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Impact of long-term wastewater irrigation on the physicochemical properties of humid region soils: "The Living Filter" site case study

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ABSTRACT

Increasing pressure on water resources is a significant challenge for the 21st century. Over the last decade, water reuse has offered a practical approach to wastewater effluent disposal while supporting agricultural production. Irrigation with wastewater can have negative impacts on the soil environment (e.g. increased salinity, reduced hydraulic conductivity) and these are well documented for soils in arid and semi-arid regions; but little research has been conducted for humid regions. Consequently, to understand the impact of wastewater irrigation on humid region soils, a field study was conducted at "The Living Filter" site (central Pennsylvania), where wastewater effluent has been used for irrigation for 50+ years. The study evaluated the differences in physicochemical soil properties throughout the soil profile (to a depth of 120 cm) at wastewater irrigated sites and non-irrigated sites at different landscape positions (summits and depressions). Results showed that both the sodium adsorption ratio (irrigated: 4.93 ± 1.22; non-irrigated: 0.88 ± 1.03) and salinity (irrigated: 0.32 ± 0.12 dS m^{-1}; non-irrigated: 0.07 ± 0.03 dS m^{-1}) of soil extracts were significantly higher in the irrigated soil profiles compared to the non-irrigated soil profiles (but not with regards to landscape position). There was no observable treatment effect on saturated hydraulic conductivity, K_s, (irrigated: 1.96 cm h^{-1}; non-irrigated: 2.39 cm h^{-1}), but K_s had moderately strong inverse relationships with soil pH (R^2 = 0.70) and percent organic carbon (R^2 = 0.67). Overall, while salts are accumulating in these soils; our data suggest that long-term irrigation with wastewater has not negatively impacted the hydraulic conductivity of this humid region soil. Ongoing monitoring of soil physicochemical properties and wastewater parameters will be needed to maintain the long-term sustainability of the site.

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1. Introduction

Increasing pressure on water resources can have significant impacts on our social, economic, and environmental security. These pressures have been linked to rapid population and economic growth as well as climate change (WWAP, 2014, 2015). The water crisis is said to be the number one global risk based on impact to society and the number eight global risk based on likelihood of occurring within 10 years (World Economic Forum, 2015). Furthermore, according to the United Nations, an estimated 700 million people in 43 countries presently suffer from water scarcity and two-thirds of the world's population is likely living under water stressed conditions (Watkins et al., 2006).

Although water scarcity is an issue of critical importance in drier areas, communities across the United States are increasingly experiencing water shortages, calling into question the durability of the nation's water supply as it remains susceptible to droughts, consumption patterns and continued population growth. The United States Geological Survey has estimated that 40 states will likely face some level of water shortage in the next 10 years (Maupin et al., 2014). As such, meeting the current and future water demand and supply needs is a significant challenge for the water industry; and the need for finding sources of water for purposes other than public drinking water (e.g. agriculture, industry, and commerce) is critical.

Water reuse offers a practical approach for managing our critically limited water source. Over the last decade there has been significant growth in the application of water reuse. Water reuse

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involves taking wastewater, giving it a high degree of treatment, and using the resulting reclaimed or recycled water for a new, beneficial purpose. Currently, land application of treated wastewater in cultivated fields is not only being used to dispose of wastewater but also to sustain agricultural production, especially in regions experiencing shortages of fresh water (Duan et al., 2010). However, irrigation with wastewater can have negative impacts on both crop production and the soil environment including but not limited to increases in soil salinity, nutrient accumulation, and heavy metal accumulation and uptake (e.g. Halliwell et al., 2001; Hamilton et al., 2007; Muyen et al., 2011).

Irrigation water salinity (electrical conductivity, EC) and the sodium adsorption ratio (SAR, defined as $(Na)/[(Ca+Mg)/2]^{0.5}$, where Na is sodium, Ca is calcium and Mg is magnesium in meq L^{-1}) are known to have an interactive effect on soil physical properties. It has been shown that an increase in SAR and a reduction in EC can result in decreased hydraulic conductivity, K (Quirk and Schofield, 1955; Ayers and Westcot, 1985; Suarez et al., 2006). This decreased K has been linked to Na-induced clay dispersion, which impacts soil structure and plugs soil pores by dispersed clay particles thereby reducing the ability of the soil to transmit water (Frenkel et al., 1978; Abu-Sharar et al., 1987; Sumner, 1993; Nelson et al., 1997; Gonçalves et al., 2007). Other negative impacts of wastewater irrigation on the soil environment are increased susceptibility to surface sealing, resulting in runoff and soil erosion problems, as well as soil compaction and decreased soil aeration (e.g. Halliwell et al., 2001; Walker and Lin, 2008; Duan et al., 2010; Tarchouna et al., 2010; Xu et al., 2010).

