Mitigating Pollution from Runoff of Roadway Deicing Salts in Virginia: A Review of Candidate Halophytes, Halophilic Microbes, and Soil Amendments for Future Remediation Efforts

by

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Abstract

Roadway deicing salt is a major pollutant of Virginia roads, damaging environmental systems, water quality, and human health. Phytoremediation of salt-affected roadside soils using salt accumulating or excreting halophytes is an inexpensive and sustainable approach to mitigating roadway pollution. An obstacle of this approach is that the highest concentrations of saline runoff occur in winter and early spring when plants are dormant. A possible solution to this challenge is adding soil amendments to increase the cation exchange capacity of soil. This would be predicted to hold Na^+ and Cl^- ions within the rhizosphere until spring when actively growing halophytes would absorb salt ions. Later, halophyte biomass could be harvested to effectively remove salt from a site. This review identifies candidate halophytes suitable for roadside soil desalination in Virginia. I consider potential microbial and fungal aids to support halophyte growth amidst salt stress and potentially increase salt uptake. I also review environmentally friendly soil amendments capable of binding salt for later absorption by halophytes before leached ions become pollutants.

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Introduction

Salinization of land is a major environmental issue that is growing rapidly. Salt contaminated soils are increasing with climate change (Hasanuzzaman *et al*., 2014, Karakas *et al.*, 2020). It is estimated that half the world's arable land will be impacted by salinization by 2050 if efforts are not taken to mitigate salt pollution (Hasanuzzaman *et al.*, 2014; Karakas *et al.*, 2020; Litalien & Zeeb, 2020; Singh *et al*., 2021). Salt pollution is a complex, interdisciplinary, global issue. Desalination of soils and water is often prohibitively expensive, difficult, and labor intensive (Hasanuzzaman *et al.*, 2014; Litalien & Zeeb, 2020). Salinity comes from both natural sources such as weathering parent material and sea salt deposition as well as anthropogenic sources such as changing water tables from human activity, irrigation with salt water, agricultural practices, soil drainage issues from construction, and the use of de-icing agents (Arora *et al.*, 2014; Hasanuzzaman *et al.*, 2014; Karakas *et al.*, 2020; Litalien & Zeeb, 2020; Singh *et al.*, 2021). This review will focus on ways of mitigating effects of roadway deicing salts.

Roadway deicing salt runoff is one of the major pollutants of transportation ecosystems in the United States. Magnesium chloride (MgCl) and sodium chloride (NaCl) are used commonly, though NaCl comprises the majority of road salt applied (Gonsalves *et al.*, 2014). After deicing salts are applied (often in excess), they are moved through precipitation events and wind and deposited into soils and water surrounding roadways. Salt pollutant negatively impacts crops, native plants, soil biota, and manmade and natural water systems, as well as human health (Hasanuzzaman *et al*., 2014; Litalien & Zeeb, 2020; Singh *et al.*, 2021) and is especially dangerous for people who suffer from high blood pressure (Gonsalves *et al.*, 2014). Salt also damages urban structures such as road surfaces, bridges, buildings, vehicles, and more

(Baeckstroem *et al.*, 2004). There is great need to reduce salt pollution from deicing salt runoff (Ashraf *et al*., 2010; Hasanuzzaman *et al.*, 2014; Karakas *et al.*, 2020; Litalien & Zeeb, 2020; Singh *et al.*, 2021).

Salinity inhibits seed germination, plant growth, and reproduction. High concentrations can kill mature plants, often leaving roadsides barren. Saline soils are more likely to leach into groundwater (Hasanuzzaman *et al*., 2014). One cost-effective and environmentally responsible solution is phytoremediation, or the use of plants and/or microbes to remove or neutralize pollutants (Ashraf *et al*., 2010; Hasanuzzaman *et al*., 2014; Karakas *et al.*, 2020; Rabhi *et al*., 2008, Suaire *et al*., 2016; Young *et al.*, 2011). Phytoremediation is defined as the use of plants and/or microbes to reduce the concentrations and toxicity of environmental pollutants (Ashraf *et al*., 2010; Hasanuzzaman *et al*., 2014; Rabhi *et al*., 2008; Suaire *et al.*, 2016). Phytoremediation as a term refers to many processes and approaches including phytostabilization, phytodegradation, phytovolatilization, and phytoextraction (Suaire *et al.*, 2016). "Phytoextraction" is the ability of some plants to extract pollutants such as salt ions, or "phytodesalination" which is the phytoextraction of salt, from the environment and accumulate them within their biomass and some halophytes, or salt-loving plants, are capable of phytoextraction (Litalien & Zeeb, 2020; Suaire *et al.*, 2016). Phytoremediation of salt-affected roadside soils is possible and an attractive possibility. Chemicals used in traditional salt Na^+ remediation approaches, such as gypsum, increase soil calcium (Ca^+) content replacing Na^+ ions on exchange sites. However, this approach is expensive and increasing in price. (Hasanuzzaman *et al.*, 2014; Litalien & Zeeb, 2020; Rabhi *et al.*, 2008). Na^+ displaced by Ca^+ can still become a pollutant in some cases. Phytoremediation can also include other inputs such as microbes and soil amendments, which support plant growth or remediation goals.

This overview is made with the intention of facilitating the future research needed to create standardized phytoremediation treatments for roadway salt pollution in Virginia. I will discuss candidate halophytes that may be suitable as one approach to remediating deicing salts from the environment. The other focus is how soil amendments can help hold salts at peak application times during winter until they can be sequestered by plants.

Literature Review

Roadway Salt Runoff Pollution in Virginia - NaCl salt is one of the most common salts applied to roadways because it is easily available and inexpensive (Snodgrass *et al.*, 2017). The Virginia Department of Transportation (VDOT) maintains more than 57,000 miles of roadway, the majority of which is subject to the anti-icing program which includes snow removal and the use of deicing agents such as NaCl salt to deice roads for driver's safety (Fitch *et al.*, 2005). Most public works departments follow a "bare pavement" policy, as advocated by the Salt Institute (Fitch *et al.*, 2005). For deicing purposes, salt application rates are in the tens of Mg/year/km of roadways (Fitch *et al*., 2005; Litalien & Zeeb, 2020), and it is estimated that more than 10 million tons of salt are applied to roadways nationally each year (Fitch *et al.*, 2005; Snodgrass *et al.*, 2017). Most of this salt dissociates into Na^+ and Cl^- ions polluting both soil and water. One study by Jahan & Pradhanang (2020) showed that runoff Cl^- concentrations were highest in the winter and early spring. The highest concentrations were found year-round close to salt input areas such as parking lot sites, showing that approximately 70% of applied road salts stay within local watersheds. Salt pollution contributes to the trend of increasing salt concentrations in urban areas due to de-icing agents. Once dissolved, salt ions cannot be removed from the water using natural processes (Jahan & Pradhanang, 2020).

