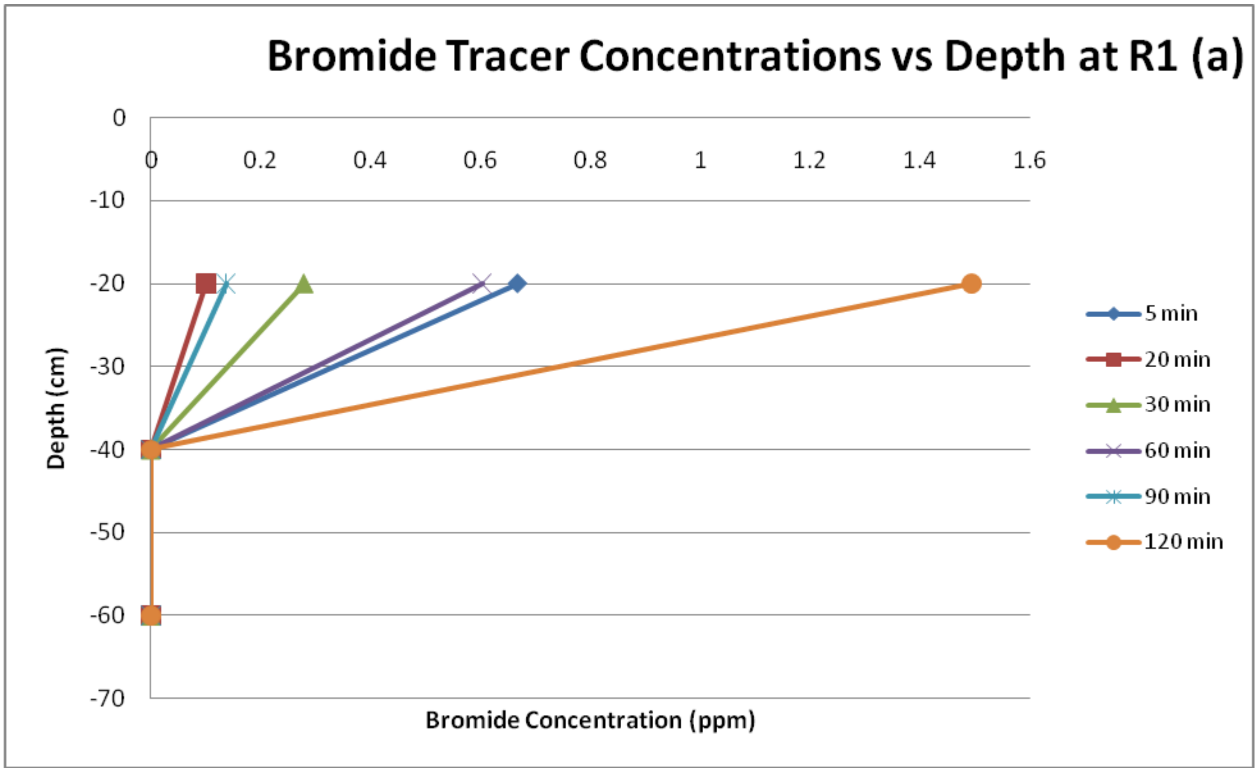


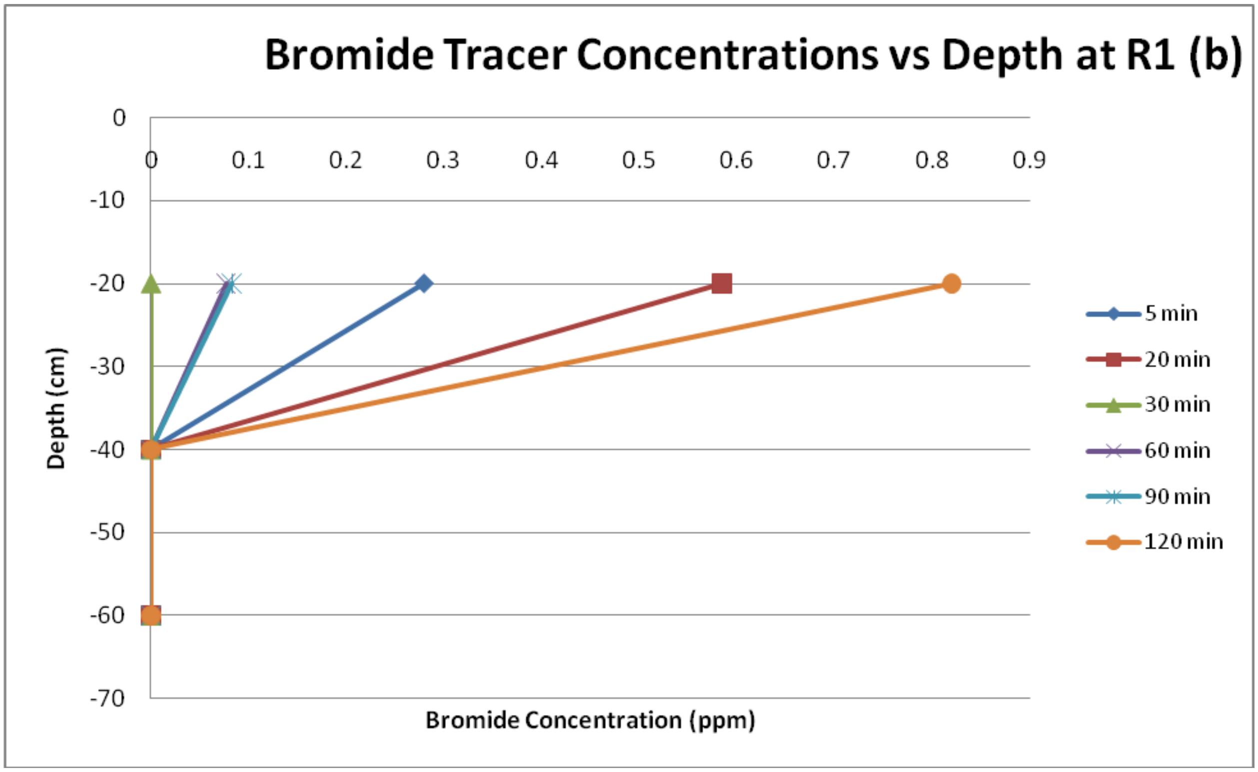
Bromide Tracer Solution Plots at the Zuleta Study Area



