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REVIEW AND INTERPRETATION

Produced water's impact on soil properties: Remediation challenges and opportunities

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Abstract

The choice of remediation of oil-produced water (aka brine) spills depends on the severity of contamination, environmental factors, cost-effectiveness, and relative efficiency of salt removal. The objective of this review is to summarize the current practices that are used to remediate brine spills or abandoned evaporation pits within the Bakken and Three Forks regions of the Williston Basin within the upper Great Plains. The most common current methods are "dig and haul" and the use of chemical amendments such as gypsum ($CaSO_4$) or organic amendments (manure, straw, etc.) to promote soil flocculation and the downward leaching of salts out of the topsoil. These methods, however, can fail to achieve sustained remediation success in a cost-effective and timely manner, making continued research into alternative methods necessary. The use of electrokinetics, crystallization inhibitors, wicking materials, and plant-growth promoting rhizobacteria hold promise for in-situ cleanup of contaminated sites.

1 | INTRODUCTION

Since 2012, North Dakota has been the second leading producer of crude oil in the United States (USEIA, 2018). The production of crude oil in the state occurs primarily from the Bakken and Three Forks formations located in the Williston Basin within the upper Great Plains, which collectively have been characterized as one of the most significant reserves of oil and gas in the world (Durham, 2010; Gleason et al., 2014). The primary by-product of oil and gas production is known as produced water or "brine" (Gleason et al., 2014), which poses a great environmental threat to soils and plants if released into the environment.

Brine is a saturated solution of dissolved salts, oil, and drilling chemicals that exhibits elevated levels of total dissolved solids (TDS), electrical conductivity (EC), and sodium adsorption ratio (SAR) (Gleason et al., 2014; Lauer, Harkness, & Vengosh, 2016). Environmental exposure to brine through accidental releases or abandoned evaporation pits can have severe deleterious effects on soil quality and vegetative health. For example, the concentrations of Na within brine can invoke swelling and dispersion of soil particles (Qadir, Ghafoor, & Murtaza, 2000), and the

Abbreviations: EC, electrical conductivity; ECe, electrical conductivity from saturated paste extract; ESP, exchangeable sodium percentage; GR, gypsum requirement; PET, potential evapotranspiration; PGPR, plant growth-promoting rhizobacteria; SAR, sodium adsorption ratio; TDS, total dissolved solids.

elevated EC levels most often kills salt-sensitive agricultural crops and native plants/vegetation (Munns & Tester, 2008).

To remediate these impacts, a variety of in-situ and ex-situ techniques are used to remove or reduce salt concentrations in the topsoil and restore previous levels of vegetation production. The technique that is chosen is dictated by where the releases occur and financial resources. Continued extraction of oil and gas will likely lead to more brine contamination, so more site-specific research is necessary to clean up releases better and more cost-effectively. Many knowledge gaps exist relating to the processes and effectiveness of current techniques, so research aimed at improving current techniques or developing new strategies may be especially impactful.

Core Ideas

- Produced water (aka brine) can impact plant health and soil and water qualities.
- Brine-impacted soils are commonly discarded to a landfill.
- Development of improved in-situ methods is needed to remediate contaminated soils.
- Alternative methods are promising to remediate brine-impacted soils.

1.1 | Aims and scope

The aims of this review are threefold. First, it provides an overview of how brine produced in the Williston Basin affects soil properties and vegetative production. This overview includes the genesis, chemistry, and production of brine, which is critical in understanding why soil and vegetation are affected and how remediation strategies can target those impacts. Second, it includes a summary of current remediation methods commonly used in the region. The summary demonstrates both shortcomings in the implementation of each method, as well as some knowledge gaps in their effectiveness. Finally, this review introduces several promising experimental methods to remediate brine contamination. These methods are still being optimized but may become viable alternatives with continued research and development.

The scope of this review is focused on, but not entirely limited to, brine production in the Williston Basin, where brine is predominantly composed of NaCl (∼90%) and lesser amounts of dissolved Ca, Mg, and K (Bader, 2016; Guerra, Dahm, & Dundorf, 2011). The climate is characterized as continental and semi-arid, with average annual precipitation and potential evapotranspiration (PET) of ≤36 cm yr^{-1} and ≥140 cm yr^{-1}, respectively (North Dakota Agricultural Network, 2018). The land use is largely agricultural, with this region producing a significant portion of the nation's wheat (*Triticum aestivum* L.), dry bean (*Phaseolus vulgaris* L.), and pea (*Pisum sativum* L.) (Preston & Kim, 2016; U.S. Department of Agriculture, 2017). Narrowing the scope for this type of review is critical because the composition of brine, environmental impacts, and procedures for remediation may vary based on region-specific characteristics, such as brine chemical composition, climate, land use, and resource availability.

Further, the scope of the review includes only techniques aimed at remediating brine-contaminated soil salinity and sodicity and does not include strategies to mitigate naturally occurring salinity and sodicity. While understanding of processes and impacts to soil and vegetation may be informed by research conducted on naturally occurring saline and sodic soils, assessment of remediation feasibility and efficacy is based only on extreme conditions associated with brine contamination.

2 | EFFECTS OF BRINE CONTAMINATION ON SOIL AND PLANT HEALTH

2.1 | Characteristics of brine within the Williston basin

The volume of brine produced from wells often varies with geographic area, geologic formation, and age, with older wells producing more brine because the amount of recoverable oil decreases (Kondash, Albright, & Vengosh, 2017). In the Williston Basin, significant volumes of brine are produced per barrel of oil, with most wells exhibiting oil/brine ratios between 1:3 and 1:18 (Guerra et al., 2011; Otton, 2006). Additionally, depending on the field, location, and the age of the well, the oil/brine ratios in the Bakken and Three Forks formations range from 2:1 to 1:4, whereas, in older formations, this ratio can be 1:2 to 1:100 (C. VanderBusch, personal communication, 2019; North Dakota Department of Mineral Resources, 2019). Based on an assumed well life of 30 yr, Kondash et al. (2017) estimated average brine production for individual wells in the Bakken of approximately 143,848 barrels.

The chemistry of oil-field brine makes it extremely hazardous to the soil and water resources of the region due to elevated concentrations of dissolved salts and organic compounds. Brines produced in the Williston Basin have been characterized as some of the most concentrated in the

United States, exhibiting TDS averaging 250 g L^{-1} and EC exceeding 200 dS m^{-1} (Table 1; Blondes et al., 2017; Gleason et al., 2014; Klaustermeier, Daigh, Limb, & Sedivec, 2017; Lauer et al., 2016). In most of the Bakken and Three Forks regions of North Dakota and in to Canada, brine is predominantly composed of NaCl (∼90%) and lesser amounts of dissolved Ca, Mg, and K (Bader, 2016; Guerra et al., 2011). However, dominant ionic composition can vary throughout the region, as some Na–Ca–Cl dominated brines are more common near the region's geographical center in Williston, ND (Iampen & Rostron, 2000).