While many laboratory studies have been conducted to identify thresholds where elevated levels of Na can become detrimental to soil quality; most evaluations are based on air-dried soil repacked in columns and saturated with saline solutions (e.g. Quirk and Schofield, 1955; Rhoades, 1977; Oster and Schroer, 1979; Abu-Sharar et al., 1987; Sumner, 1993; Morshedi and Sameni, 2000; Zhang and Norton, 2002). Furthermore, though the effects of SAR and EC are well documented for soils in arid and semi-arid regions; little research has been conducted for humid region soils where rainfall is typically thought to be sufficient to leach out accumulated salts, and where B horizon soils may contain iron or aluminum oxide clays; which tend to increase aggregate stability and encourage flocculation (Shainberg and Singer, 1985; Duiker et al., 2003). As such, the impact of SAR and EC on the saturated K (K_s) on a humid region soil irrigated by wastewater is of interest.

In Pennsylvania, water reuse is considered an important component of water resource management (PA Department of Environmental Protection, 2012). At the field site, "The Living Filter", Centre Co., PA (Richardson, 2010), land application of wastewater effluent has been used as tertiary treatment of the wastewater since the 1960s; and the concentration of salts in the effluent has increased dramatically over the years. In 1975, concentrations of Na^+, Ca^{2+}, and Mg^{2+} were 21, 31, and 15 mg L^{-1} respectively (Richenderfer et al., 1975) and in 2011, these concentrations had increased to 196, 60 and 30 mg L^{-1} respectively; while the SAR increased from 1.6 to 5.1 over that time period.

This increase in salt concentrations (especially Na^+) and SAR in the wastewater is mainly due to the increased use of water softeners, as well as water conservation efforts. Since salts are known to be added to the soil profile with every irrigation event, long-term irrigation with high salinity and high Na^+ water can be expected to cause accumulation of salts in the soil and increases in soil SAR (Ayers and Westcot, 1985; Rahman et al., 2015). Thus, given the increases in wastewater SAR with low effluent ECs at this site, concerns about soil SAR values increasing to the point where soil structure and K would be negatively impacted has arisen.

With these concerns, we conducted a field study at this research site to evaluate the differences in physicochemical soil properties (specifically K_s, SAR, and EC) throughout the soil profile (120 cm) at wastewater irrigated sites and non-irrigated sites at different landscape positions (summits and depressions). The purpose of the study was to determine the extent to which wastewater irrigation was impacting soil EC and SAR, and to identify whether increases in SAR were causing reductions in K_s within the soil profile as one of the most critical concerns about effluent wastewater reuse is the negative impact on soil physical properties, particularly hydraulic conductivity (Gonçalves et al., 2007).

2. Materials and methods

2.1. Site description

This study was conducted at a long-term water resource management experimental site, "The Living Filter" (Fig. 1), established in 1962 where wastewater is used for irrigation. The site is approximately 3.2 km from Penn State's University Park campus (University Park, PA) and was established 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). In 1984, the site was expanded to include 708 ha of land with 27% located at the Astronomy Site (original site) and 73% located at the Gamelands Site (Dadio, 1998).

There are three different land uses – forested, grassed, and cropped land. The cropped lands are under rotation with primarily corn (*Zea Mays*), wheat (*Triticum aestivum*), rye (*Secale cereale*), sweet clover (*Melilotus albus*), and soybeans (*Glycine max*) (Salada, 2010). The grassed land has been propagated with mainly fescue, *Festuca arundinacea*, (Salada, 2010), and the forested area is composed of mixed hard woods; predominantly white oak, *Quercus alba* (Richenderfer et al., 1975).

The Astronomy Site soil has been mapped as mostly Hagerstown silty clay loam, a fine, mixed, semiactive, mesic Typic Hapludalf and Hublersburg silt loam, a clayey, illitic, mesic Typic Hapludult.

The Astronomy Site has been utilized for almost 15 years longer than the Gamelands Site, receiving over 50 years of irrigation with effluent, so to observe the maximum effects of irrigation with wastewater, this study focused on the Astronomy Site (Fig. 1).

2.2. Wastewater irrigation at the "The Living Filter" site

While the site is permitted to apply 5 cm of wastewater per week year-round (260 cm per year), the typical application is only ~60% (~160 cm per year) of the permitted amount. Fields are irrigated with the wastewater for a 12-h period and then allowed to rest for six and a half days until the next irrigation cycle begins (Personal communication with Wastewater Utility Systems Engineer, John Gaudlip, 2012). Wastewater irrigation is applied regardless of weather conditions. Irrigation is performed using solid set overhead sprinklers. The effluent is a combination of campus laboratory, campus residential and municipal wastewater, with the dominant source being dependent on the time of year. The site also receives an average of 100 cm of precipitation annually (average for 2012–2015).

Irrigation volumes are determined using an electromagnetic flow meter (ABB MagMeter, ABB Limited, Switzerland) which is located within the effluent pump house at the treatment plant. Sampling frequency for irrigation wastewater quality (and groundwater quality) range from yearly to monthly to event (or research project) based depending on parameter. Parameters measured include Ca^{2+}, Mg^{2+}, Na^+, potassium (K^+), chloride (Cl^-), nitrate-nitrogen, phosphate, total dissolved solids, and bacteria (*E. coli*).

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