The Pennsylvania State University

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LONG-TERM TREATED WASTEWATER IRRIGATION EFFECTS ON HYDRAULIC CONDUCTIVITY AND SOIL QUALITY AT PENN STATE'S LIVING FILTER

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ABSTRACT

Increased awareness of the impacts of eutrophication on streams and estuaries from the disposal of treated waste water (TWW) has resulted in finding alternate means for effluent disposal that will improve water quality. Concerns about water quality have become particularly important within the Chesapeake Bay Watershed, with states committing to reduce the discharge of nitrogen and phosphorus from point and non-point sources within the bay. As a means of renovation TWW irrigation has been utilized worldwide to address those concerns with the added benefit of meeting crop water demands and acting as a source of groundwater recharge.

Penn State’s Office of Physical Plant has been using The Living Filter to irrigate crop and forest land with TWW for over 40 years and it has served as a research site for the soil’s ability to remove nutrients. However, physical changes that occur due to the irrigation of over 250 cm of TWW per year in addition to 100 cm of rainfall has not been as well researched. Most research concerning soil physical properties under TWW irrigation has been performed on soils of arid lands, with a focus on issues resulting from high sodium concentrations in TWW or naturally occurring in the soil. Far less research has been performed in temperate regions and under their vastly different soils.

Land use managers at The Living Filter reported that there appeared to be an increase in runoff of irrigation from the site than when it was first developed. It was hypothesized that soil water infiltration rates declined due to the long term application of TWW. Therefore, in 2008 8 sampling blocks were laid out radiating from sprinklers, encompassing irrigated and non-irrigated areas of the Living Filter. Infiltration rates of

both areas were compared using a tension infiltrometer at the soil surface and the top of the Bt1 horizon. In addition, surface soil bulk density and surface horizon clay and organic matter contents were evaluated with respect to distance from the sprinklers. Finally, soil cores were taken in 2009 and comparison of irrigated and non-irrigated areas were made between soil pH, electrical conductivity (EC), sodium adsorption ratio (SAR), total organic carbon (TOC) and clay content for each identified soil horizon. All experiments were arranged in a complete block or split-plot design.

Results suggest that irrigated areas have greater surface horizon hydraulic conductivities than comparable non-irrigated areas. Analysis of Bt horizon hydraulic conductivity rates revealed that there was no difference between irrigated and non-irrigated areas. Analysis of bulk density suggests that distance from the sprinkler head has an effect on 0-10 cm bulk density, with areas within the sprinkler irrigated radius having lower bulk densities. Increases in soil structure resulting form increased soil microbial production, increased plant rooting and a greater number of freezing-thawing cycles many be causes for the differences between treatments for Ap horizon hydraulic conductivity and bulk density. Additionally, distance from the sprinkler head had an effect on clay content, with reduced clay contents within the irrigated area. Although this suggests that irrigation is translocating clay to lower horizons, further analysis needs to be performed before any conclusion can be made.

Analysis of soil cores revealed that soil pH was approximately 1.0 unit greater in the irrigated area than the non-irrigated area for all identified horizons, with irrigated-area pH values reflecting that of the irrigation water. Soil EC was also greater in the irrigated area, with the greatest differences between areas occurring in the Bt2 through Bt4 horizons. Soil SAR was greater in the irrigated area when compared to the non-irrigated area, with SAR increasing with depth throughout the profile. This suggests a removal of sodium from the Ap horizon and the consequent movement and deposition of sodium deeper in the soil profile. The increased SAR values combined with relatively low EC values may result in reductions in hydraulic conductivity in the Bt2 through Bt4 horizons and monitoring should be performed to determine if the higher sodium concentrations are negatively impacting the soil.

Initial findings suggest that TWW irrigation does not have a negative effect on soil hydraulic conductivity. Also, soil quality appears to have improved with TWW irrigation, resulting in a greater potential for increased water renovation and crop yields. When considering the lack of negative effects of TWW irrigation, one can see that the Living Filter should continue to serve as a viable way of eliminating nutrient discharge into local waterways and demonstrates that TWW irrigation can be an effective alternative for the tertiary treatment of wastewater.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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Chapter 1

INTRODUCTION

The degradation of water quality due to the discharge of excess phosphorus and nitrogen from anthropogenic sources and the resulting formation of hypoxic zones in watersheds and estuaries has been noted worldwide (Diaz, 2001). These high nutrient levels are often synonymous with eutrophication, which is an increase in primary biotic production. Decomposition of such growth results in excess oxygen consumption within the system resulting in the formation of hypoxic zones and the associated decline or elimination of aquatic species, which can impact commercial fisheries and natural areas (Diaz, 2001). Hypoxic zones are detrimental both ecologically and economically and have become the focus of government agencies and non-profit organizations to substantially reduce nutrient discharges from both point and non-point sources.

In Pennsylvania and particularly areas within the Chesapeake Bay Watershed, proper management of nitrogen and phosphorus is of great concern; however the physical and demographic characteristics of the Chesapeake Bay Watershed make management difficult. Recent US Geological Survey findings estimate the population within the watershed at 16.6 million, with an expected population of 18 million by 2020 (Cheapeake Bay Program, 2006). In addition, the Chesapeake Bay has the largest land to water discharge ratio (14:1) of any coastal estuary in the world, resulting in the potential for extremely high concentrations of pollutants from sources within the watershed (Cheapeake Bay Program, 2009). To address these issues the states of Pennsylvania, Maryland and Virginia and the District of Columbia in conjunction with the US

Environmental Protection Agency (EPA) and Chesapeake Bay Foundation signed the Chesapeake Bay Agreement in 1983, with a second agreement signed in 1987 (Pennsylvania DEP, 2002). Commitments to reduce the discharge of excess nutrients in the bay were strengthened in 2000, with an agreement to voluntarily reduce nutrient loads to a determined amount by 2010, or be subject to a total maximum daily load (TMDL) set by the EPA. In addition to the initial members, the states of West Virginia, Delaware, and New York consented to the agreement, resulting in the inclusion of all land within the Bay (Pennsylvania DEP, 2002).

Pennsylvania was given a voluntary discharge cap of 105 and 4.29 million pounds of nitrogen and phosphorus per year, respectively, which calls for a reduction of 15.5 million pounds of nitrogen and 0.15 million pounds of phosphorus from 1983 levels (Protection, 2002). In order to reach these levels, Pennsylvania identified sources of nitrogen and phosphorus contribution, with point sources contributing to 11% and 19% of nitrogen and phosphorus loads, respectively. Pennsylvania's nutrient reduction strategy makes point sources accountable for reductions proportionate to the overall required reduction, resulting in treated wastewater discharge limits of 6 mg/l for nitrogen and 0.8 mg/l for phosphorus (Pennsylvania DEP, 2002). In addition, a cap and trade system is being established to allow organizations that reduce nutrient discharges beyond mandated requirements to sell credits to those that may be less able to achieve the necessary reduction levels.

Government agencies and corporations throughout the world have addressed the management of nitrogen and phosphorus through the use of treated wastewater (TWW) irrigation (Toze, 2006). In addition to reducing watershed impacts, TWW irrigation often meets crop water demands in areas of scarce groundwater resources while providing supplemental nutrients necessary for plant growth. Such systems are in use under a variety of soil and climatic conditions, with each system designed to address specific environmental and economic concerns. However, the use of such systems are not without negative effects, as wastewater composition and the process of land application can result in numerous issues that need to be addressed for the management of a sustainable TWW treatment system (Tillman and Surapaneni, 2002; Toze, 2006).

In Pennsylvania, irrigation of TWW has great potential to reduce nutrient loads in streams while providing trading credits and potential profits for those implementing such systems. When determining the feasibility and performance of such systems, one should analyze Penn State's Living Filter (figure 1.1), which has irrigated TWW on forest and cropland as a means of tertiary and quaternary treatment for over 40 years (Dadio, 1998; Parizek et al., 1967). The system has proved to be a viable way of reducing nutrient discharges in surface waters while supplementing crop water and nutrient needs. However, to continue operation of the system, Pennsylvania Department of Environmental Protection (DEP) (2004) regulations requires that no runoff shall leave the Living Filter.

Though the Living Filter's ability to remove nutrients has been well demonstrated, the impact of TWW irrigation on soil physical properties is not as well understood. Initial research revealed both positive and negative impacts on physical properties, depending on management scenarios (Sopper and Richenderfer, 1978). Much less is known about long term impacts and current system performance, as cropping practices and irrigation scheduling have changed significantly since the installation of the system and may have affected the experimental factors observed in early studies. In addition, the operational requirement that no runoff shall leave the Living Filter (Pennsylvania DEP, 2004) creates a need to identify weather soil-water transport properties have changed as a result of long term operation. Therefore a need exists to compare treated areas of the Living Filter with those that receive similar land management practices, yet have not been impacted by long term TWW irrigation.

The purpose of this study is to identify if and to what extent 25+ years of TWW irrigation has impacted hydraulic conductivity and measures of soil quality when compared to adjacent non-irrigated sites. To address these potential impacts the following null hypotheses were tested:

1. Treated wastewater irrigation has no effect on surface and Bt1 horizon hydraulic conductivity;
2. Distance from the sprinkler has no effect on bulk density at the 0 to 10 and 0 to 20 cm sampling depth and clay content and organic matter content at the 0 to 20 cm sampling depth;
3. Treated wastewater irrigation has no effect on pH, EC, SAR, total organic carbon, and clay content for Ap and Bt1 through Bt4 soil horizons.

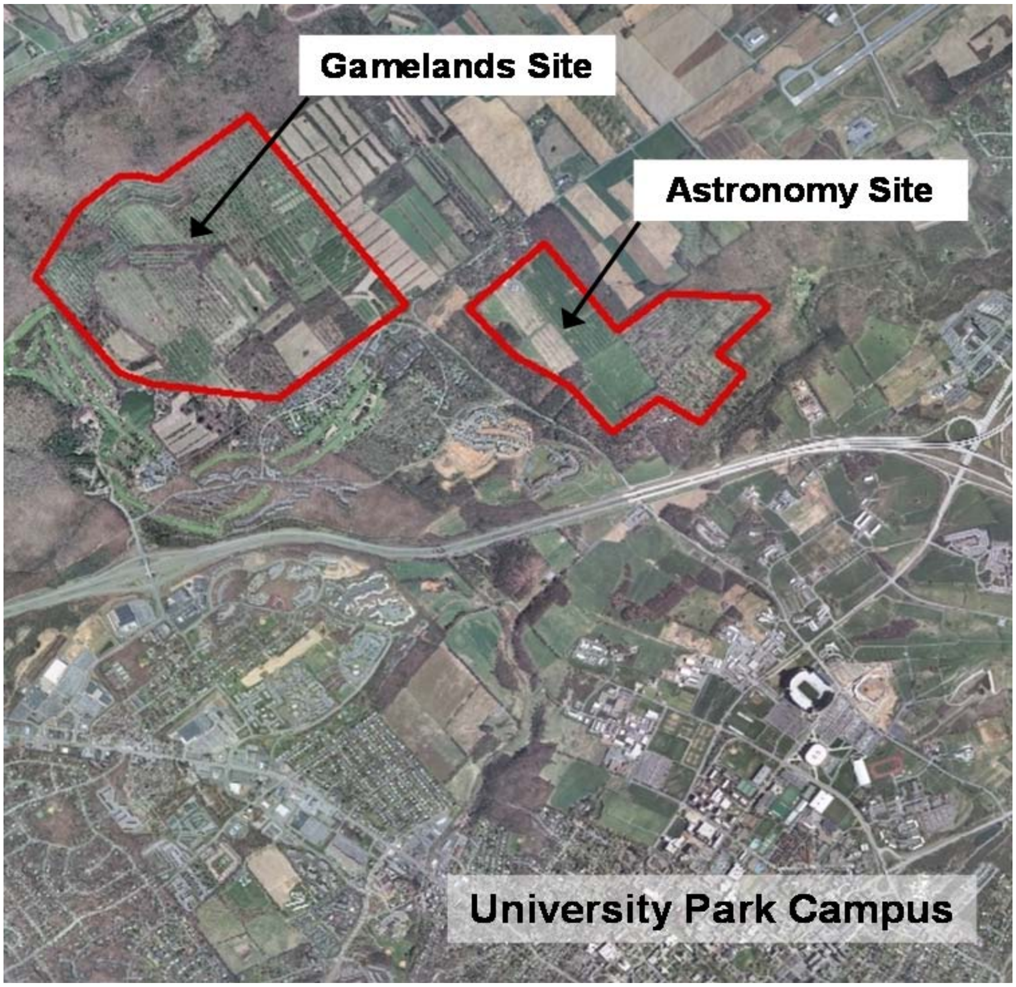

Figure 1.1. Location of Living Filter Astronomy and Gamelands sites. The Astronomy site was established in 1964 and currently occupies approximately 191 ha. The Gamelands site was completed in 1983 and occupies approximately 517 ha.

Chapter 2

LITERATURE REVIEW

Irrigation of Treated Wastewater

The impact of treated wastewater irrigation on soil physical and chemical properties varies from beneficial to detrimental in studies throughout the world (Coppola et al., 2003; Hati et al., 2007). The effects of TWW irrigation vary due to soil type, water quality and overall management, with issues resulting from biological, chemical and physical changes to the soil. A review of the literature suggests that the underlying conditions of each system must be considered to understand the potential consequences of TWW irrigation on soil properties and system management.

Positive and neutral effects of TWW irrigation

Treated wastewater irrigation has been shown to have positive effects on soil physical properties and measures of soil quality. Application of TWW on both sands and silt loams in New Zealand resulted in increases in hydraulic conductivity and reductions in bulk density when compared to control treatments (Vogeler, 2009). Distillery effluent applied to clay soils under a soybean-wheat rotation in India showed similar results (Hati et al., 2007). In both cases increases in hydraulic conductivity and reductions in bulk density were attributed to greater aggregate stability due to increases in organic matter content.

In some cases no positive or negative effects have been observed with TWW irrigation. Seven years of irrigation on sandy soils in New Zealand resulted in no measurable changes to unsaturated hydraulic conductivity (K(ψ), with ψ being soil tension, or -1 x soil matric potential, in cm) and bulk density (Magesan et al., 1999). A similar study in New Zealand, except on silt loams, showed no differences in hydraulic conductivity at 0, 1 and 4 cm of tension when compared to control plots (Menneer et al., 2001). However, K(12 cm) was greater in the non-irrigated treatments, suggesting a change in soil pore size distribution. In addition, rainfall simulations on loams and sandy clays in Israel that received 15 years of irrigation showed no difference in runoff rates or soil loss between TWW, tap water and simulated rainfall sources (Agassi et al., 2003).

Negative effects of TWW irrigation

Though long-term TWW irrigation may improve soil physical properties, negative effects are possible, as effluent application has been shown to reduce hydraulic conductivity and porosity and alter pore size distribution (Coppola et al., 2004; Wang et al., 2003). Observations at Bakersfield, California's municipal treatment fields revealed that seventy years of TWW application increased soil bulk density (Wang et al., 2003). A comparison of irrigated Israeli citrus orchards receiving freshwater and 23 years of TWW showed that sites receiving TWW had reduced saturated hydraulic conductivity (K_{sat}) and increased bulk density (Bhardwaj et al., 2007). A similar study of citrus orchards in Israel resulted in an increase in soil water repellency and a reduction in infiltration when compared to freshwater irrigated sites (Wallach et al., 2005). Finally, observations of TWW irrigation of cropping systems on Vertisols in India demonstrated that when compared to untreated sites, 2, 5, and 15 years of irrigation reduced K_{sat}, with reductions increasing with each length of application (Gharaibeh et al., 2007). However, there were no differences between the bulk densities of the four sites, suggesting a shift in pore size distribution rather than a reduction in porosity.

Mechanisms for Reduction in Infiltration

Sodicity

One of the most prevalent causes of reductions in hydraulic conductivity under TWW irrigation is the accumulation of excess sodium, resulting in the dispersion of clays and consequent clogging of pores (Halliwell et al., 2001). Sodicity inhibits the process of flocculation by reducing the proportion of polyvalent cations adsorbed to negative exchange sites of clay particles, thus prohibiting the formation of microaggregates (Brady and Weil, 2008). This inhibition of flocculation is due to the large hydrated radius and single positive charge of sodium that weakly binds the ion to clays. The dominance of sodium ion absorption to clays therefore results in particles with thick ionic layers that inhibit the van Der Walls forces that attach individual clay particles to each other (Brady and Weil, 2008). Conversely, the small hydrated radius and two positive charges of calcium and magnesium results in a thin ionic layer, allowing van Der Walls forces to flocculate clay particles. As excessive amounts of sodium attach to ion exchange sites, soil swelling and physical dispersion of clays occur, with swelling resulting in the closing of spaces between peds and dispersion resulting in the clogging of pores (Brady and Weil, 2008).

To measure the relative amount of sodium to calcium and magnesium in the soil solution, the sodium adsorption ratio (SAR) is used

$$SAR = \frac{[Na^{+}]}{\sqrt{\frac{[Ca^{2+} + Mg^{2+}]}{2}}} \qquad [2.1]$$

where [] represents concentrations in $mmol_c/L$ (Halliwell et al., 2001) .

Responses to SAR and subsequent changes in hydraulic conductivity are affected by many factors. Clay type has an impact on dispersion with smectite being the most susceptible due to a 2:1 expanding lattice structure, while 1:1 clays such as kaolinite are much less susceptible (Lado et al., 2007; Ruiz-Vera and Wu, 2006). Organic matter influences dispersion as well, with increased organic mater content promoting soil aggregation, thus somewhat counteracting the effects of an elevated SAR (Barzegar et al., 1997; Nelson et al., 1999).

Reductions in infiltration due to irrigation of high SAR water are well known (Abu-Sharar and Salameh, 1995; Halliwell et al., 2001; Suarez et al., 2006). Application of high SAR water can reduce macroporosity and increase microporosity, resulting in reduced K_{sat} and increased unsaturated hydraulic conductivity at greater tensions (Goncalves et al., 2007). Irrigation of high-SAR water in sandy soils has been shown to enhance the dispersion of the small amount of clay that is present, increasing the likelihood of surface sealing and soil loss while reducing hydraulic conductivity when compared to freshwater sources (Lado et al., 2005; Mamedov et al., 2001). A column study in Israel on silty clays revealed that three years of irrigation with high SAR sources of spring water (SAR = 8.0) and Jordan River water (SAR = 14.7) reduced K_{sat} when compared to TWW (SAR = 6.2) and a control (SAR = 1.0) (Bhardwaj et al., 2007;

Mandal et al., 2008). Additionally, infiltration with waters having SAR values ranging from 10 to 30 on columns of sandy loams and clays resulted in a linear reduction in hydraulic conductivity to under 10% of the initial values (Bagarello et al., 2006).

The U. S. Salinity Laboratory defines a soil as sodic when the SAR > 13; however many factors can cause sodicity-related issues when the soil SAR is less than 13 (Halliwell et al., 2001). Dispersion of clay is influenced by the electrical conductivity (EC) of the applied water in addition to soil SAR, resulting in a point at which clays form microaggregates, known as the flocculation value (Brady and Weil, 2008). For a soil at a given SAR, the application of water with an increased EC will result in the development of two concentration gradients (Brady and Weil, 2008). First, the addition of anions in the soil solution results in the diffusion of anions towards soil colloids as the concentration around the colloids is initially near zero. Second, the increased cation concentration in the soil solution results in a positive gradient from the solution towards soil colloids. These two processes create thin, compressed ionic layers allowing clays to bind. Conversely, as EC decreases, anions and cations diffuse away from soil colloids, resulting in thicker ionic layers that hinder flocculation. Due to this phenomenon rainwater or irrigation water with an EC of less than 0.2 dS/m nearly always reduces infiltration (Ayers and Westcot, 1985).

Dispersion of clays and subsequent reductions in infiltration have been shown to occur in soils with SAR values well below 13. In a study of Aridisols with SAR's ranging from 5 to 20, a steady decrease of EC resulted in reduced hydraulic conductivity (Abu-Sharar and Salameh, 1995). Further decreasing the EC to slightly below the flocculation value decreased hydraulic conductivity by 41 to 57%. Similarly, a study of

Alfisols showed the same behavior when increasing soil SAR under applied water salt concentrations ranging from 5 to 100 mmol/L, with the greatest amount of dispersion occurring at the lowest concentrations of 5 and 10 mmol/L (Panayiotopoulos et al., 2004).