While deicing salts are effective at melting frozen precipitation, they are also a concerning source of environmental pollution. In addition to NaCl, which is damaging on its own, deicing agents often contain other chemicals such as anti-caking agents like sodium ferrocyanide or ferric ferrocyanide, as well as sodium hexametaphosphate and chromate salts to prevent automobile corrosion (Fitch *et al.*, 2005; Karakas *et al*., 2020; Litalien & Zeeb, 2020; Robinson & Thomson, 2015). As precipitation washes salt from roadways, the saline runoff contaminates groundwater, surface water, and has adverse effects on roadside vegetation (Fitch *et al.*, 2005, Karakas *et al.*, 2020; Litalien & Zeeb, 2020; Robinson & Thomson, 2015). Runoff polluted with salt has wide ranging effects, negatively impacting urban areas (Fitch *et al.*, 2005; Baeckstroem *et al.*, 2004), agricultural lands (Hasanuzzaman *et al.*, 2014; Litalien & Zeeb, 2020), streams and other water systems (Baeckstroem *et al.*, 2004; Litalien & Zeeb, 2020; Suaire *et al.*, 2016), human health and public water systems (Baeckstroem *et al.*, 2004; Litalien & Zeeb, 2020; Singh *et al.*, 2021; Snodgrass *et al.*, 2017). Only an estimated 35% of deicing salts used on roadways make it to detention sites for treatment. The majority are released to the environment, either by soaking into soil before it reaches the detention pond or overflowing once it's been contained within detention ponds (Suaire *et al.*, 2016).

The term for soils impacted by salt pollution is "salt-affected soils." This describes saline, sodic, and saline-sodic soils and refers to the accumulation of salts in soil to the extent that plant growth and other soil processes are limited (Karakas *et al.*, 2020; Litalien & Zeeb, 2020). Excessive salt negatively affects the physicochemical properties of soil, causing soil particle dispersion, reduced hydraulic capabilities, salt crusting, increased erosion, increased pH, mobilization of trace metals, and electrical conductivity (EC) (Baeckstroem *et al.*, 2004; Karakas *et al.*, 2020; Litalien & Zeeb, 2020). These negative effects contribute to groundwater contamination (Baeckstroem *et al.,* 2004; Robinson & Thomson, 2015). Salt pollution and decreased plant matter from salt-killed vegetation negatively impact biodiversity in soil and aquatic systems to the point of loss and reduces richness of detritivore, macroinvertebrate, and fish populations. Salt pollution also impacts nutrient cycling and water quality in both soil and aquatic systems (Gonsalves *et al.,* 2014; Litalien & Zeeb, 2020; Snodgrass *et al.*, 2017). Salt pollution remobilizes trace metals in soil, increases the bioavailability of trace metals in water (Baeckstroem *et al.,* 2004; Suaire *et al.,* 2016), and depletes soil carbon stocks with an average of 3.47 tons lost per hectare (Litalien & Zeeb, 2020). Salt pollution decreases the soil's capability to act as a carbon sink contributing to global climate change by releasing CO_2 into the atmosphere. Thus, desalination of roadway runoff is imperative to global environmental health (Litalien & Zeeb, 2020; Suaire *et al.,* 2016).

Phytoremediation of Salt-Affected Soils - Phytoremediation of salt-affected soils using halophytes is advantageous for many reasons. Using this strategy, the need to purchase expensive chemical amendments is eliminated. There is potential for financial return by utilizing halophyte crops or products of secondary value harvested during the phytoremediatio process. Vegetation, soil, and water impacts are lessened through phytoremediation. Vegetation-stabilized soil encourages beneficial soil aggregation and macropore formation which improves hydraulic properties of the soil which subsequently improves soil structure, drainage, and biota supporting capabilities of soil (Ashraf *et al.,* 2010; Karakas *et al.*, 2020; Young *et al.*, 2011). Carbon is also sequestered in soil post-remediation. Another advantage of this strategy is that the burden of cost and maintenance for phytoremediation projects are eased over time as the vegetation systems become more established (Hasanuzzaman *et al.,* 2014).

Phytoremediation of salt-affected soils has been found to be comparable to remediation with chemical amendments (Hasanuzzaman *et al.*, 2014). However, there are some challenges to overcome for phytoremediation of salt-affected soils. Phytoremediation is time consuming, taking one or more growing seasons to be effective. Remediation ability is limited to the rhizosphere, where plants can actively glean pollutants from cation exchange sites. Phytoremediation is proportional to the biomass that can be produced as well as the accumulation capacity of that aboveground biomass (Hasanuzzaman *et al.,* 2014). Also, there is a seasonal aspect to phytoremediation of salt-affected soils (Snodgrass *et al.,* 2017). Seasonal salt concentrations vary, as most salt applications occur in the winter when plants are quiescent (Alden, 2021; Baeckstroem *et al.,* 2004; Snodgrass *et al.,* 2017). Hence, there is a need to find a method to sequester salt in the rhizosphere until salt uptake can occur during active growth periods. Increasing the cation exchange capacity of soil using amendments that can adsorb salt ions is one approach which is covered later in this review.

Lastly, remediation potential of saline soils using halophytes increases over time. As halophytes age, the salt-storing capabilities and size of salt glands of their leaves increase and plateau (Litalien & Zeeb, 2020). Dicotyledonous plants are more capable of storing large amounts of salt in older leaves than monocots because of higher respiration rates, more Na^+ transporter activity in some plant tissues, and higher vacuole densities (Albert, 1975; Dashtebani *et al.*, 2014; Sleimi & Abdelly, 2003). Additionally, halophytes with previous salt exposure have higher capacities for phytodesalination (Barcia-Piedras *et al.*, 2019) which increases phytoremediation potential over time.

Halophytes Overview - Halophytes are useful in reclaiming salt-affected soils (Hasanuzzaman *et al.*, 2014). Some halophytes are able to decrease the soil EC of the soil solution by absorbing and accumulating or conducting soluble salts (Rabhi *et al.*, 2008). Phytoextraction of salts in this manner can bring damaged or unusable land back into cultivation and increase sustainability of the land in question (Hasanuzzaman *et al.*, 2014). This is a strategy long used by the Dutch to reclaim sea land along the coast of the Netherlands for cultivation (Welbaum, 2021). Studies have shown that cultivating halophytes on saline soils will reduce salt contamination, increase soil organic matter (OM), and increase stability through improved structure (Ashraf *et al*., 2010; Hasanuzzaman *et al.*, 2014; Karakas *et al.*, 2020).