From the sources provided in Table 1, the average concentrations of Cl, Na, K, Ca, and Mg are 137.2, 72.0, 3.49, 11.7, and 1.21 g L^{-1}, respectively. Reflecting the prevalence of Na, average SAR values for brine produced in North Dakota are among the highest in the nation, with values often approaching or even exceeding 300 (Guerra et al., 2011). In addition to elevated concentrations of salts and hydrocarbons, analyses of numerous brine samples have shown that brine produced in the region also contains high amounts of naturally occurring radioactive materials and trace metals including B, As, Ra, and Sr (Lauer et al., 2016). These trace elements have received significant attention in the literature due to the risks they pose to human health (Cozzarelli et al., 2017; Guerra et al., 2011; Lauer et al., 2016).

2.2 | Soil chemical and physical effects

The discharge of brine into the environment results in significant alterations to soil chemistry and structure. These changes are caused by the chemical consistency (i.e., ionic species) and high concentrations of solutes found in brine that interact with the soil matrix. In the Bakken and Three Forks regions, brine-impacted soils are most commonly dominated by the monovalent cation Na (≥90%) and, to a lesser degree, the divalent cations Ca and Mg; thus, following a spill, Na dominates the exchange sites. For example, in a study of seven locations within two counties of North Dakota that were impacted by brine, the electrical conductivity from saturated paste (ECe) in the top layer of soil (0–15 cm) ranged from 0.4 to 126 dS m^{-1} and the SAR ranged from 0.3 to 72, with Cl being the dominate anion (Klaustermeier et al., 2016). In addition, soil used for evaporation pits within the same region had maximum ECe and SAR values of 100 dS m^{-1} and 300, respectively (Murphy, Kehew, Groenewold, & Beal, 1988).

Sodium-dominated brines affect the soil chemistry in the same manner as documented in occurring saline and sodic soils. Swelling and dispersion of soil clays will occur when the level of soluble salts falls below the flocculation threshold for levels of Na on the exchange sites.

TABLE 1 Number (*n*), mean, median (MD), and standard deviation (SD) of total dissolved solids (TDS), chloride, Na, K, Ca, Mg, and sodium adsorption ratio (SAR) of brine samples obtained across the Williston Basin from various sources

Source	TDS				Chloride				Sodium				Potassium				Calcium				Magnesium				SAR			
	n	Mean	MD	SD	*n*	Mean	MD	SD	*n*	Mean	MD	SD	*n*	Mean	MD	SD	*n*	Mean	MD	SD	*n*	Mean	MD	SD	*n*	Mean	MD	SD
		g L^{-1}				g L^{-1}				g L^{-1}				g L^{-1}				g L^{-1}				g L^{-1}				g L^{-1}		
NDSU, 2019[a]	26	271	295	74.0	26	159	173	37.9	26	83.7	84.8	16.7	26	6.81	7.89	3.04	26	12.6	14.3	4.77	26	1.20	1.20	0.26	26	200	189	53.0
Peterman & Thamke, 2016	33	106	61.5	85.2	33	64.1	36.0	53.1	33	38.3	22.6	31.2	33	0.59	0.47	0.50	33	1.57	0.86	1.80	33	0.18	0.12	0.17	33	248	205	148
ND DMR, 2013	7,103	245	289	102	7,103	149	176	63.4	7,103	75.5	86.3	32.9	3,958	3.27	2.86	2.97	7,103	15.6	12.2	15.1	7,103	1.41	1.14	1.48	7,103	184	178	121
Shouakar-Stash, 2008	33	268	301	79.4	33	162	185	48.0	33	75.3	80.8	23.6	33	4.92	5.31	2.66	33	20.1	18.2	16.0	33	1.95	1.53	1.31	33	176	159	97.8
Jensen, 2007	11	284	274	27.2	11	183	182	12.6	11	96.4	92.8	9.90	11	4.94	4.88	0.35	11	14.4	13.8	3.79	11	1.46	1.49	0.21	11	209	214	36.6
Iampen, 2003	44	302	305	62.3	44	177	180	20.4	44	81.9	85.5	16.3	44	5.77	5.88	2.49	44	22.9	19.0	15.3	44	2.08	1.76	1.10	44	181	154	112
Breit & Otton, 2002	3,400	166	150	132	3,399	98.9	88.0	80.5	3,400	55.2	50.3	44.0	750	2.10	1.16	2.42	3,400	6.59	3.03	9.31	3,400	1.03	0.57	1.33	3,400	192	167	143
Rostron, Kelley, Kreis, & Holmden, 2002	26	213	251	118	26	121	148	67.1	26	68.4	86.1	36.5	26	3.05	3.27	1.89	26	6.62	3.01	9.01	26	0.76	0.46	0.79	26	263	269	141
Reiten & Tischmack, 1993	20	204	210	73.1	20	121	126	48.9	20	73.4	77.6	25.7	0	0	0	0	20	5.07	4.34	2.89	20	0.78	0.66	0.55	20	259	248	59.4

[a]Unpublished data obtained from brine samples collected by various researchers at North Dakota State University and provided by the ND Department of Health.

Recent research suggests that reductions in EC <2 dS m^{-1} can result in the dispersion of montmorillonite clays at SAR values as low as 5 (He, DeSutter, & Clay, 2013). Suarez, Wood, and Lesch (2008) observed that the application of irrigation water exhibiting SAR values of 4 and EC values <2 dS m^{-1} resulted in an overall decline in saturated hydraulic conductivity in loam soils as a result of clay swelling. Thus, following historical metrics to define saline and sodic soils, where sodic soils have an ECe <4 dS m^{-1}, exchangeable sodium percentage (ESP) >15% with pH >8.5, while saline–sodic soils have an ECe >4 dS m^{-1}, ESP >15% with pH >8.5 (Richards, 1954), can lead to ineffective management and remediation of brine-impacted soils.

Additionally, capillary action promotes the upward movement of water and dissolved solutes toward the soil surface (Jambhekar, Helmig, Schröder, & Shokri, 2015; Thimm, 1990). Over time, continual salt accumulation and precipitation form soil crusts (Keiffer & Ungar, 2002; Mullins, MacLeod, Northcote, Tisdall, & Young, 1990; Qadir, Oster, Schubert, Noble, & Sahrawat, 2007). Crusting of the soil surface results in a reduction of infiltration rates, as well as gas diffusion into and out of the soil, which may decrease plant growth and increase soil erosion potential (Aschenbach & Kindscher, 2006; Leskiw, Sedor, Welsh, & Zeleke, 2012; Young et al., 2011).

2.3 | Soil biological effects

Soil biology, including various species of fungi, bacteria, nematodes, and other microbes, can be negatively impacted by both direct and indirect effects of brine releases. For example, Sublette et al. (2007) discovered an average reduction in phospholipid fatty acid (PLFA) concentrations, a measure of microbial biomass, of approximately 50% in brine-impacted soils in Oklahoma. Similarly, Rhykerd, Weaver, and McInnes (1995) found a decrease in microbial activity and CO_2 production from soils contaminated with brines at increasing levels of EC. The primary direct effect of salts on microbial communities in the soil occurs through the induction of osmotic stress, which reduces microbial metabolic activity and results in the mortality of many species (Chowdhury, Marschner, & Burns, 2011). Indirect effects of salinity on soil biology include the loss of vegetation following a spill, which over time reduces the organic matter required by organisms for metabolic processes (Sublette et al., 2007).