In addition to dispersion occurring under soil solutions with constant SAR or EC values, single or non-consecutive low EC events can induce dispersion at even lower SAR values. Column studies of silt loams with initial SAR's as low as 3.5 showed reductions in K_{sat} when leaching them with distilled water (Menneer et al., 2001). Observation of silty clays and sandy loams irrigated with water EC's of 1-2 dS/m showed that increasing the soil SAR from 2 to 4 can significantly reduce hydraulic conductivity (Suarez and Wood, 2008; Suarez et al., 2006). In addition, a linear regression of SAR's from 2 to 10 demonstrated that at any given EC, an increase in SAR may decrease hydraulic conductivity. Finally, a column study of leaching waters with salt contents of 0 to 100 mmol/L on sandy loams and loamy sands showed that reducing EC increased particle detachment and reduced hydraulic conductivity, with a final conductivity of less than 10% of the initial values when using deionized water (Dikinya et al., 2008). Additionally, it was noted that the most clogging occurred near the soil surface

With sprinkler irrigation sources, sodium-induced dispersion and subsequent clogging can be enhanced by kinetic forces caused by the impact of water droplets on the soil surface. Irrigating with waters of varying EC's and droplet impact energies on a sandy loam resulted in crust formation and a 40% reduction in infiltration when using low EC water with a high impact energy (Ben-Hur and Letey, 1989). Similarly, a comparison of freshwater and TWW sources at 4 droplet kinetic energy levels on clayey and loess derived soils showed that at lower kinetic energy levels areas under TWW irrigation had lower infiltration rates than freshwater areas (Mamedov et al., 2000). In addition to irrigation water EC, soil texture affects the rate of pore clogging, as rainfall simulations on soils with clay contents ranging from 3% to 65% revealed that soils with approximately 20% clay are most susceptible to clogging and associated infiltration reductions (Ben-Hur et al., 1985).

Pore clogging by suspended solids

A second cause of reductions in hydraulic conductivity under TWW irrigation is the physical clogging of soil pores due to high amounts of suspended solids in irrigation water (Dikinya et al., 2008; Viviani and Iovino, 2004). Infiltration observations on columns of fine-textured Aridisols resulted in K_{sat} reductions of 15 to 21% when using turbid water in place of clean water (Abu-Sharar and Salameh, 1995). Column studies also revealed that finer textured soils are more susceptible to clogging than those with high sand contents and demonstrated that the coarse fraction of suspended solids is most responsible for reducing infiltration, with the most clogging occurring in the top 5 to10 mm of the soil (Vinten et al., 1983; Viviani and Iovino, 2004).

Biological clogging

Pore clogging and reductions in hydraulic conductivity can also be the result of biological activity, often from the excretion of polysaccharides and humic substances by bacteria or fungi which are often associated with elevated microbial feedstocks and optimum moisture conditions (McKinley and Siegrist, 2007; Seki et al., 1998). Both can reduce hydraulic conductivity, although bacterial clogging can occur at a faster rate than fungal clogging (Seki et al., 1998). The effects of biological clogging can vary depending upon the presence of aerobic or anaerobic conditions, with aerobic conditions causing a slow reduction in infiltration and anaerobic condition resulting in an initially large decrease in infiltration followed by slow reductions (Thomas et al., 1965).

Column studies have shown staggering decreases in hydraulic conductivity from biological clogging that occur in very little time. Incubation of bacterial strains in sand revealed that a single strain can reduce K_{sat} by 100 times with potential for reductions of 10,000 times if multiple bacterial populations are present (Vandevivere and Baveye, 1992). Observations of silt-loam columns at two ambient temperatures showed biological clogging can cause reductions in K_{sat} in as little as one day, with a 70% reduction after 4 days (Balks et al., 1997). Following the reduction, a minimum of 22 days was needed to return K_{sat} to initial levels under an incubation temperature of 25º C. However, results were not as drastic at lower temperatures, as an incubation of 13º C resulted in K_{sat} reductions of 50%, although recovery was longer, taking 50 days. Varying effluent C:N ratios on a sandy loam showed that increasing the C:N ratio from 2.5:1 to 27:1 resulted in a decrease in K_{sat} of nearly 45% (Magesan et al., 2000). Also, increasing the C:N ratio from 2.5:1 to 66:1 resulted in a decrease of nearly 80%, suggesting that increased carbon will result in greater extra-cellular carbohydrate production and microbial growth

In addition to column studies, hydraulic conductivity reductions from biological clogging have been demonstrated in the field. Clogging has been shown in New Zealand, where three years of irrigation on an Andisol resulted in conductivity reductions of over

75% (Cook et al., 1994). Biological clogging can combine with other processes as well, as a study of silt loams in New Zealand revealed that irrigating only 35 mm of water with a suspended solids content of 0.6% reduced K_{sat} by 46% within 2 days, with repeat applications reducing infiltration to nearly 1 mm per day (McAuliffe et al., 1982). In the study immediate clogging was attributed to physical clogging while long-term clogging was attributed to biological processes.

Water repellency

In addition to processes that alter the physical structure of the soil, infiltration can be reduced by the presence of water repellent soils under TWW irrigation. Water repellency decreases infiltration rates due to a reduced water-soil contact angle and the presence of unstable wetting fronts (Graber et al., 2006; Tarchitzky et al., 2007; Wallach et al., 2005). The assumed cause of water repellency is the presence of long-chained hydrophobic organic compounds on soil particles (Thwaites et al., 2006). However, there has been difficulty in correlating the presence or intensity of water repellency with organic compounds, as compounds associated with repellency have been observed in non-repellent soils (Tarchitzky et al., 2007; Wallach et al., 2005).

A rapid transition of repellency to non-repellency has been observed with only a slight increase in water content, resulting in a critical value where soils become non-repellent (Dekker and Ritsema, 1994; Thwaites et al., 2006). Also, water repellency appears to be most prevalent under dry soils and the establishment of an irrigation regime can reduce water repellency (Thwaites et al., 2006). This was observed in Australia, where irrigating eucalyptus on water repellent soils with TWW at low (1/2 of evapotranspiration) and high (equal to evapotranspiration) rates eliminated repellency in 2 months at the high rate and 4 months at the low rate (Thwaites et al., 2006).

Other Effects of TWW Irrigation

Soil acidity

The effect of treated wastewater irrigation on soil pH varies widely among field studies. In the Muskegon County (MI) Wastewater Treatment System, over 30 years of TWW irrigation increased the pH of three sandy soils from 5.0-5.6 to 7.4-7.8 (Hu et al., 2006). Observations of loamy soils in Northern Victoria, Australia under 5 to 30 years irrigation of dairy manure, dairy factory effluent and sewage treatment plant effluent revealed an increase in soil pH of 1.1 to1.8 pH units (Tillman and Surapaneni, 2002). In silt loams and sands in New Zealand receiving TWW irrigation since 1995 and 1985, respectively, pH increased from 4.02 to 5.89 in silt loams (irrigated since 1995) and 5.34 to 5.59 in sands (irrigated since 1985) when compared to their respective controls (Vogeler, 2009). Flood irrigation of TWW (pH = 8.4) in Mexico resulted in increased soil pH for two soils receiving 25, 65, and 80 years of irrigation, although observed differences were not shown to be statistically significant (Friedel et al., 2000). However, in all instances it is important to note that the pH of the applied water was greater than the initial soil pH of the experimental sites.

Decreases in pH are possible under TWW irrigation, as flood irrigation of sugarcane production waste (pH = 5.02) in Cuba reduced soil pH from 7.1 to 6.7 at the 0 to 10 cm depth and from 6.2 to 5.9 at the 10-100 cm depth (Rosabal et al., 2007). Similar reductions, though not statistically significant, occurred at 5 other depths between 10 and

70 cm. Finally, the release of exchangeable cations by mineralizing organic matter can lower pH, which was observed in soils that were flood-irrigated for 30 years in Turkey (Angin et al., 2005).

Organic matter content

The irrigation of TWW seems to have no negative effect on soil organic matter (OM) content, with many studies showing an increase in OM. Thirty years of TWW application on the Muskegon County Wastewater Treatment system increased total OM by 0.70 to 1.20 percent (Hu et al., 2006). Observation of areas treated with 30 years of TWW in Turkey resulted in an increase in OM of over 1.0% to a depth of 30 cm (Angin et al., 2005). Accumulations can be seen at deeper depths as well, as irrigation of sugar cane processing effluent in Cuba showed increased OM content throughout the 100 cm profiles (Rosabal et al., 2007). Similar results were seen in 40 cm profiles of Vertisols irrigated for 2, 5, and 15 years in Jordan, with the 15 year site having the greatest OM content (1.26%) compared to the control treatment (0.67%) (Gharaibeh et al., 2007). The most drastic increases in OM were observed on Vertisols in Mexico under 25, 65, and 80 years of irrigation, with significant increases in total organic carbon ranging from 0.6% for 25 years of irrigation to 1.6% for 80 years of irrigation (Friedel et al., 2000)

In other instances increases in OM were observed, but were not significantly higher. Observations of silt loams and sands irrigated with TWW for 14 and 24 years revealed higher OM contents in irrigated sites for both soils (Vogeler, 2009). Similar results were obtained at the 0 to 10 and 10 to 20 cm depths for sandy Andisols and Entisols in New Zealand receiving 5 to 20 years of irrigation, respectively, and Vertisols receiving 23 years of irrigation in Israel (Bhardwaj et al., 2007; Magesan et al., 1999). Up to 80 years or TWW irrigation on Mollisols in Mexico showed increases in TOC when compared to sites receiving no irrigation as well (Friedel et al., 2000). Although instances where no statistically significant differences in OM are found, it is noteworthy that of all reviewed literature, no decreases in OM content were observed.

Penn State's Living Filter

Wastewater irrigation as a means of final treatment at Penn State started with the construction of a small test site in 1963 (Parizek et al., 1967). The purpose of the site was to address 1) eutrophication of Slab Cabin Run resulting from the discharge of wastewater and 2) reduced crop yields due to a multi-year drought that was occurring at the time (Parizek et al., 1967). It was believed that the new facility would be a viable means of recharging groundwater supplies and reducing nutrient loading into Slab Cabin Run while providing a sustainable irrigation source (Sopper, 1986).

A 26 ha site was constructed to irrigate various vegetation types with up to 1,890 m^3 of wastewater per day (Dadio, 1998). Initial cover included an abandoned field, a mixed hardwood forest, a red pine plantation and a cornfield, with a reed canarygrass site established in 1964 (Sopper and Richenderfer, 1978). A second site consisting of mixed hardwoods was then established in 1965 on State Gamelands #176. The first sites were irrigated with secondary treated wastewater at rates of 2.5 to 15 cm/week (Sopper, 1986).

The system was originally configured as a 24.4 x 24.4 m grid designed to irrigate 0.63 cm of effluent per hour (Dadio, 1998). Initially, graduate students operated the system, turning laterals off and on every 8 hours (Dadio, 1998). Due to safety concerns when operating the system in icy conditions, management of the facility was later shifted to faculty and staff members and eventually the Office of Physical Plant. Then, in an effort to reduce labor costs, the spacing was widened to 24.4 x 36.6 m, and laterals were operated for 12 hours, resulting in an average application rate of 0.42 cm per hour (Dadio, 1998). This modification allowed for the same amount of effluent to be applied, only over a longer irrigation cycle.

Initial research proved to be favorable, with 90% of the wastewater percolating to groundwater, with the remaining 10% consumed by the various crops and trees at the site (Sopper, 1986). Early analysis of water quality from nearby monitoring wells showed no accumulation of pollutants as well (Parizek et al., 1967). Due to the positive initial research, a permanent facility capable of irrigating up to 15,140 m^3 of wastewater per day was completed in 1983 (Sopper, 1986). The current facility consists of 96 km of piping and 3,100 Rain Bird 70 EW (Rain Bird Corp, Tuscon AZ) sprinklers with 6.35 mm nozzles operating at approximately 350 to 480 kPa and having a designed irrigated radius of approximately 20 to 22 m (Dadio, 1998; A. R. Jarrett, personal communication, Department of Agricultural and Biological Engineering, The Pennsylvania State University). The facility irrigates 708 ha of cropland and forest, with 27% of the facility located at the Penn State Astronomy Site and 73% of the facility located in PA State Gamelands #176 (Dadio, 1998). Pennsylvania DEP (2004) permits the application of 5.1 cm of wastewater per week, with the facility operating 365 days a year.

Previous research

Four major studies of soil physical and morphological properties have been performed on the Living Filter since its construction; Sopper and Richenderfer (1978), Simpson and Cunningham (1979), Dadio (1998), and Walker (2005). These studies have directly or indirectly measured soil physical properties and most have analyzed soil morphological features that relate to the infiltration and flow of water.

Sopper and Richenderfer first analyzed soil physical properties of the site in 1978. Their work included analysis of infiltration, saturated hydraulic conductivity, porosity, aggregate stability and bulk density. Infiltration analysis performed with an Alderfer-Robinson rainfall simulator on Hublersburg soils revealed reduced infiltration rates in mixed hardwood (p=0.01), red pine (p=0.05), and reed canarygrass (p=0.01) effluent treated plots when compared to untreated areas. However, increased infiltration rates were observed in irrigated corn plots (p=0.01) and differences in infiltration were noted on Morrison soils located in the Gamelands site. Similarly, infiltration measurements taken with a double-ring infiltrometer on non-forested land showed reduced infiltration rates for treated areas in the reed canarygrass plots (p=0.01) but increased infiltration in the corn plots (p=0.01) plots and abandoned field (p=0.01). Though little differences were observed between land uses in laboratory hydraulic conductivity experiments, water retention (0-7.5 cm depth) at 50 cm of tension was greater in Hublersburg soils in the mixed hardwood (p=0.01), red pine (p=0.01), reed canarygrass (p=0.05), and corn (p=0.01) land uses receiving effluent. However, mixed hardwoods under irrigation on Morrsion soils showed reduced water retention (p=0.01) at 50 cm of tension.

Simpson and Cunningham reported their analysis of morphological properties of the site in 1979. Their work included an examination of 15 soil pits in the corn and reed canarygrass irrigated and non-irrigated areas. A total of three irrigation rates were examined, with reed canarygrass sites receiving 231 cm of irrigation per year (5 cm/week Jan-Dec) and corn sites receiving 59 and 118 cm of irrigation per year (2.5 and 5 cm/week Apr-Oct). A qualitative scale was developed to analyze soil structure, color, redoxomorphic features, texture, and consistence, with a total score derived from the components. Their work showed an increase in structure size in the 118 (corn) and 231 (reed canarygrass) cm treatments (p=0.05), suggesting the potential for reduced permeability and degradation of structure. In addition, soil consistence was firmer and more resistant to rupture (p=0.08) in the 118 and 231 cm treatments (p=0.01), though this was believed to be associated with compaction in the upper subsoil.

Redoxomorphic feature size, contrast, abundance, and depth ratings were significantly worse for the effluent treated sites as well. Results revealed that redoxomorphic features were more abundant (p=0.05), had increased contrast (p=0.01), increased size (p=0.01), and occurred at shallower depths (p=0.01) in the areas receiving 118 (corn) and 231 (reed canarygrass) cm of irrigation per year, suggesting an overall greater period of wetness due to reduced permeability or the presence of a perched water table. Overall, the rating scale determined that the 118 (corn) and 231 cm per year (reed canarygrass) treatments were not suitable for irrigation and that the 59 cm (corn) treatment was marginally suitable. However, irrigation continued with current permitted application rates in excess of 250 cm per year.

A final component of Simpson and Cunningham's analysis was the identification of 'channels,' or vertical, conical-shaped bodies 1-10 cm wide and having a lower bulk density than the surrounding matrix. The channels began in the upper subsoil and expanded to lower horizons and may or may not have aligned with solution channels in bedrock. A greater number of channels were observed in the irrigated sites than untreated areas and the K_{sat} of the channels was 4x to 18x greater than that of the surrounding soil.

Walker revisited the work of Simpson and Cunningham and Sopper and Richenderfer in 2005. Six soil pits were excavated and 47 soil cores were taken at the locations of the Simpson and Cunningham study were examined and rated with the 1979 scale. The results of Walker's ratings were similar to those of Simpson and Cunningham in many categories. However, in the 26 years since the 1979 study, redoxomorphic feature size increased (p=0.03) for all landscape positions, although there was no change in depth, abundance, or contrast. Also, there was no difference between structure grade and type, although structure size increased (p=0.046) from the 1979 control area (22 years irrigation). However no change was noted in areas that had been irrigated prior to the Simpson and Cunningham study (40 years irrigation).

In addition to soil morphological properties, Walker compared saturated hydraulic conductivity data to that of Sopper and Richenderfer. He revealed a decrease in K_{sat} for sites that received irrigation for 40 years, with a K_{sat} of 6.50 cm/hr compared to 9.06 cm/hr recorded by Sopper and Richenderfer. A much larger decrease was noted in sites that received only 22 years of irrigation, with a K_{sat} of 1.20 cm/hr on irrigated areas compared to 14.23 cm/hr on non-irrigated areas, suggesting that the greatest reductions in saturated hydraulic conductivity may occur in the first few years of wastewater irrigation. Also, differences in bulk density were noted between Walker's and Sopper and Richenderfer's data, with average irrigated bulk densities of 1.42 to 1.51 g/cm^3, depending on landscape position for Walker, compared to 1.27 g/cm^3 in the control and 1.41 g/cm^3 in the irrigated areas of the Sopper and Richenderfer study.

In addition to the infiltration studies performed by Sopper and Richenderfer and Walker, Dadio predicted time to ponding during irrigation in 1998. Although predicted time to ponding was determined through a variety of parameters, it was found that a high amount of variability existed between predicted and actual time to ponding. The study also concluded that infiltration rates did not correlate well with landscape position, although a pattern of the highest infiltration rates occurring in depressions was present. In addition, piezometer measurements on hillslope transects revealed that ponding in the depressions was a result of runoff and not lateral flow. Finally, pedological observations to determine limiting layers showed that the depth to limiting layers increased with downslope location.

Measuring Hydraulic Conductivity with Tension Infiltrometers

Design and operation

Tension infiltrometers are often utilized to determine hydraulic conductivity at saturated and near saturated conditions. Due to their ability to measure conductivity over a range of pore sizes they are widely used in studies of tillage, compaction and land use changes where alterations to soil structure and pore size distribution can be identified (Angulo-Jaramillo et al., 2000). The design is based on Clothier and White's (1981) sorptivity tube, but addresses its shortcomings of a small infiltrative surface and potential for air entry under high-sorptivity conditions (Perroux and White, 1988). A tension infiltrometer (figure 2.1) consists of a porous infiltration plate connected to an airtight reservoir, which in turn is connected via tubing to a bubbling tower (Perroux and White, 1988). To achieve contact with the soil and eliminate air entry into the device, the infiltration plate is covered with a nylon membrane and a contact material such as sand is placed between the plate and soil. Operation of the infiltrometer consists of setting the tension by adjusting the air entry tube relative to the water level in the bubbling tower and determining the amount of flow from the reservoir (Perroux and White, 1988).

Water entry into the soil is a function of infiltrometer tension and soil matric potential (Perroux and White, 1988). For water to enter the soil, matric forces of the soil must overcome the resistance of the entry of air into the bubbling tower. When lowering the air entry tube, greater soil matric forces must be exerted to extract water from the infiltrometer, thus flow through larger soil pores is eliminated and flow is reduced. Conversely, raising the air entry tube results in reduced matric forces being required to extract water from the infiltrometer, resulting in flow from larger pores and increased flow from the infiltrometer. Due to limitations caused by air entry through the contact membrane, the practical limit of the infiltrometer is approximately 15 cm of tension (Angulo-Jaramillo et al., 2000).

The basic design of Perroux and White (1988) has remained relatively unchanged, with most improvements focusing on automation of the device. The first revision of the device was the installation of a transducer at the top and base of the reservoir (Ankeny et al., 1988). Determining the difference in pressure between the transducers and calibrating them against reservoir heights allowed for automatic data collection through the use of a datalogger. However, errors were possible due to improper synchronizing of the two transducers, in which bubbling in the reservoir resulted in false readings. This was corrected with the use of a single differential transducer connected via tubing to the base and top of the reservoir (Casey and Derby, 2002). The design eliminated the bubbling errors observed by Ankeny et al. (1988) and has become the standard for automated measurement. Further revisions of the design include the use of multiple air inlet tubes at different depths (tensions) in the bubbling tower, allowing for a solenoid-controlled valve on each tube to select infiltrometer tension (Spongrova et al., 2009). Other recent suggestions for improvement include a connected tube-within-tube reservoir in which air travels in the inner tube and water level is measured in the outer tube, reducing the effects of bubbling in the supply reservoir (Spongrova et al., 2009).

Many errors in tension infiltrometer measurement are the result of poor contact with the infiltration surface and poor contact material selection. Contact materials are used to provide a level, homogeneous surface for the infiltration plate and adjust for roughness and inconsistency of the soil surface (Perroux and White, 1988; Reynolds and Zebchuk, 1996). A proper contact material should have a hydraulic conductivity that is greater than that of the soil over the entire range of observed tensions and have conductivities and matric potentials that are stable and repeatable, with fine sand recommended as a suitable material. It is also suggested that a proper contact material should have a water entry value that is more negative than that of the infiltration membrane (Reynolds and Zebchuk, 1996). Additionally, reusing contact sand may create issues due to the washing of finer particles into the soil, and the use of reusable glass spheres in place of sand has been suggested (Bagarello et al., 2001; Reynolds, 2006).

A second source of error in infiltrometer measurement is due to an increase in tension from the infiltrometer caused by flow restrictions from the reservoir under high conductivity scenarios (Walker et al., 2006). Under most current designs this restriction occurs at flows greater than 200 cm^3/sec, although under field conditions such flow rates are usually not encountered. However, the use of larger tubing to connect the infiltration plate to the reservoir can reduce flow restrictions and pressure head offset at greater flow rates (Walker et al., 2006).

