The production of oil and gas from the Bakken and Three Forks formations in western North Dakota has increased exponentially over the past decade. During oil extraction, upward of 18 barrels of salt water or "brine" are produced for each barrel of oil (Clark and Veil, 2009). Accidental releases of brine have become a common occurrence in recent years. Brines produced in the region are largely composed of NaCl and exhibit electrical conductivities (EC) of 200 dS m\(^{-1}\) (Gleason et al., 2014). In the event of a release, the chemistry of brine often causes soil structure disturbance and vegetation mortality.

Brine spill mitigation using the ex situ method of excavation and removal (i.e., dig and haul) is the predominant practice used in the North American Williston Basin as it is an expedient and effective means of contaminant removal. Although widely used, the application of dig and haul can be limited in some situations due to high financial costs (US$2650 m\(^{-3}\); D. Anderson, personal communication, 2018), scarcity of replacement soil, and the potential for equipment to adversely affect well pad infrastructure or nearby sensitive resources such as wetlands. In situ remediation of brine-contaminated soils is often attempted through the provision of divalent cation rich amendments to displace Na\(^+\) from soil exchange sites and subsequent leaching by precipitation events or irrigation to remove it from the soil profile. These methods in semiarid climates, where the evaporative demand exceeds precipitation, often achieves limited results. This study assessed the effectiveness of remediating brine-contamination by "wicking" salts from the soil surface when a shallow water table is present. During a 5-wk period, two engineered paper-based humidifier wicks and two nonengineered wicks (wheat straw and hydraulic mulch) placed on the surface of brine-contaminated soils reduced the total soil Na concentrations by 65 to 88% and 5 to 80%, respectively. Our results indicate that deployment of engineered wicks or similar, more cost effective materials may be an effective in situ remediation strategy that merits further field-scale investigation.

**Abstract:** Accidental releases of brine, derived from oil and gas development, in the Williston Basin in North America have become frequent in recent years. Oil-field brines are primarily composed of sodium chloride and exhibit electrical conductivities exceeding 200 dS m\(^{-1}\) and total dissolved solids exceeding 250 g L\(^{-1}\). Current in situ remediation strategies involve the incorporation of divalent-cation rich amendments to displace and then rain and irrigation to leach sodium out of the soil profile. These methods in semiarid climates, where the evaporative demand exceeds precipitation, often achieves limited results. This study assessed the effectiveness of remediating brine-contamination by "wicking" salts from the soil surface when a shallow water table is present. During a 5-wk period, two engineered paper-based humidifier wicks and two nonengineered wicks (wheat straw and hydraulic mulch) placed on the surface of brine-contaminated soils reduced the total soil Na concentrations by 65 to 88% and 5 to 80%, respectively. Our results indicate that deployment of engineered wicks or similar, more cost effective materials may be an effective in situ remediation strategy that merits further field-scale investigation.
The objective of this proof-of-concept study was to determine the efficacy of using highly absorbent “wicking” materials to draw water and dissolved salts from the soil profile as a means of permanent salt removal (Fig. 1A). We hypothesize that under constant soil water conditions and the presence of a high evaporative demand, significant quantities of Na may be removed from brine-contaminated soils.

Materials and Methods

This study was conducted over a 5-wk period (13 Nov.–18 Dec. 2017) in a greenhouse located on the campus of North Dakota State University (Fargo, ND). Mean air temperature and relative humidity within the greenhouse were 26.5 ± 3.2°C and 18.6 ± 0.07%, respectively.