Brine spills may also have significant effects on aquatic and terrestrial biota. In a study of brine spills across the states of Pennsylvania, New Mexico, Colorado, and North Dakota, Maloney et al. (2017) estimated that brine spills in these states occurred an average distance 580 m away from streams, causing brine releases to be particularly hazardous to the health of aquatic ecosystems. In a study testing the effects of major ionic constituents most commonly found in brine (i.e., Na, Cl, K, Ca) on aquatic organisms, Wang, Kunz, Cleveland, Stevens, and Cozzarelli (2019) found that over a period of 7 d, the survival and growth of fathead minnow (*Pimephales promelas*) and fatmucket (*Lampsilis siliquoidea*) were significantly decreased at salt concentrations of four times and two times reference conditions, respectively, following a brine spill near Blacktail Creek, ND (Williams County). In terrestrial environments, Efroymson et al. (2004) suggested the deleterious effects of brine and hydrocarbon spills on habitat quality may harm vertebrates more than the potential for direct toxicity and, over time, may result in population declines and decreased species richness.

2.4 | Seed germination and plant growth

Across the various growth stages of a plant's life cycle, seed germination is one of the most crucial, particularly in salt-affected soils (Keiffer & Ungar, 2002; Schmer, Xue, & Hendrickson, 2012; Shaygan, Baumgartl, & Arnold, 2017; Ungar, 1978). In brine-contaminated soils, a number of indirect and direct processes play a role in impeding seed germination and plant establishment. Indirect effects, such as physical changes to soil structure including salt crust formation, dispersion, and hardsetting, can significantly reduce seed germination rates and the chances of plant establishment (Aschenbach & Kindscher, 2006; Leskiw et al., 2012; Qadir et al., 2007). These effects on soil structure inhibit the growth and elongation of the radical, epicotyl, and hypocotyl of newly germinated seeds (Aschenbach & Kindscher, 2006; Mullins et al., 1990; Qadir, Steffens, Yan, & Schubert, 2003; Shainberg, Warrington, & Rengasamy, 1990). In addition, these structural changes reduce the ability of water and gases to infiltrate into the soil, resulting in either a lack of soil water for seed imbibition or the prolonged inundation of the soil surface, both of which severely restrict plant establishment and survival (Grieve, Grattan, & Maas, 2012; Qadir et al., 2007; Shainberg & Letey, 1984).

The direct effects of brine contamination on seed germination and plant growth are caused primarily by the ionic saturation of the soil solution, which inhibits plant productivity through a number of deleterious processes (Grieve et al., 2012). The ability of a seed or plant root to uptake water is based on the establishment and maintenance of an osmotic gradient with the soil solution (Lauchli & Epstein, 1990). In soils exhibiting high salt concentrations, the osmotic potential of the soil solution becomes increasingly negative, resulting in the reversal of this osmotic relationship (Aschenbach & Kindscher, 2006; Lauchli & Epstein, 1990). This change in hydraulic gradient severely limits the imbibition of soil water by both plant roots and seeds, often resulting in induced seed dormancy (i.e., delayed seed germination) and the expression of drought-like symptoms in plants at later growth stages (Keiffer & Ungar, 2002; Lauchli & Epstein, 1990; Ungar, 1978).

In conjunction with these effects, high concentrations of NaCl also disrupt the absorption of essential plant nutrients needed for germination and growth (Grattan & Grieve, 1998; Grieve et al., 2012). Grattan and Grieve (1998) indicated that the adsorption of NO_3, K, PO_4, and Ca by plants can be inhibited by the presence of high concentrations of both Na and Cl in the soil solution. In addition, nutrient imbalances and osmotic stress have been shown to significantly inhibit plant metabolic and photosynthetic processes through the closure of stomata, the reduction of CO_2 diffusion into the plant, and the production of hormones which limit cellular growth and division (Chaves, Flexas, & Pinheiro, 2009; Munns & Tester, 2008).

Although brines produced in the Williston Basin contain a number of essential plant nutrients (i.e., Ca, Mg, K), their elevated concentrations, in conjunction with Na and Cl, can render them toxic (Keiffer & Ungar, 2002; Munn & Stewart, 1989). In addition, various trace elements found in solution, such as B and Se, can cause direct toxicity if adsorbed into plant tissue (Grieve et al., 2012; Lauchli & Epstein, 1990; Ungar, 1978). Similar to plants at later growth stages, the effects of ionic adsorption on seed germination vary considerably across plant species and the concentration of salts found in solution (Neumann, 1997; Ungar, 1978). Ion toxicity in seeds, which is caused primarily by the absorption Na and Cl, occurs through the disruption of the metabolic processes required for cell division and germination (Neumann, 1997). In addition, the uptake of salts into seeds may result in the expression of oxidative stress in cells, which is caused by an imbalance in the production of various reactive oxygen species (Ibrahim, 2016). High levels of reactive oxygen species in cells often causes cell death by damaging cellular structures such as membrane lipids and enzymes (Ashraf & Foolad, 2005; Ibrahim, 2016).

3 | CURRENT REMEDIATION STRATEGIES

3.1 | Factors influencing remediation

Due to the solubility of NaCl (360 g L^{-1} at 25 °C) (Haynes, 2014) and its prevalence in the brine within the Williston Basin, the deleterious effects of brine to soil and plant health can persist, if not remediated, for years to decades following spills and can spread quickly to adjacent areas. The simultaneous reduction in agricultural productivity, surface/groundwater quality, and ecosystem services of contaminated land often requires that the soils of these sites be remediated, and vegetation be restored in some capacity. Remediation of brine-contaminated land is attempted utilizing a variety of in-situ or ex-situ methods. The choice of remediation method is based on site characteristics, the cost-effectiveness of inputs, and the potential for contamination to migrate to land and water resources adjacent to the site (Harris, Bryan, & Sublette, 2005; Sublette et al., 2007). Important site characteristics that determine the applicability of remediation methods include the severity of contamination, soil texture, drainage capability, depth of contamination, depth to ground water, the topography of the site, and the prevailing climatic conditions (Harris et al., 2005; Qadir et al., 2000; Qadir et al., 2007; Vavrek, Hunt, Colgan, & Vavrek, 2004).

The boundaries of the spills are determined by field and laboratory methods. For example, field technicians/scientists will commonly sample soils by breadth and depth and field-screen samples using Cl as an indicator since Cl is not highly concentrated in the soils of this region but is highly concentrated in the brine. Then, subsets of soil are sent to certified laboratories for analysis of ECe, SAR, and Cl and further delineations are defined. For on-well pad cleanups, the Cl level in the soil material needs to be less than 1,000 mg L^{-1} whereas for off-pad cleanups the Cl level is typically targeted to be less than 250 mg L^{-1} but is subject to landowner approval (Samantha Croat, personal communication, 2020). The results from soil testing, in addition to the above-mentioned site characteristics, guide the reclamation process.