Interpreting infiltrometer data

Since the inception of the tension infiltrometer, scientists have developed ways to calculate K_{sat} using flow data from the device, with the first proposed solutions using measurements of sorptivity (Angulo-Jaramillo et al., 2000). Perroux and White's (1998) proposed solution used their prior (1987) equation relating the differences of sorptivites at positive and negative supply heads, with a similar approach taken by White and Perroux (1989) using Smiles' (1981) transformation of Philip and Knight's (1974) sorptivity expression . In addition to using sorptivity data, a number of solutions of Richards' equation have been used to calculate K_{sat} for both steady-state and time-dependent scenarios (Angulo-Jaramillo et al., 2000; Warrick, 1992). These solutions have many advantages as they account for 3-D flow, but they are dependent on proper parameter estimation. Richards' equation was further utilized with the development HYRDUS 2-D (PC-Progress, Prauge, Czech Republic), which uses cumulative flow rates at several tensions and solves for the equation through a weighted least squares model of parameter estimation (Simunek and van Genuchten, 1996; Simunek and van Genuchten, 1997). Finally, some scientists have taken a different approach to determine K_{sat} by using flow data from discs of two different radii (Hussen and Warrick, 1993b; Vandervaere et al., 2000) . However, double disc models can result in the estimation of unrealistic parameter values due to spatial variability and negative conductivity values may be calculated (Hussen and Warrick, 1993b).

Though many solutions to determine K_{sat} from infiltrometer data have been proposed in the last 20 years, one of the most widely accepted solutions has been Wooding's (1968) equation for infiltration from a shallow circular pond

$$Q_s = \phi_0 \left[\frac{4r}{\alpha} + \pi r^2 \right] \qquad [2.2]$$

where Q_s is saturated flow (L^3/T), ϕ_0 is matric flux potential (L^2/T), r is infiltration radius (L), and α is a fitting parameter. The α parameter is taken from Gardner's (1958) equation for matric flux potential, and is defined as the integral of unsaturated hydraulic conductivity over the range in pressure head, which equals

$$K_{\psi} = K_{sat} e^{\alpha\psi} \qquad [2.3]$$

where K is conductivity (L/T), ψ is matric potential (L), and α is a coefficient that relates the forces of gravity and capillarity in an undisturbed soil. Wooding's (1968) equation and Gardner's (1958) equation can be combined to form

$$Q_h = K_{sat} e^{\alpha\psi} \left[\frac{4r}{\alpha} + \pi r^2 \right] \qquad [2.4]$$

The solution was utilized in many early models to determine K_{sat} from infiltrometer flow data, with different approaches taken to determine α (Hussen and Warrick, 1993a; Reynolds and Elrick, 1991). Reynolds and Elrick (1991) and Ankeny et al. (1991) solved for α with a straight line relationship of ψ and the natural log of Q by

$$\alpha_{x,y} = \frac{\ln\left[\mathrm{Q_x}/\mathrm{Q_y}\right]}{\psi_{\mathrm{x}} - \psi_y} \qquad [2.5]$$

where Q_x and Q_y are flows at matric potentials of ψ_x and ψ_y, respectively, and x is a measured tension level, with y being the next measured tension level. Fitting parameter α can be solved over any range of tensions, although due to the exponential relationship between matric potential and hydraulic conductivity, a piecewise approach should be taken as successive values α and *K* will have different magnitudes (Ankeny et al., 1991; Reynolds and Elrick, 1991).

Though α was determined using similar equations, Ankeny et al. (1991) and Reynolds and Elrick (1991) took two different approaches to determining K(ψ). Reynolds and Elrick first solved for α using successive pairs of flow data (e.g. Q at 2 and 4 cm). Then an 'average K(ψ)' value, $\overline{K}$, is determined at the midpoint of the flow data (3 cm) using the equation

$$\overline{K}_{x,y} = \frac{\alpha_{x,y} Q_x}{4r(1+0.25\alpha_{x,y}\pi r)(Q_x / Q_y)^{\psi_x/(\psi_x-\psi_y)}} \qquad [2.6]$$

with flow Q, matric potential ψ, α fitting parameter and infiltration radius, *r*. The $\overline{K}$ value is then inserted in place of K_{sat} in equation 2.3 to determine K(ψ) at the midpoint of each pair of measured tensions and saturation (0 cm) (Reynolds and Elrick, 1991).

Ankeny et al. (1991) took a different approach by averaging K(ψ) values at each tension using Wooding's (1968) equation with α values determined at two successive pairs of tensions. At the highest and lowest measured tensions K(ψ) is calculated using α determined at the closest pair of measured tensions. For instance K(0 cm), K(2 cm), K(4 cm) and K(8 cm) would be calculated using the following equations.

$$K(0\text{ cm}) = K(0)_{0,2}$$

$$K(2\text{ cm}) = [K(2)_{0,2} + K(2)_{2,4}]/2$$

$$K(4\text{ cm}) = [K(4)_{2,4} + K(4)_{4,8}]/2$$

$$K(8\text{ cm}) = K(8)_{4,8} \qquad [2.7]$$

where the numbers in subscript represent tensions at which α is determined (Ankeny et al., 1991). Each method has its respective advantage, with the Reynolds and Elrick (1991) solution avoiding errors resulting from soil heterogeneity and the Ankeny et al. (1991) solution allowing for the determination of K(ψ) over a larger range of tensions as intermediate values are not used. However, both solutions have proven to be robust yet simple ways to evaluate K(ψ) and have been utilized extensively (Angulo-Jaramillo et al., 2000; Hussen and Warrick, 1993b).

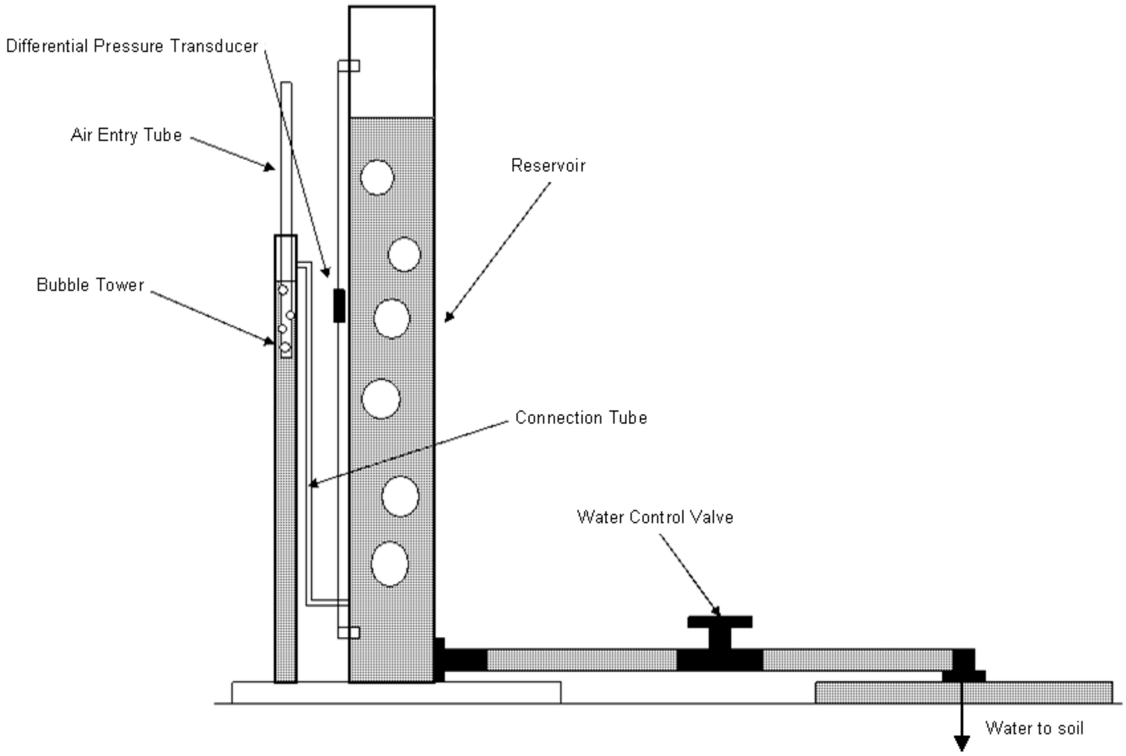

Figure 2.1. Design and operation of a tension infiltrometer. For water to move from an infiltrometer into the soil, air enters the entry tube and moves into the bubble tower. At this point air moves through the connection tube and fills the reservoir, allowing water to exit the reservoir and enter the soil through the infiltration plate.

Chapter 3

MATERIALS AND METHODS

Site Selection

Locating an experimental control to compare with irrigated areas at the Living Filter is challenging as the early success of the site combined with the need to maintain consistent crop maturity windows resulted in the majority of the property being irrigated, including the control areas of Sopper and Richenderfer and Simpson and Cunningham. Additionally, the rolling nature of the site precludes many areas from use as a control as they may receive run-on from adjacent irrigated areas. After extensively surveying the cropped area of the Astronomy Site, it was determined that the northeast side of the site could be used as an experimental control. The area is currently not irrigated and historical data suggests that it has never received TWW. Though the identified area does not receive irrigation, the field slopes downhill from southwest to northeast, resulting in run-on to the area in some locations. However, a series of local summits running parallel to the direction of water flow are present and analysis of the topography suggests that they do not receive run-on. Soils mapped within the area include the Hagerstown (fine, mixed, active, mesic Typic Hapludalf) and Hublersburg (clayey, illitic, mesic Typic Hapludult) series (NRCS, 2009). Relevant irrigation water composition data (table 3.1) for the site was taken at the discharge of the wastewater treatment plant and from sampling weirs at the site from multiple sampling dates in 2009.

After examining the local summits, 8 blocks were selected (figure 3.1) such that the irrigated area is paired with a non-irrigated area of similar local topography. Blocks were placed originating from the sprinklers radiating outward along the local summits encompassing the irrigated and non-irrigated areas. Each block was then divided into 8 sampling locations, placed every 4 meters from a sprinkler, with the farthest sampling location at 32 meters from the sprinkler. The resulting blocks included 4 sampling locations (4, 8, 12, 16 m) within the sprinkler's designed wetted radius and 4 sampling locations that receive little to no irrigation. For this study, the 20 m location was treated as a transition area as the designed distribution of the sprinkler and Dadio's (1998) analysis of sprinkler distribution patterns suggest that little water is irrigated at that distance. For each experiment, all 8 sites in each transect may or may not have been used depending upon the intended data comparisons and desired statistical analysis.

Hydraulic Conductivity

Hydraulic conductivity measurements were taken at the soil surface in August 2008 at 4, 8, and 12 m from the sprinklers within the irrigated area and at approximately 24, 28, and 32 m from the sprinklers in the non-irrigated area for a total of 48 observations. Measurements were performed with a tension infiltrometer as described by Perroux and White (1988) with tubing modifications as described by Walker et al. (2006) and water reservoir level measurement via a differential transducer as described by Casey and Derby (2002). For surface measurements, sites were cleared and plant matter was trimmed to ground level. Once sites were prepared, metal rings, 27 cm dia. x 10 cm deep were hammered into the ground to a depth of approximately 5 cm, and a 1-2 cm layer of contact sand was placed inside the ring to even the surface and provide contact with the infiltration plate.

Infiltration measurements were performed at 8, 4, 2, and 0 cm of tension, run from greatest to lowest tension and were run for 60, 45, and 30 minutes at 8, 4 and 2 cm of tension, respectively. For measurements at 0 cm of tension, infiltrometers were run for 30 minutes or until the reservoir was depleted, whichever occurred sooner. At all tensions, water level measurements from the transducer were recorded every 30 seconds with a Campbell CR 1000 datalogger (Campbell Scientific Inc., North Logan, UT). In addition, soil samples at the 0 to 8 cm depth were collected before and after infiltration measurements to determine soil gravimetric water content, with the initial sample taken next to the infiltration ring and final sample taken inside the ring once the contact sand was removed.

Bt horizon measurements were performed in May of 2009 at 8 and 28 m from the sprinkler in each block for a total of 16 measurements. To reach the Bt1 horizons, the Ap horizon was excavated with a shovel, at which point a soil knife was used to carefully expose the surface of the Bt horizon. A tension infiltrometer was then used in a similar fashion to that of the surface measurements, although measurements were taken for 90, 60, and 45 minutes for the 8, 4 and 2 cm tensions, respectively. The 0 cm tension was run for 30 minutes or until the reservoir was depleted.

Data analysis began by plotting the water level readings over time in an x, y scatter plot for each sampling location and infiltrometer tension level. Steady state flow, which was subsequent to the change of water entry from a function liner in the square root of time to linear in time was then determined. Next, a regression line was fit to the data points, with the slope of the line corresponding to drawdown within the reservoir.

Field saturated hydraulic conductivity was calculated using the methods of Ankeny et al. (1991) and Reynolds and Erick (1991) as described in the literature review.

Statistical testing of the H_0, no difference in hydraulic conductivity exists between irrigated and non-irrigated areas, was performed using a split-plot analysis of variance (ANOVA), with irrigation treatment and infiltrometer tension as whole-plot and sub-plot factors, respectively. Statistical significance was tested at p=0.05 for all data. Both surface and Bt1 hydraulic conductivity data was log-normally distributed and appropriate transformations were made before analysis.

Soil Surface Characterization

In addition to hydraulic conductivity, soil surface measurements of bulk density, organic matter content and soil texture were taken in order to determine the impact of TWW irrigation on measures of surface soil quality. In order to capture potential trends due to sprinkler distribution, measurements were taken from the Ap horizon at 4, 8, 12, 16, 20, 24, 28, and 32 m from the sprinklers.

Bulk density

Bulk density was measured with a Troxler 3411-B Nuclear Moisture Density Gauge (Troxler Electronic Laboratories, Research Triangle Park, NC). Such gauges have proved to be very accurate in measuring in situ bulk density and are well suited for determining differences due to land use effects (Ahuja et al., 1985; Ward and van Deventer, 1993). The device uses emits photons from a Cesium-137 source rod, which in turn travel though the soil and collide with electrons in soil particles, with some of the scattered photons returning to the gauge (Troxler, 2007). The gauge then counts the number of retuning photons, which is proportionate to the wet density of the soil. Moisture is determined by emitting neutrons from an Americium-241 source, which collide with hydrogen in soil water, with the device counting the number of thermalized, or slowed, neutrons (Troxler, 2007). Dry bulk density is then determined by subtracting the mass per unit volume of water in the soil from the wet bulk density.

Measurements were taken at the 0 to 10 cm depth (approximately ½ of the Ap horizon thickness for most sites) in October 2008 and May 2009. In addition, measurements were taken at the 0 to 20 cm depth during the May 2009 sampling period to observe potential differences in bulk density for the majority of the horizon. Sampling holes were prepared by driving a metal rod into the soil, with the gauge then aligned in the hole, making sure that the source rod was in contact with the soil. A 90 second measurement was used and all data was recorded in lbs/ft^3, which was converted to g/cm^3 for analysis.

Textural and organic matter analysis

Soil texture and organic matter content were determined at the 0 to 20 cm sampling depth, with textural analysis determined by the rapid method of Kettler et al. (2001). The method has been shown to correlate well with the pipette method and can be more consistent than the hydrometer method. For this, a 15 g oven-dry sample of the <2 mm faction was mixed with 45 ml of 30% hexametaphosphate and shaken for 2 hours. The solution was then wet-sieved through a #270 (0.053 mm) sieve to separate the sand (0.05 – 2 mm) and silt/clay (<0.05 mm) fractions, at which point the sand fraction was collected and dried. The silt and clay fractions were then filled to the 1,200 ml mark of a 1,500 ml beaker, stirred, and allowed to settle for 6 hours, at which point the clay in suspension was decanted and the remaining silt was oven-dried and weighed. The percent sand, silt and clay were then determined by dividing the measured masses of sand and silt into the original soil mass, and inferring the clay content from the difference of the original soil mass and the silt and sand contents. For the purpose of this study, statistical comparisons were made using the calculated clay faction.

Organic matter was obtained from oven-dry samples through loss on ignition at 450º C for 16 hours as described by Nelson and Sommers (1996), using a 5 g sample of the < 2 mm fraction. After heating, crucibles were removed from the oven as soon as possible, placed in desiccators and cooled to room temperature prior to final determination of mass.

Statistical analysis

Statistical testing of the H_0, distance from the sprinkler has no effect on 0 to 20 cm bulk density, clay content, and organic matter content was performed using a complete-block analysis of variance (ANOVA). Bulk density at the 0 to 10 cm depth was analyzed using a split-plot ANOVA with distance from the sprinkler as the whole plot and sampling date as the sub-plot factors. For both models, all variables and interactions were tested for statistical significance at $p=0.05$, with differences between means tested using Tukey's test of multiple comparisons at a significance level of $p=0.05$.

Soil Profile Analysis

To determine TWW irrigation's effect on subsurface soil properties, soil cores were taken in each sampling block and chemical and pedological properties were examined throughout the soil profiles. Fifteen cores, approx 6.5 cm dia. x 120 cm long were taken with a hydraulically-driven probe (Giddings Machine Co., Windsor, CO) in June 2009. Two cores were collected per block; one at 8 m from the sprinkler located in the irrigated area and one at approximately 28 m from the sprinkler located in the non-irrigated area. An irrigated sample was not obtained from block 3 due to wetness and sample compression within the sampling tube when attempting to retrieve a usable sample. Once collected, cores were taken to the lab and refrigerated at 1^{o} C until analyses was performed.

For examination, the cores were removed from the sampling tubes and split in half lengthwise. Horizons were then identified and described using the *Field Book for Describing and Sampling Soils* (Schoeneberger et al., 2002) identifying structure type, size and grade with color identified using Munsell notation. In addition, redoxomorphic feature size, quantity and color were noted. To determine texture, a representative sample was collected along the entire length of each horizon, with texture determined using the method of Kettler et al. (2001) as described under surface analysis. Due to the greater depths of the Bt2 horizon in the block 6-irrigated sample and Bt3 horizon in the block 4-irrigated sample, horizons were split into two subsamples. Texture and chemical properties were determined for the block 6-irrigated Bt2 horizon sample while the relatively shorter block 4-irrigated Bt3 horizon sample warranted subsampling for chemical properties, with one texture determined for the entire horizon.

Total organic carbon

Samples from each core were analyzed for total organic carbon, using the methods of Nelson and Sommers (1996) utilizing a Shimadzu CNHS-O flash combustion furnace. In this process, the sample, contained in a tin or silver capsule, is inserted into the furnace and heated to 1,000º C. A pulse of O_2 is injected, at which point combustion occurs at 1,700-1,800º C, oxidizing the capsule and combusting soil organic matter. The combustion products of CO_2, H_2O and N-compounds are passed through Cu and $Mg(ClO_4)_2$ columns to remove excess oxygen and water, respectively. Masses of the combusted products are then determined in a gas chromatograph and compared to original sample masses to determine percent carbon and nitrogen. The use of a gas chromatograph to measure ignited carbon results in greater analytical precision when compared to loss on ignition and due to the need to compare low total organic carbon contents of the subsurface samples this method was preferred for TOC analysis.

For analysis, representative oven-dry samples taken from the entire length of each horizon were ground and passed through a 150 µm (#100 mesh) sieve and 9 to 10 mg the of sample was then placed in silver capsules. In order to remove potential carbonates, samples were treated with 10 µl of 2 N HCl and heated at 80º C until dry, with little to no effervescence noted during acidification. Analysis was performed in two runs, with calibration checks performed before and after each sampling run as well as after every 10 samples. If any discrepancy was noted during a calibration check, analysis was stopped and any sample analyzed after the last satisfactory calibration check was rerun.

Soil SAR, EC & pH

Soil SAR, EC and pH were determined by the procedures described in *Methods of Soil Analysis* using a 1:1 soil-water extract (Rhoades, 1996; Thomas, 1996). For all measurements, a representative 30 g oven dry sample of the < 2 mm fraction was taken from each horizon. Then, 30 ml of deionized water was added and samples were shaken on a rotary shaker for 2 hours. After shaking, samples were centrifuged at 5,000 RPM for 30 minutes and the extracted supernatant was placed in 25 ml centrifuge tubes for pH and EC analyses.

Electrical conductivity and pH were measured using a VWR SB80PC (VWR International, West Chester, PA) conductivity/pH meter. The conductivity probe was calibrated with KCl solutions using the same 25 ml centrifuge tubes as the samples and measurements were standardized at 20º C. The pH probe was calibrated using standard buffers and 25 ml centrifuge tubes as well. After pH and EC were determined, samples were analyzed for Ca, Mg, and Na concentrations by the Penn Sate Agriculture Analytical Services Laboratory using inductively coupled plasma (ICP) analysis, with SAR calculated using equation 2.1.

Statistical analysis

Statistical testing of the H_0, no difference exists between clay content, TOC, pH, EC, and SAR of the irrigated and non-irrigated treatments, was performed using 2 sample t-tests. For analysis, data was sorted by horizon and tested separately from adjoining horizons, with differences between means tested for statistical significance at $p=0.05$.

