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The effect of mineral-ion interactions on soil hydraulic conductivity

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ABSTRACT

The reuse of winery wastewater (WW) could provide an alternative water source for vineyard irrigation. The shift of many wineries and other food processing industries to K^+-based cleaners requires studies on the effects of K^+ on soil hydraulic conductivity (HC). Depending on clay content and mineral composition, K^+ additions can affect the HC either positively or negatively. Soil mineralogy was anticipated to exhibit a strong influence on HC responses and, therefore, soils of contrasting mineralogy were evaluated for changes in soil HC resulting from applications of solutions elevated in Na^+ and K^+. To examine the impact of mineral-ion relationships on HC, soils dominant in montmorillonite, vermiculite, or kaolinite from the Napa and Lodi wine regions of California, were packed into soil columns to observe changes in leachate chemistry and HC. Irrigation with Na^+- and K^+-rich WW was simulated by applying solutions at sodium absorption ratio (SAR) values of 3, 6, and 9 and potassium absorption ratio (PAR) values of 1, 2, 4, and 9. While HC was reduced in the 2:1 clay soils (montmorillonite and vermiculite) for all SAR treatments, the vermiculite and the kaolinite rich soils exhibited equal or greater reductions in HC for PAR treatments, as compared with the SAR treatments. Findings from this evaluation of the interaction of Na^+ and K^+ with three different mineral soils suggest that the reuse of WW with increasing PAR are least problematic for montmorillonite dominated soils and most detrimental to the HC of the vermiculite dominated soil. The presence of minerals with a high affinity for K^+ (e.g., vermiculite, mica) in this soil suggest that the interlayer binding of K^+ could lead to greater reductions in HC. Full analysis of soil and WW is recommended prior to all land applications.

1. Introduction

The reuse of wastewater is an attractive solution to address water scarcity. While the salt concentration of wastewater is typically moderate (~1.5 dS m^{-1}) and can be applied to land, applications of sodium (Na^+)-rich water increase the risk of sodic conditions occurring in the soil profile, degrade soil quality, and limit productivity (Laurenson et al., 2012). The total salinity of irrigation water (measured as electrical conductivity in dS m^{-1} or electrolyte concentration in mEq L^{-1}) can also influence the permeability of a soil and its hydraulic conductivity (HC) (Abusharar et al., 1987; Keren and Singer, 1989). The organic components of winery-wastewater (WW) are effectively reduced by most forms of treatment, whereas salts persist in the water after treatment. A companion study conducted in 2013, looking at California WW composition, revealed that the SAR and PAR of California WW after on-site water treatment ranged from 1 to 9 (Buelow, 2013). Typically, WW has a salt composition dominated by Na^+, but the adoption of potassium (K^+)-based cleaners is shifting the composition of these waste streams. The impacts of Na^+-rich water on soil physical and chemical properties and plant health have been studied and debated extensively (Arienzo et al., 2012; Benitez et al., 1999; Chen et al., 1983; Frenkel et al., 1978; Frenkel, 1985; Hamilton et al., 2007; Hermon et al., 2008; Jayawardane et al., 2011; Laurenson et al., 2012; Nightingale, 1959; Quirk and Schofield, 1955). However, K^+ is less well understood (Arienzo et al., 2012). Our recent WW survey in Northern California has shown that pre- and post-treatment concentrations of K^+ to range from 2-772 mg L^{-1}, with a maximum PAR of 11.8, and thus research is needed to examine how these wastewaters might impact vineyard production systems (Buelow, 2013).

Ubiquitous in wine industry cleaners, Na^+ and K^+ salts are not removed by typical or affordable WW treatment processes (Mosse et al., 2011), presenting a considerable hurdle to its reuse in agriculture. In order to assess the hazard posed by Na^+ to soil structure and HC, the sodium adsorption ratio (Eq. (1)—SAR), a weighted ratio

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of Na^+ to other divalent cations in solution, is used as the standard water quality measurement, where concentrations of cations are in mEq L^{-1} (Endo et al., 2002). A similar calculation exists for the potassium adsorption ratio (Eq. (2)PAR) (Chen et al., 1983). Equivalent equations for exchangeable ions of the soil surface are exchangeable sodium percentage (Eq. (3)—ESP) (Endo et al., 2002) and exchangeable potassium percentage (Eq. (4)—EPP) (Chen et al., 1983). Guidelines for interpretations of water quality for irrigation have shown SAR values from 3 to 9 to fall into the slight to moderate risk for reductions in infiltration at EC > 0.3–0.5, and are severely hazardous if EC < 0.3–0.5 dS m^{-1} (Ayers, 1985).

$$SAR = \frac{Na^+}{\sqrt{1/2(Ca^{2+} + Mg^{2+})}} \quad \text{Concentrations in mEq L}^{-1} \quad (1)$$

$$PAR = \frac{K^+}{\sqrt{1/2(Ca^{2+} + Mg^{2+})}} \quad \text{Concentrations in mEq L}^{-1} \quad (2)$$

$$ESP = \frac{Na^+}{Na^+ + K^+ + Mg^{2+} + Ca^{2+}}(100) \quad \text{Concentrations in mEq 100g soil}^{-1} \quad (3)$$

$$EPP = \frac{K^+}{Na^+ + K^+ + Mg^{2+} + Ca^{2+}}(100) \quad \text{Concentrations in mEq 100g soil}^{-1} \quad (4)$$