Some halophytes can complete their entire life cycles under saline conditions close to sea water (Hasanuzzaman *et al.*, 2014; Karakas *et al.*, 2020). There is a spectrum of halophytic plants, including a range of obligate, facultative, and habitat-indifferent halophytes. Obligate halophytes require saline environments for optimal performance (Hasanuzzaman *et al.*, 2014). There are many obligate halophytes within the Chenopodiaceae family (Hasanuzzaman *et al.*, 2014; Shekhawat *et al*., 2006). Facultative halophytes are able to grow and establish in saline environments, but it is not their optimal environment. There are many facultative halophytes within the Poaceae, Cyperaceae, and Brassiceae families. Habitat indifferent halophytes are able to tolerate saline soils, but prefer non-saline soils (Hasanuzzaman *et al.*, 2014). For phytoremediation of roadside runoff, halophytes which are obligate or facultative which can tolerate fluctuating salinity throughout the season.

To be most effective for phytoremediation, halophyte species that actively uptake large amounts of Na^+ and/or Cl^- are needed. Some halophytes can compartmentalize salt ions within cell vacuoles to avoid salt stress or to use for osmotic adjustment and water uptake. There are three classifications of halophytes based on how they deal with salt stress: 1. salt excluding (those whose roots possess ultra-filtering mechanisms), 2. salt excreting halophytes or "recretohalophytes" (those which regulate salt levels by excretion through foliar salt glands), and 3. salt accumulating halophytes (those which build up salts within cells, tissues, or organs such as salt bladders to minimize salt toxicity through succulence) (Hasanuzzaman *et al.*, 2014; Karakas *et al.*, 2020; Litalien & Zeeb, 2020). Salt exclusion is a very efficient means of preventing excessive buildup of salts in plant tissues. Exclusion is much more common strategy used by halophyte species compared to accumulating or excreting plants (Hasanuzzaman *et al.*, 2014; Litalien & Zeeb, 2020). Salt excretors and accumulators are the classifications of highest value for phytodesalination because of their ability to remove salt from the soil system. Some species are capable of both accumulating and excreting salts (Shabala & Mackay, 2011).

Salt excreting halophytes, or recretohalophytes, exist within the families Asterid, Caryophalles, Rosid, and Poaceae. There are four types of salt glands within these families. The most basic is a type of salt bladder found exclusively within Aizoaceae and Amaranthaceae members. Next are plants with multicellular salt glands that exist in the families Plumbaginaceae, Acanthaceae, and Tamariceae. The last two types are bicellular and unicellular salt glands such as those found in monocot grass species *Chloridoid* and *Porteresia* (Litalien & Zeeb, 2020). Salt glands (bicellular and unicellular) are present in trichomes, known as microhairs, that contain many small vacuoles within cap and basal cells that store salts (Hasanuzzaman *et al.*, 2014). Salt excretors generally are capable of taking up more salt from soils than accumulators. By excreting salts from their leaves, wind can disperse crystals over large areas effectively reducing soil concentrations to less damaging levels. This method is called “haloconduction” and can be incorporated into long-term, natural attenuation approaches to phytoremediation of salt-affected soils (Litalien & Zeeb, 2020). Salt excretors are useful for some types of phytoremediation such as agricultural soils, but are not solely ideal for roadside remediation. Excretors may have some value in a mixed or established, stratified system. They can reduce the salt load of soils surrounding roadways where the salt stress will be the highest. Examples of species that excrete salt that may be useful for roadside phytoremediation in Virginia include *Spartina* and *Distichlis* (Table 1) (Litalien & Zeeb, 2020).

Salt accumulating halophytes are able to uptake and hold salt within plant tissues. Salt bladders in leaves, which are comprised of a swollen epidermal cells with large vacuoles, or within cell vacuoles sequester salts that are used for osmotic adjustment (Hasanuzzaman *et al*., 2014; Karakas *et al*., 2020; Litalien & Zeeb, 2020; Shabala & Mackay, 2011; Rabhi *et al.*, 2008; Shekhawat *et al.*, 2006; Zhao *et al*., 2005). Epidermal salt bladder cells, or EBC, are characteristic of the families Chenopodiaceae, Oxalidaceae, and Mesembryanthemaceae. These salt bladders accumulate excess Na^{+}, Cl^{-}, and K^{+} ions, metabolic compounds like malate, flavonoids, cysteine, pinitol inositol, and calcium oxalate crystals. At least 50% of halophytes do not use EBC to tolerate salt stress (Shabala & Mackay, 2011). Cell vacuoles likely take the role of salt storage in bladderless species, and even in species which possess bladders, salt may still be stored largely in cell vacuoles of mature leaves (Shabala & Mackay, 2011). EBC storage and vacuole storage mechanisms often result in succulence (Karakas *et al.*, 2020; Litalien & Zeeb, 2020). Salt bladders may rupture once maximum salt content has been reached. Physical disturbance on leaves, such as touch, wind, precipitation, or other forces, will leave salt deposits on the leaf surface. Salt residues from ruptured bladders do not expel salt in the same volume as recretohalophytes do (Litalien & Zeeb, 2020). Once salt has been accumulated by the plant, it can be mechanically harvested to effectively remove salt from the soil (Karakas *et al.*, 2020; Rabhi *et al.*, 2008; Suaire *et al.*, 2016). Harvested plant tissues can then be disposed of in a different location, which relocates the salt to less sensitive areas. Alternatively, harvested tissues can be recycled into other materials such as biochar, which will be covered in a later section of this review (Shabala & Mackay, 2011).

Hyperaccumulators are halophytes which accumulate or conduct amounts of salts large enough to be used reliably for phytoremediation of salt-affected soils (Robinson *et al.*, 2003). Some can accumulate more than 20% of their dry weight biomass as salt ions (Litalien & Zeeb, 2020; Shabala & Mackay, 2011; Suaire *et al.*, 2016; Zhao *et al.*, 2005). Some can haloconduct over 90% of salt taken up (Litalien & Zeeb, 2020; Sleimi & Abdelly, 2003). Examples of well-studied hyperaccumulating halophytes, not all native to Virginia, include *Atriplex* spp., *Suaeda* spp., *Salsola* spp., *Chenopodium* spp., *Mesembryanthemum crystallinum*, and *Portulaca* spp. (Karakas *et al.*, 2020; Litalien & Zeeb, 2020). One study (Suaire *et al.*, 2016) recorded *Atriplex* species (*A. halimus* and *A. hortensis*) that accumulated more than 50 mg of Na^+ ions in their aerial tissues over 60 days when exposed to a 2g/L NaCl solution. This demonstrates the promise for using these species for phytodesalinization of saline road runoff. *Salicornia europaea* accumulated up to 426-475 kg salt/ha in biomass in one study (Yucel *et al.*, 2017) and 139g Na^+/kg dry weight and 180g Cl^-/kg dry weight in another (Litalien & Zeeb, 2020). Ravindran *et al.* (2007) studied six halophytes for their capacity to desalinate the upper 40 cm of soil. *Suaeda maritima* and *Sesuvium portulacastrum* decreased the EC of the soil solution from 4.9 to 1.4-2.5 dSm^{-1}. Shekhawat *et al.*, (2006) observed effects of salinity on biomass production, water content, and ion accumulation of six members of the Chenopodiaceae family (*Atriplex amnicola, Atriplex calotheca, Atriplex hortensis, Chenopodium album, Salsola kali,* and *Suaeda nudiflora*). They found that all species accumulated salt and survived a 6000 mg/L NaCl treatment. Of the six species, the most suitable for phytodesalination was *Suaeda nudiflora* as it accumulated the most Na^+ ions with increasing salinity treatments and produced the greatest biomass overall (Shekhawat *et al*. 2006). Rabhi *et al.* (2008) observed halophytes *Anthrocnemum indicum, Suaeda fruticosa,* and *Sesuvium portulacastrum* can desalinate soils under non-leaching conditions, such as arid and semiarid soils where precipitation is too low to leach salts from the rhizosphere. All halophytes used in the Rabhi *et al*. (2008) study had the ability to accumulate significant amounts of sodium from their substrates, though their absorption and accumulation effectiveness varied.