3.2 | Excavation and disposal

The most prevalent ex-situ remediation method used for brine-contaminated soils consists of the excavation and disposal of impacted soils and vegetation (Table 2). Excavation and removal, which is commonly referred to as "dig and haul" within the Williston Basin, is used for impacted sites that are contaminated with salts, situated near important water resources, or incompatible with in-situ remediation methods (Gleason et al., 2014; Harris et al., 2005; Sanchez, 2017). Excavation is done using large equipment and contaminated soil is disposed in landfills that have been pre-approved by state agency officials to accept these materials (Young et al., 2011; ND DOH, 2016). Soil that has been removed from the spill site is often replaced with locally sourced topsoil exhibiting similar pre-disturbance physical and chemical properties (Derby, Casey, & DeSutter, 2016). The estimated cost for this

TABLE 2 Remediation strategies for the clean-up of brine-contaminated soils

Location	Strategy	Pros	Cons
Ex-situ	Excavation and disposal	Immediate removal of contamination; excavated site is suitable for land use soon after soil replacement	Need to find an approved landfill for the waste; difficulty in finding suitable topsoil for replacement; highly disruptive to soil structure
	Washing or scrubbing	Same soil is returned after cleaning; can potentially be done on-site	Specialized equipment is necessary, copious quantities of suitable water may be needed; highly disruptive to soil structure; need a location to dispose of the highly saline supernatant
In-situ	Natural attenuation	Relatively low cost compared to other methods	May take years to decades to see improvement in soil function; dilution of brine to subsoil and surrounding soils occurs
	Leaching	With use of drainage tiles the brine can be collected and properly disposed offsite; quality of leachate is easily monitored; soil structure is only disturbed where drainage tiles are installed	Depending on soil texture and the quantity of leaching water, may take months to years to see improvement in soil function; quantity of suitable leaching water may be a barrier to success; continual monitoring and removal of leachate is needed
	Amendments	Calcium-based amendments help counteract the negative effects of Na; organic amendments may help increase soil microbiological activity and decrease time to improved soil function	Need to be applied where the brine is located; usually are only effective if the soil water content is greater than the amendment's (salt) solubility
	Phytoremediation	Plants help build soil structure and prevent erosion; the contaminated area is more eye-pleasing to the landowner and responsible party;	Germination and establishment of plants is challenging; heavily dependent on climate; soluble salt levels are not uniform across spill sites; time to successful cleanup may range from years to decades
	Electrokinetics	Ions at anodes and cathodes can be easily collected and discarded; soil disturbance is minimal; can easily target certain areas due to placement of electrodes	Soil water content needs to be sufficient for mobility of ions; carbonates, which are present in the soil throughout the Williston Basin, may decrease removal efficiency; requires trained technicians to install and operate
	Crystallization inhibitors	Soil disturbance is minimal; removal of contamination can be days to weeks; minimal chemicals are required; salts are removed from the soil surface properly disposed	Field testing is still needed; soil water content needs to be maintained to allow capillary action to bring salts to the soil surface; an evaporative front needs to be maintained; collection of salts from soil surface needs specialized equipment
	Wicking	Soil disturbance is minimal; no chemicals are required; salts are permanently removed from the soil; installation is performed using common equipment; effective in harsh weather conditions	Unproven to work in field conditions; requires soil water to be near saturation; wicked area will require maintenance to ensure that wicks remain upright; may not work well on sloped areas unless subsurface irrigation is used
	Plant-growth promoting rhizobacteria	Plants help build soil structure and prevent erosion; the contaminated area is more eye-pleasing to the landowner and responsible party	Treated seeds are proprietary; heavily dependent on climate; soluble salt levels are not uniform across spill sites; time to successful cleanup may range from years to decades

practice is US$90 Mg^{-1} (Dustin Anderson, personal communication, 2020). While being the most prevalent remediation technique used in the Williston Basin due to its expediency, the dig and haul method requires the use of heavy equipment and the construction of transportation infrastructure, which may cause damage to adjacent, non-contaminated soils through compaction and vegetation removal. Additionally, locating high-quality replacement topsoil is often difficult in this region, and the costs of purchasing and transporting replacement topsoil makes the technique even more expensive. The use of this method for spills on the well pad may be limited due to the buried infrastructure used to extract and mobilize oil, gas, and brine.

3.3 | Soil washing or scrubbing

Another form of ex-situ remediation that has been used for brine-impacted soils is soil washing or scrubbing (Table 2). The washing of excavated soil occurs in a separation unit which utilizes aqueous solutions composed of either fresh or brackish water in conjunction with various chemical amendments to remove Na from soil exchange sites (Kuppusamy, Palanisami, Megharaj, Venkateswarlu, & Naidu, 2016). Following the washing process, soil can then be placed back in its original location. This method has been reported as costing $154 Mg^{-1} (Kuppusamy et al., 2016), though treatment costs will be dictated by distance from spill site to washing plants, accessibility of water, and efficiency of the washing to remove Na and Cl. As with all ex-situ methods, the extreme disturbance typically requires additional management (e.g., soil amendments) to restore soil function after its replacement, and these costs need to be included in any final assessment of this method.

3.4 | Natural attenuation

In many cases, for various reasons that are beyond the scope of this review, brine spills have not been properly cleaned up and thus are left for onsite remediation (Kuppusamy et al., 2016). Natural attenuation, a passive, or hands-off form of in-situ remediation, relies on natural precipitation and drainage regimes to leach salts out of the topsoil, allowing for subsequent revegetation of the site and the recovery of soil function (Auchmoody & Walters, 1988; Leskiw et al., 2012) (Table 2). The capability of brine-contaminated sites to recover through natural attenuation has received little attention in the literature, however, factors including climate, soil texture, and water table depth have been identified as the primary determinants for the success of this method (Leskiw et al., 2012). In their analysis of a brine spill site in British Columbia, Leskiw et al. (2012) found that over a period of 8 yr, annual precipitation amounts were adequate to significantly leach brine salts from a sandy loam topsoil and clay loam subsoil. In northwestern Pennsylvania, Auchmoody and Walters (1988) concluded that high amounts of precipitation in the study area during a 4-yr period was able to sufficiently remove salts from a silt loam soil and allowed for the re-establishment of vegetation. However, in their study of an abandoned brine disposal pit in North Dakota, Murphy et al. (1988) found that little dilution of salts had occurred over a 10-yr period and estimated that salt concentrations at this site would remain high for decades or even centuries without active remediation.

Barriers to success using this method are the texture of the soil, the depth to water table, and most importantly the amount of infiltrating water and potential evapotranspiration within the region. In the Williston basin, the average annual precipitation and PET are $\leq$36 and $\geq$140 cm yr^{-1}, respectively, which may not allow for excessive leaching water. Leaching is further reduced in this region due to the prevalence of soils with appreciable clay contents or those soils having a Bt horizon (zone of clay accumulation). Additionally, even if brine is leached below the root zone following precipitation events, the effects of capillary rise, due largely to the clays and high PET, may redistribute the brine back into the plant root zone.