Constituent	Concentration (mg/l)
Ammonia-N	0.730
Nitrate-N	8.47
Nitrite-N	0.637
Orthophosphate-P	2.14
Sulphate	30.6
BOD	3.39
COD	21.7
TOC	3.90
Total alkalinity	197
Total hardness	232
TDS	688
Chloride	217
Calcium	61.9
Magnesium	29.5
Sodium	124
EC	1.06 dS/m
SAR	9.56
pH	7.17

Table 3.1. Composition of irrigation water. Data was taken at the discharge of the wastewater treatment plant and sampling weirs at the site. Sampling frequency ranged from once per year to once per month and testing methods were consistent with EPA and PA DEP requirements.

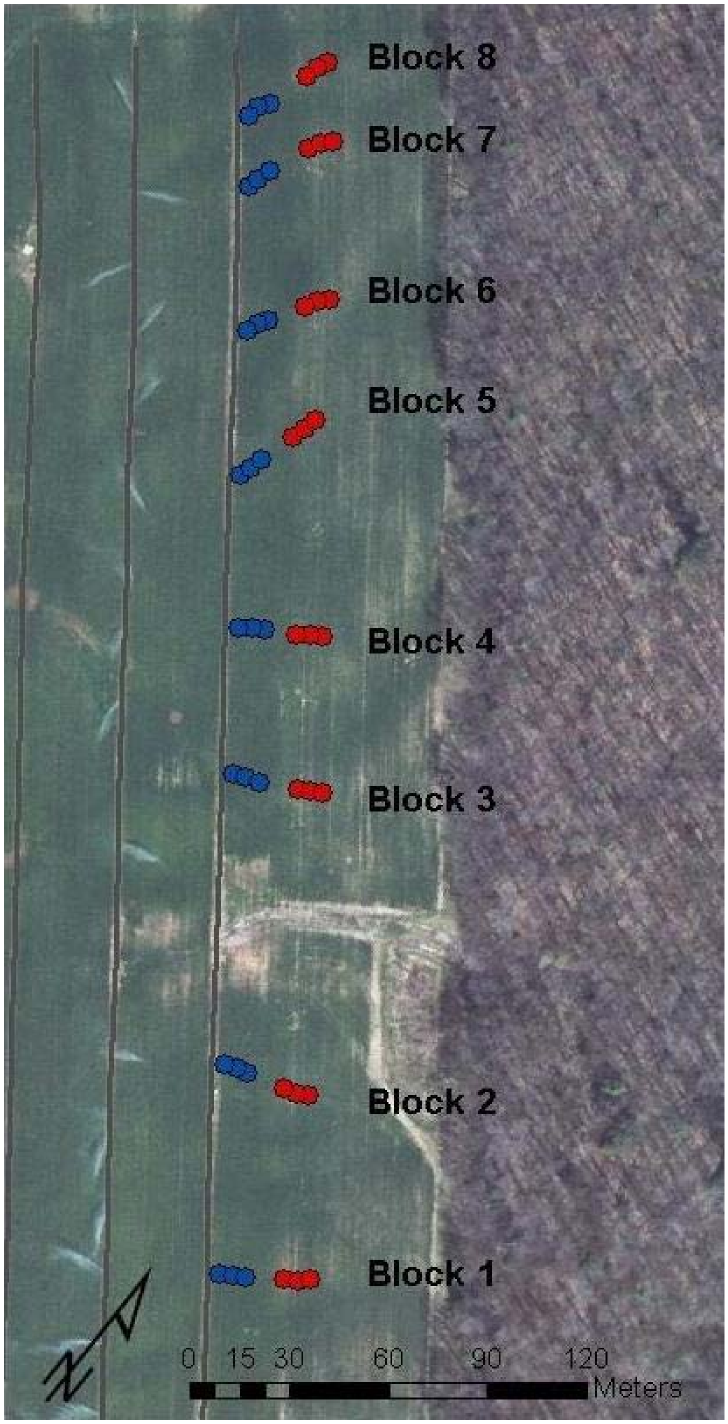

Figure 3.1. Layout of sampling blocks. Eight sampling blocks situated on local summits radiating from sprinklers were established at the edge of the cropped area of the astronomy site. The area has been irrigated for approximately 26 years and been under no till practices for over 15 years. Irrigated hydraulic conductivity sampling points are marked in blue and non-irrigated points are in red.

Chapter 4

RESULTS

Hydraulic Conductivity

The split-plot statistical model allows one to determine the effects of the treatment (whole plot) and tension (sub-plot) factors and the treatment x tension interaction on hydraulic conductivity. We can also analyze their respective p-values to determine the likelihood we would be in error to conclude that a variable or interaction has an effect on hydraulic conductivity. When determining if the experimental variables have an effect on hydraulic conductivity, the treatment x tension interaction must first be analyzed, which allows one to compare differences in hydraulic conductivity at each calculated tension. However, if no interaction exists, statistical comparisons can only be made within the limitations of the separate experimental variables. If the interaction does not exist but the treatment factor has a significant effect on hydraulic conductivity, one can then compare the effects of irrigation across the entire range of calculated values, but not at separate tensions. Similarly, if tension has a significant effect on hydraulic conductivity, one can compare hydraulic conductivities between tensions, but not between treatments. For both surface and Bt1 hydraulic conductivity measurements, tension had a significant effect on hydraulic conductivity, but since such differences were expected, there is no need to make any further analysis and one only needs to examine the effects of the irrigation treatment and the treatment x tension interaction.

Surface hydraulic conductivity

Although two different models were used to calculate hydraulic conductivity, the Ankeny et al. (1991) and Reynolds and Elrick (1991) (herein referred to as Ankeny and Reynolds, respectively) models produced similar p-values for the treatment and treatment x tension interaction. For both models we cannot conclude that the treatment x tension interaction had a statistically significant effect on hydraulic conductivity, with p-values of 0.1292 for the Ankeny model and 0.0798 for the Reynolds model (table 4.1). Although differences between calculated hydraulic conductivities due to irrigation were not found to be statistically significant for the Ankeny model (p=0.0602), differences were found to be statistically significant using the Reynolds model (p= 0.0468). However, differences observed using either approach indicate a small likelihood of making a Type I error if we conclude that hydraulic conductivities are different due to irrigation.

A comparison of the plots of mean hydraulic conductivity over infiltrometer tension (figure 4.1) allows us to visually compare the differences between the irrigated and non-irrigated treatments of the Ankeny and Reynolds conductivity models. At 0 cm of tension (saturation) both methods resulted in calculated K_{sat} values of 19.0 cm/hr in the non-irrigated area and 19.2 cm/hr in the irrigated area (table 4.2), which is expected, as both models use measured flow values at 0 and 2 cm of tension. However, as infiltrometer tension was applied, the methods behaved differently in regards to differences in conductivity between the irrigated and non-irrigated areas.

Using the Ankeny model, the irrigated area had a calculated mean K(2 cm) of 7.4 cm/hr and a non-irrigated area mean K(2 cm) of 7.5 cm/hr. Considering the similar conductivities of the irrigated and non-irrigated areas at 0 and 2 cm of tension and the variability inherent in hydraulic conductivity measurements we can assume that there is no difference in hydraulic conductivity at or near saturation between the irrigated and non-irrigated areas of the Living Filter. However, differences in K(4 cm) due to treatment began to develop, with mean values of 0.74 cm/hr in the non-irrigated area and 1.2 cm/hr in the irrigated area. Although differences are somewhat apparent at 4 cm of tension, mean K(8 cm) values began to converge, with irrigated and non-irrigated values of 0.19 and 0.15 cm/hr, respectively.

Differences in calculated mean hydraulic conductivity rates between treatments for the Reynolds model are similar to those of the Ankeny model for the lower tensions, with K(1 cm) values of 11.4 cm/hr in the non-irrigated area and 11.7 cm/hr in the irrigated area. However, conductivity values began to diverge at 3 cm of tension, with mean K(3 cm) values of 3.2 and 2.5 cm/hr in the irrigated and non-irrigated areas, respectively. Mean hydraulic conductivities further diverge at 6 cm of tension, with K(6 cm) being 0.49 cm/hr in the irrigated area and 0.29 cm/hr in the non-irrigated area, contrasting the Ankeny model that converged at the highest calculated tension.

At this point we see how the differences in conductivity models can affect the calculated conductivity values. To calculate K(4 cm) the Ankeny model utilizes 3 measured flow values (2, 4, and 8 cm), while the Reynolds model uses 2 values (2 and 4 cm) to calculate K(3 cm). Similarly, the Reynolds model uses two known flow values at 8 and 4 cm to obtain the K(6 cm) value. However, since only two values are available to calculate K(8 cm), the Ankeny model uses two known flow values (8 and 4 cm) instead of three. Although the models present slightly different trends relative to infiltrometer tension, both result in notable visual differences in conductivity between 3 and 6 cm of tension, which is assumed to be the cause for the differences in treatment p-values.

Bt1 horizon hydraulic conductivity

For both conductivity models, no statistically significant differences in hydraulic conductivity relative to irrigation treatment were present (figure 4.2), with the Ankeny model having a p-value of 0.3861 and the Reynolds model having a p value of 0.6282. Additionally, the treatment x tension interaction p-values were not statistically significant, with p-values of 0.9577 and 0.9587 for the Ankeny and Reynolds and models, respectively.

Surface Analysis

Bulk density

Analysis of soil bulk density at the 0 to 10 cm depth revealed that distance from the sprinkler had a statistically significant effect on bulk density, with the lowest values located within the sprinkler’s irrigated radius. In addition, differences in bulk density between the fall 2008 and spring 2009 sampling dates were statistically significant, although there was no distance x time interaction between the two experimental factors (table 4.3). A comparison using Tukey’s test of the 2008 and 2009 combined mean bulk densities with respect to distance from the sprinkler (figure 4.3, table 4.4) revealed that the 3 samples nearest the sprinkler (4, 8, 12 m) had lower bulk densities than samples at 20 and 24 m from the sprinkler. Additionally, the overall trend of the data demonstrates that the bulk density in the irrigated area is lower than the non-irrigated area, with the 20 m measurement that receives a negligible amount of irrigation having a value similar to those in the non-irrigated area. Further, the overall trends in the data remained constant in the 2008 and 2009 sampling periods, with bulk densities being 0.05 to 0.1 g/cm^3 greater in the 2009 sampling period. It is also noteworthy that little variability was present in the sampling area, with standard deviations ranging from 0.04 to 0.08.

Analysis of bulk density at the 0 to 20 cm sampling depth revealed that distance from the sprinkler did not have a statistically significant effect on bulk density, with densities ranging from 1.60 to 1.69 g/cm^3. In addition, no real trend existed similar to the 0 to 10 cm measurements and individual sampling points were more widely distributed than the bulk densities measured at the 0 to 10 cm sampling depth.

Surface horizon clay and organic matter content

The effect of distance from the sprinkler on clay content at the 0 to 20 cm sampling depth was statistically significant with a p-value of 0.0192 (table 4.3). However, Tukey's test was not able to separate the means at a significance level of 0.05. Although differences could not be quantified through the use of Tukey's test, visual analysis of the plot of mean clay content (table 4.4, figure 4.4) over distance from the sprinkler shows behavior similar to that of the bulk density results. In this instance the lowest mean clay contents at the 0 to 20 cm depth were within the irrigated radius of the sprinkler, with contents ranging from 14.3% to 19.9% and the 20 m measurement again having values similar to those outside of the irrigated radius. Outside of the designed irrigated radius clay contents ranged from 19.9% to 20.7%. Organic matter contents ranged from 4.8% to 5.0% across the sampling area and with a p-value of nearly 1.0, no statistically significant differences due to distance from the sprinkler were observed.

Soil Profile Analysis

Soil acidity

For all sampled horizons, mean soil pH values were greater in the irrigated area than the non-irrigated area, with the Ap, Bt1, Bt2 and Bt3 horizons having p-values less than 0.001 and the Bt4 horizon having a p-value of less than 0.05 (table 4.5). In the irrigated area, pH's ranged from 5.32 to 6.40 throughout the sampled profile, while pH's ranged from 4.48 to 5.40 in the non-irrigated area. A comparison of the plots of pH at the mean horizon midpoint depths (figure 4.5) reveals two interesting trends. First, the overall trends for both areas revealed that from the Ap to Bt1 horizons, pH increased slightly followed by a steady decrease through the Bt2, Bt3, and Bt4 horizons. Additionally, irrigated area pH's were approximately 1.0 pH unit greater than non-irrigated pH's for all horizons, resulting in an entire shift of the plot of pH vs. horizon midpoint depth, with a retention of the overall shape of the non-irrigated area, but at greater soil pH's in the irrigated area.

Electrical conductivity

The soil solution EC's of the irrigated and non-irrigated areas have two different trends relative to horizon depth (figure 4.6). A comparison of the two reveals that there is no statistically significant difference in mean Ap horizon EC's, although differences relative to irrigation treatment were significant in the Bt1 horizon, with a p-value of less than 0.05 and p-values of less than 0.0001 in the Bt2, Bt3 and Bt4 horizons (table 4.5). When comparing the plots of EC at the mean horizon midpoint depths, both areas had the highest EC values in the Ap horizons, at 0.821 and 0.695 dS/m for the irrigated and non-irrigated areas, respectively. For both treatments, EC decreased dramatically from the Ap to the Bt1 horizons and relative differences between treatments began to develop, with an irrigated EC of 0.347 dS/m and a non-irrigated EC 0.245 dS/m in the Bt horizons. However, differences in EC remained relatively constant in the Bt2 through Bt4 horizons, with EC values ranging from 0.247 to 0.287 and 0.089 to 0.121 in the irrigated and non-irrigated areas, respectively.

Sodium adsorption ratio

The sodium adsorption ratio (SAR) remained relatively constant throughout the profile in the non-irrigated area, with values ranging from 0.42 to 0.75 (figure 4.7). However, a trend of increasing SAR's with depth was present in the irrigated area of the Living Filter, with differences between the irrigated and non-irrigated areas being statistically significant and having p-values of less than 0.0001 for the Ap, Bt1, Bt2, and Bt3 horizons and less than 0.001 for the Bt4 horizons (table 4.5). In the irrigated area, the Ap horizon had the lowest SAR of the profile at 1.61, with the biggest relative increase occurring between the Ap and Bt1 horizons, which had an SAR of 3.33. A further increase occurred from the Bt1 to Bt2 horizons, with SAR's remaining relatively constant in the Bt3 and Bt4 horizons.

Clay content and total organic carbon

Observations of clay content with depth revealed no statistically significant differences in clay content between irrigated and non-irrigated areas, with clay contents ranging from 14.6 to 35.8% in the irrigated area and from 16.3% to 33.3% in the non-irrigated area (table 4.5). For both areas, the Ap horizons had the lowest clay contents, with relative increases in clay content going from the Ap to Bt1 and Bt1 to Bt2 horizons and relative decreases in the Bt3 and Bt4 horizons. Additionally, irrigation had no statistically significant effect on mean total organic carbon content for all horizons in the observed profile. Of all horizons, the greatest differences in TOC were in the Ap horizon ($p=0.1089$), with mean irrigated TOC of 1.34% and a non-irrigated mean TOC of 1.19%. From the Ap to Bt1 horizons TOC decreased drastically, at which point decreases were steady although less drastic for the Bt2 through Bt4 horizons, with mean TOC's ranging from 0.248% to 0.303% in the Bt1 through Bt4 horizons for both the irrigated and non-irrigated areas.

Treatment	Num DF	Den DF	F Value	Pr > F
Ankeny - Surface				
Treatment	1	7.8	4.82	0.0602
Tension	3	168	564.39	<0.0001
Treatment*tension	3	168	1.91	0.1292
Reynolds - Surface				
Treatment	1	7.6	5.63	0.0468
Tension	3	168	538.10	<0.0001
Treatment*tension	3	168	2.29	0.0798
Ankeny - Bt1 horizon				
Treatment	1	5.5	0.76	0.3861
Tension	3	52	69.52	<0.0001
Treatment*tension	3	52	0.10	0.9577
Reynolds - Bt1 horizon				
Treatment	1	6.5	0.26	0.6282
Tension	3	45.7	66.98	<0.0001
Treatment*tension	3	45.7	0.10	0.9587

Table 4.1. Analysis of variance (ANOVA) tables for hydraulic conductivity measurements. Ankeny denotes the Ankeny et al. (1991) conductivity model and Reynolds denotes the Reynods and Elrick (1991) conductivity model. Surface denotes conductivity at the soil surface and Bt1 denotes measurements on the top of the Bt1 horizon.

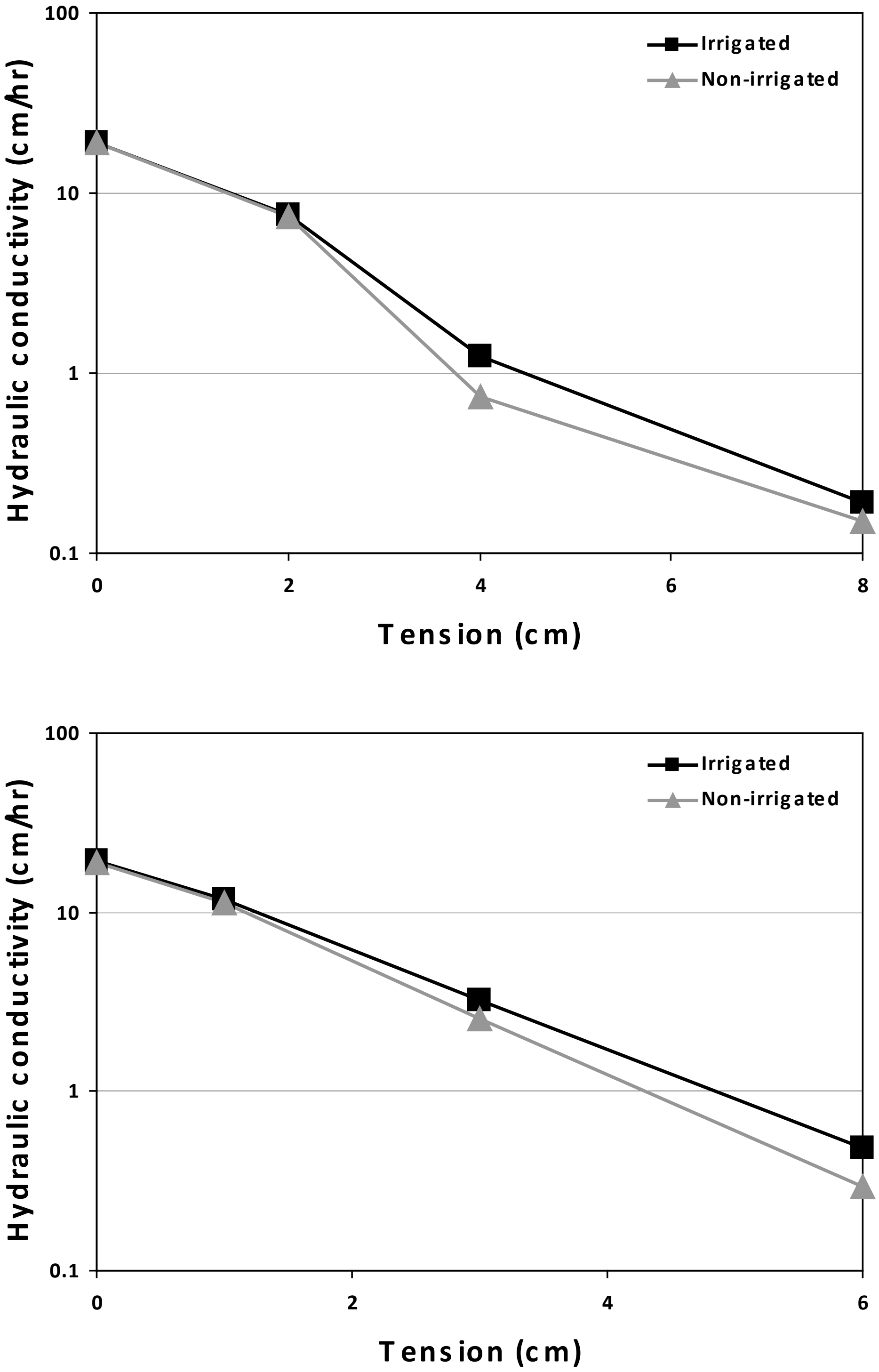

Figure 4.1. Mean surface hydraulic conductivity. The Ankeny et al. (1991) model (top) has calculated conductivities at 0 to 8 cm of tension while the Reynolds and Elrick (1991) model (bottom) has calculated values at 0 to 6 cm of tension.

	Ap horizon		Bt horizon	
	Irrigated	Non-irrigated	Irrigated	Non-irrigated
Tension (cm)	Hydraulic conductivity (cm/hr)			
Ankeny et al.				
0	19.2	19.0	2.5	2.6
2	7.5	7.4	0.7	0.8
4	1.2	0.7	0.2	0.3
8	0.2	0.2	0.1	0.1
Reynolds & Elrick				
0	19.2	19.0	2.5	2.6
1	11.7	11.4	1.4	1.5
3	3.2	2.5	0.4	0.5
6	0.5	0.3	0.1	0.1

Table 4.2. Calculated mean hydraulic conductivity values. Ap horizon denotes surface measurements and Bt horizon denotes measurements at the top of the Bt1 horizon.