To simulate brine-contamination, 3.3-kg batches of a fine sandy loam soil (EC_{1:1} < 0.5 dS m^{-1}) were mechanically mixed with 265 mL of oil field brine (EC ≈ 226 dS m^{-1}). After mixing, the soil was allowed to air dry for a 7-d period before being ground to pass a 2-mm sieve and mixed again for a 5-min period. The resulting brine and soil mixtures exhibited average EC_{1:1} values of 18 dS m^{-1} and average %Na value of 70.5%, as determined using the methods outlined in DeSutter et al. (2015). The soil was then packed into 30 polyvinyl chloride columns (10.2-cm diam. by 38.1-cm height) to 30-cm depths (Fig. 1B). The top of each column was left open to the atmosphere to allow for the placement of wicking materials and permit an evaporative flux. The bottom of each column was sealed using a polyvinyl chloride test cap modified with a nylon garden hose barb. Water reservoirs consisted of 30 4-L Mariotte siphons filled with degassed, purified water (reverse osmosis) and sealed using #6 rubber stoppers containing two separate 0.16-cm by 0.32-cm tubes to act as a water supply line and an air intake, respectively. Siphons were connected to each soil column and assigned one of two water table depths, water table at 5 cm (WT-1) and water table at 15 cm (WT-2) below the soil surface (Fig. 1B). Wicking treatments were (i) a bare soil surface (control) (ii) ground wheat straw (straw), (iii) Second Nature Wood Fiber Plus Hydraulic Mulch (Profile Products) (HM), (iv) 1043 Super Wick (Essick Air Products, Inc.) (SW), and (v) CBW9 Humidi-Wick (BestAir Pro) (HW) (Fig. 1C). Soil columns were then placed into wooden stands in a completely random arrangement. Wicking materials were chosen on the basis of their availability to the researchers; it should be noted that other materials are available that may have greater absorbency and be more economical for future studies.

The straw and HM were placed into soil columns to form a 7.5-cm-thick layer above the soil surface. The SW and HW materials were 10 cm in height and were placed into the soil to a depth of 2.5 cm and with an areal height of 7.5 cm above the soil surface. Wicking materials were carefully removed, and any soil adhering to the wicks were placed back into the column and replaced at 7-d intervals. Evaporation losses (mL d^{-1}) were determined by recording the weight (g) of the Mariotte siphons daily over 14 d. After 5 wk, soil columns were frozen at temperatures of −12°C for 3 d. Once frozen, columns were cut and the soil was dissected into 5-cm sections. Soil samples were air-dried, weighed, and prepared using 1:20 soil/1 M ammonium acetate (pH = 7). Cation concentrations (Na^{+}, Mg^{2+}, and Ca^{2+}) from the extracts were determined using an atomic absorption spectrophotometer (Model 200A, Buck Scientific) and %Na determined (DeSutter et al., 2015). The EC_{1:1} of soil samples was measured from suspensions of 10 g of soil and
10 mL of deionized water using a Sension 378 conductivity probe (Hach Co.). Wicking materials were washed in 1 L of distilled water and the extracts quantified for Na, Mg, and Ca and EC as above. A mass balance analysis was then conducted to determine the total mass Na reduction (%) from each of the soil columns using Eq. [1]:

\[
\% \text{Na reduction} = 100 \times \frac{\text{wick}_f}{(\text{wick}_f + \text{soil}_f)}
\]  [1]

where wick\(_f\) is the Na extracted by the wicking material and soil\(_f\) is the Na remaining in the soil expressed on a mass basis (mg).

To determine if water table depth and wicking material affected the percentage reduction of Na in the soil profile and the average rate of evaporation, a mixed model analysis of variance was used in SAS with means separated using LSD at the 0.05 level of confidence (version 9.4, SAS Institute, 1994). Control columns were not compared in the analysis for %Na reduction in the soil; however, they were used in the analysis of average evaporation rate. Regression analysis was used to determine the relationship between average evaporation rate (mL d\(^{-1}\)) and total mass Na reduction in the soil (%) and fit by a logarithmic model in SigmaPlot 10.0 (Systat Software, 2006).