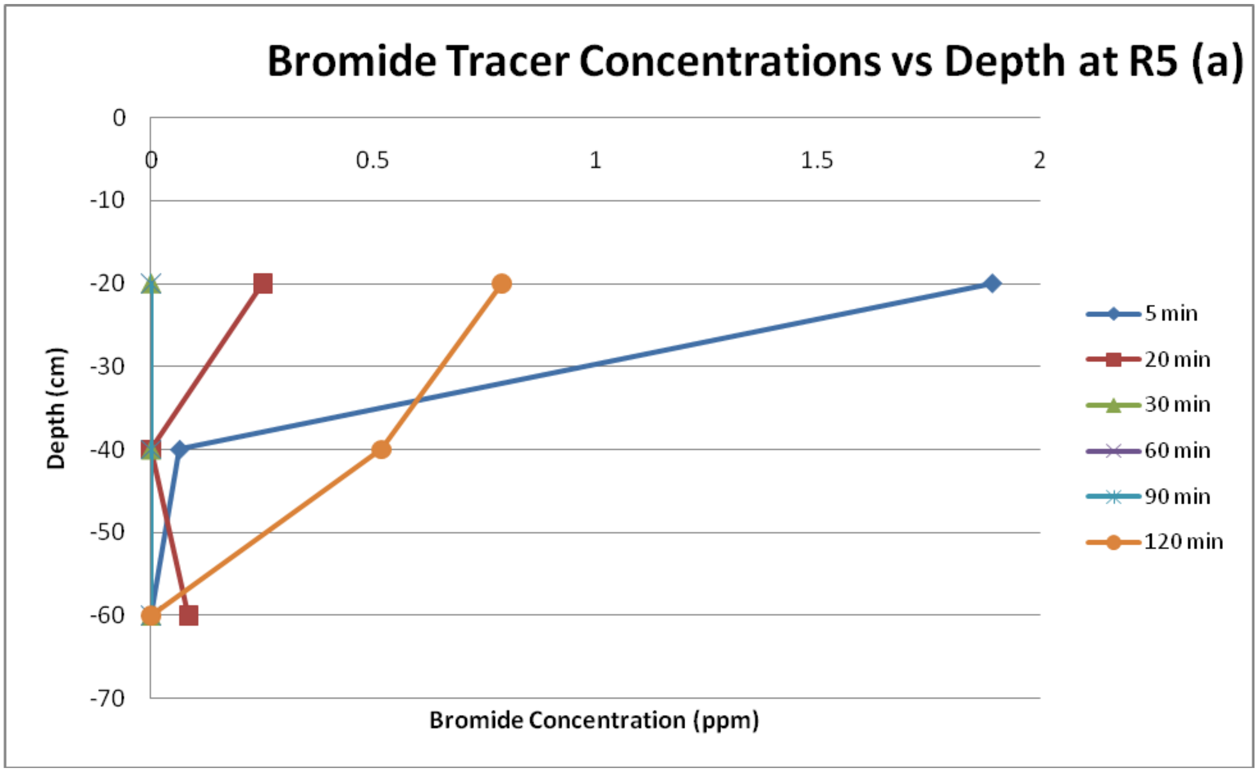


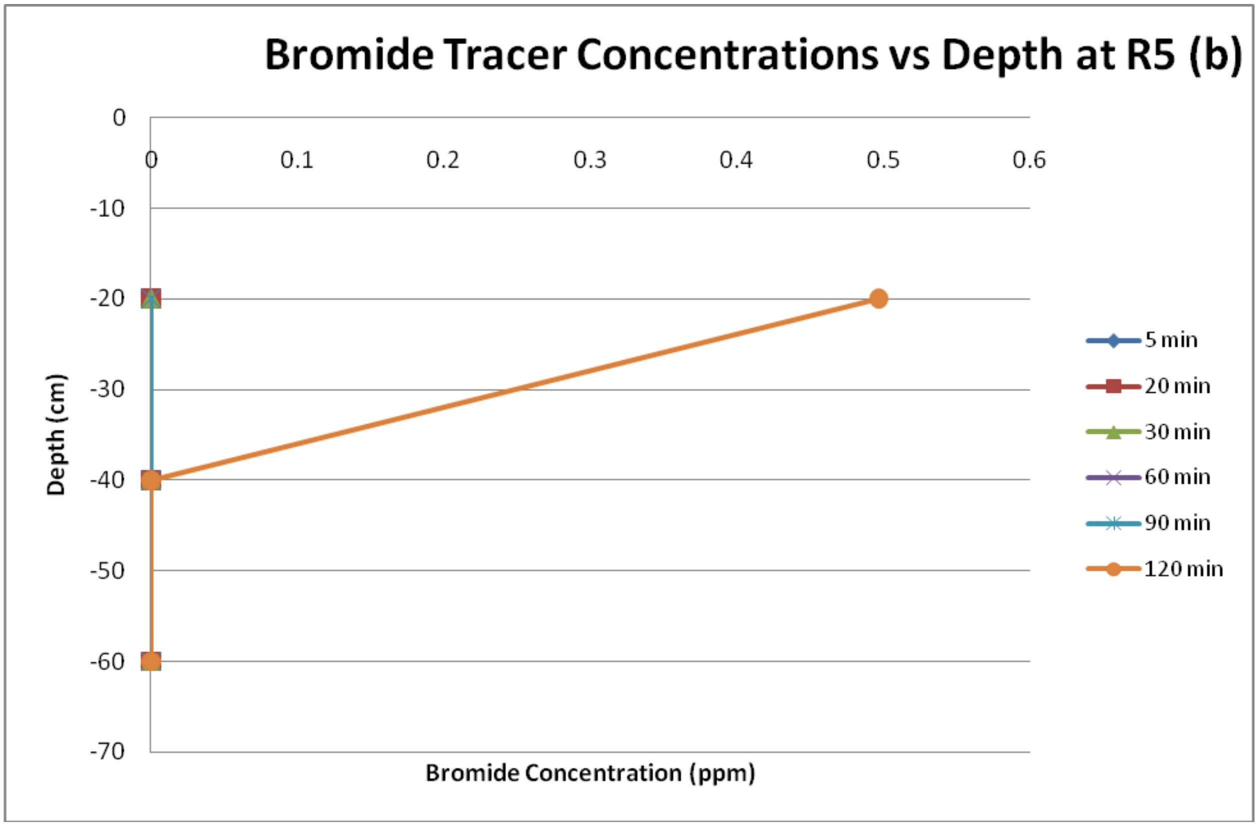
Bromide Tracer Solution Plots at the Mazar Wildlife Reserve Study Area