There is plenty of evidence showing the potential of halophytes in phytodesalinization projects. However, more studies are needed to determine extraction and accumulation rates for halophyte species, as well as their bioregional suitability. There is also a need for more studies on the efficacy of pure accumulator, pure recretohalophyte, and mixed halophyte stands for different phytoremediation needs. It is essential to avoid invasive species during phytoremediation efforts. More research is needed on native halophytes that can be used in phytoremediation in Virginia and the mid-Atlantic region.

***Halophyte Candidates for Phytoremediation of Roadway Salt Runoff in Virginia* -** In order to fulfill the need to identify bioregionally suitable candidate halophytes for Virginia and the mid-Atlantic region, the parameters for “ideal” had to be identified. The ideal halophytes for roadway salt runoff phytoremediation in Virginia would be native or non-invasive, perennial or reliably self-seeding annuals, obligate or facultative halophytes that are low maintenance, low growing, winter hardy, easily established by seed, drought resistant, tolerant of roadside stress conditions such as high traffic and low nutrition, and have a substantial and explorative root system to maximize salt uptake potential (Alden, 2021; Hasanuzzaman *et al.,* 2014; Welbaum, 2021). Candidate halophytes must also be prolific biomass producers that are easily mechanically harvested. Hyperaccumulators are particularly desirable, as they are well suited for this type of remediation (Hasanuzzaman *et al.*, 2014; Litalien & Zeeb, 2020).

A mixed stand of hyperaccumulators and recretohalophytes could be useful for dispersing salt to a density which can be more readily remediated within plant uptake limitations. A possible approach is to stratify vegetation according to salt levels. Hyperaccumulators closer to the road may desalinate higher salt loads before leaching. Salt excretors planted farther away from the road may dilute salt concentrations in soil (Litalien & Zeeb, 2020). Another stratified system to consider is using plants which prefer dry soils near roadsides and plants which prefer wetter soils along ditches. For the most effective phytoremediation effort, candidate halophytes should be active in the early spring. One challenge to the phytoremediation of deicing salts is that saline runoff is highest in the winter and early spring months when most plants are dormant (Hasanuzzaman *et al.*, 2014; Jahan & Pradhanang, 2020; Wahls *et al*., 2016).

Additionally, halophytes which have higher economic importance and offer secondary value would be most desirable for phytoremediation projects (Hasanuzzaman *et al.*, 2014; Karakas *et al.,* 2020; Litalien & Zeeb, 2020; Snyder, 1991). Some halophytes have additional value as products, such as a substitute for conventional crops, fuel, forage, fodder, timber, or fiber. Additional potential uses could be essential oil extraction, or medicinal uses (Hasanuzzaman *et al.*, 2014; Karakas *et al.*, 2020; Litalien & Zeeb, 2020; Snyder, 1991).

Candidate Halophytes List - The following is a list of candidate halophytes. Most are native to Virginia, those which are not are introduced or naturalized. The halophytes chosen were suitable to be used in an immediate roadside vegetation band or in seeps and wet ditches close to the road in Virginia and the mid-Atlantic region. Candidate halophytes and their salt accumulation were found in a search containing or combining keywords such as: halophyte, salt, NaCl, ion, compartmentalization, content, accumulat***, hyperaccumulating, mechanism, removal, sequestering, stress, tolerance, transport, uptake; sodium, chloride; roadway, roadside, road salt. A more concise layout of this information can be found in Table 1.

Table 1. An alphabetical list of candidate halophytes by species, common name, growth cycle, status, salt tolerance classification, halophyte type, and accumulation rates found from literature review.

Species	Common name	Growth Cycle	Status	Salt Tolerance Classification	Halophyte Type	Approximate Salt Accumulation Rates
Agropyron smithii/Pascopyrum smithii	Barton' Western wheatgrass	Perennial	Native	Facultative	Recretohalophyte	Unknown
Alopecurus arundinaceus	Garrison' creeping meadow foxtail	Perennial	Introduced	Facultative	Likely Recretohalophyte	17 mg Na/g DW (Riedell, 2016)
Atriplex glabriuscula	Smooth orach	Annual	Native, threatened	Facultative	Accumulator	>35 g Na/kg FM (Ievinsh, 2020)
Atriplex patula	Spear orach	Annual	Native	Facultative	Accumulator	4826 µmol Na/g DW (Glenn & O'leary, 1984); 490 kg Cl/ha/season (Litalien & Zeeb, 2020); Mean concentration of 40 mg Cl/g DW and mean mass of 50 mg Cl/plant (Morteau *et al.*, 2009); 5-20% Na DW biomass (Young et al., 2011)
Baccharis halimifolia	Groundsel-tree	Perennial	Native	Obligate	Accumulator	Up to 60 mg Na/g DW (Caño *et al.*, 2016)
Bolboschoenus robustus	Sturdy bulrush	Perennial	Native	Facultative	Unknown	Similar species *B. maritima* showed ~400 mmol Na/L and 500 mmol Cl/L (Albert, 1975); 200-400 mmol L Na (Ievinsh *et al.*, 2021)
Chenopodium album	Lambsquarters	Self-seeding annual	Introduced	Facultative or obligate	Accumulator	570 kg NaCl/ha/season (Litalien & Zeeb, 2020); 7.63 mg Na ions/g DW (Shekhawat *et al.*, 2006)
Distichlis spicata	Saltgrass	Perennial	Native	Obligate	Recretohalophyte	64.10±3.14 mg Na/g DW plant in shoot and 30.35± 1.66 mg Na/g DW root (Sabzalian *et al.*, 2018)
Eleocharis parvula	Drawf spikerush	Perennial	Native	Likely facultative	Unknown	1.0 mol Na (Ievinsh *et al.*, 2021)
Festuca rubra	Red fescue	Perennial	Native	Facultative or indifferent	Likely Recretohalophyte	9.6 mg Na/g DW (Cooper, 1982); Crowns accumulated >30 mg Na/g DW, young leaves accumuated >30 mg Na/g DW, old leaves accumulated up to 35 mg Na/g DW (Krishnan & Brown, 2009)
Hibiscus moscheutos	Swamp rose-mallow	Perennial	Native	Unknown	Unknown	Unknown
Hordeum jubatum	Foxtail barley	Perennial	Native in Western US, naturalized in Eastern US	Facultative	Likely Accumulator	166.9 mEq Na/100g DW and 216.0 mEq Cl/100 g DW stem tissue, 152.9 mEq Na/100g DW and 246.2 mEq Cl/100g DW leaf tissue (Badger &Ungar, 1990)
Impatiens capensis	Jewelweed	Self-seeding annual	Native	Unknown	Unknown	Unknown
Juncus gerardii	Saltmarsh bulrush	Perennial	Native	Obligate	Likely Accumulator	66.3 mg Na/g DW (Cooper, 1982); ~300 mmol Na/L and >400 mmol Cl/L (Albert, 1975); 40-150 mmol Na in leaf sap (Shabala & Mackay, 2011)
Medicago sativa	Alfalfa	Perennial	Introduced, naturalized	N/A	Accumulator	>450 mmol Na/kg DW and 450 mmol Cl/kg DW (Grieve et al., 2004); up to 43.1% Na concentration in salt intolerant cultivars and 40.8% Na concentration in salt tolerant cultivars (Winicov, 1991)
Panicum virgatum	Shawnee' switchgrass	Perennial	Native	Facultative	Accumulator or Recretohalophyte	Between 9.92-38.86g Na/kg DW depending on cultivar (Cordero *et al.*, 2019); 25 mg Na/g DW (Riedell, 2016)