3.5 | Leaching

The movement of salts out of the root zone in solution via leaching can help expedite the establishment of plants but may require large volumes of water (Bahceci, 2009; Qadir et al., 2000; Young et al., 2011), which may be a limiting factor in arid and semi-arid environments (Bahceci, 2009; Keiffer & Ungar, 2002). In these conditions, irrigation is often required to supplement natural precipitation. For saline soils, Qadir et al. (2000) identified three irrigation techniques (continuous ponding, intermittent ponding, and sprinkling) that are commonly used to leach salts out of the topsoil. The leaching efficiency of these three methods has previously been tested by Oster, Willardson, and Hoffman (1972) and were found to decrease in the following order: intermittent ponding, sprinkling, and continuous ponding.

The amount of time and volume of water needed to leach salts from brine-impacted soils depends on the depth to be remediated, the soil texture, soil amendments applied, the quality of irrigation water, and the prevailing climatic conditions (Bahceci, 2009; Oster, Shainberg, & Abrol, 1999; Shainberg & Letey, 1984). For brine-contaminated soils, various estimates concerning the amount of time and water needed for sufficient leaching of Na have been given by a number of authors in the literature. For example, Jury and Weeks (1978) estimated approximately 31 pore volumes of a saturated gypsum solution would be needed to leach Na from a fine-textured soil, while Munn and Stewart (1989) estimated that a 100-fold dilution of freshwater was necessary to decrease salt concentrations of a brine-contaminated soil in Ohio to levels in which crop species would be able to survive. Using Hydrus 1-D software to model solute travel times of brine through a homogenous, silt loam soil under continuous ponding conditions of freshwater, Klaustermeier (2016) indicated that a prohibitive amount of time would be needed to completely remove Na from a 150-cm profile. These studies suggest that significant amounts of time and water would need to be applied to sufficiently leach salts from the topsoil, and these factors may preclude its use in many situations.

In addition to the need for adequate volumes of water for leaching, soil drainage is an important factor that can determine the effectiveness of this remediation method (Conway, 2001; Qadir et al., 2000). For leaching to be effective, salts must either be transported deep enough in the subsoil to reduce the risk of capillary rise, or they must be translocated to a natural or manmade outlet for collection and removal. Limiting factors for soil drainage include the presence of a high water table, impermeable subsoil layers, and reduced infiltration/permeability rates of the topsoil caused by swelling and dispersion of clay particles (Oster & Shainberg, 2001; Bahceci, 2009; Harris et al., 2005; Vavrek et al., 2004). In situations where high water tables or impermeable subsoil layers are present, artificial subsurface drainage may be used to lower water table depths and collect the leachate from the topsoil for disposal (Derby et al., 2016; Harris et al., 2005; He et al., 2015; Young et al., 2011).

With the increase in freshwater water use for oil development and the continued need for agricultural irrigation, competition for water resources of the region may limit the water availability for remediation purposes (NDSWC, 2016). If sufficient water resources can be found, drainage may also become an issue for many brine spill sites. The presence of high water tables, fine-textured soils with low infiltration rates and permeabilities, and impermeable subsurface layers have been found to be the main determinants of remediation failure or success when using leaching to remove Na from the soil profile (Harris et al., 2005; Oster & Shainberg, 2001; Qadir et al., 2000; Vavrek et al., 2004). When these conditions are found, the installation of subsurface tile drainage has been used to collect the leachate and permanently remove it from the soil profile. However, high installation costs and/or topography may limit this option in some instances (Derby et al., 2016; Harris et al., 2005; Young et al., 2011).

A final factor which may limit the long-term success of this methodology for brine spill remediation is the potential for resalinization of the topsoil through capillary rise of groundwater and dissolved solutes (Derby et al., 2016; Thimm, 1990). Overall, the use of this remediation strategy in semi-arid environments can often produce mixed results, while in most situations, incurring significant costs to stakeholders. Thus, most in-situ remediation of brine-contaminated soils attempts to remove salts from the soil profile via leaching in combination with soil amendments, irrigation, and drainage (Artiola, Gebrekidan, & Carty, 2000; Ashworth, Keyes, & Crepin, 1999; Atalay, Pyle, & Lynch, 1999; Bahceci, 2009; Chaganti & Crohn, 2015; Dejong, 1982; Harris et al., 2005; Qadir et al., 2003; Qadir et al., 2014; Vavrek et al., 2004).

3.6 | Amendments

The use of amendments to improve soil function has a long-standing history in agriculture. For example, the first documented use of gypsum was in 1893 in Hungary for the reclamation of sodic soils (Arany, 1956). Soil amendments are often classified as either chemical or organic, with the choice of amendment(s) determined by their availability, cost, and effectiveness in improving soil physical, hydraulic, and edaphic properties (Atalay, Pyle, & Lynch, 1999; Chaganti & Crohn, 2015; Vavrek et al., 2004). In the remediation of sodic and saline-sodic soils, chemical amendments provide a source of divalent cations, such as Ca, which aid in the displacement of Na from soil exchange sites and help promote the aggregation of soil particles, thereby improving the ability of water to move through the soil profile (Dejong, 1982; Vavrek et al., 2004).

Many chemical amendments including $CaCO_3$, $CaCl_2$, $Ca(NO_3)_2$, $MgSO_4$, $MgCl_2$, and H_2SO_4 have been used in research applications to reclaim sodic and saline–sodic soils with varying amounts of success (Artiola et al., 2000; Atalay et al., 1999; Clark & Thimm, 1975; Merrill, Lang, & Doll, 1990; Prather, Goertzen, Rhoades, & Frenkel, 1978). However, gypsum ($CaSO_4 \cdot 2H_2O$), has traditionally been employed as the primary chemical amendment for ameliorating the effects of sodic soils (Oster et al., 1999; Sanchez, 2017). Although gypsum exhibits a relatively low solubility in water (2.1–2.6 g L^{-1}), it provides a significant amount of Ca for the mobilization of Na in the soil and, in low EC soils, provides enough electrolytes to increase the EC of the soil solution and promote a state of flocculation between clay particles (Artiola et al., 2000; Dejong, 1982; Shainberg & Letey, 1984). In an experiment comparing the Na removal efficiencies of $CaSO_4$, $CaCl_2$, and organic {manure, alfalfa [*Medicago sativa* L.], and sorghum [*Sorghum bicolor* (L.) Moench]} treatments, Robbins (1986) found that gypsum provided the most significant increase in Na removal efficiency. However, the low solubility causes gypsum to only be effective to the depth at which it is applied, which in most cases is not to the entire depth of soil contamination (Robbins, 1986; Ilyas, Qureshi, & Qadir, 1997; Artiola et al., 2000; Qadir et al., 2000; Harris et al., 2005; Sublette et al., 2007). Further, a significant amount of irrigation water and time is needed to leach salts from these soils, even with the addition of amendments (Jury & Weeks, 1978; Kieffer & Ungar, 2001; Munn & Stewart, 1989).

The gypsum requirement (GR) (Mg ha^{-1}) for Na-impacted soils can be calculated using a variety of different formulas available in the literature. However, significant variation is often found between the values calculated using these equations (Oster et al., 1999; Ashworth et al., 1999). A commonly used equation to determine the GR for sodic soils was developed by Oster et al. (1999) and is based on the initial and desired (final) ESP of the soil, the cation exchange capacity of the soil, a correction factor, soil depth, soil bulk density, and gypsum purity. An app for iOS and Android mobile devices has been developed by the North Dakota State University that can be used to calculate GR, which can be accessed by searching "gypsum requirement" in one's app store.