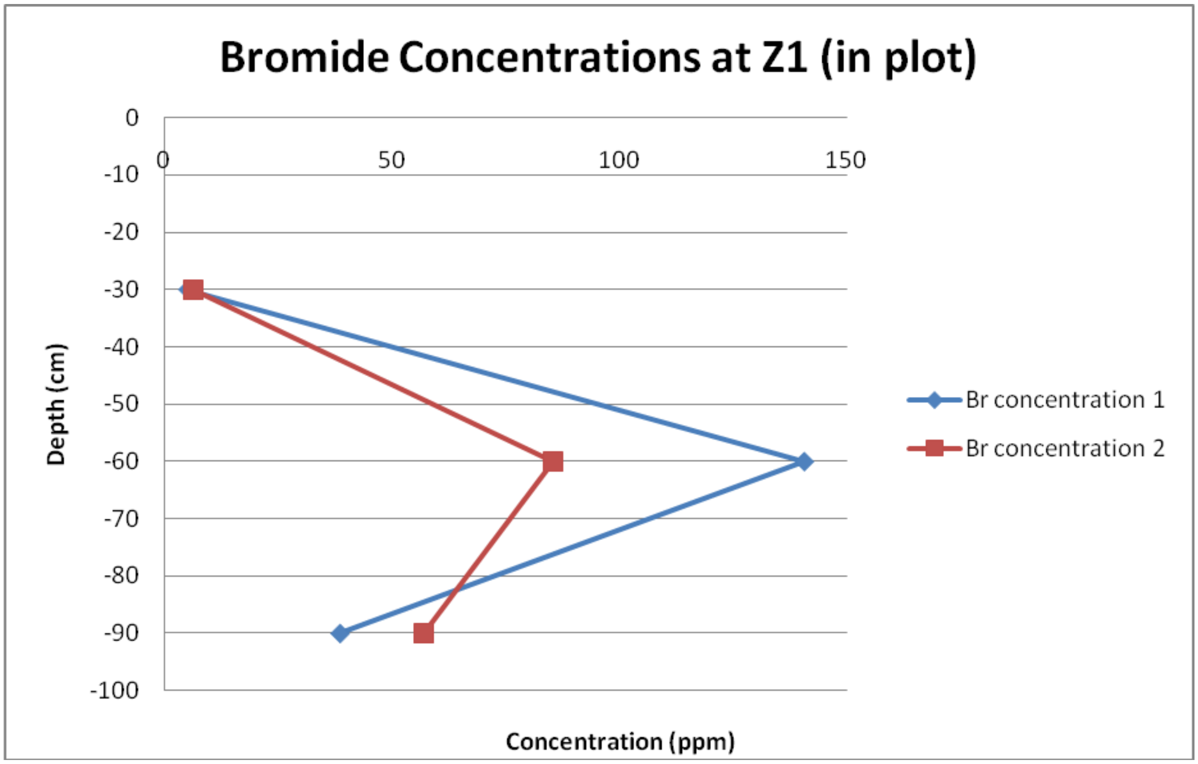


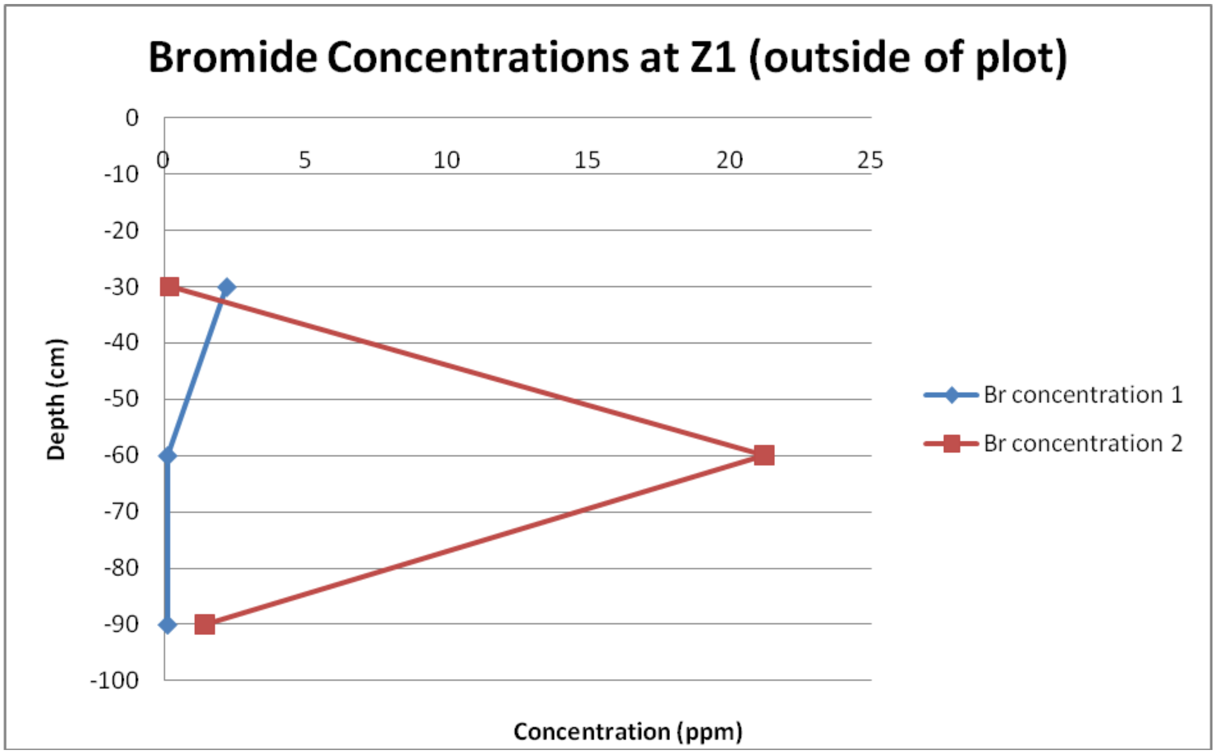
Bromide Tracer Solution Plots at the Mazar Wildlife Reserve Study Area