Species	Common name	Growth Cycle	Status	Salt Tolerance Classification	Halophyte Type	Approximate Salt Accumulation Rates
Puccinellia distans	Weeping alkali grass	Perennial	Introduced	Obligate	Accumulator	125-250 mg Na/gDW (Dashtebani *et al.*, 2014); 400 mmol Na/L and 500 mmol Cl/L (Albert, 1975); 50-130 mmols Na in leaf sap (Shabala & Mackay, 2011)
Salicornia virginica	Jointed glasswort	Perennial	Native	Obligate	Accumulator	19.17-37.94 mmol/L Na (Ownbey & Mahall, 1983; Shabala & Mackay, 2011); Accumulated Cl concentration up to 30% of DW tissue (Ralph & Manley, 2006)
Schoenoplectus pungens var pungens	Common threesquare	Perennial	Native	Unknown	Accumulator	Unknown
Solidago mexicana	Seaside goldenrod	Perennial	Native	Facultative	Accumulator	Unknown
Spartina alterniflora	Smooth cordgrass	Perennial	Native	Obligate	Recretohalophyte	~1050 µg Na/gDW (Chai et al., 2013); 2.0 mmol Na/kg 0.4 M NaCl treatment (Vasquez et al., 2006); 1.5 mM NaCl/gDW and 1.5 mM Cl/gDW (Sleimi & Abdelly, 2003)
Spartina patens	Saltmeadow cordgrass	Perennial	Native	Obligate	Recretohalophyte	~2.7% of leaf tissue in Na (Tobias *et al.*, 2014)
Sporobolus airoides	Alkali sacaton	Perennial	Native	Facultative	Recretohalophyte	62.12-200.87 mmol Na/g leaf FW weekly, 16.22-75.31 mmol Cl/g leaf FW weekly (Weragodavidana, 2016); ~550 mmol Na/kg DW and ~525 mmol Cl/kg DW per season (Grieve *et al.*, 2004); 0.318-0.637% Na of aboveground biomass (Burris, 2017).
Suaeda maritima	Herbaceous sea-blite	Annual/perennial	Native	Obligate	Accumulator	504 mg NaCl/plant/season (Hasanuzzaman et al., 2014); 147 mmol Na in 200 mmol NaCl treatment (Clipson & Flowers, 1986); 700 mmol cations in biomass after 7 weeks (Flowers *et al.*, 1986); 380-660 mmols Na in leaf sap (Shabala & Mackay, 2011)
Typha latifolia	Common cattail	Perennial	Native	Facultative	Accumulator	Mean concentration of 65 mg Cl/gDW, mean mass of 70 mg Cl/plant (Morteau *et al.*, 2009)

Agropyron smithii (also referred to as *Pascopyrum smithii*), or Western wheatgrass, is a cool-season, rhizomatous grass native to the western U.S. which grows to 1-3’ tall (Aschenbach, 2006). It comes out of dormancy in March for Virginia (Alden, 2021; Wahls *et al*., 2006). It is generally a prairie plant and is found in its natural habitats alongside plants such as *Sporobolus airoides, Buchloe dactyloides, Koeleria macrantha, Hesperostipa comata, Nassella viridula,* and *Schizachyrium scoparium*. Western wheatgrass handles drought, flooding, and cold, and shade stress (Alden, 2021; Tirmenstein, 1999) such as what is found on many Virginia roadsides. It has secondary value as a forage and fodder plant and is used in grazing pastures. It is an aggressive sod-forming grass, and rhizomes can penetrate soil depths to 7’ or more, making it a very suitable plant for erosion prevention. It has been used in reclamation of disturbed sites such as surface coal mines and other sites with weak soil structure. It is also used for revegetation of saline-alkali areas. It rapidly establishes on abandoned or disturbed land. Western wheatgrass is not highly dependent upon vesicular arbuscular mycorrhiza, or “VAM,” for survival. It establishes well through broadcast seeding in either the fall or spring. It has strong, rapid vegetative growth in the early spring, flowers in June, and fruits from August to September (Tirmenstein, 1999). There are many cultivars available for use, as it is commonly used in seeding mixtures for revegetation projects. The best candidate varieties for salt-polluted roadside soil phytoremediation in Virginia are expected to be: “Barton,” a native variety from clay bottomlands in Kansas, and “Recovery,” a variety which has excellent seedling vigor and establishment and is intended for use in revegetating disturbed rangelands, high traffic areas, and areas with high soil erosion and disturbance events (Ogle *et al.*, 2009). This plant tolerates high salinity and salt fluctuations well and is deemed to be a good candidate plant for salt remediation projects (Aschenbach, 2006; Deeter, 2002). Salt accumulation has not yet been determined for this species.