The application of organic amendments, in conjunction with chemical amendments, to brine-contaminated soils has been shown to provide several benefits that aid in the successful remediation of brine spill sites (Table 2). Commonly used organic amendments include straw, wood chips, hay, composted livestock manure, food processing wastes, green manure, biochar, and humates such as leonardite (Barzegar, Nelson, Oades, & Rengasamy, 1997; Conway, 2001; Vavrek et al., 2004; Sublette et al., 2007; Zhang et al., 2008). In general, organic amendments improve soil structure, enhance the growth and activity of microbial communities, increase percolation and infiltration rates of the soil, and decrease water loss to evaporation from the soil surface ((Barzegar et al., 1997; Conway, 2001; Vavrek et al., 2004; Sublette et al., 2007; Zhang et al., 2008). In their work remediating a brine spill site in Oklahoma, Harris et al. (2005) found that the application of a thick layer of native hay in combination with an artificial subsurface drainage system was effective in maintaining soil permeability, reducing evaporation from the soil surface, and removing significant concentrations of Na and Cl from the soil. Barzegar et al. (1997) found that the addition of pea straw to soils at increasing levels of sodicity had a positive influence on the structural stability of the soil and could aid in the removal of Na from salt-affected soils.

The use and cost of any amendment will be a function of its availability and, for chemical amendments, the volume of water that is required for them to solubilize in. One way to concentrate water, which may help solubilize amendments, is snow capture. Snow capture, such as concentrating snow within windbreaks of trees or tall wheatgrass [*Thinopyrum ponticum* (Podp.) Z.-W. Liu & R.-C. Wang] has been used successfully in southern Saskatchewan, combined with subsurface drainage, to successfully leach natural salts (Steppuhn, 2006). However, the use of plastic snow fence may be required in areas impacted with brine since the impacted soils may not freeze as readily and, due to having high entropy, melting water may infiltrate more readily compared to that in non-impacted soils.

3.7 | Phytoremediation

Phytoremediation, also referred to as phytoextraction, is the use of growing vegetation to ameliorate the effects of various pollutants found in the environment (Manouski & Kalogerakis, 2011). Phytoremediation has been identified as a potential method for the remediation of brine-impacted soils in oil-producing regions, although no published research has been reported to its efficacy in the Williston Basin (Table 2). In some situations, phytoremediation utilizes halophytic (salt-tolerant) plants that are capable of completing their lifecycles in soils exhibiting EC values upwards of 20 dS m^{-1} (Flowers, Galal, & Bromham, 2010; Keiffer & Ungar, 2001; Keiffer & Ungar, 2002). The establishment of halophytes stabilizes salt-affected soils and promotes the removal of NaCl through direct uptake and improvement of soil structure and chemistry (Qadir et al., 2007).

In sodic and saline–sodic soils, various halophytes have been shown to accumulate significant amounts of Na in the vacuoles of leaf and stem tissues in an effort to maintain the osmotic gradient between the soil solution and the plant (Ke-Fu, 1991; Ashraf and Harris, 2004; Flowers & Colmer, 2008; Grieve et al., 2012; Manouski & Kalogerakis, 2011). Through the harvest and disposal of the aboveground biomass, this process has been used to decrease the overall concentration of Na in the soil profile (Keiffer & Ungar, 2001; Keiffer & Ungar, 2002; Qadir et al., 2000; Qadir et al., 2003; Qadir et al., 2007; Young et al., 2011). For example, Ke-Fu (1991) estimated that through the establishment and harvest of the halophyte species seepweed [*Suaeda salsa* (L.) Pall.], approximately 3,090–3,860 kg Na ha^{-1}, or 4.5% of total Na, could be removed from a saline, medium-textured soil. In their research of brine spill site in Ohio, Keiffer and Ungar (2001) found that the halophyte species triangle orache (*Atriplex prostrata* Bouchér ex DC.), glasswort (*Salicornia europaea* L.) Pursh seepweed [*Salicornia calceoliformis* (Hook.) Moq.]

and foxtail barley (*Hordeum jubatum* L.) decreased Na concentrations in the soil by 17, 10, 10, and 9%, respectively, over the course of a single growing season.

The establishment of halophytic vegetation has also been proven to enhance several of the physical and hydraulic properties of salt-affected soils. Root systems established by halophytic plants, especially those that protrude deep into the soil profile, provide numerous pathways by which water can move through the soil profile, thus increasing the leaching efficiency of Na and Cl out of the topsoil (Ilyas et al., 1997; Manousaki & Kalogerakis, 2011; Qadir et al., 2000; Qadir et al., 2003). For example, Ilyas et al. (1997) found that the growth of alfalfa roots in a fine-loamy, saline-sodic soil, resulted in an increase of saturated hydraulic conductivity of approximately 258% when used in association with gypsum, allowing for significant reductions in Na and soluble salt concentrations of the upper profile over a 1-yr period. Plant roots, through the respiration of CO_2, have also been shown to increase the rate of calcite ($CaCO_3$) dissolution in calcareous soils, providing a source of Ca to displace Na from cation exchange sites and flocculate soil particles (Qadir et al., 2000; Qadir et al., 2007). Similarly, microorganisms in the soil increase the partial pressure of CO_2 in the soil profile and produce organic acids that further promote the dissolution of calcite in calcareous-sodic soils (Qadir, 2000).

Phytoremediation has the potential to provide a relatively inexpensive alternative to stakeholders (Manousaki & Kalogerakis, 2011; Qadir et al., 2003; Young et al., 2011). However, the effectiveness of phytoremediation in brine-impacted soils has received little attention in the literature, particularly in the Williston Basin (Keiffer & Ungar, 2001; Keiffer & Ungar, 2002; Manouski & Kalogerakis, 2011; Young et al., 2011). The lack of information concerning the use of this method in these soils extends to the identification of appropriate halophytic plant species and their tolerance to various contaminants found in oil-field brine (Vavrek et al., 2004). In addition, the time needed for phytoremediation to be effective in brine-impacted soils may prove to be a limiting factor in many situations, as the salt concentrations of these soils are much greater than those found in agricultural settings where this method has been proven to have the most success. Qadir et al. (2007) state that in highly sodic soils, the establishment of halophytic species is often uneven, reducing their effectiveness in promoting the leaching of Na from the soil profile and uptake through aboveground biomass. For example, at a brine spill site in Alberta, Canada, Young et al. (2011) found that there was significant spatial variation in the establishment of the halophyte spear saltbush (*Atriplex patula* L.), with some areas showing little establishment over a 3-yr period. In addition, salt uptake by halophytes contributes little to their efficiency in reducing Na from the soil profile, indicating that reductions through harvest and removal of aboveground biomass may take decades to be effective, even under optimal growing conditions (Qadir et al., 2007; Jesus, Danko, Fiúza, & Borges, 2015).