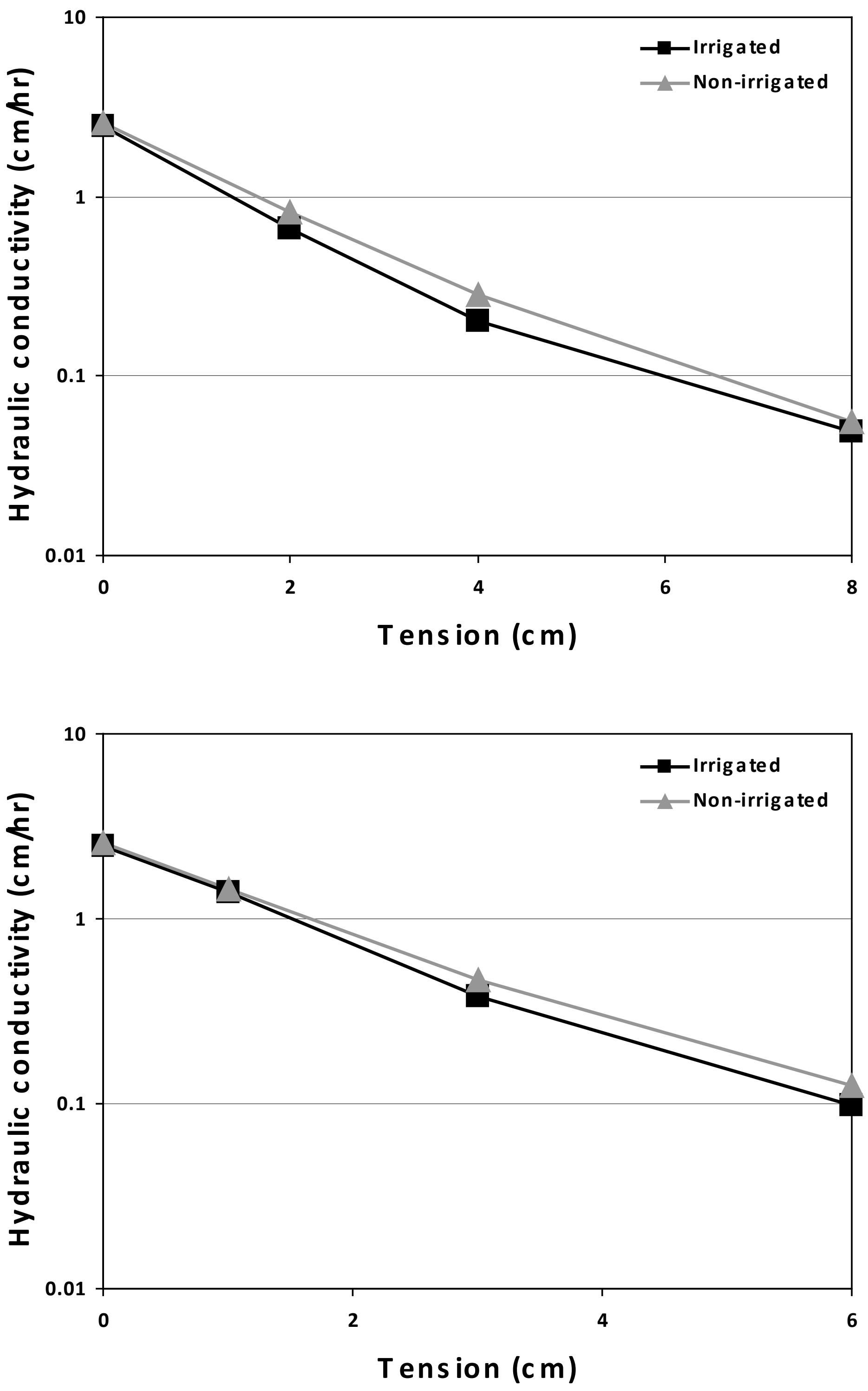

Figure 4.2. Bt1 horizon mean hydraulic conductivity. The Ankeny et al. (1991) model (top) has calculated conductivities at 0 to 8 cm of tension while the Reynolds and Elrick (1991) model (bottom) has calculated values at 0 to 6 cm of tension.

Treatment	Num DF	Den DF	F Value	Pr > F
2008 + 2009 BD				
Distance	7	56	5.78	<0.0001
Time	1	64	50.24	<0.0001
Distance*time	7	64	1.33	0.2531
2009 20 cm BD				
Treatment	7	56	1.49	0.1904
Clay content				
Distance	7	56	2.65	0.0192
Orgainc matter				
Distance	7	56	0.19	0.9854

Table 4.3. Analysis of variance (ANOVA) tables for surface bulk density and clay and organic matter contents. The 2008 and 2009 bulk density measurements were sampled at the 0 to 10 cm depth and the 2009 (only) data was sampled at the 0 to 20 cm depth. Both the clay content and organic matter content measurements were sampled at the 0 to 20 cm depth.

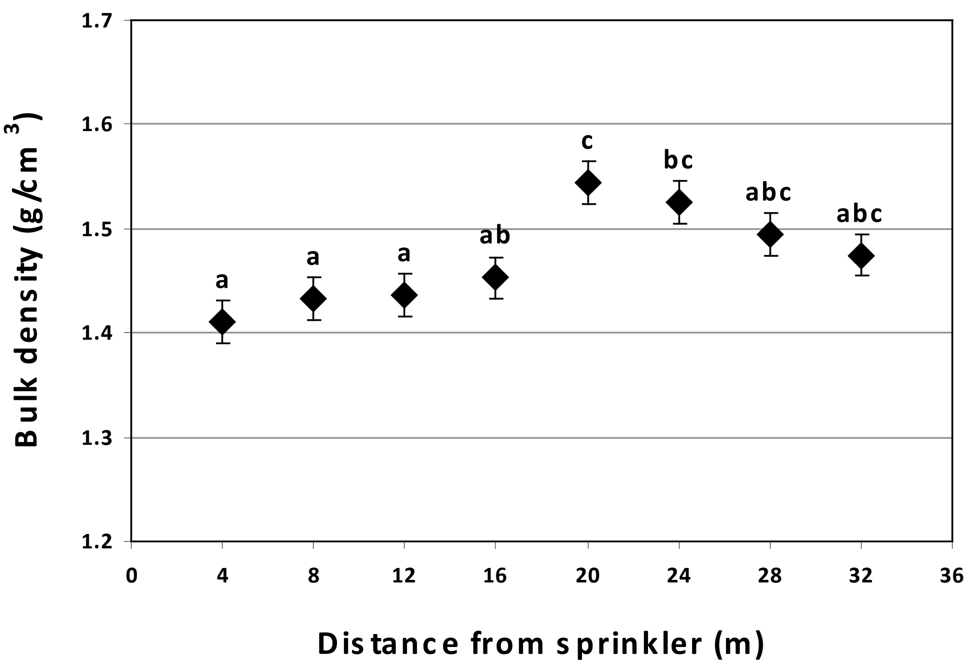

Figure 4.3. Mean bulk density with respect to distance from the sprinkler. The designed irrigated radius is approximately 22 m. However, prior analysis of sprinkler distribution patterns indicate that areas at 20 m from the sprinkler receive little irrigation.

	10 cm depth			20 cm depth		
	2008	2009	08 + 09	2009	% Clay	% OM
Distance	Bulk Density (g/cm^3)					
4	1.37	1.45	1.41	1.60	14.3	4.84
8	1.41	1.46	1.43	1.65	16.5	4.87
12	1.39	1.48	1.44	1.63	15.4	4.82
16	1.39	1.52	1.45	1.66	17.1	4.92
20	1.50	1.59	1.54	1.69	19.9	4.88
24	1.51	1.54	1.53	1.67	20.7	4.98
28	1.46	1.52	1.49	1.62	19.9	4.82
32	1.46	1.49	1.47	1.60	19.5	4.75

Table 4.4. Living Filter soil surface analysis. Bulk density at the 0 to 10 cm sampling depth is presented for the 2008, 2009 and average of both sampling dates. Bulk density at the 0 to 20 cm sampling depth was recorded only once. Clay and organic matter content measurements were taken at the 0 to 20 cm sampling depth.

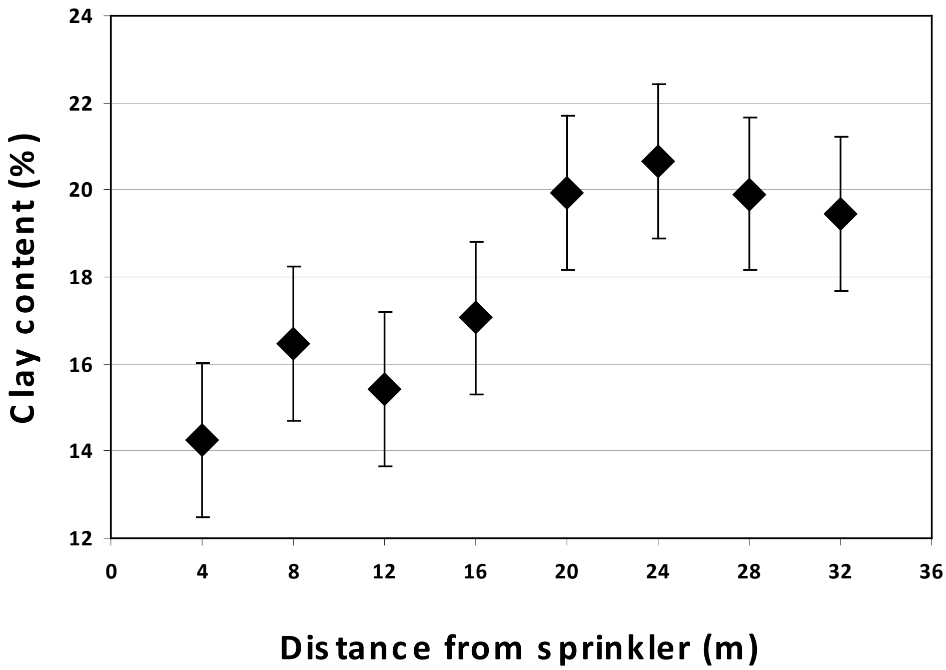

Figure 4.4. Mean clay content with respect to distance from the sprinkler. Letters are not used as Tukey's test was not able to separate the means. Designed irrigation radius is approximately 22 m although prior analysis of sprinkler distribution patterns indicate that areas at 20 m from the sprinkler receive little irrigation.

Horizon	Irr	No irr	Irr	No irr	Irr	No irr	Irr	No irr	Irr	No irr
	pH		EC (dS/m)		SAR		% clay		% TOC	
Ap	6.31	5.18 **	0.821	0.695 NS	1.61	0.42 ***	14.6	16.3	1.340	1.190
Bt1	6.40	5.40 **	0.347	0.245 *	3.33	0.69 ***	25.2	26.1	0.373	0.367
Bt2	6.16	4.98 ***	0.287	0.121 ***	3.95	0.65 ***	35.5	29.9	0.303	0.266
Bt3	5.71	4.73 **	0.271	0.101 ***	3.93	0.75 ***	35.8	33.3	0.272	0.252
Bt4	5.32	4.48 *	0.247	0.089 ***	4.25	0.68 **	35.8	33.3	0.268	0.248

Table 4.5. Mean values and statistical significance for soil profile analysis. For statistical significance '*' denotes that p-values were less than 0.05, '' less than 0.001, '***' less than 0.0001 and 'NS' being not significant. Differences in means were not statistically significant for all horizons for the analysis of percent clay and percent total organic carbon (TOC) and thus no annotations are present.**

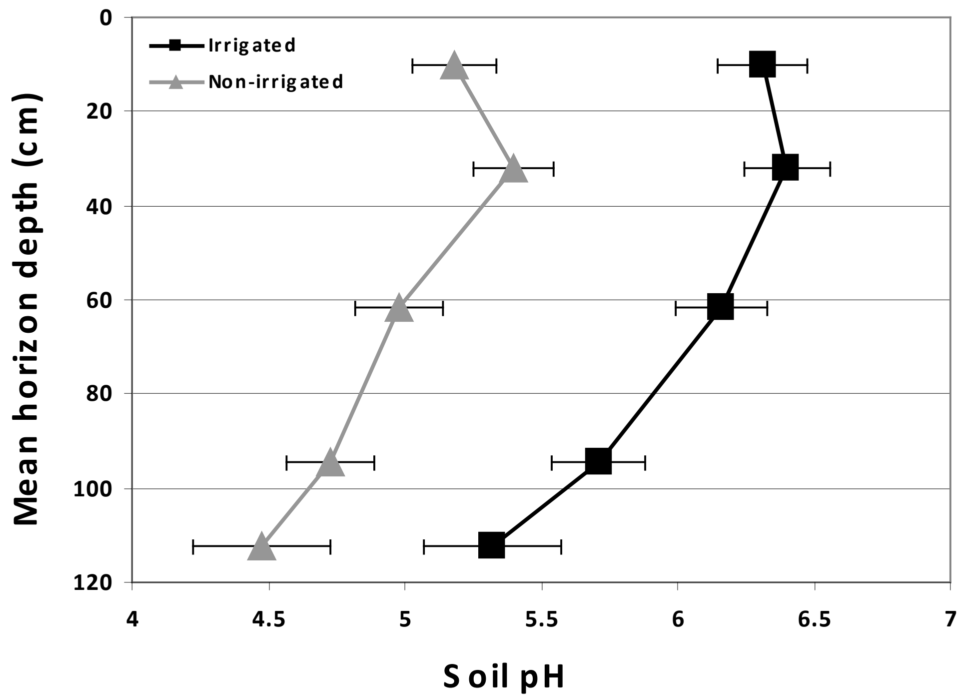

Figure 4.5. Mean soil pH at mean horizon midpoint depths. Error bars denote standard errors of the mean, with differences between means being statistically significant at all horizons.

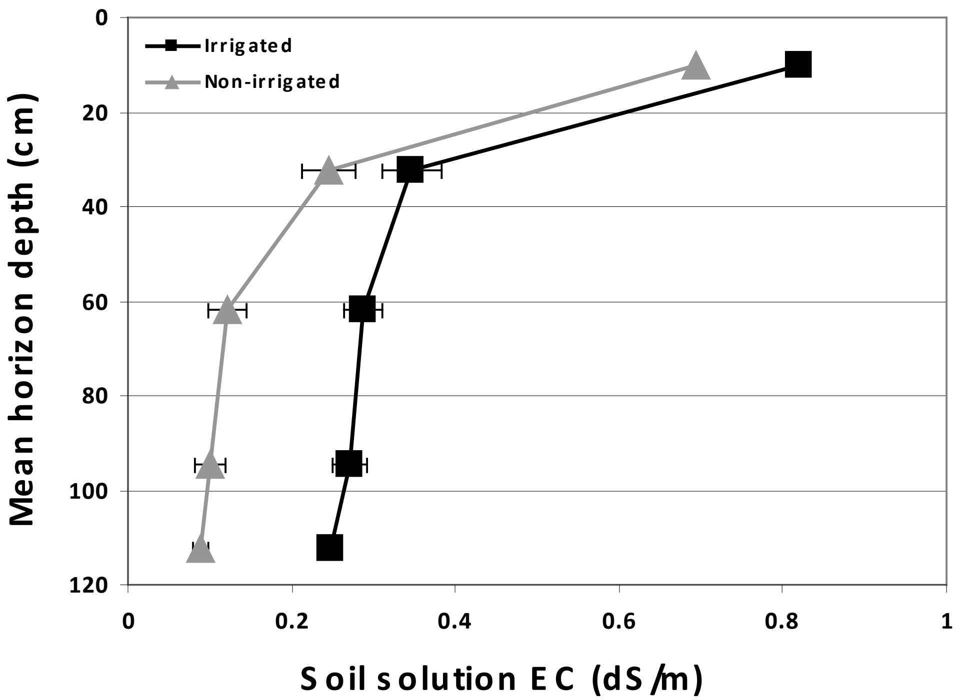

Figure 4.6. Mean soil electrical conductivity (EC) values at mean horizon midpoint depths. Error bars denote standard errors of the mean. No error bars are present at 9 cm (Ap horizon) as differences between EC were not statistically significant. Error bars at 115 cm (Bt4 horizon) are present, but are masked by the icons.

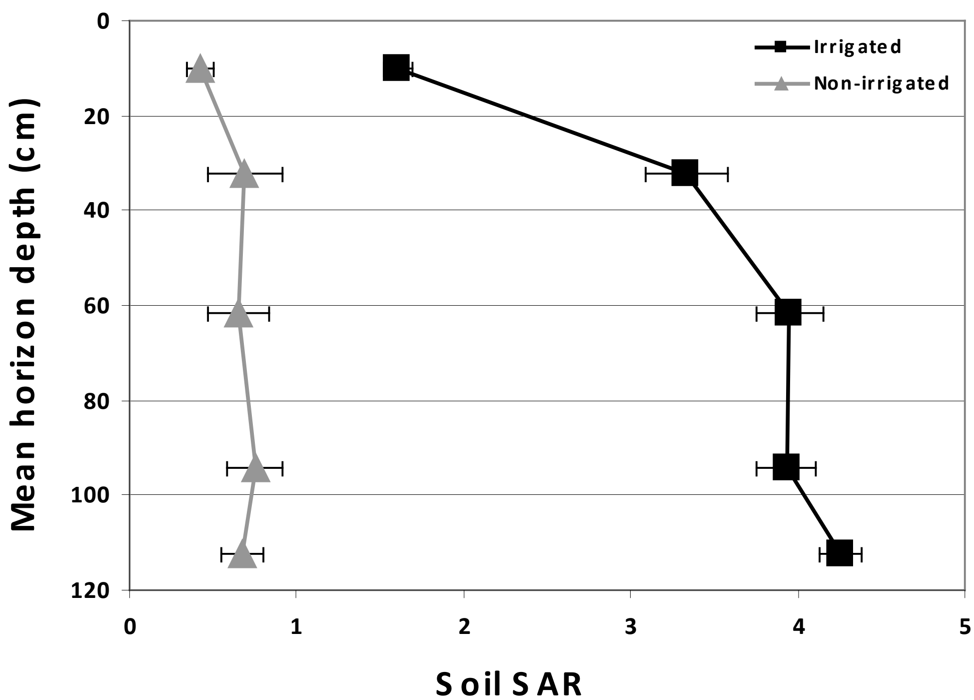

Figure 4.7. Mean soil sodium adsorption ratio (SAR) values at mean horizon midpoint depths. Error bars denote standard errors of the mean. Error bars at the 9 cm depth (Ap horizon) are present, but masked by the icons.

Chapter 5

DISCUSSION

The sustainable operation of the Living Filter as both a means of wastewater renovation and area of agricultural production is highly dependent on not having negative impacts on hydraulic conductivity and soil quality. However, these processes can impact one another and may be affected by naturally-occurring and management-based factors. Although many of the soil properties of the Living Filter will be evaluated separately, each process has some effect on each other and collectively combines to affect the processes that influence runoff formation.

Hydraulic Conductivity and Bulk Density

The trend of greater surface hydraulic conductivity in the irrigated area of the study site contrasts many of the published results of wastewater irrigation systems. However, the findings of this study are similar to a few published works that showed positive effects of TWW irrigation, notably those of Vogeler's et al.'s (2009) study on sands and silt loams in New Zealand and Hati et al.'s (2007) observations of soybean-wheat rotations on clay soils. These studies are similar to this work in that reduced bulk density and increased hydraulic conductivity were observed in irrigated areas when compared to non-irrigated areas.

Considering that increases in hydraulic conductivity and reductions in bulk density were observed in irrigated areas of the Living Filter, we should analyze the effects of changes in soil porosity and pore size distribution on hydraulic conductivity. Fortunately, the tension infiltrometer allows us to analyze flow over a range of tensions and subsequent pore sizes and allows us to better understand the pore size distribution of the soil. To determine through what size pores flow is occurring at each tension, the maximum equivalent pore radius as defined by Hanks and Ashcroft (1980) can be used,

$$C_0 = \frac{-2\sigma}{\rho g P_0} \qquad [5.1]$$

where C_0 is the maximum equivalent pore radius in mm, σ is water surface tension in dyne/cm, ρ is the density of water in g/cm^3, g is gravity in cm/sec^2 and P_0 is the pore water pressure in cm. The maximum equivalent pore radius can be calculated for all tensions greater than zero up to the maximum operating range of the infiltrometer.

For both hydraulic conductivity models, visual observations of the plots of the log of hydraulic conductivity over infiltrometer tension show that the smallest differences between non-zero cm treatments occurred at 1 cm of tension for the Reynolds model and 2 cm of tension for the Ankeny model, with maximum equivalent pore radii of 0.149 and 0.074 mm, respectively. Using the Reynolds model the largest differences between treatments occurred at 3 and 6 cm, representing pore radii of 0.050 and 0.025 mm, respectively. With the Ankeny model the biggest differences between treatments occurred at 4 cm of tension, having a maximum equivalent pore radius of 0.037 mm, with less drastic differences at 8 cm, having a maximum equivalent pore radius of 0.019 mm. Considering that the biggest differences in hydraulic conductivity between treatments for both conductivity models occur between 3 and 6 cm of tension, it appears that an increase in pore radii in the 0.025 to 0.050 mm size range attributed to both increases in hydraulic conductivity and decreases in bulk density in the irrigated area.