Alopecurus arundinaceus, or 'Garrison' creeping meadow foxtail, is a perennial, rhizomatous, cool-season grass growing to 3-6' tall (Alden, 2021; USDA-NRCS, 2013). This variety is not native to the U.S. but is introduced and present around the U.S. (USDA-NRCS, 2013). It is vegetative in early spring and is tolerant of drought, flooding, poor drainage, frost, alkalinity, acidity, and salt conditions (Alden, 2021; Markovskaya *et al*., 2020). It is aggressively rhizomatous, able to quickly recover from aboveground damage like harvest, and is valuable for erosion control. It tolerates a wide range of habitats and soil conditions, including a broad range of pH (5.6-8.4) and salinities, usually performing well at moderate salinity. These features made it valuable on critically disturbed areas and difficult terrain such as roadsides and saline seeps. It competes well with species such as *Juncus* spp. and *Carex* spp. It has secondary value as grazing forage. Seeding is most successful with a cover of hay, firm packing of seeds into soil, on moistened soil, and with early precipitation to promote germination. Coated seeds help germination rates. This species can become weedy and requires management in the form of mechanical harvest or control through competition (USDA-NRCS, 2013). Riedell (2016) found that creeping meadow foxtail accumulated 17 mg Na^+/g of dry weight plant material (DW).

Atriplex glabriuscula, or smooth orach, is a native, annual, obligate halophyte growing 20-60 cm in height with a creeping stem (Markovskaya *et al.*, 2020). Smooth orach is a species of concern in some New England states. It is presumed to be extirpated from its previous range in Virginia, thus using this plant for phytoremediation may also have additional conservation value (Flora of North America, 2003b; Kartesz, 1999). Smooth orach prefers sandy and stony soils much like what is found on many roadsides (Markovskaya *et al.*, 2020). *Atriplex* spp. have secretory trichomes or vesicular microhairs as a characteristic feature of the genus (Markovskaya *et al.*, 2020; Weragodavidana, 2016). They also have salt bladders on their epidermal tissue (Markovskaya *et al*., 2020). Smooth orach preferentially accumulates Na^+ in its aboveground biomass for osmotic regulation. It was shown to accumulate approximately >35 g Na^+/kg fresh mass (Ievinsh, 2020). Not all *Atriplex* spp. accumulate Na^+ in this manner, some species in the genus clearly exclude Na^+ from shoots and accumulate the ions in roots instead, such as *Atriplex halimus* (Ievinsh, 2020).

Atriplex patula, or spear orach, is an annual found in most northern and coastal US states (Flora of North America, 2003b; USDA NRCS, 2021) and Canada (Young *et al.,* 2011). It grows to a height of 2-3' tall and prefers full light and moist soils but is drought tolerant. This plant, like many *Atriplex* sp., has secondary value as an edible crop (Flora of North America, 2003b). Spear orach germinates best and produces highest yield when shallow seeded in the spring versus broadcast seeding (Young *et al.*, 2011). Spear orach has been shown to accumulate around 4826 μmol Na^+/g DW (Glenn & O'Leary, 1984), a mean concentration of 40 mg Cl^-/g DW, a mean mass of 50 mg Cl^-/plant (Morteau *et al.*, 2009), and 490 kg Cl^-/ha in a growing season (Litalien & Zeeb, 2020).

Baccharis halimifolia, or groundsel-tree, is a perennial shrub native to the Eastern coastal states that grows up to a height of 5m. It commonly inhabits moist soils with high organic matter such as pond or bay margins, swamps, wet prairies, marshes, salt marshes, and everglade hammocks. It rapidly colonizes disturbed sites and readily regrows if aboveground parts are trimmed (Van Deelen, 1991). *B. halimifolia* associates with both AMF and ectomycorrhizal species, with root colonization rates between 20-45% for AMF and 10-20% for ectomycorrhiza

(Younginger *et al.*, 2009). *B. halimifolia* was reported to accumulate up to 60 mg Na^+/g DW and was shown to accumulate more Na^+ as salinity treatments increased (Caño *et al*., 2016).

Bolboschoenus robustus, also known as sturdy bulrush, is a native, rhizomatous, perennial sedge growing 2.5-5' tall. It is an obligate wetland species and a fast spreading halophyte with high germination rates (95% in lower saline environments, inhibited to 50% around 9000 ppm NaCl, and halted around 2,000 ppm NaCl but retains dormancy until conditions are favorable again) and high survival rate (88%) in wetland conditions. It establishes quickly when conditions are suitable, doubling its vegetative cover within a month. It has value as food and habitat for wildlife. Muskrats and waterfowl eat the seeds, and the vegetation is cover for fiddler crabs and nesting ducks. It has recorded use in remediation work to improve habitat for largemouth bass. Sturdy bulrush would be best utilized in detention ponds or wet ditches along roadsides. It thrives in salinities between 3,000-22,000 ppm NaCl with an optimal growth range between 3,000-7,000 ppm NaCl and pH between 4.3-6.4. It tolerates fluctuating water levels and performs best in disturbed environments such as post-fire systems. It sprouts in early spring, flowers in April-August and fruits from July-October. It resprouts in the fall if inundated. Excellent companion plants for sturdy bulrush include: common reed (*Phragmites communis*), switchgrass (*Panicum virgatum)*, cordgrass (*Spartina* spp.), American bulrush (*Schoenoplectus americanus*), widgeon grass (*Ruppia maritima*), coastal saltgrass (*Distichlis spicata* var. *spicata*), sedge (*Carex* spp.), buckbrush (*Baccharis halimifolia*), marsh button (*Achyranthes philoxeroides*), seaside goldenrod (*Solidago mexicana*), cattail (*Typha* spp.), bulltongue (*Sagittaria* spp.), and cutgrass (*Zizaniopsis miliacea*) (Snyder *et al.,* 1991). One study by Albert (1975) showed that a similar species, *B. maritimus,* accumulated concentrations close to 400 mmol Na^+/L and 500 mmol Cl^-/L in its aboveground biomass. Another study (Ievinsh *et al.*, 2020) showed that *B. maritimus* accumulated 200-400 mmol Na^+/L.

Chenopodium album, or lambsquarters, is an annual, herbaceous, obligate halophyte growing 0.2-2m tall (CABI, 2019; Deeter, 2002). It is an introduced species which has been present in the U.S. since colonization and has a wide distribution with frequent, ubiquitous occurrence throughout the U.S. including Virginia. It establishes better when seeded early in spring. It has secondary value as an edible crop, fodder, and as a traditional medicinal plant (CABI, 2019). *C. album* is very salt tolerant (Deeter, 2002) and is a common volunteer in saline soils (Young *et al.*, 2011). In one study (Shekhawat *et al.*, 2006), increased salinity reduced *C. album* biomass production, but stunted growth from salt stress did not stop the plant from accumulating NaCl at the maximum salinity tested. Relative succulence increased with salinity (Shekhawat *et al.*, 2006). Lambsquarters is an excellent biomass producer capable of producing 3.23 tons of biomass per hectare and 20% of that biomass is accounted for by salt content, which is roughly 570 kg $NaCl^-$/ha (Litalien & Zeeb, 2020).