4 | NOVEL EXPERIMENTAL REMEDIATION STRATEGIES

Due to the increase in frequency of brine spills over the past decade throughout the Williston Basin, an urgent need exists for alternative methods to expedite and improve the effectiveness of brine spill remediation. Over this time period, several methods have been proposed to fulfill these needs including electrokinetics, crystallization inhibitors, wicking materials, and microbial-assisted phytoremediation. Although these methods have not widely been used in brine remediation, each method has benefits that should attract more investigative research into their use for aiding cleanup.

4.1 | Electrokinetics

Electrokinetics is a method of in-situ remediation that utilizes electrical fields established in the soil matrix using low intensity direct currents (Acar & Alshawabkeh, 1993). These electrical fields induce the migration of soil contaminants to an anode (positive) or cathode (negative) inserted into the soil profile (Cameselle, Chirakkara, & Reddy, 2013). In brine-impacted soils, a phenomenon known as electromigration causes positively charged ions such as Na, Ca, and Mg to migrate toward the cathode and negatively charged ions such as Cl and SO_4 to migrate toward the anode (Athmer, Ruef, Jones, & Wilkens, 2012). Ion migration also occurs through electro-osmotic, or fluid, flow to the cathode, which enhances the accumulation of cations such as Na but limits the absorption of anions such as Cl by the anode. In laboratory studies using electrokinetics to remediate a clay/silt loam soil contaminated with NaCl (1,000 mg L^{-1}), Athmer and Wilkens (2013) found Na and Cl concentrations could be reduced by 85 and 65%, respectively. In-depth reviews of electrokinetic theory and technology can be found in Alshawabkeh (2009) and Virkutyte, Sillanpaa, and Latostenmaa (2002).

As with most in-situ methods the soil water concentration needs to be great enough so that salts have solubilized into their respective ions. Along with soil water, Virkutyte et al. (2002) outline five main parameters that dictate the successful use of electrokinetics and influence overall costs: (a) the properties of the soil (texture, clay mineralogy), (b) the depth of soil that is needing to remediated, (c) number and location of electrodes, (d) overall time for clean-up, and (e) labor and power costs. While not suitable in every situation, electrokinetics has shown promise in cleanup of brine-contaminated sites and warrants more research into widening its applicability.

4.2 | Crystallization inhibitors

In semi-arid environments where PET is much greater than precipitation, the upward capillary transport of both water and solutes to the soil surface is a common process. This characteristic process of dryland environments often limits the effectiveness of many conventional methods of in-situ remediation, such as leaching, and contributes to the high costs internalized by various stakeholders. To work with this process rather than against it, Daigh and Klaustermeier (2016) and Klaustermeier et al. (2017) suggested the use of the crystallization inhibitor ferric hexacyanoferrate $\{Fe_4[Fe(CN)_6]_3\}$ to induce hopper crystal growth of NaCl on the soil surface, which could then be harvested and permanently removed from the soil profile. Conceptually, this method would utilize the evaporative flux established at the soil surface following a brine spill and the capillary rise of soil water to accumulate salts in the upper portions of the soil profile, where the crystallization inhibitor would then induce the growth of NaCl hopper crystals.

In laboratory experiments utilizing a surficial application of the crystallization inhibitor to NaCl-contaminated sandy loam, loam, and silty clay soils, this method was found to reduce the mass of NaCl (34.75 g total) in the soil by 460, 570, and 290 g kg^{-1} (grams harvested salt at the soil surface per total grams of NaCl applied to the soil), respectively (Klaustermeier et al., 2017). In subsequent experiments, the authors found that the re-application of the crystallization inhibitor following the initial harvest of salts produced little to no additional salt growth, indicating that this method may only be applicable for the partial remediation of brine-impacted soils (Klaustermeier et al., 2017; Swallow & O'Sullivan, 2019). Furthermore, it was found that the effectiveness of the crystallization inhibitor was limited at low salt concentrations (<0.5 M NaCl) and produced little efflorescence when either soils were only dominated with SO_4-based salts or when soil Ca levels where high enough to form Ca-based crusts before NaCl hopper crystal growth could initiate (Klaustermeier et al., 2017). Irrespective of challenges, the potential use of these chemicals, especially on spills on well pads where soil removal may not be possible, deserves further exploration.

4.3 | Wicking

To overcome the limitations confronted by the methodology tested by Klaustermeier et al. (2017), Swallow and O'Sullivan (2019), Green, DeSutter, Daigh, and Meehan (2019) suggested the use of highly absorbent "wicking" materials treated with or without the crystallization inhibitor potassium ferrocyanide to remediate brine-impacted soils (Figure 1a). Wicking materials contain high amounts of fine- to medium-sized pores which, through capillary suction, can absorb significant volumes of water and dissolved solutes from the soil medium. Highly absorbent materials have previously been applied for several uses including the removal of heavy metals from aqueous solutions (Yu et al., 2018), desalinization of seawater (Hansen, Narayanan, & Murugavel, 2015), and oil spill clean-up (Adebajo, Frost, Kloprogge, Carmody, & Kokot, 2003). In part one of their experiment, Swallow and O'Sullivan (2019) used sphagnum peat moss and wood pulp pots that had been treated with 50 mL of 0.01 M potassium ferrocyanide as a wicking medium. Treatments included: (a) a control consisting of surficial application of the crystallization inhibitor and no wick, (b) a wick treated with a crystallization inhibitor connecting the soil and water reservoir, (c) a wick treated with a crystallization inhibitor placed on the soil surface, and (d) a combination of treatments one and two. Following a 14-d incubation period, Na concentrations in treatments one, two, three, and four were reduced by 50, 5, 50, and 81%, respectively. In part two of the experiment, the authors used the design of treatment four in part one to test the effectiveness of 0.01 , 0.005 , 0.001 , and 0 M concentrations of the inhibitor over a 30-d incubation period. Of the inhibitor concentrations tested, the 0.01 M solution caused the greatest reduction in Na concentration of approximately 90% (Swallow & O'Sullivan, 2019). Although proven effective in the laboratory, the authors note that field implementation still needs to be conducted to prove its effectiveness in these conditions.

The use of cellulose-based materials by Green et al. (2019) assessed the feasibility 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 non-engineered wicks (wheat straw and hydraulic mulch) placed on the surface of brine-contaminated soils reduced the total soil Na concentrations by 65–88 and 5–80%, respectively. Although the wicks used by the authors may not have enough structural stability to be used in the field, the act of wicking salts does hold promise where soil–water concentrations can allow for solubilizing salts and being able to allow salts to move into wicks via capillary rise.

