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Salt leaching in fine-grained, macroporous soil: Negative effects of excessive matrix saturation

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ABSTRACT

Irrigation and tile drainage are commonly used to reclaim salt-affected soils, but salt leaching can be hindered in low permeability soils when infiltrating water preferentially flows along vertically connected macropores and bypasses the saline soil matrix. To identify the important controls on salt leaching effectiveness in fine-grained, macroporous soil, a two-year irrigation and drainage field experiment was undertaken to return a salt-affected soil to agricultural production. Salt leaching effectiveness in a 20 × 20-m irrigated test plot was evaluated using time-lapse electrical resistivity tomography, soil sampling, drainage monitoring and subsurface water sampling. Results were compared to an adjacent unirrigated control plot. During the first year of the irrigation experiment, effective leaching resulted in a 23–40% decrease in salt mass over a depth of 0–2.4 m. In the second year, similar amounts of applied water (irrigation + precipitation) resulted in negligible salt leaching due to a rise in the regional water table and wetter soil conditions that limited macropore-matrix interaction. Chloride mass recovery in tile drainage water, which was greater in Year 2 due to upward seepage, was not a reliable indicator of leaching from the root zone. Proper monitoring and control of irrigation and drainage to avoid overly wet soil matrix conditions can increase salt leaching efficiency, giving shorter reclamation timelines and reduced volume of applied water.

1. Introduction

Sources of high levels of salt in soil include: direct deposition from irrigation; uptake from shallow groundwater; and release from numerous industrial sources, including saline geothermal fluids and oilfield brines (e.g., Jury and Weeks, 1978; Hendry and Schwartz, 1982; Merrill et al., 1990; Funukawa et al., 2007; Leskiw et al., 2012). Salt-affected soils may require reclamation to improve plant growth, or industrially related impacts may require remediation to meet regulatory guidelines. Leaching of salts from the rooting zone in conjunction with leachate collection using tile drains is a common method used to reclaim or remediate salt-affected agricultural soils (Abrol et al., 1988; Qadir et al., 2000). In dry climates, rainfall alone is often insufficient to leach salt from the soil profile. Therefore, the addition of irrigation water and subsurface drainage is often used to accelerate the leaching process and maintain agricultural productivity (Ayers and Westcot, 1994; Letey et al., 2011).

The importance of macropore flow on solute transport in soils has long been recognized (e.g., Thomas and Phillips, 1979; Beven and Germann, 1982; Wagenet, 1983; White, 1985; Nielsen et al., 1986; Hendrickx and Flury, 2001; Jarvis, 2007). Within the paradigm of groundwater or surface water protection, preferential flow and rapid migration of contaminants along macropores can have deleterious consequences for water quality. Therefore, much of the research on flow and solute transport in macropores has been developed from monitoring the migration of pesticides, herbicides, fertilizers, tracers, and colloids applied to the soil surface (e.g., Kladivko et al., 1991; Kung et al., 2000; Cey et al., 2009; Nielsen et al., 2011; Frey et al., 2012). In contrast, the influence of macropores on removal of in situ contaminants, such as salt, within the vadose zone and shallow groundwater has received far less attention. Salt leaching effectiveness in fine-grained, macroporous soils has traditionally been studied from the perspective of the method

Abbreviations: AES, atomic emission spectroscopy; bgs, below ground surface; EC, electrical conductivity; ERT, electrical resistivity tomography; ET, evapotranspiration; FAO, Food and Agriculture Organization; GP, Guelph permeameter; IC, ion chromatography; ICP, inductively coupled plasma; PET, potential evapotranspiration; SPE, saturated paste extract.

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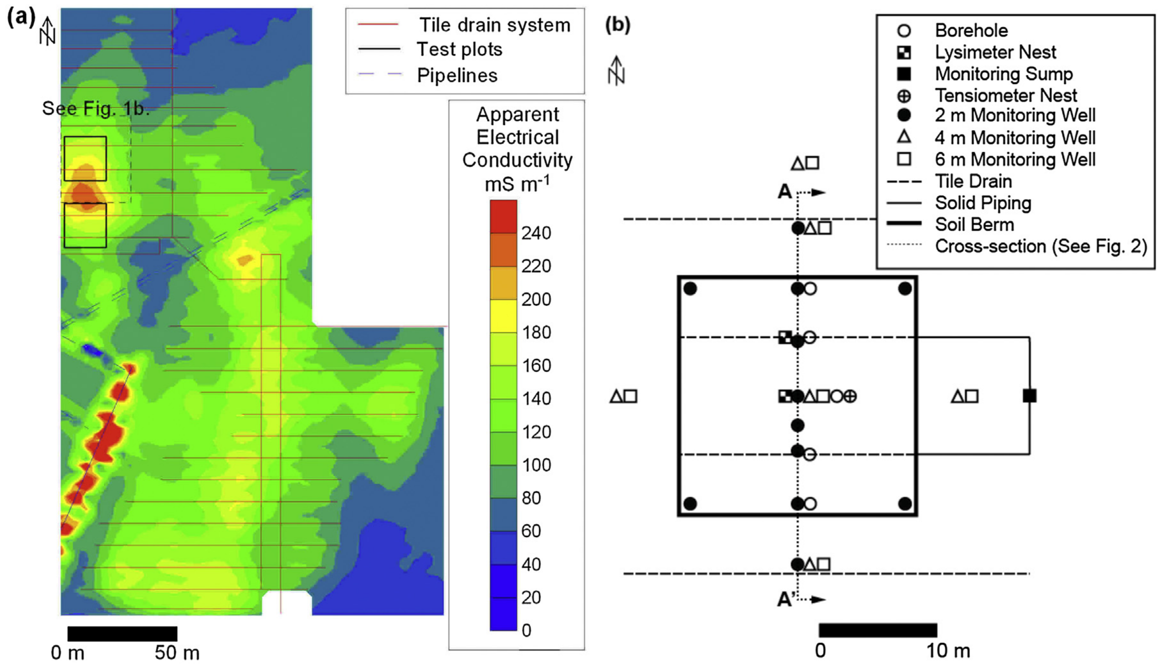