Distichlis spicata, or saltgrass, is a perennial, strongly rhizomatous, warm-season, low growing, obligate halophyte graminoid. It is native to coastal regions of the U.S. as well as some inland salt marshes and similar saline wet soils. It grows up to 1' tall and forms dense colonies, and rhizomes can grow to depths of 10" into soil, forming a dense sod which makes this species excellent for erosion control (Hauser, 2006; Sabzalian *et al.*, 2018). It can grow in a wide range of habitats including tidal salt marshes, deserts, and grasslands (Hauser, 2006). Saltgrass volunteers on disturbed sites (Perry & Atkinson, 1997) and prefers full light environments (Hauser, 2006). It is most competitive in disturbed areas and is eventually outcompeted as succession advances. It has secondary value as forage as it stays green into cold season and is a source of food for wildlife, namely migrating birds (Hauser, 2006). Rhizomes are its primary means of reproduction. Root systems are notably colonized by VAM fungi which aid its survival in hypersaline soils (Hauser, 2006). Saltgrass deals with salt stress by excretion and is able to significantly reduce the salinity of the top 10 cm of soil over time (Litalien & Zeeb, 2020; Sabzalian *et al.*, 2018). One study (Aschenbach, 2006) showed that saltgrass' growth is stunted at salinity levels above 9.85 dS/m, though it can survive in higher salinities and is deemed a good candidate for salt remediation projects. Another study (Sabzalian *et al.*, 2018) suggested that optimal salinity for this plant was around 12 dS/m. It was shown to survive in substrates of 20 dS/m salt concentrations without showing significant stress (Pessarakli *et al.*, 2012). Saltgrass grows well in nature with many of the halophytes listed here, including but not limited to *Agropyron smithii*, *Salicornia* spp., *Juncus gerardii, Atriplex* spp., *Sporobolus airoides*, *Puccinellia* spp., and *Spartina* spp. (Bertness, 1988; Hauser, 2006). A study by Sabzalian *et al*. (2018), showed that *D. spicata* accumulated 64.10±3.14 mg Na^+/g DW plant in shoot and 30.35±1.66 mg Na^+/g DW roots.

Eleocharis parvula, or dwarf spikerush, is a perennial, grass-like, herbaceous halophyte native to North America which grows to roughly 10 cm tall (Calflora). Dwarf spikerush is a facultative halophyte usually found in wetlands and coastal soils (USDA). Ievinsh *et al.* (2020) showed that *Eleocharis parvula* accumulated 1.0 mol Na^+ ions.

Festuca rubra, or red fescue, is a perennial, cool-season, rhizomatous grass native to the northern U.S. states. It has value in remediation and often volunteers on severely disturbed sites such as abandoned coal mines and roadsides (Krishnan & Brown, 2009; Walsh, 1995). Red fescue germinates quickly and at high rates. This fescue holds up well against foot traffic and roadside stresses and has high pest and disease resistance (Krishnan & Brown, 2009). It has value as a wildlife food source. It is used to prevent erosion on irrigation ditches, waterways, channels, highways, and hillsides. It can spread through seed or vegetative propagation. It is drought and flood tolerant, and grows on a broad range of soil types. It tolerates soil pH between 4.5-6.0 well and doesn't require much soil fertility but does require high light. It becomes vegetative in early spring and grows slowly until midsummer then grows vigorously until frost. It regenerates readily when aboveground parts have been harvested or removed (Walsh, 1995). A study by Khan & Marshall (1981) showed that red fescue accumulated 371.4 mEq Na^+/100 grams DW and 297.4 mEq Cl^-/100g DW. Another study by Cooper (1982) showed that *F. rubra* accumulated 9.6 mg Na^+/g DW in dry saline substrate. Krishnan & Brown (2009) showed that red fescue crowns accumulated up to 30 mg Na^+/g DW, young leaves accumulated up to 30 mg Na^+/g DW, and old leaves accumulated up to 35 mg Na^+/g DW.

Hibiscus moscheutos, or swamp rose-mallow, is a native shrubby, herbaceous, perennial forb growing 1-2.5' tall and forming a large woody rootstock. It is often found in moderately saline tidal marsh communities in nature. It is able to sprout vegetatively from the caudex. It handles drought and inundation stress well. This plant is aesthetically pleasing with beautiful, prominent blossoms (Reeves, 2008).

Hordeum jubatum ssp. *jubatum*, or foxtail barley, is a short-lived, perennial, fibrous-rooting, cool-season, facultative halophyte grass native to western North America and naturalized in eastern North America due to increasing soil salinity in urban areas as a result of human activity (Badger & Ungar, 1990; Tesky, 1992). It grows 1-2' tall and is capable of producing two cohorts a year, one in spring and the other in the fall. It is native to the Western US and is naturalized in the Eastern states. It grows vegetatively from April onward, with flower and seedset occurring from late May to late July (Tesky, 1991) and grows densely, providing up to 90-100% vegetative cover at moderate salinities (Badger & Ungar, 1990). It commonly volunteers in disturbed, saline soils. It has extensive, aggressive rooting habits which make it valuable for erosion control. It is a prolific seeder and also propagates vegetatively, especially when salinity is high enough to inhibit seed germination (1% salinity and above can impact germination). It has value as food for wildlife, especially the seed, though the dry seed heads can be dangerous to grazing animals due to their spiky nature and ability to penetrate flesh. Mechanical harvest would be a good management strategy to prevent seed issues as well as removing salt-laden biomass from the site. It has potential where forage value is of secondary importance to remediation importance. Additionally, it has value as an ornamental flower when dried (Tesky, 1992). At 1.0% NaCl substrate, *H. jubatum* was found to accumulate concentrations of 166.9 mEq Na^+/100g DW and 216.0 mEq Cl^-/100 g DW in stem tissue, and 152.9 mEq Na^+/100g DW and 246.2 mEq Cl^-/100g dry weight in leaf tissue (Badger & Ungar, 1990).

Juncus gerardii Loisel, also known as saltmarsh bulrush, is a frost tolerant, rhizomatous, perennial graminoid growing over 1' tall. It is a brackish species native to coastal US regions. It has been naturalized in the Great Lakes region (Cao *et al.*, 2021). It forms extensive colonies in salt marshes and coastal meadows. It is a facultative halophyte with a preference for non-saline soils. It doesn't tolerate inundation well. It is most competitive in high light conditions, with shoots emerging in March and lasting until June, then fruits from May to August (Cao *et al.*, 2021). *J. gerardii* is restricted to coastal distributions in nature. Its vegetative biomass is reduced in saline conditions, but overall number of shoots produced was not affected, showing that *J. gerardii* shows potential to carry out vegetative propagation under saline conditions (Rozema & Blom, 1977). A study by Albert (1975) showed that *J. gerardii* accumulated around 300 mmol/L concentration of Na^+ and >400 mmol/L concentration of Cl^- in its aboveground biomass. Shabala & Mackay (2011) showed that *J. gerardii* contained 40-150 mmols Na^+ in leaf sap within 200-500 mM NaCl range treatments. Another study (Cooper, 1982) showed that *J. gerardii* accumulated 66.3 mg Na^+/g DW in waterlogged saline soils and 41.3 mg Na^+/g DW in dry saline soils.