**Results and Discussion**

Over a 5-wk period, the wicking treatments, SW, HW, HM, and straw, reduced the mass of Na in the soil columns by an average of 87, 74, 79, 39%, respectively, at WT-1 (Fig. 2A). Similarly, SW, HW, HM, and straw decreased the mass of Na in the soil profile by an average of 88, 81, 60, and 14%, respectively, at WT-2. No significant difference (\(p > 0.05\)) in %Na reduction occurred between the two water table depths (WT-1 and WT-2) for SW, HW, and the HM wicking treatments. However, water table depth did significantly affect the reduction of Na in the soil for the straw wicking treatment. The ratio of average daily evaporation rate (mL d\(^{-1}\)) between the control and each of the respective wicking materials at both water table depths is presented at the top of Fig. 2A. The average evaporation rate for HW at WT-1 (32.9 mL d\(^{-1}\)) and for SW at both WT-1 (32.7 mL d\(^{-1}\)) and WT-2 (30.9 mL d\(^{-1}\)) were significantly higher than the control (23.6 mL d\(^{-1}\)), while HW at WT-2 (22.6 mL d\(^{-1}\)) and HM at WT-1 (24.8 mL d\(^{-1}\)) and WT-2 (23.2 mL d\(^{-1}\)) exhibited no significant differences. The relationship between water loss through evaporation into the atmosphere (mL d\(^{-1}\)) and reduction of Na (%) was fit using a logarithmic model and was found to be highly significant (\(p < 0.0001\)) (Fig. 2B).

The amount of soluble salts accumulated by the wicking materials was dependent on the soil water content, the difference in matric potential between the soil matrix and the material, and the evaporative demand of the atmosphere. Wicking treatments that absorbed greater amounts of water from the soil (i.e., SW, HW, and HM), as indicated by higher daily evaporation rates, were able to accumulate the largest quantities of Na over the 35-d experimental period. The capillary suction exerted by SW, HW, and HM was greater than that of straw due to the distribution of fine-sized pores in these materials. The size distribution of straw used in this experiment (>2.5 cm) most likely did not provide the necessary pore size distribution and pore connectivity to draw water out of the soil profile, thereby reducing the effectiveness of this material to decrease Na concentrations in the soil.

Swelling and/or dispersion of soil particles can significantly restrict water movement into and through the soil.
In soils exhibiting elevated levels of exchangeable Na, soil flocculation and water movement can be maintained if the EC of the soil solution is above a critical threshold (Suarez et al., 2008). To examine the potential for soil swelling and dispersion as it is affected by the relationship between EC and extractable Na, Fig. 2C depicts the average EC and %Na across columns treated with the SW at WT1, the combination of which resulted in the greatest reduction in both parameters over the duration of the experiment. As salts were removed from the soil by the wicking materials, the EC of the soil solution decreased at depths between 5 and 30 cm (Fig. 2C). The reduction of soil EC to <1 dS m\(^{-1}\), however, did not cause Na to have significant effect on soil physical properties or water movement, as the soil used in this experiment had a relatively low percentage of clay (<8%). In applications of this method to other soil textures, a source of divalent cations (i.e., Ca\(^{2+}\)) may need to be provided over time to maintain electrolyte concentrations in the soil solution to prevent swelling and dispersion.

**Conclusions**

In situ remediation of brine-contaminated soils by the placement of highly absorbent wicking materials onto the soil surface may provide a low disturbance alternative to conventional ex situ and in situ remediation methods, particularly in sensitive environments such as wetlands and areas with high water tables. The current study demonstrates the proof of concept for a new method for which the technical hurdles and pitfalls of scaling up to field applications will need further investigation. The use of wicks warrants additional investigation due to other reclamation strategies’ costs (e.g., millions of dollars for excavation and removal), their limited effectiveness, and unfeasible use in specific circumstances (e.g., well pads, wetlands). Further research is needed (i) to determine the effectiveness of this method in other soil textures, (ii) to identify wicking materials that can maximize salt uptake as well as provide durability to withstand field conditions and be reused for multiple deployments, (iii) to optimize placement and layout designs in field conditions to maximize salt reduction and minimize costs, and (iv) to evaluate the most cost effective treatment in terms of Na removal.

**References**