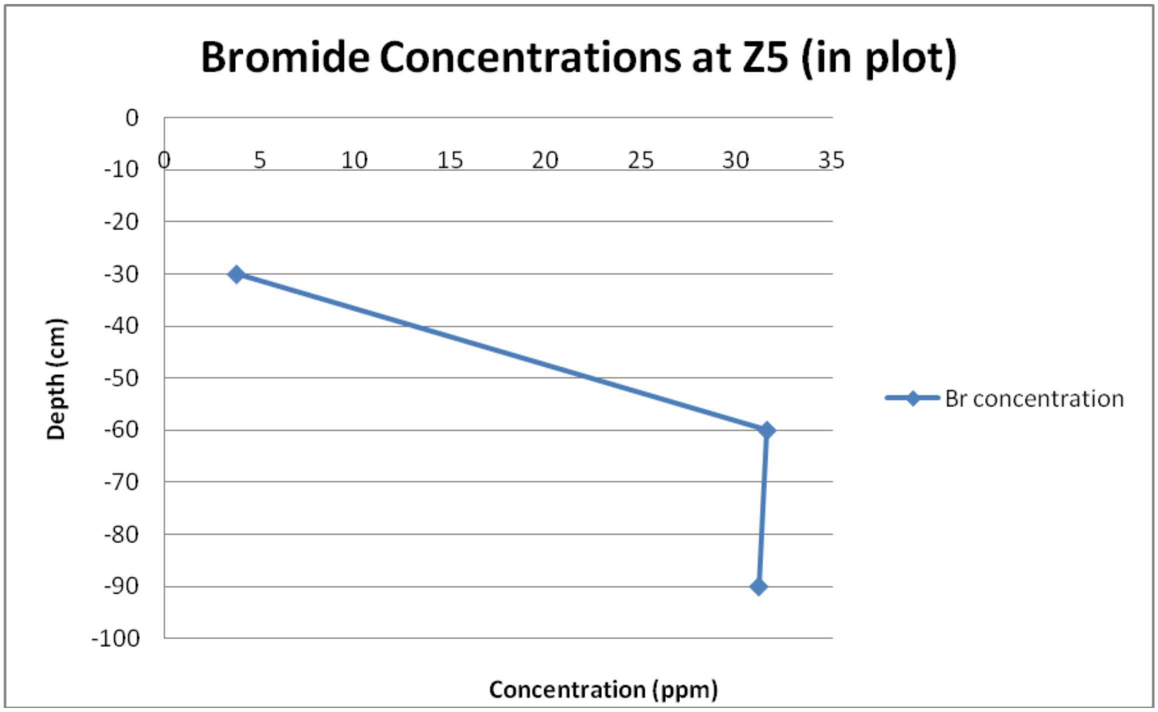


Bromide Tracer Crystal Plots at the Zuleta Study Area

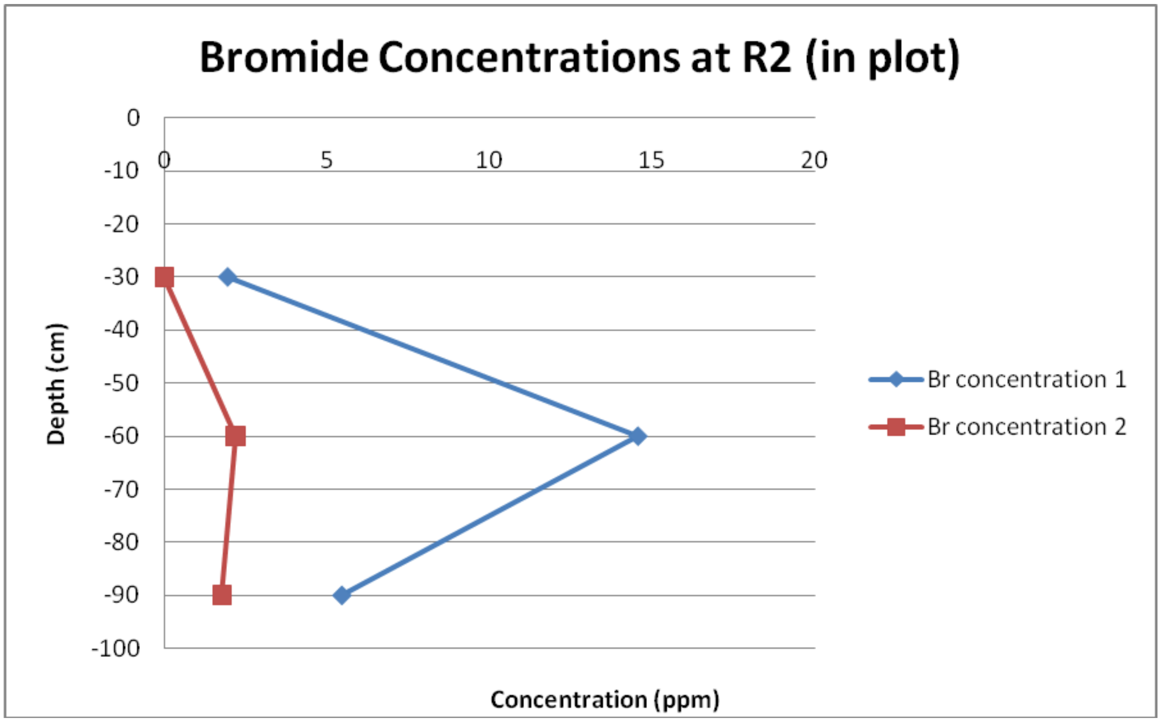