Although reduced bulk density was observed in the irrigated area, the causation for such reductions is not as apparent. Increases in organic matter content are often associated with increased soil structure and consequent reductions in bulk density (Bronick and Lal, 2005), however there were no detectable differences in organic matter content at the 0 to 20 cm depth and TOC analysis of selected Ap horizons revealed similar results. Thus, it appears that differences in bulk density are not a result from increases in organic matter content. However, changes in bulk density may be a result of a change in soil structure influenced by increased fungal and microbial growth, greater freeze-thaw cycling or increased plant root growth, all of which can result in increased soil aggregation, reduced bulk density, and changes in the soil pore size distribution (Bronick and Lal, 2005, Oades, 1984). Examples of increased fungal and microbial growth include observations of increased fungal hyphae length and fungal biomass that were associated with increases in soil moisture in an analysis of a precipitation gradient in the Midwest (Frey, et al, 1999). Additionally, Bear et al.'s (1997) study of tillage systems correlated increased fungal population and carbohydrate production with increased soil aggregation.

Increased soil aggregation may also be the result of greater free-thaw cycling due to irrigation in the late fall and early spring. Laboratory experiments on a silty till revealed that 10 to 18 freeze-thaw cycles increased permeability for compacted samples, with reductions in bulk density occurring after 1 to 3 cycles (Viklander, 1998). Similarly, in observations of a clay loam in Texas, Unger (1991) attributed freeze-thaw processes to reductions in bulk density and penetration resistance and increases in soil aggregate mean weight diameter. In addition, Konrad (1989) concluded that freeze-thaw cycling increased hydraulic conductivity and reduced bulk density on clayey silts in Canada. However, he noted that the majority of the changes in hydraulic conductivity and bulk density occurred after only three to four cycles, which would most likely occur in the non-irrigated area of the Living Filter in any given spring or fall.

In addition to influences from fungal and microbial growth and freeze-thaw cycling, increases in hydraulic conductivity and reductions in bulk density may be a result of increased root growth in the Ap horizon which can also increase soil aggregation (Bronick and Lal, 2005, Angers and Caron, 1998). In two different studies of wheat (which preceeded surface infiltration and bulk density measurements), it was shown that irrigation increased root mass when compared to non-irrigated treatments (Katterer et al., 1993, Zhang et al., 1998). This phenomenon is possible, as visual observations of crop growth at the Living Filter over the course of this study suggested increased growth in corn and wheat in the irrigated side, which was confirmed by greater crop yields (J. Loughran, personal communication, Farm Operations, The Pennsylvania State University).

Clay and Organic Matter Content

Although Tukey's test was not able to separate mean clay contents with respect to distance from the sprinkler, the statistically significant effect of distance from the sprinkler on clay content should still be noted. The trend of lower clay contents in the irrigated area reflects the sprinkler distribution, with the increase in clay content between 16 and 24 m occurring concurrently with the transition from the irrigated area to the non-irrigated area, suggesting that irrigation may be causing reductions in clay content at the

0 to 20 cm depth. This is not necessarily unheard of as the process of clay translocation is a function of precipitation (Schaetzl and Anderson, 2005). This has been demonstrated in a short time-frame laboratory study, as Warrington et al. (2007) observed translocation of clays in lysimeters irrigated with fresh water and wastewater, with clay contents going from 17% to approximately 14% in loams and from 44% to less than 40% in clayey soils after only 600 cm of irrigation. Also, a trend of greater clay translocation was noted for all but one sampling depth in lysimeters irrigated with TWW when compared to freshwater, with the additional losses attributed to the higher SAR's of the wastewater. Similar observations of clay translocation have been demonstrated in the field, including the work of Presley and Ransom (2004), who observed clay contents and fine clay to total clay ratios in soil profiles inside and outside of the irrigated areas of irrigation pivots in Kansas. In their work they observed that 30 years of irrigation increased the total clay content and fine clay to total clay ratio in subsurface horizons when compared to non-irrigated areas, suggesting the translocation of fine clays from surface horizons. In addition, the clay content measurements were reinforced by observations of thin sections that revealed the filling of pores with fine clays, further suggesting clay translocation.

Although only visual trends of the 0 to 20 cm clay content relative to distance from the sprinkler can be analyzed, supporting data is lacking to make any decisive conclusions as to what processes may be occurring. Results of the comparison of clay contents in the profile cores revealed no statistically significant differences in clay content in the Bt1 through Bt4 horizons. With that considered, clay may be leaving the Ap horizon, but it is without a definitive area of accumulation and due to the inherent limitations of the sampling design one cannot make a conclusion, as the lower clay contents may be an artifact of antecedent conditions. In order to make any further judgments about clay losses from irrigated area Ap horizons, the fine clay to total clay ratios should be determined and thin sections should be analyzed as in the Presley and Ransom study.

The lack of differences in organic matter content relative to distance from the sprinkler, although inconsistent with many studies of treated wastewater irrigation, shows similar trends to those of Voegler et al. (2009), Freidel et al (2000) and others as mentioned in the literature review. The lack of differences in organic matter content at the Living Filter are plausible as the irrigation water has a low total organic carbon content and is most likely not adding any measurable amount of material.

Sodium Adsorption Ratio, pH and Electrical Conductivity

Although the relative differences in pH are in line with many of the published studies of TWW irrigation, the consistent change in pH throughout the profile contrasts with much of the literature. These differences throughout the profile may be due to the climate of the site and the intended design of the system to dispose of effluent water as opposed to only meeting crop water demands. This intentional movement of irrigation water to the water table thus may be resulting in the deposition of base cations from the irrigation water to soil colloids in the Bt1 through Bt4 horizons. This would contrast with a shallow irrigation depth as seen in most studies, which would result in the majority of t base cation deposition in the Ap horizon. However, this study is similar to others in that the pH of the soil reflected the pH of the irrigation water. In addition, differences in EC between irrigated and non-irrigated areas of the Living Filter are comparable with much of the published work as TWW irrigation increased EC in the soil profile, with a decrease in EC occurring with depth throughout the profile.

In contrast to the similarities in pH and EC of this study and those reviewed in the literature, SAR trends with depth in the irrigated area are exclusive to this work. The increase in SAR due to irrigation is common with many studies of TWW, however the irrigated areas of the Living Filter have SAR values that are much lower than much of the reviewed work. In many of those cases SAR's were higher from the geomorphic properties of the arid areas in which TWW irrigation often occurs. Additionally, the SAR of the applied irrigation water is lower than many of the noted studies, which may contribute to the lower sodium accumulations and reduced (compared with literature values) SAR's in the soil profile.

A second trend unique to the Living Filter is the increase in SAR's with depth in the soil profile, although the reasons for such trends are somewhat vague. As demonstrated with the consistent increases in soil profile pH from non-irrigated to irrigated areas, sodium, calcium, and magnesium cations are likely being deposited in deeper in irrigated area's soil profile. However, this leaves an inconsistency as to why the concentration of sodium is greater than that of calcium and magnesium. This may be due in part to the large irrigation volume and resultant deposition of ions in the soil profile combined with sodium's low strength of bonding to cation exchange sites relative to calcium and magnesium. With wastewater additions of calcium and magnesium with each irrigation event, sodium ions may be removed from colloids in the upper horizons of the soil before moving through the profile and being deposited in the Bt2, Bt3 and Bt4 horizons. Thus the concentration of sodium ions increases relative to calcium and magnesium, increasing the SAR of the Bt2 through Bt4 horizons.

According to the FAO soil sodicity hazard graph (figure 5.1), the combination of high soil SAR and low EC would be expected to reduce hydraulic conductivity for all horizons. However, the FAO graph may not be telling the entire story as it does not account for the overall conditions of the site and the characteristics of the soil.   Even though the potential for hydraulic conductivity reductions is high for the Ap horizon, the presence of organic matter combined with illite and kaolonite clay types appear to minimize any sodicity-induced effects as demonstrated through the greater conductivity of the irrigated areas. Similarly, the lack of statistically significant differences in hydraulic conductivity for the Bt1 horizons indicates that dispersion is not occurring. However, the potential for dispersion to occur in the Bt1 through Bt4 horizons may still be high as the horizons have greater SAR's and reduced EC's in combination with lower soil organic matter contents.

Comparisons with Prior Studies at the Living Filter

Many of the results of this study can be compared to that of Sopper and Richenderfer (1978) and Walker (2006). Both measured hydraulic conductivity and bulk density, although different methods were used between the two studies and this work. However, we can observe the relative differences between treatments to determine if differences have remained consistent between irrigated and non-irrigated areas of the three studies.

Sopper and Richenderfer's (1978) determination of field infiltration using a double ring infiltrometer yielded infiltration rates of 54.8 cm/hr in irrigated areas, which was more than twice that of the mean K_{sat} value of the present study, and 4.3 cm/hr in non-irrigated areas, which was approximately 1/5 of the K_{sat} value of the current work. Though some differences between the prior work and the current study many be attributed to differences in analytical methods, there is no conclusion as to why infiltration rates were greater in the irrigated areas of the Sopper and Richenderfer study or why differences in saturated flow between the treatments have become nonexistent.

Although a less direct comparison can be made between a tension infiltrometer and the Alder-Robinson infiltrometer of the Sopper and Richenderfer study, both reflect infiltration rates under natural conditions, with infiltration assumed to be at soil water tensions that are slightly less than zero. With the Alder-Robinson infiltrometer Sopper and Richenderfer observed that irrigated areas again had greater infiltration rates, with irrigated values of 12.41 and 12.44 cm/hr compared to non-irrigated values of 4.64 and 2.81 cm/hr for wet and dry antecedent conditions, respectively. Although these values are less than the calculated K_{sat} values in this study, the irrigated values of Sopper and Richenderfer are similar to the mean K(1 cm) value of the current work. However, this may not be a true one-to-one comparison as the Alder-Robinsion infiltrometer does not operate at a specific tension. Additionally, it is not known as to why statistically significant differences between treatments were present with the Alder-Robinson infiltrometer or why these differences have diminished over the past 30+ years.

A much more direct comparison with the current data is with that of Walker (2005), who observed hydraulic conductivity along two transects with a tension infiltrometer at similar tensions to this study. An overall mean K_{sat} of approximately 15 cm/hr was similar to the current data. However, a better comparison may be with the midslope K_{sat} observations of Walker, which at 7 cm/hr was nearly 1/3 of the current data. Additionally, mean K(6 cm) values were approximately 0.2 cm/hr for all observed landscape positions, which was nearly ½ of the current data. Differences in conductivity may be due to the variability in sampling sites and sampling times and when considering the inherent variability of hydraulic conductivity measurements, differences may not seem as extreme. Additionally, the antecedent soil moisture conditions of this study were somewhat lower than that of the Walker study, which may have resulted in lateral flow and thus greater calculated hydraulic conductivity rates in the present work.

Both Sopper and Richenderfer and Walker determined soil bulk density, although cores were used instead of nuclear methods. When comparing the current data to that of Sopper and Richenderfer differences arise, with prior bulk densities of 1.41 g/cm^3 and 1.27 g/cm^3 at the 0 to 7.5 cm depth compared to approximately 1.43 g/cm^3 and 1.50 g/cm^3 at the 10 cm depth for irrigated and non-irrigated areas, respectively. When analyzing the two studies, the irrigated bulk densities at the 0 to 10 cm depth have remained somewhat the same over the past 30+ years, with the non-irrigated bulk densities appear to have increased at the Living Filter. At Sopper and Richenderfer's 10 to 17.5 cm sampling depth, bulk densities were 1.47 g/cm^3 in the irrigated side and 1.37 g/cm^3 in the non-irrigated side compared to this study's 0 to 20 cm sampling depth bulk densities of approximately 1.64 g/cm^3 for both areas. Again, increases in bulk density are evident, although non-irrigated bulk densities have increased at a greater rate.

Bulk density values observed by Walker were similar to this study, with Walker recording densities of 1.42 g/cm^3 on sideslope positions and 1.51 g/cm^3 on summit positions. Additionally, Walker concluded that increases in bulk density were attributed to changes in agricultural practices and when observing the non-irrigated data, this study is in agreement. However, it is this author's conclusion that the potential changes in soil structure caused by increased plant rooting, freeze-thaw cycling and biological activity resulted in little change to the bulk density in the irrigated area, minimizing possible inputs from the changes in agricultural practices that may have increased bulk density in the non-irrigated area.

Soil profile pH in this study behaved similarly to that of Walker, who also showed an increase in pH throughout the profile when using Hook's (1971) data as a control. Additionally, the pH values of Hook are similar to the non-irrigated pH values of the current work. Although soil pH values were consistent between Walker, Hook, and the current study, organic matter contents varied somewhat between the three. A comparison of organic matter content with depth (assuming the conversion of TOC to organic matter content is 1.78 x TOC) the current work and that of Hook shows similar trends in organic matter relative to depth, with slightly higher organic matter contents at depths greater than 60 cm in the current work (figure 5.2). These similarities not only help to confirm that organic matter contents in the irrigated areas of the Living Filer have not drastically changed, but also suggests that organic matter contents have not changed significantly across non-irrigated areas as well. However, similar trends were not present with the Walker data which revealed a much more even distribution throughout the soil profile, with Bt1 through Bt4 horizon organic matter contents being much higher than those of Hook and the present work.

Differences between the Living Filter and Other Studies

As important as it is to understand why hydraulic conductivities in the irrigated areas of the Living Filter are greater than those of the non-irrigated areas, it is equally important to understand why the Living Filter contrasts many of the other researched sites receiving TWW irrigation. Also, when comparing the Living Filter to other TWW irrigation systems, one must consider the physical characteristics and desired operational goals for each system.

One of the most obvious differences between the Living Filter and other TWW irrigation systems are soil types. A review of the literature revealed that most sites irrigating TWW have soils dominated by smectitic clays having a 2:1 lattice structure, which are much more susceptible to sodium-induced dispersion than the 1:1 clays of kaolonite and illite found at the Living Filter. Additionally, soils at the Living Filter have a low SAR when compared to other studies, with SAR's of less than 1.0 in the irrigated are and the non-irrigated (the assumed pre-irrigation condition) area having an SAR that is near zero. Irrigation water SAR is relatively low as well, resulting in lower accumulations of sodium throughout the profile.

In addition to the differences in soils between the Living Filter and other studies are the climates of the sites and the intended uses of the systems. Most of the reviewed studies are located in areas having moisture deficits and irrigate to meet crop water demands, which make soils more susceptible to the accumulation of sodium and the resultant dispersion of clays. Conversely, the Living Filter irrigates TWW as a means of final treatment and thus exceeds crop water demands, resulting in the movement of water and associated salts through the profile, with less sodium and a reduced likelihood of clay dispersion in the Ap horizon. However, this excess of irrigation may be moving salts deeper into the profile, resulting in the increased SAR's and pH's of the Bt1 through Bt4 horizons that is unique to the Living Filter

Management Recommendations

When determining the best way to effectively apply water without causing runoff, Living Filter site managers should consider the limitations of hydraulic conductivity throughout the entire soil profile when scheduling irrigation events. However, this can be highly dependent on antecedent soil moisture conditions and the planned application rate. In conditions of low initial water content, the current application rate of 5 cm every 12 hours will most likely completely infiltrate into the Ap horizon, resulting in little to no runoff.   However, when the Ap horizon is saturated from rain or snow events the rate at which water percolates to groundwater is influenced by the hydraulic conductivity of the most limiting layers, which is likely the Bt1 through Bt4 horizons. In this instance, as water moves through the Ap horizon and meets the Bt1 horizon, it will accumulate at the Ap-Bt1 interface due to the reduced conductivity of the Bt1 horizon, resulting in the filling of the Ap horizon to saturation followed by the formation of overland flow.

From a management standpoint the most practical way to address potential runoff formation is to reduce the sprinkler application rate or application cycle length. The application rate could be reduced through the use of smaller nozzles while keeping the same sprinkler spacing, although it would come at the cost of lengthened irrigation cycles and increased pumping costs. A second means of addressing runoff is by reducing the irrigation cycle time while maintaining the same application rate. Reducing application cycles time, but running multiple cycles during a 24 hour period with rests between irrigation cycles would result in the same application rate as a continuous 12 hour cycle. Or if necessary, shorter cycles run over a period of 36 or 48 hours could be run to achieve the maximum 5 cm per week application rate. Additionally, multiple laterals running perpendicular to hillslopes could be run at alternating times to ensure that if small amounts of runoff are occurring they are infiltrated by areas downslope before running off the site. With the current infrastructure this would require extremely high labor inputs, as the amount of time spent manually cycling irrigation laterals could increase as much as six fold. However, this could be addressed by automation of the system through the use of such equipment as automatic valves on each irrigation lateral, resulting in reduced labor costs and greater operational control of the irrigation system.

In addition to the physical properties of the site, the chimerical properties should be considered as well. As shown and discussed in this work, excess sodium and the resulting higher SAR values in the irrigated area may have negative effects on soil hydraulic conductivity. Although the SAR values of the Bt1 through Bt4 horizons are somewhat low when compared to other systems, the higher clay contents and reduced EC and organic matter contents may pose as potential risks to long-term system operation. It is the recommendation of this author that soil sodium contents be monitored on a regular basis at multiple sites throughout the Living Filter to determine if soil SAR's are increasing. Additionally, more research is needed to determine if the current SAR values are limiting hydraulic conductivity in the Bt2 through Bt4 horizons.

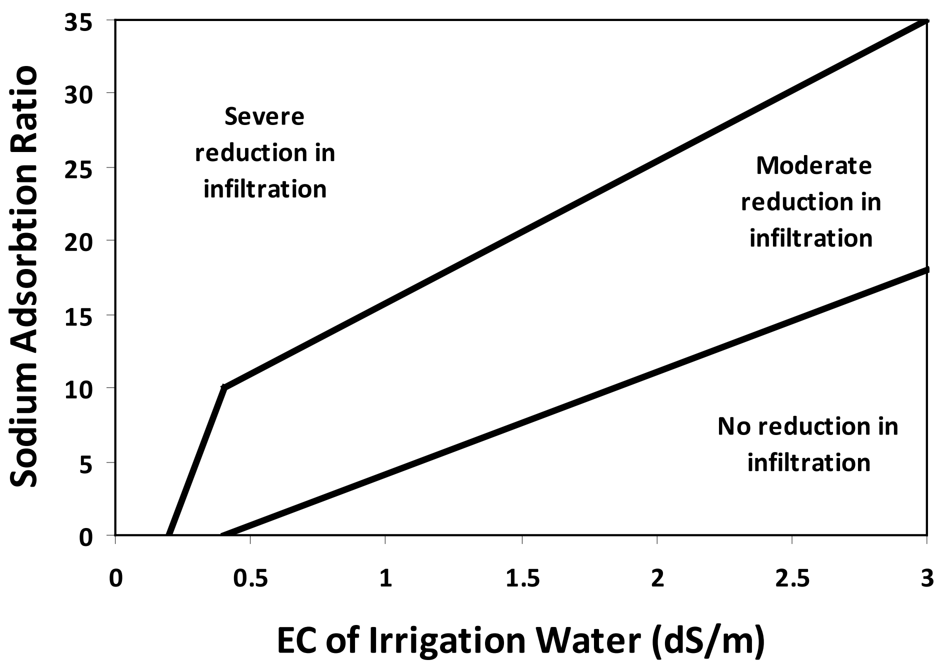

Figure 5.1. Potential sodicity-influenced reductions in hydraulic conductivity. Adopted from Ayers and Wescot (1985). The observed Ap horizons are classified as 'no reduction' while the Bt1 through Bt4 horizons are classified as 'severe reductions.'