Fig. 1. Plan view of the study site. (a) Location of tile-drainage network and test plots overlain on a map of subsurface apparent electrical conductivity derived from EM-31 measurements (modified after Head, 2013). Warm colors indicate elevated salinity. Black squares show the location of the irrigated (north) and unirrigated (south) test plots in the northwest portion of the site. (b) Soil, groundwater, and tile drain monitoring locations in the vicinity of the irrigated test plot (modified after Bishop et al., 2015).

of irrigation application (e.g., ponding, progressive ponding, sprinkler, drip, and furrow irrigation) (Moreno et al., 1995; Prendergast, 1995; Youngs and Leeds-Harrison, 2000; Crescimanno et al., 2007), as well as water application intensity (Tanton et al., 1995). Although field studies (Qadir et al., 2000) and numerical modeling (Xin et al., 2016) suggest that macropores may decrease the efficiency of salt leaching, our understanding of the influence of macropores and matrix-macropore exchange is limited. Similarly, regional and local groundwater conditions can contribute significantly to the development of soil salinization (Salama et al., 1999), but the role of soil moisture and shallow groundwater conditions on salt leaching and subsurface drainage in fine-grained, macroporous soils is not well studied. Strategies for optimizing salt leaching through controlled irrigation or drainage are desired for reducing soil reclamation timelines and water usage.

In this paper, we present results from two years of detailed monitoring of a pilot-scale irrigation and drainage field experiment designed to return salt-affected soil to agricultural production at a former industrial facility. A tracer study conducted at the same field site identified preferential flow as a major solute transport pathway in the fine-grained, macroporous soil present there (Bishop et al., 2015). The objectives of the current study were to examine multi-year salt leaching behavior in order to improve understanding of the hydrologic processes that influence salt leaching in fine-grained, macroporous soil. In particular, we sought to characterize the effects of macropore flow and transport on salt leaching. Large-scale test plot results were analyzed with respect to water flow and salt transport processes and were used to make inferences on increasing the speed and water efficiency of saline soil remediation.

2. Methods and materials

2.1. Site description

A field study was conducted at a former oil and gas production facility in central Alberta, Canada that historically experienced accidental releases of NaCl brine, co-produced during oil production, resulting in salt-affected soil and shallow groundwater. Although oil production facilities were removed from the site by 1976, subsurface salinity remains problematic decades later due to the fine-grained, low permeability soils at the site. The areal extent of salt-affected soils is shown in Fig. 1a, as a region of elevated apparent electrical conductivity (EC). Chloride was measured at a concentration of 120 000 mg L^{-1} in produced water samples collected from nearby oil producing formations in 2009 and is the dominant anion in the produced water, comprising 99.6% of total anions by mole fraction. Residual Cl impacts at the study site, measured in 2008, ranged up to 5900 mg kg^{-1} (dry soil basis) in the upper 2 m of soil and 8900 mg L^{-1} in shallow groundwater sampled from wells screened over 2- to 4-m depth. Natural Cl concentrations in background areas of the site are relatively low, <20 mg kg^{-1} in soil and <10 mg L^{-1} in shallow groundwater. Chloride was selected as the principal parameter for monitoring remediation progress, given its dominant fraction in the released water and its low background concentration at the site.

Land use in the area is primarily agricultural, with livestock farming and cereal/legume cropping being dominant. The study site is planted with a mix of forage species, mainly perennial grasses. The regional climate is classified as Continental Humid according to the Köppen Climate Classification. Local average daily temperatures range from 15 °C in summer (Jun.–Aug.) to −11 °C in winter (Dec.–Feb.) (Environment Canada, 2014a). Average annual precipitation is 446 mm, while average annual potential evapotranspiration (PET) is estimated to be in the range of 476–500 mm by the Thornthwaite method (Barker et al., 2011). High average annual PET in relation to precipitation limits leaching under natural conditions and motivates the use of irrigation to increase leaching rates.

Soil at the study site is classified as an Orthic Black Chernozem (Navarre series) in the Canadian System of Soil Classification (Soil Classification Working Group, 1998) and is developed on slightly saline glaciolacustrine sediment of silt loam texture (Bowser et al., 1962). The glaciolacustrine layer (B and C horizons) extends to 2.4-m depth and is shown in cross-section in Fig. 2. This layer comprises the plant rooting zone and is the target interval for salt remediation.