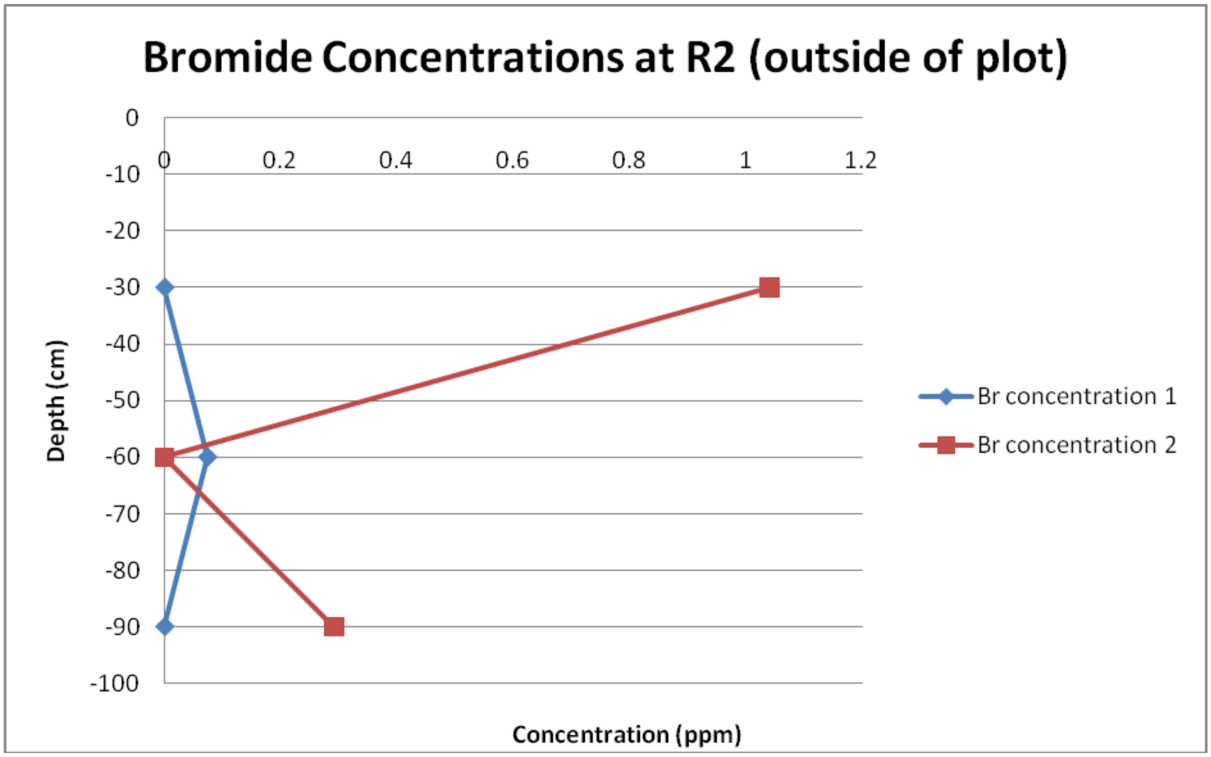
Bromide Tracer Crystal Plots at the Zuleta Study Area