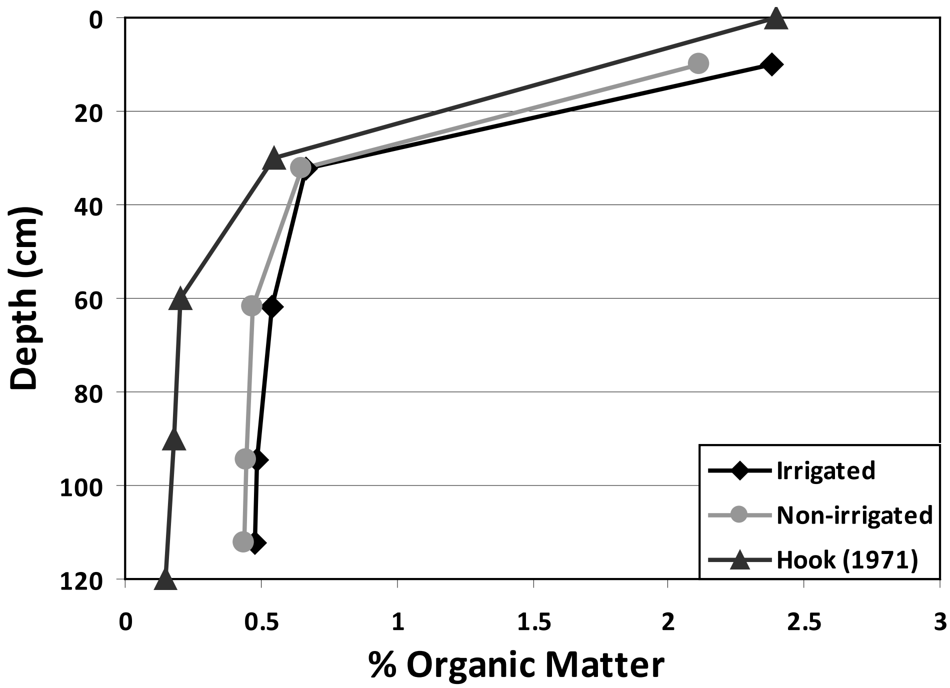

Figure 5.2. Comparison of current calculated organic matter contents with the data of Hook (1971). Current data (irrigated and non-irrigated) is measured at the mean horizon midpoint, with the Hook (1971) data measured at sample depth. Mean organic matter contents were not available for the Walker (2005) data.

Chapter 6

CONCLUSIONS

The Living Filter is a unique system due in part to its climate, soils and intended use and for more than 40 years it has been an effective means of final treatment for wastewater. However, it is the uniqueness of the Living Filter that makes it hard to compare with other studies, thus site-specific observations are needed to understand the processes that are occurring. It was the goal of this study to analyze the effects of long-term treated wastewater irrigation on hydraulic conductivity and soil quality and these goals were achieved by analyzing physical and chemical properties both at the soil surface and throughout the soil profile.

This study determined that soil surface hydraulic conductivity was greater in areas that received TWW irrigation than those that did not, which contrasts much of the published work. Increases in hydraulic conductivity at 3 to 6 cm of tension suggest that this is due to an increase in pores having maximum equivalent radii of 0.025 to 0.050 mm. Although the differences in hydraulic conductivity this study were in agreement with the findings of Sopper and Richenderfer (1978), the magnitude of the differences between the irrigated and non-irrigated areas was significantly lower. Overall hydraulic conductivity rates were closer to those of Walker (2005), although lateral flow may have attributed to the slightly higher values in this study. Additionally, observations of Bt1 horizon hydraulic conductivity rates determined that there were no differences in hydraulic conductivity between the irrigated and non-irrigated areas of the study site.

Analysis of bulk density demonstrated that areas receiving irrigation had lower densities than non-irrigated areas. A comparison with the work of Sopper and Richenderfer (1978) revealed that irrigated bulk densities have changed little, while non-irrigated densities have increased. This suggests that the increases in hydraulic conductivity and reductions in bulk density in the irrigated area are the result of TWW irrigation, with differences possibly due to greater soil aggregation from increased microbial activity, freeze-thaw cycling or plant rooting. Also, this study is in agreement with Walker's suggestion that changes in agricultural practices have increased bulk density, although the factors above may have minimized or eliminated the effects of the changes in the irrigated area, resulting in the larger increase in bulk density in the non-irrigated area.

In addition to bulk density, differences in clay contents relative to distance from the sprinkler were observed, although only visual analysis of the results could determine that clay contents were lower in the irrigated area than the non-irrigated area. However, analysis of soil profiles revealed that there were no regions of significant clay accumulation in the irrigated-area Bt1 through Bt4 horizons. Over 25 years of TWW application may have contributed to the differences in the 0 to 20 cm clay contents, although further analysis is needed to make a decisive conclusion. Additionally, surface and profile analysis of organic matter and TOC contents revealed that there were no differences in the properties between the irrigated and non-irrigated areas, suggesting that additions in organic matter due to wastewater irrigation is not occurring.

Observations of soil acidity reveled that the soil pH in the irrigated areas was approximately 1.0 pH unit greater than those in the non-irrigated areas for all observed horizons in the soil profile. These results were consistent with other studies at the Living Filter although they contrasted most, if not all, published works on TWW irrigation. Similarly, EC was greater in the irrigated areas when compared to non-irrigated areas, though relative differences in EC varied with soil horizons. For both analyses, increases were attributed to additions of base cations from the wastewater.

The sodium adsorption ratios (SAR's) in the irrigated area were significantly higher than those in the non-irrigated for all observed soil horizons. Still, the irrigated SAR values were less than most sites that irrigate TWW, even though the sampling area has been irrigated with up to 260 cm of TWW per year for over 25 years. However, what is most interesting is the increase in SAR with soil profile depth, relative to both the non-irrigated values and those of the horizons above, which contrasts with all of the studies reviewed in the literature. As seen with the increases in pH and EC in the irrigated area, it is believed that increases in SAR are resulting from the deposition of base cations, although it is thought that additions of calcium and magnesium from the irrigation water are dislodging sodium ions from soil colloids in the Ap horizon. This is followed by the deposition of the sodium ions in the subsurface horizons, raising the concentrations of sodium relative to calcium and magnesium and thus increasing the SAR's of the Bt1 through Bt4 horizons.

From a management standpoint, this work suggests that TWW irrigation has not had a negative effect on the processes that affect runoff formation at the Living Filter. If runoff is occurring, it may be due to the saturation of the Ap horizon followed by a restriction of flow in the Bt1 through Bt4 horizons, with values decreasing to less than that of the sprinkler application rate. However, these restrictions may be entirely due to the inherent properties of the soil and not TWW irrigation. To minimize runoff formation, the author suggests that the Office of Physical Plant reduce irrigation cycle times but run multiple cycles in a 24 or 48 hour period to achieve the same application rate as a single 12-hour cycle. However, increased labor requirements may restrict such changes, although automation of the system would offset the increased labor needs and allow for greater control of the irrigation system.

This study has shown that soil hydraulic conductivity and selected measures of soil quality in the irrigated areas of the Living Filter have been maintained or improved when compared to non-irrigated areas. This work has also shown the differences between the Living Filter and other studies and explained why such differences are present. When considering these points one can see that the Living Filter has effectively moved wastewater through the soil for renovation while meeting crop water demands and should continue to meet these goals for the foreseeable future.

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Appendix A:

Calculated surface horizon hydraulic conductivity data using the Ankeny et al. (1991) and Reynolds and Elrick (1991) conductivity models.

Block	Dist from head (m)	Irrigated hydraulic conductivity (cm/hr)				Dist from head (m)	Non-irrigated hydraulic conductivity (cm/hr)			
		Tension (cm)					Tension (cm)			
		8 cm	4 cm	2 cm	0 cm		8 cm	4 cm	2 cm	0 cm
1	4	0.30	0.94	5.04	17.90	24	0.19	0.42	6.70	22.34
	8	0.25	1.28	9.30	10.16	28	0.11	0.26	5.49	4.80
	12	0.25	0.96	5.32	17.82	32	0.15	1.54	6.08	38.56
2	4	0.51	1.56	8.47	22.93	24	0.47	1.04	2.15	3.87
	8	—	0.82	9.29	25.42	28	0.08	0.30	3.18	14.79
	12	—	0.62	9.35	12.44	32	—	1.76	12.65	32.23
3	4	0.14	1.94	10.66	23.15	24	0.12	0.33	12.08	29.43
	8	0.20	0.65	2.56	13.70	28	—	3.61	11.97	20.51
	12	0.31	1.27	9.60	8.88	32	0.09	0.19	2.76	19.94
4	4	0.22	0.69	3.20	17.24	24	0.22	0.65	6.50	15.11
	8	0.17	3.48	16.21	28.69	28	0.14	8.91	16.24	16.88
	12	0.12	1.98	10.76	20.22	32	0.12	0.55	5.18	16.28
5	4	0.17	1.23	10.59	16.81	24	0.15	1.00	11.55	32.48
	8	0.15	1.32	7.85	27.84	28	—	0.24	4.13	19.38
	12	0.27	2.65	9.05	31.60	32	0.14	0.30	4.65	21.56
6	4	0.25	1.02	6.60	15.98	24	0.14	0.31	11.07	28.65
	8	0.31	3.73	14.67	32.18	28	0.12	5.09	15.09	21.98
	12	0.31	1.97	12.35	30.26	32	0.11	0.37	11.01	28.66
7	4	—	1.11	8.60	25.39	24	0.34	1.43	8.19	12.93
	8	0.07	1.04	4.97	9.90	28	0.29	4.95	20.94	24.39
	12	0.09	0.85	4.17	13.86	32	0.10	0.26	2.14	14.66
8	4	0.17	0.65	5.15	15.48	24	0.16	0.47	8.72	25.57
	8	0.12	0.86	4.77	22.92	28	0.13	0.29	7.74	28.97
	12	0.10	1.50	10.85	34.46	32	0.18	0.94	14.62	14.29

Block	Dist from head (m)	Irrigated hydraulic conductivity (cm/hr) Tension (cm) 6 cm	3 cm	1 cm	0 cm	Dist from head (m)	Non-irrigated hydraulic conductivity (cm/hr) Tension (cm) 6 cm	3 cm	1 cm	0 cm
1	4	0.51	2.30	9.44	17.90	24	0.25	1.89	12.02	22.35
	8	0.55	3.90	8.72	10.16	28	0.15	1.48	4.33	4.80
	12	0.47	2.37	9.65	17.82	32	0.48	3.05	15.45	38.57
2	4	0.85	3.87	13.73	22.93	24	0.66	1.57	2.87	3.87
	8	—	2.82	15.02	25.42	28	0.15	1.04	6.80	14.80
	12	—	2.59	9.98	12.44	32	—	4.82	19.75	32.24
3	4	0.52	4.70	15.31	23.15	24	0.19	2.23	18.25	29.44
	8	0.35	1.33	5.97	13.71	28	—	6.79	15.15	20.52
	12	0.60	4.07	7.94	8.88	32	0.10	0.86	7.39	19.95
4	4	0.37	1.54	7.46	17.25	24	0.35	2.23	9.64	15.11
	8	0.78	7.80	20.78	28.69	28	1.14	12.70	14.96	16.89
	12	0.49	4.80	14.25	20.22	32	0.25	1.77	9.03	16.28
5	4	0.45	3.88	12.65	16.81	24	0.37	3.56	18.95	32.49
	8	0.44	3.30	14.65	27.85	28	0.00	1.01	8.84	19.38
	12	0.85	4.91	16.92	31.61	32	0.16	1.43	9.92	21.56
6	4	0.48	2.75	10.05	15.99	24	0.18	2.13	17.28	28.66
	8	1.07	7.58	21.30	32.18	28	0.78	9.05	17.34	21.99
	12	0.76	5.15	18.92	30.26	32	0.19	2.21	17.25	28.66
7	4	—	3.15	14.52	25.40	24	0.67	3.70	9.79	12.94
	8	0.27	2.35	6.81	9.91	28	1.19	11.03	20.64	24.39
	12	0.28	1.92	7.54	13.86	32	0.15	0.79	5.60	14.67
8	4	0.32	1.94	8.78	15.48	24	0.26	2.21	14.59	25.58
	8	0.31	2.06	10.44	22.93	28	0.17	1.69	14.71	28.98
	12	0.38	4.14	19.06	34.47	32	0.40	4.29	12.59	14.30

Appendix B:

Calculated Bt1 horizon hydraulic conductivity data using the Ankeny et al. (1991) and Reynolds and Elrick (1991) conductivity models.

Block	Dist from head (m)	Irrigated hydraulic conductivity (cm/hr) Tension (cm) 8 cm	4 cm	2 cm	0 cm	Dist from head (m)	Non-irrigated hydraulic conductivity (cm/hr) Tension (cm) 8 cm	4 cm	2 cm	0 cm
1	8	0.05	0.20	0.48	0.46	28	0.04	0.21	1.18	9.75
2	8	0.08	0.13	0.13	—	28	0.06	0.47	1.99	2.55
3	8	0.07	0.17	1.18	22.19	28	0.01	0.27	1.11	5.84
4	8	0.21	0.51	1.11	4.91	28	0.04	0.42	2.13	4.03
5	8	0.02	0.12	0.47	1.19	28	0.25	0.52	0.86	1.49
6	8	—	0.17	0.55	2.27	28	0.06	0.13	0.17	0.70
7	8	0.03	0.13	0.26	0.35	28	0.05	0.13	0.20	0.27
8	8	0.03	0.46	7.77	15.77	28	0.09	0.42	1.19	11.68

Block	Dist from head (m)	Irrigated hydraulic conductivity (cm/hr)				Dist from head (m)	Non-irrigated hydraulic conductivity (cm/hr)			
		Tension (cm)					Tension (cm)			
		6 cm	3 cm	1 cm	0 cm		6 cm	3 cm	1 cm	0 cm
1	8	0.10	0.35	0.42	0.46	28	0.09	0.51	3.41	9.75
2	8	0.11	0.12	—	—	28	0.17	1.05	2.09	2.55
3	8	0.10	0.48	5.17	22.19	28	0.06	0.54	2.55	5.84
4	8	0.32	0.75	2.41	4.91	28	0.13	0.98	2.83	4.03
5	8	0.05	0.25	0.74	1.19	28	0.36	0.68	1.15	1.49
6	8	—	0.30	1.12	2.27	28	0.10	0.11	0.40	0.70
7	8	0.06	0.19	0.29	0.35	28	0.08	0.16	0.23	0.27
8	8	0.12	1.99	10.64	15.77	28	0.19	0.69	3.81	11.68

Appendix C:

Surface bulk density for the 2008 and 2009 sampling dates: 0 to 10 cm sampling depth.

Block	Dist from head (m)	October 2008 Wet BD (g/cm3)	VWC (g/cm3)	Dry BD (g/cm3)	GWC (g/g)	May 2009 Wet BD (g/cm3)	VWC (g/cm3)	Dry BD (g/cm3)	GWC (g/g)
1	4	1.66	0.36	1.30	0.23	1.72	0.26	1.47	0.18
	8	1.74	0.34	1.40	0.21	1.73	0.27	1.47	0.19
	12	1.65	0.34	1.32	0.21	1.76	0.27	1.49	0.23
	16	1.75	0.32	1.43	0.16	1.73	0.24	1.50	0.17
	20	1.86	0.30	1.56	0.17	1.92	0.25	1.66	0.16
	24	1.76	0.28	1.48	0.19	1.88	0.26	1.62	0.15
	28	1.83	0.27	1.56	0.17	1.73	0.21	1.52	0.15
	32	1.60	0.24	1.36	0.16	1.61	0.22	1.39	0.16
2	4	1.76	0.35	1.41	0.17	1.67	0.27	1.40	0.22
	8	1.77	0.34	1.44	0.18	1.83	0.25	1.58	0.18
	12	1.76	0.36	1.40	0.19	1.80	0.26	1.53	0.18
	16	1.79	0.35	1.44	0.17	1.80	0.24	1.56	0.17
	20	1.84	0.34	1.51	0.17	1.87	0.22	1.64	0.16
	24	1.83	0.29	1.53	0.17	1.81	0.21	1.60	0.14
	28	1.77	0.26	1.51	0.17	1.89	0.21	1.68	0.13
	32	1.87	0.25	1.62	0.17	1.75	0.24	1.51	0.15
3	4	1.71	0.36	1.35	0.23	1.72	0.28	1.44	0.21
	8	1.64	0.36	1.27	0.23	1.70	0.32	1.38	0.30
	12	1.77	0.34	1.44	0.25	1.75	0.28	1.47	0.26
	16	1.63	0.29	1.34	0.19	1.66	0.29	1.37	0.18
	20	1.73	0.30	1.44	0.19	1.85	0.24	1.61	0.18
	24	1.83	0.31	1.52	0.18	1.88	0.24	1.64	0.18
	28	1.82	0.28	1.54	0.17	1.78	0.22	1.56	0.17
	32	1.59	0.28	1.37	0.18	1.86	0.25	1.62	0.16
4	4	1.78	0.39	1.39	0.24	1.66	0.28	1.39	0.28
	8	1.73	0.34	1.39	0.22	1.60	0.22	1.38	0.18
	12	1.70	0.32	1.38	0.18	1.74	0.25	1.49	0.21
	16	1.76	0.33	1.42	0.20	1.91	0.24	1.67	0.21
	20	1.92	0.33	1.59	0.18	1.87	0.25	1.61	0.15
	24	1.79	0.33	1.46	0.20	1.80	0.21	1.59	0.18
	28	1.62	0.29	1.34	0.21	1.72	0.27	1.45	0.18
	32	1.81	0.33	1.48	0.20	1.77	0.28	1.49	0.20

Block	Dist from head (m)	October 2008 Wet BD (g/cm3)	VWC (g/cm3)	Dry BD (g/cm3)	GWC (g/g)	May 2009 Wet BD (g/cm3)	VWC (g/cm3)	Dry BD (g/cm3)	GWC (g/g)
5	4	1.85	0.36	1.48	0.21	1.69	0.25	1.44	0.17
	8	1.78	0.30	1.48	0.20	1.81	0.28	1.53	0.22
	12	1.73	0.32	1.42	0.20	1.83	0.22	1.61	0.18
	16	1.77	0.36	1.42	0.22	1.88	0.26	1.62	0.16
	20	1.74	0.30	1.44	0.19	1.80	0.26	1.54	0.15
	24	1.93	0.28	1.65	0.19	1.84	0.27	1.56	0.17
	28	1.75	0.27	1.48	0.22	1.80	0.28	1.52	0.20
	32	1.63	0.29	1.34	0.22	1.71	0.24	1.46	0.19
6	4	1.76	0.31	1.45	0.23	1.74	0.24	1.50	0.16
	8	1.85	0.34	1.50	0.24	1.68	0.25	1.43	0.19
	12	1.81	0.33	1.48	0.22	1.66	0.25	1.41	0.21
	16	1.65	0.33	1.32	0.24	1.73	0.26	1.47	0.21
	20	1.78	0.33	1.46	0.22	1.75	0.27	1.49	0.21
	24	1.75	0.31	1.44	0.23	1.65	0.26	1.39	0.16
	28	1.78	0.31	1.46	0.22	1.73	0.29	1.43	0.20
	32	1.87	0.30	1.57	0.19	1.82	0.31	1.52	0.21
7	4	1.66	0.45	1.29	0.21	1.76	0.26	1.50	0.23
	8	1.65	0.44	1.29	0.22	1.68	0.28	1.41	0.20
	12	1.70	0.35	1.35	0.24	1.66	0.25	1.41	0.23
	16	1.77	0.33	1.44	0.23	1.81	0.25	1.56	0.19
	20	1.84	0.32	1.52	0.20	1.74	0.24	1.50	0.17
	24	1.85	0.33	1.52	0.20	1.72	0.23	1.48	0.18
	28	1.78	0.28	1.50	0.20	1.80	0.25	1.55	0.19
	32	1.72	0.29	1.43	0.21	1.79	0.25	1.54	0.17
8	4	1.67	0.35	1.32	0.23	1.71	0.25	1.46	0.18
	8	1.85	0.34	1.51	0.22	1.76	0.28	1.48	0.21
	12	1.72	0.35	1.37	0.23	1.69	0.26	1.43	0.19
	16	1.66	0.37	1.29	0.26	1.66	0.26	1.40	0.20
	20	1.87	0.37	1.50	0.21	1.92	0.27	1.65	0.17
	24	1.79	0.33	1.46	0.22	1.71	0.24	1.47	0.18
	28	1.62	0.29	1.34	0.19	1.75	0.26	1.49	0.19
	32	1.81	0.33	1.48	0.20	1.70	0.26	1.44	0.19

Appendix D:

Surface bulk density for the 2009 sampling date: 0 to 20 cm sampling depth.