Clay mineralogy has also been shown to have a large influence on reductions in HC (Churchman et al., 1993; McNeal and Coleman, 1966). Smectites show extensive swelling and dispersion, due to their 2:1 layer structure, which accommodates a high amount of exchangeable Na^+ within its interlayer space (Arienzo et al., 2012; Churchman et al., 1993). Na^+ is a large monovalent ion and more effectively forces clay tactoids (i.e., particles) apart than Ca^{2+} or Mg^{2+} (Quirk, 1986). Swelling occurs with increasing Na^+ concentration, as hydration of Na^+ leads to the expansion of the interlayer (ESP > 15). Dispersive conditions are described as mutual repulsion of tactoids fully surrounded by associated Na^+ and waters of hydration (ESP < 15) Essington (2004). Smectitic soils usually disperse more in weak salt solution at low SAR values than do kaolinitic soils, as indicated by a more abrupt and larger decrease in HC (Frenkel et al., 1978; Keren and Singer, 1988). Soils high in kaolinite have been found to be quite stable, even when exposed to 3.13 mEq L^{-1} NaCl (McNeal and Coleman, 1966). Intermediate in their behavior are soils that contain primarily 2:1 layer silicates other than smectites, such as vermiculite or illite (McNeal and Coleman, 1966).

The diversity of the behavior of K^+ in soil has also been suggested as dependent on clay content, soil mineralogy, and possibly K^+-fixation (Jayawardane et al., 2011; Shainberg et al., 1980; Sumner, 1993). Solutions enriched in K^+ can improve soil HC, possibly through Na^+ displacement (Chen et al., 1983; Levy and Torrento, 1995; Ravina and Low, 1972; Ravina and Markus, 1975). However, additions of K^+ led to reductions in HC in an illite soil and a low cation exchange capacity (CEC) montmorillonite soil (Chen et al., 1983; Laurenson et al., 2011). In one study, the effect of exchangeable K^+ on permeability was examined in three soils, a loamy sand, a light clay, and a heavy clay, each containing close to 50% montmorillonite (Chen et al., 1983). Increases in EPP up to 20 did not destabilize the loamy sand or the heavy clay. In the light clay, which contained 16% illite, any increase in EPP lead to a decrease in HC, likely due to illite binding additional K^+ (Chen et al., 1983). Similarly, the addition of K^+ (3 mEq L^{-1}) to irrigation water (<60 mg L^{-1} soluble salts) significantly reduced water infiltration in a vermiculitic San Joaquin sandy loam, as compared to an untreated control (Peacock, 2007). The aforementioned soils, which contained K^+-fixing clays like vermiculite and illite, showed greater reductions in HC associated with high K^+ concentrations than in soils without K^+-fixation.

Little published research exists specifically on WW reuse for irrigation of grapevines. In California there are examples of wineries reusing treated WW for landscaping and frost protection (Hamilton et al., 2007), and several case studies of wastewater characterization and treatment for reuse have been published, including research conducted in Australia (Christen et al., 2010; Laurenson et al., 2012), Spain (Bustamante et al., 2005), South Africa (Mulidzi, 2007), and Mexico (Mendoza-Espinosa et al., 2008). A recent study compared the effects of solutions, ranging in SAR and PAR from 5 to 40, on a predominantly montmorillonite Australian vineyard soil (Arienzo et al., 2012). Treatment solutions combining either Na^+ or K^+ with Ca^{2+}, Mg^{2+}, or Ca^{2+}–Mg^{2+} were applied to repacked soil columns, and the reductions in HC were found to be greater in magnitude for the Na^+ than for the K^+ solutions (Arienzo et al., 2012). The treatment solutions were applied to only one soil type, and it remains that the effects of reusing K^+-rich WW on the HC of soils with contrasting mineralogy requires further investigation (Jayawardane et al., 2011).

As such, we present for the first time the effects of Na^+ and K^+-rich solutions on the HC of three vineyard soils of contrasting mineralogy, dominant in montmorillonite, vermiculite, or kaolinite from Northern California, treated with aqueous salt concentrations that reflect conditions found in a WW survey of California wineries (Buelow, 2013). Selected soils represent common soil types supporting vineyard production in Northern California (O'Geen et al., 2008). Soil column studies were conducted to obtain HC measurements and reductions in HC were then used to compare the effects of saline solutions on water movement in three contrasting soils.

2. Materials and methods

2.1. Soil sampling and preparation

The three soil types chosen for this study are representative of Northern California vineyard soils with differing mineralogy. They included; (1) Bale fine loam from Napa (fine-loamy, mixed, superactive, thermic Cumulic Ultic Haploxeroll), (2) Redding gravelly loam from Lodi (fine, mixed, active, thermic Abruptic Durixeralf), and (3) San Joaquin loam from Lodi (fine, mixed, active, thermic Abruptic Durixeralf) (NRCS, 2011). Bale was the only soil containing montmorillonite, Redding contained predominantly kaolinite, and vermiculite was unique to San Joaquin (Table 1). The horizon of illuvial clay and salt accumulation (Bt1 horizon) was selected. This focused the study on the layer with highest clay content and most distinct representation of mineralogical characteristics for a given soil type. The intent was to focus on a soil horizon often impacted by salts under irrigated conditions; irrigated soils generally possess lower salinity at the surface and show increasing salinity with depth (Frenkel et al., 1978; Halliwell et al., 2001). Collected soils were air dried and sieved to isolate the ≤2 mm fraction.

2.2. Soil characteristics

Characteristics of the three soils: (1) Bale dominated by montmorillonite (Bale-mont), (2) Redding rich in kaolinite (Red-kao), and (3) San Joaquin dominant in vermiculite (SJ-ver) are provided in Table 1. Soil particle size distribution was determined on a mass basis by the pipette method (Burt and Staff, 2014), soil pH (Thermo Scientific Orion 4 Star meter; Fisher Scientific Accumet Gel-filled Pencil-Thin Epoxy Body pH Combination Electrodes-Mercury-Free 13-620-252) and EC (Thermo Scientific Orion 4 Star