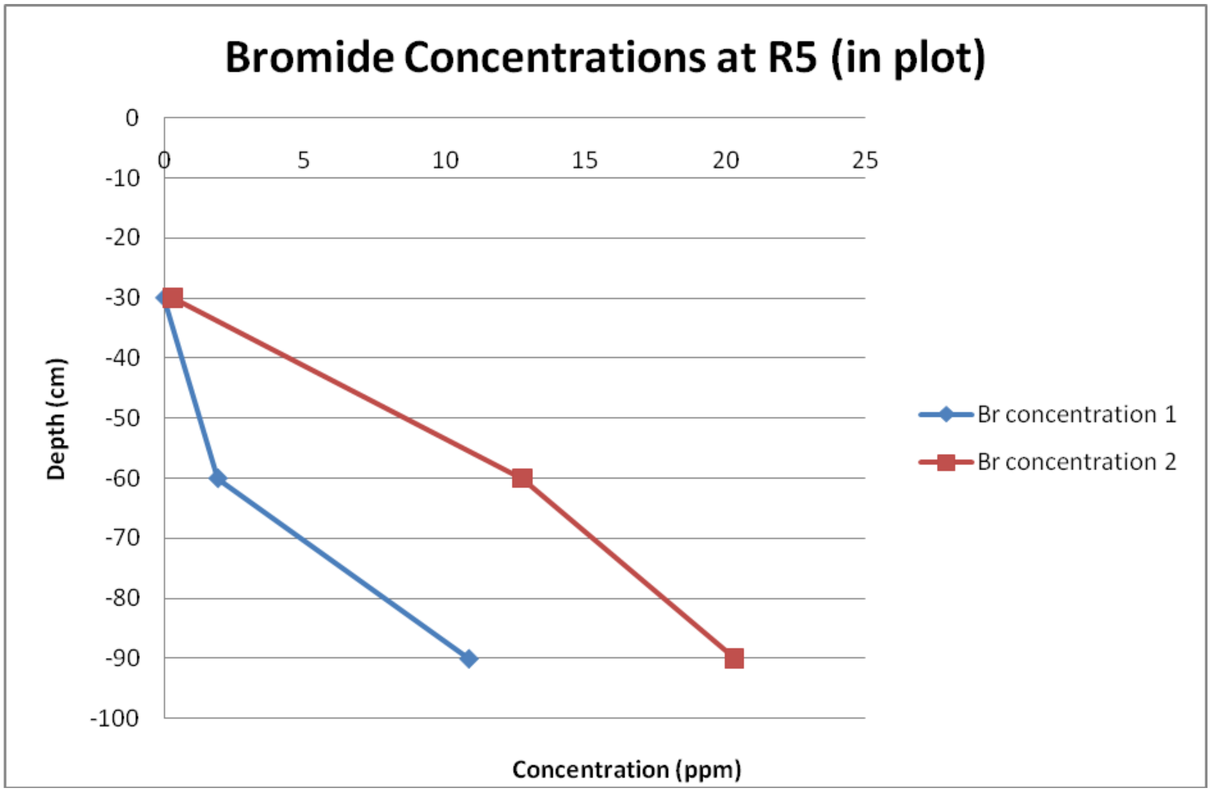


Bromide Tracer Crystal Plots at the Mazar Wildlife Reserve

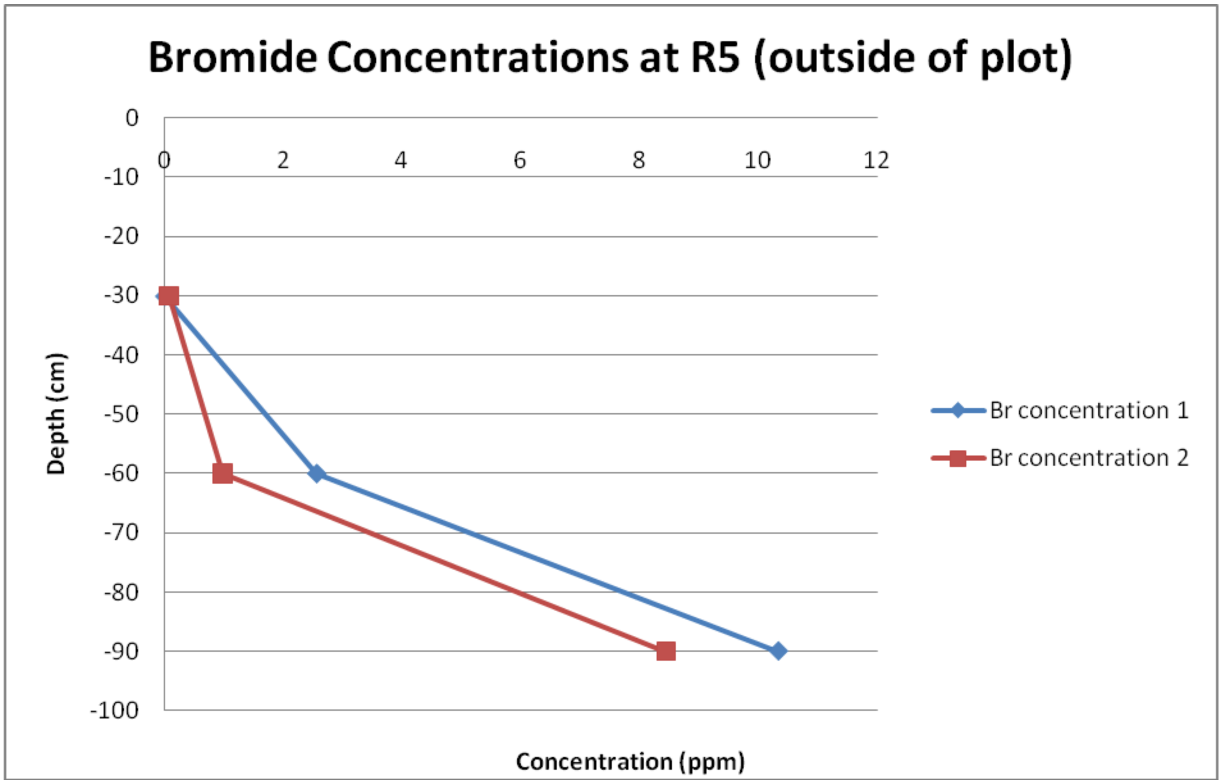


Bromide Tracer Crystal Plots at the Mazar Wildlife Reserve





Bromide Tracer Crystal Plots at the Mazar Wildlife Reserve



Vita

James Joseph Hartsig received his Bachelor of Science degree in Soil Science in 2009 before receiving his Master of Science degree in Geography in 2011 from the University of Tennessee. His passion for soil science developed in the early part of his undergraduate career and blossomed when he joined the University of Tennessee Soil Judging Team. This experience led him to better understand the morphology and genesis of the soils in this thesis. He hopes to use that passion to pursue a career in soil conservation.