Block	Dist from head (m)	Wet BD (g/cm3)	VWC (g/cm3)	Dry BD (g/cm3)	GWC (g/g)
1	4	1.85	0.25	1.60	0.18
	8	1.83	0.27	1.56	0.19
	12	1.92	0.27	1.65	0.23
	16	1.93	0.23	1.71	0.17
	20	2.01	0.25	1.76	0.16
	24	1.94	0.26	1.68	0.15
	28	1.87	0.23	1.64	0.15
	32	1.79	0.22	1.57	0.16
2	4	1.81	0.27	1.54	0.22
	8	1.95	0.26	1.69	0.18
	12	1.92	0.25	1.67	0.18
	16	1.91	0.24	1.67	0.17
	20	1.93	0.22	1.71	0.16
	24	2.09	0.21	1.89	0.14
	28	1.96	0.22	1.75	0.13
	32	1.89	0.24	1.65	0.15
3	4	1.84	0.28	1.56	0.21
	8	1.80	0.34	1.46	0.30
	12	1.84	0.28	1.56	0.26
	16	1.83	0.29	1.54	0.18
	20	1.93	0.24	1.69	0.18
	24	1.93	0.25	1.68	0.18
	28	1.87	0.22	1.65	0.17
	32	1.95	0.24	1.72	0.16
4	4	1.85	0.26	1.59	0.28
	8	1.80	0.21	1.58	0.18
	12	1.92	0.24	1.68	0.21
	16	1.96	0.24	1.72	0.21
	20	1.95	0.25	1.70	0.15
	24	1.89	0.21	1.68	0.18
	28	1.82	0.26	1.56	0.18
	32	1.84	0.27	1.58	0.20

Block	Dist from head (m)	Wet BD (g/cm3)	VWC (g/cm3)	Dry BD (g/cm3)	GWC (g/g)
5	4	1.85	0.23	1.62	0.17
	8	1.93	0.28	2.08	0.22
	12	1.93	0.23	1.70	0.18
	16	2.00	0.27	1.73	0.16
	20	1.93	0.25	1.68	0.15
	24	1.91	0.26	1.66	0.17
	28	1.86	0.28	1.58	0.20
	32	1.81	0.26	1.55	0.19
6	4	1.86	0.24	1.62	0.16
	8	1.88	0.25	1.63	0.19
	12	1.84	0.24	1.60	0.21
	16	1.82	0.26	1.56	0.21
	20	1.85	0.26	1.58	0.21
	24	1.80	0.24	1.56	0.16
	28	1.83	0.31	1.52	0.20
	32	1.88	0.31	1.58	0.21
7	4	1.90	0.27	1.63	0.23
	8	1.88	0.28	1.60	0.20
	12	1.88	0.26	1.61	0.23
	16	1.92	0.25	1.68	0.19
	20	1.88	0.23	1.65	0.17
	24	1.84	0.24	1.60	0.18
	28	1.88	1.60	1.64	0.19
	32	1.85	0.24	1.60	0.17
8	4	1.88	0.24	1.63	0.18
	8	1.93	0.30	1.63	0.21
	12	1.86	0.27	1.59	0.19
	16	1.92	0.26	1.67	0.20
	20	2.00	0.26	1.74	0.17
	24	1.88	0.23	1.64	0.18
	28	1.85	0.26	1.59	0.19
	32	1.81	0.26	1.55	0.19

Appendix E:

Surface texture and organic matter content: 0 to 20 cm sampling depth.

Block	Dist from head (m)	Sand	Silt	Clay	% SOM
		————	% size fraction	————	
1	4	35.3	52.3	12.3	4.67
	8	30.5	57.5	11.9	4.24
	12	35.3	54.4	10.3	4.49
	16	34.1	49.4	16.5	3.79
	20	32.6	40.3	27.1	4.49
	24	30.5	38.7	30.9	5.14
	28	32.4	41.8	25.8	4.27
	32	34.2	45.1	20.7	3.69
2	4	33.6	54.7	11.7	3.51
	8	32.8	52.7	14.5	4.00
	12	31.7	54.4	13.9	3.94
	16	33.7	50.7	15.6	4.12
	20	34.8	48.3	16.9	3.62
	24	37.5	47.3	15.1	3.76
	28	34.5	48.5	17.0	3.67
	32	29.8	49.3	20.9	4.07
3	4	27.9	60.7	11.3	5.16
	8	22.3	67.6	10.1	5.17
	12	21.1	69.3	9.7	4.89
	16	27.7	58.6	13.7	5.29
	20	25.3	57.5	17.2	4.77
	24	26.1	52.0	21.9	4.87
	28	31.0	48.7	20.3	5.16
	32	30.9	50.3	18.7	4.62
4	4	27.3	64.5	8.1	4.86
	8	28.6	60.8	10.6	4.69
	12	26.7	57.2	16.1	4.11
	16	28.1	57.3	14.5	4.23
	20	27.5	58.0	14.5	3.93
	24	26.5	59.5	14.1	4.21
	28	26.5	60.5	13.0	4.45
	32	27.4	62.2	10.4	4.18

Block	Dist from head (m)	Sand	Silt	Clay	% SOM
		————	% size fraction	————	
5	4	24.3	59.8	15.9	4.46
	8	25.2	58.9	15.9	4.59
	12	22.9	58.9	18.1	4.04
	16	24.7	54.0	21.3	5.37
	20	25.7	52.9	21.5	5.29
	24	24.3	57.9	17.8	4.62
	28	24.2	61.9	13.9	4.11
	32	26.2	61.2	12.6	4.59
6	4	28.6	58.1	13.3	5.01
	8	25.5	50.2	24.3	5.50
	12	27.9	56.1	16.1	6.17
	16	26.8	58.1	15.1	5.73
	20	27.8	49.5	22.7	6.15
	24	24.5	49.9	25.6	7.14
	28	22.9	46.6	30.5	7.31
	32	20.9	42.8	36.3	7.23
7	4	19.6	57.3	23.1	5.07
	8	18.3	57.7	24.0	5.37
	12	18.0	60.1	21.9	5.34
	16	15.4	62.3	22.3	4.76
	20	19.3	61.4	19.3	4.97
	24	20.6	61.0	18.4	4.88
	28	22.8	59.3	17.9	4.86
	32	21.5	63.4	15.1	4.54
8	4	24.2	57.5	18.3	5.98
	8	24.3	55.2	20.5	5.37
	12	23.3	59.5	17.3	5.57
	16	25.5	57.1	17.5	6.08
	20	25.9	53.9	20.3	5.80
	24	25.9	52.5	21.5	5.24
	28	25.2	53.9	20.9	4.77
	32	21.9	57.2	20.9	5.04

Appendix F:

Soil profile measurements of physical and chemical properties.

Block - treatment	Horizon	Depth (cm)	% N	% C	pH	EC	SAR	Sand	Silt	Clay
								————	% size fraction	————
1 - Irr	Ap	0-32	0.190	1.725	6.82	968	1.28	34.9	57.3	7.8
	Bt1	32-55	0.102	0.549	6.94	446	2.42	31.7	55.7	12.7
	Bt2	55-72	0.084	0.371	6.93	339	3.05	30.1	49.1	20.8
	Bt3	72-105	0.078	0.312	6.95	300	3.84	22.9	40.9	36.2
	Bt4	105-120	0.073	0.280	6.81	277	3.83	21.9	43.3	34.8
1 - Non-irr	Ap	0-20	0.173	1.479	6.01	874	0.36	34.9	46.1	19.0
	Bt1	20-43	0.082	0.429	6.20	398	0.36	27.1	39.1	33.8
	Bt2	43-83	0.062	0.244	5.76	123	0.44	34.5	25.5	39.9
	Bt3	83-120	0.063	0.257	5.22	106	0.59	18.1	39.1	42.7
2 - Irr	Ap	0-17	0.173	1.650	6.08	717	1.58	35.3	53.9	10.8
	Bt1	17-45	0.063	0.326	6.43	270	4.23	37.4	26.5	36.1
	Bt2	45-85	0.058	0.260	6.15	208	4.29	24.9	41.1	34.0
	Bt3	85-115	0.061	0.263	5.54	232	3.87	22.1	65.2	12.7
	Bt4	115-120	0.062	0.294	5.06	259	4.16	11.0	66.5	22.5
2 - Non-irr	Ap	0-15	0.126	1.141	5.00	532	0.36	33.7	53.1	13.3
	Bt1	15-37	0.062	0.356	5.47	158	0.49	24.6	54.9	20.5
	Bt2	37-57	0.053	0.264	5.19	98	0.45	34.5	33.7	31.9
	Bt3	57-83	0.050	0.274	4.90	92	0.48	26.9	39.2	33.9
	Bt4	83-120	0.047	0.227	4.61	78	0.48	28.5	41.3	30.2
3 - Non-irr	Ap	0-16	0.136	1.171	5.13	510	0.40	29.1	51.9	19.0
	Bt1	16-31	0.063	0.330	4.97	241	0.48	14.3	57.7	28.0
	Bt2	31-80	0.053	0.271	4.68	105	0.38	20.7	60.8	18.5
	Bt3	80-112	0.048	0.231	4.71	66	0.41	18.3	45.9	35.8
	Bt4	112-120	0.048	0.258	4.67	81	0.52	25.4	47.5	27.1

Site - treatment	Horizon	Depth (cm)	% N	% C	pH	EC	SAR	Sand	Silt	Clay
								———% size fraction———		
4 - Irr	Ap	0-21	0.178	1.780	6.32	933	1.52	32.5	60.7	6.8
	Bt1	21-45	0.063	0.396	6.55	211	3.66	19.4	59.1	21.5
	Bt2	45-69	0.050	0.267	6.42	189	4.30	22.0	47.7	30.3
	Bt3	69-94	0.047	0.248	5.53	180	3.88	21.1*	49.7*	29.1*
	Bt3	94-120	0.049	0.251	5.36	220	4.18			
4 - Non-irr	Ap	0-23	0.140	1.382	5.45	693	1.02	29.1	61.0	9.9
	Bt1	23-42	0.059	0.429	5.49	234	2.19	19.6	47.0	33.4
	Bt1	42-73	0.049	0.273	5.02	179	1.85	16.5	35.6	47.9
	Bt2	73-120	0.047	0.271	4.70	168	2.13	17.9	40.4	41.7
5 - Irr	Ap	0-20	0.123	1.155	5.84	590	1.79	25.4	60.3	14.3
	Bt1	20-30	0.062	0.450	6.07	461	2.26	28.1	60.7	11.2
	Bt2	30-51	0.055	0.342	6.28	262	4.31			
	Bt2	51-63	0.056	0.526	6.09	243	4.72	18.5*	65.3*	16.3*
	Bt2	63-75	0.050	0.270	6.14	245	4.63			
	Bt3	75-102	0.050	0.268	5.56	203	4.35	17.5	46.7	35.7
	Bt4	102-120	0.049	0.247	4.67	218	4.45	16.9	55.2	27.9
5 - Non-irr	Ap	0-21	0.151	1.256	5.04	1135	0.47	31.3	57.2	11.5
	Bt1	21-41	0.071	0.421	5.36	426	0.91	16.4	64.9	18.7
	Bt2	41-89	0.059	0.301	4.84	160	0.93	27.2	54.3	18.5
	Bt3	89-106	0.042	0.246	4.59	98	0.98	13.6	51.9	34.5
	Bt4	106-120	0.057	0.245	4.44	94	1.02	11.1	55.1	33.9

Site - treatment	Horizon	Depth (cm)	% N	% C	pH	EC	SAR	Sand	Silt	Clay
								———% size fraction———		
6 - Irr	Ap	0-20	0.115	1.084	5.87	845	1.62	27.6	52.0	20.4
	Bt1	20-52	0.053	0.316	6.09	328	3.91	19.9	56.3	23.7
	Bt2	52-88	0.051	0.281	5.54	275	4.00	10.1	27.1	62.8
	Bt2	88-120	0.052	0.296	5.14	313	3.70	9.2	31.1	59.7
6 - Non-irr	Ap	0-21	0.130	1.094	4.60	582	0.27	21.7	49.7	28.5
	Bt1	21-61	0.048	0.252	4.51	101	0.55	15.6	41.1	43.3
	Bt2	61-88	0.045	0.215	4.32	78	0.60	15.1	46.0	38.9
	Bt3	88-114	0.050	0.231	4.27	77	0.72	18.7	53.6	27.7
	Bt4	114-120	0.036	0.237	4.29	74	0.75	23.9	49.5	26.6
7 - Irr	Ap	0-20	0.092	0.857	6.00	737	1.98	21.9	56.7	21.4
	Bt1	20-33	0.043	0.292	6.06	339	3.36	16.1	44.0	39.9
	Bt2	33-52	0.039	0.257	5.41	280	4.44	22.5	37.1	40.5
	Bt3	52-100	0.041	0.253	5.03	263	4.44	21.5	52.3	26.2
	Bt4	100-120	0.043	0.269	4.70	259	4.94	27.0	57.2	15.8
7 - Non-irr	Ap	0-20	0.100	0.939	5.22	536	0.21	22.4	63.6	14.0
	Bt1	20-58	0.051	0.343	5.72	166	0.26	20.8	62.7	16.5
	Bt2	58-114	0.043	0.269	5.09	89	0.30	18.7	50.8	30.5
	Bt3	114-120	0.037	0.231	4.85	75	0.35	18.5	47.5	34.1

Site - treatment	Horizon	Depth (cm)	% N	% C	pH	EC	SAR	Sand	Silt	Clay
								———% size fraction———		
8 - Irr	Ap	0-19	0.125	1.140	7.27	955	1.48	25.5	55.1	19.4
	Bt1	19-58	0.046	0.302	6.90	376	3.49	17.9	50.9	31.3
	Bt2	58-89	0.046	0.309	6.68	465	3.17	12.7	42.7	44.6
	Bt3	89-120	0.044	0.262	6.23	407	3.45	12.5	36.5	51.0
8 - Non-irr	Ap	0-14	0.125	1.057	5.00	697	0.27	27.0	58.2	14.8
	Bt1	14-36	0.063	0.379	5.45	238	0.28	22.5	63.3	14.2
	Bt2	36-73	0.053	0.290	4.92	138	0.29	24.5	62.1	13.4
	Bt3	73-113	0.050	0.272	4.59	122	0.36	25.5	58.9	15.7
	Btg	113-120	0.050	0.271	4.37	118	0.44	17.7	70.7	11.7

Appendix G:

Soil profile descriptions.

Block: 1 Treatment: Irrigated

			Structure			Manganese		Redoxomorphic features		
Horizon	Depth (cm)	Color	Type	Size	Grade	Size	(%)	Size	(%)	Color
Ap	0-32	10YR 3/3	GR	F	3					
Bt1	32-55	10YR 4/6	SBK	F	2					
Bt2	55-72	10YR 5/8	SBK	M	2					
Bt3	72-105	7.5YR 5/6	PL	M	2	2/3	10-20			
Bt4	105-120	10YR 5/8	PL	M	2			3/4	10-20	10YR 7/2

Block: 1 Treatment: Non-irrigated

			Structure			Manganese		Redoxomorphic features		
Horizon	Depth (cm)	Color	Type	Size	Grade	Size	(%)	Size	(%)	Color
Ap	0-20	10YR 4/6	GR	F	3					
Bt1	20-43	7.5YR 5/6	SBK	M	2					
Bt2	43-83	5YR 5/8	SBK	M	2	3	10-20			
Bt3	83-120	5YR 5/8	PL	M	2	3	2-5			

Block: 2 Treatment: Irrigated

			Structure			Manganese		Redoxomorphic features		
Horizon	Depth (cm)	Color	Type	Size	Grade	Size	(%)	Size	(%)	Color
Ap	0-17	10YR 3/6	GR	F	3					
Bt1	17-45	7.5YR 5/8	SBK	M	2					
Bt2	45-85	7.5YR 5/8	SBK	M	2	3	2-5	4	5-10	10YR 5/3
Bt3	85-115	10YR 5/8	PL	M	2	3	5-10	4/5	20-30	10YR 6/1
Bt4	115-120	7.5YR 5/8	SBK	CO/M	2					

Block: 2 Treatment: Non-irrigated

			Structure			Manganese		Redoxomorphic features		
Horizon	Depth (cm)	Color	Type	Size	Grade	Size	(%)	Size	(%)	Color
Ap	0-15	10YR 4/6	GR	F	3					
Bt1	15-37	10YR 5/8	SBK	M	2	3	10-20			
Bt2	37-57	7.5YR 5/8	SBK	M	2	3	2-5			
Bt3	57-83	5YR 5/8	SBK	M	2	3	2-5			
Bt4	83-120	7.5YR 5/6	SBK	M	2	3	10-20			

Block: 3 Treatment: Non-irrigated

			Structure			Manganese		Redoxomorphic features		
Horizon	Depth (cm)	Color	Type	Size	Grade	Size	(%)	Size	(%)	Color
Ap	0-16	10YR 4/6	GR	F	3					
Bt1	16-31	10YR 5/8	SBK	M	2	2	2-5			
Bt2	31-80	10YR 5/6	PL	M	2	3	10-20			
Bt3	80-112	10YR 6/8	PL	M	2	1	<2			
Bt4	112-120	10YR 6/8	PL	M	1	2/3	10-20			

Block: 4 Treatment: Irrigated

			Structure			Manganese		Redoxomorphic features		
Horizon	Depth (cm)	Color	Type	Size	Grade	Size	(%)	Size	(%)	Color
Ap	0-21	10YR 3/6	GR	F	3					
Bt1	21-45	10YR 5/8	SBK	M	2					
Bt2	45-69	7.5YR 5/8	PL	M	2	3/4	10-20			
Bt3	69-120	7.5YR 5/8	PL	TN	2	2/3	10-20			

Block: 4 Treatment: Non-irrigated

			Structure			Manganese		Redoxomorphic features		
Horizon	Depth (cm)	Color	Type	Size	Grade	Size	(%)	Size	(%)	Color
Ap	0-23	10YR 3/6	GR	F	3					
Bt1	23-73	7.5YR 5/8	SBK	M	2	2	2-5			
Bt2	73-120	10YR 5/8	PL	TN	2					

Block: 5 Treatment: Irrigated

			Structure			Manganese		Redoxomorphic features		
Horizon	Depth (cm)	Color	Type	Size	Grade	Size	(%)	Size	(%)	Color
Ap	0-20	10YR 3/6	GR	F	3					
Bt1	20-30	2.5 YR 4/6	GR	F	2	2/3	10-20			
Bt2	30-75	10YR 5/8	SBK	M	2					
Bt3	75-102	10YR 5/8	PL	M	2	2/3	10-20			
Bt4	102-120	5YR 5/8	PL	TN	2	2	5-10			

Block: 5 Treatment: Non-irrigated

			Structure			Manganese		Redoxomorphic features		
Horizon	Depth (cm)	Color	Type	Size	Grade	Size	(%)	Size	(%)	Color
Ap	0-21	10YR 3/6	GR	F	3					
Bt1	21-41	10YR 5/8	SBK	M	2	1/2	2-5			
Bt2	41-89	10YR 5/8	PL	TN/M	2	2/3	10-20			
Bt3	89-106	7.5YR 5/8	PL	M	1	2/3	10-20			
Bt4	106-120	10YR 5/8	SBK/MA	M	1	1	<2			

Block: 6 Treatment: Irrigated

			Structure			Manganese		Redoxomorphic features		
Horizon	Depth (cm)	Color	Type	Size	Grade	Size	(%)	Size	(%)	Color
Ap	0-20	10YR 4/6	GR	F	3					
Bt1	20-52	7.5YR 5/6	SBK	M	2	2/3	2-5			
Bt2	52-120	5YR 5/6	PL/SBK	M	1	2	2-5			

Block: 6 Treatment: Non-irrigated

			Structure			Manganese		Redoxomorphic features		
Horizon	Depth (cm)	Color	Type	Size	Grade	Size	(%)	Size	(%)	Color
Ap	0-21	10YR 4/6	GR	F	3					
Bt1	21-61	7.5YR 5/8	SBK/PL	M	2	3	2-5			
Bt2	61-88	7.5YR 6/8	PL	M	1	3	<2			
Bt3	88-114	7.5YR 6/8	PL	M	2	3/4	10-20			
Bt4	114-120	10YR 5/8	PL	M	2	3/4	10-20			

Block: 7 Treatment: Irrigated

			Structure			Manganese		Redoxomorphic features		
Horizon	Depth (cm)	Color	Type	Size	Grade	Size	(%)	Size	(%)	Color
Ap	0-20	10YR 4/6	GR	F	2					
Bt1	20-33	10YR 5/8	SBK	M	2	3/4	40-50			
Bt2	33-52	7.5YR 5/8	SBK/PL	M	2	3/4	20-30			
Bt3	52-100	10YR 5/8	PL/SBK	M	2	3/4	10-20			
Bt4	100-120	10YR 5/8	PL/SBK	M	2	3	5-10			

Block: 7 Treatment: Non-irrigated

			Structure			Manganese		Redoxomorphic features		
Horizon	Depth (cm)	Color	Type	Size	Grade	Size	(%)	Size	(%)	Color
Ap	0-20	10YR 3/6	GR	F	3					
Bt1	20-58	10YR 5/8	SBK	M/F	2	3/4	<2			
Bt2	58-114	7.5YR 5/8	SBK/PL	M	2	3/4	10-20			
Bt3	114-120	5YR 5/8	SBK	M	1	2	<2			

Block: 8 Treatment: Irrigated

			Structure			Manganese		Redoxomorphic features		
Horizon	Depth (cm)	Color	Type	Size	Grade	Size	(%)	Size	(%)	Color
Ap	0-19	10YR 3/6	GR	F	3					
Bt1	19-58	7.5YR 5/8	SBK	M	2	4	10-20			
Bt2	58-89	7.5YR 5/8	SBK/PL	M	2	3/4	2-5			
Bt3	89-120	5YR 5/8	PL	M	2	3	2-5			

Block: 8 Treatment: Non-irrigated

			Structure			Manganese		Redoxomorphic features		
Horizon	Depth (cm)	Color	Type	Size	Grade	Size	(%)	Size	(%)	Color
Ap	0-14	10YR 3/6	GR	F	3					
Bt1	14-36	10YR 4/6	SBK	M	2	3/4	10-20			
Bt2	36-73	10YR 5/8	PL/SBK	M	2	3/4/5	2-5			
Bt3	73-113	10YR 5/8	PL/SBK	M	2	2/3/4	10-20			
Btg	113-120	10YR 5/8	PL	M	2	3/4	10-20	3/4	40-50	10YR 6/4