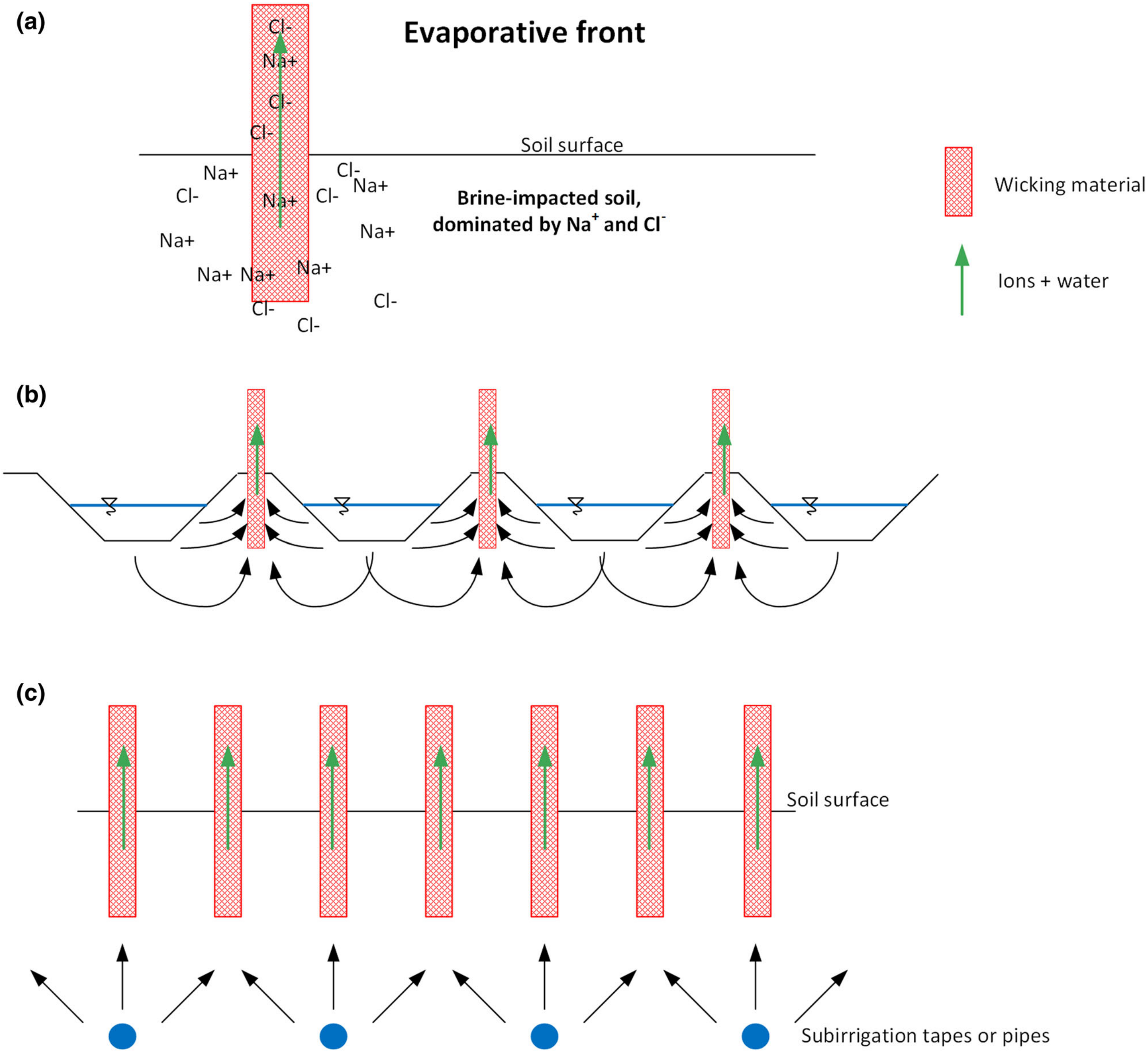

FIGURE 1 Conceptual diagrams of (a) how wicks can remove salts from soil, (b) the use of furrow irrigation to remove salts into wicks, and (c) the use of subsurface irrigation to remove salts into wicks

Conceptually, wicks would be sized to be used with silt–fence installers so that adequate soil–wick contact could be created or that wicks would be individually installed into the soil by hand. The distance between the wicks would be dictated by the method of installation. The soil–water content would need to be great enough to solubilize salts and also great enough so that the wicking material can "suck" water away from soil particles. Soil water content could be maintained through furrow irrigation (Figure 1b) or through the installation of subirrigation tapes or pipes positioned below the zone of contamination (Figure 1c).

4.4 | Plant growth promoting rhizobacteria

Another experimental method for the remediation of brine-impacted soils that has been proposed for commercial use consists of a form of phytoremediation that utilizes plant growth in association with the synergistic effects of soil microbes to achieve successful contaminant reduction or removal (Gerhardt, Huang, Glick, & Greenberg, 2009). A subset of soil microbial communities commonly referred to as plant growth-promoting rhizobacteria (PGPR) have been identified for their potential in soil impacted with salts and heavy metals (Glick, 1995; Glick, 2010). Plant-growth promoting rhizobacteria reduce plant stress by decreasing the levels of the plant hormone ethylene, which is responsible for reducing plant metabolism and growth when osmotic or edaphic stressors, such as high concentrations of salts, are present in the soil (Cheng, Park, & Glick, 2007; Glick, 2010; Mayak, Tirosh, & Glick, 2004; Chang et al., 2014).

Following a brine release, soil microbial communities may experience significant declines in both species richness and density, requiring the isolation and introduction of various strains PGPR to plant seed, often through inoculation or seed coatings (Chang et al., 2014; Cheng et al., 2007; Rhykerd et al., 1995; Sublette et al., 2007). Using seed inoculated with various strains of the bacteria *Psuedomonas putida*, Chang et al. (2014) observed an increase in roots biomass and growth of barley (*H. vulgare* L.) and oat (*Avena sativa* L.) in salt-affected soils (EC = 9.4 dS m^{-1}), when compared to the control (non-treated seed), of 200 and 50%, respectively. In field trials located in Saskatchewan, Canada, Chang et al. (2014) also observed enhanced growth rates of treated barley and oat in soils exhibiting EC between 4 and 24 dS m^{-1}. Similarly, Cheng et al. (2007) found that the growth canola (*Brassica napus* L.) seed inoculated with *Psuedomonas putida* was equal to or greater than the growth of non-treated seed in salt solutions at 10 and 20 °C, respectively. Although the use of PGPR in association with phytoremediation has shown promising results, the practice has not been implemented in many different climates or soil types, so this method may require additional field-scale trials to be conducted to ascertain effectiveness in other locations. In addition, the current source of the seed (Canada) may limit its availability in the United States, which can be overcome by filing the proper importation documentation.

5 | CONCLUSIONS

The harmful effects of brine on the environment, coupled with the semi-arid climate of the Bakken and Three Forks regions, often necessitates the use of anthropogenic remediation techniques to expedite the removal of contaminants and limit the risk of further contamination to surrounding areas. Remediation of brine-contaminated soils is often conducted through ex-situ methods such as excavation and disposal (i.e., dig and haul) or in-situ methods including soil amendment application and leaching. Current remediation methods are associated with high costs to stakeholders and often achieve only partial or short-term amelioration of contaminated soils. To confront the expanding issue of brine contamination and reduce the time and financial resources needed for remediation, several novel remediation techniques have been proposed including the use of electrokinetics, crystallization inhibitors, wicking materials, and plant growth-promoting rhizobacteria. Many of these methods have been shown to be relatively effective in removing NaCl from contaminated soils in laboratory and limited field settings, however, further research in field trials needs to be conducted before these methods can be efficiently used at a commercial scale.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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