Medicago sativa, or alfalfa, is a long-lived, perennial legume which is naturalized in much of the U.S. It grows 2-3' tall. Alfalfa commonly volunteers on disturbed sites and is suited to roadside stress conditions. It fixes atmospheric nitrogen and does not need nitrogen fertilizer to perform optimally. It has great value as a food plant for wildlife and livestock. It also supports honey production and pollinator migration. It is regarded as the most valued legume. Seed mixes intended for revegetating disturbed lands often include alfalfa varieties. Alfalfa replenishes soil nutrients, supports growth of other plants, reduces erosion and compaction while stabilizing soil with its deep roots, increases forage value, acts as a soil conditioner for future growth, and handles difficult soils and high traffic well. It seeds easily through broadcasting and does well with a firm seedbed (Sullivan, 1992). There are many varieties and subspecies, some of which have been bred for salt tolerance (Alden, 2021). While alfalfa itself is very salt tolerant (Deeter, 2002), it excludes salt (especially Na^+ ions, making it natrophobic) (Grieve *et al*., 2004; Scasta *et al.*, 2012). However, alfalfa enriches soil and supports the growth of plants around it. For this reason, more salt-tolerant varieties such as 'Ameristand 90' (Alden, 2021), 'Barstow,' 'Salado,' 'Malone,' and 'Mesa Sirsa' cultivars are valuable in salt-affected soils (Greub *et al.,* 1985; Scasta *et al*., 2012).. 'Ameristand 90' alfalfa is a recommended variety for Virginia roadside phytoremediation (Alden, 2021). A study by Winicov (1991) showed that alfalfa was able to grow well in 1.0% saline substrate and that salt tolerant varieties were able to accumulate between 2.2-40.8% Na^+ concentration.

Panicum virgatum, or 'Shawnee' switchgrass, is a very salt tolerant, native, warm-season, perennial grass growing to 3-5' tall (Alden, 2021; Deeter, 2002). It is sod and bunch forming. Most growth occurs in the early summer but it grows fast and matures early. It is tolerant to shallow soil, drought, flooding, poor drainage. *P. virgatum* has higher salt tolerance than other switchgrass cultivars (Alden, 2021; Wahls *et al.*, 2006), tolerating up to moderate soil salinities (Uchytil, 1993). It can also tolerate a soil pH range between 4.5-6.5. It is an excellent biomass producer that can produce 2-4 tons of aboveground biomass per acre. It produces both through seed and vegetative propagation. Shawnee switchgrass has secondary value as a valuable grazing pasture and forage plant, especially in early summer. It also serves as a valuable shelter source for many wildlife species. Shawnee switchgrass is used for revegetation on disturbed sites such as abandoned mine lands. It is also used for erosion control on soils with weak structures, along waterways, in areas of high disturbance, and for prairie restoration. There are many cultivars available as this plant is very popular for revegetation efforts. Aboveground harvesting may damage the plant over time. Replanting after a few years may be necessary (Uchytil, 1993). Shawnee switchgrass accumulates salt in its aerial parts but also excretes salt onto leaf surfaces. A study by Riedell (2016) showed that *P. virgatum* accumulated 25 mg Na^+/g DW. Another study found that accumulation rates of Na^+ for *P. virgatum* were found to vary according to cultivar, with 'Alamo' accumulating a concentration of 4.53 g/kg in leaves and 5.39 in stems, 'Kanlow' accumulating 16.23 g/kg in leaves and 13.55 in stems, and 'Trailblazer' accumulating 15.47 g/kg in leaves and 23.39 g/kg in stems (Cordero et al., 2019). Variation in accumulation rates by cultivar are expected to occur in most halophytes, though more studies need done.

Puccinellia distans, or weeping alkali grass, is a non-native introduced species, commonly occurring in Virginia. It is a perennial, cool-season, sod-forming bunchgrass that is well adapted to alkaline and saline soils (Burris, 2017; USDA-NRCS, 2021). It is naturalized in the Great Lakes area (USDA-NRCS, 2021). Weeping alkaligrass has volunteered and migrated along the corridor of interstate I-77 where high volumes of deicing salts are applied (Alden, 2021). Weeping alkaligrass is also excellent for soil stabilization due to its prominent roots (Dashtebani *et al.*, 2014). It's natural occurrence in roadside environments in addition to its salt, drought, and flood tolerance makes it a candidate for this type of phytoremediation (Alden, 2021; Deeter, 2002). A study by Dashtebani *et al.* (2014) showed that *P. distans* produced higher biomass when inoculated with *Claroideoglomus etunicatum*, an arbuscular mycorrhizal fungus species which resides naturally in saline soils alongside *P. distans*. In addition to higher biomass production, AMF inoculated plants showed reduced salt stress compared to plants which were not inoculated. The biomass of inoculated plants was not significantly affected by the higher salinity treatments of the study. In addition to AMF, *P. distans* can avoid salt toxicity with its thick endodermis, vacuolar compartmentalization and sequestration of Na^+ which is used as an osmolyte (Dashtebani *et al.,* 2014; Shabala & Mackay, 2011). A study by Albert (1975) showed that *P. distans* accumulated concentrations around 400 mmol Na^+/L and 400 mmol Cl^-/L in its aboveground biomass. Another study by Shabala & Mackay (2011) showed that *P. distans* contained 50-130 mmols Na^+ in leaf sap within 200-500 mM NaCl range treatments.

Salicornia virginica, or jointed glasswort, is a rhizomatous, perennial, obligate halophyte native to Western US states, growing 1' tall (Ball, 2012; Ownbey & Mahall, 1983). It prefers full sun and moist soils. It flowers from July to November in Western states (Ball, 2012). *S. virginica* was found to take up 4.52-7.56 mOsmol NaCl per unit in dry weight and 19.17-37.94

mOsmol/kg through evapotranspiration (Ownbey & Mahall, 1983). Shabala & Mackay (2011) showed that *S. virginica* had 19-38 mM Na^+ in xylem within 200-500 mM NaCl range treatments. Ralph & Manley (2006) showed accumulated Cl^- concentrations up to 30% of *S. virginica*'s DW tissue.

Schoenoplectus pungens var. *pungens*, or common threesquare, is a rhizomatous, perennial grass-like herb native to most of the US growing 4-6' tall. It is commonly found in floodplains, ditches, streams, marshy areas, and pond or lake margins. It is moderately halotolerant and can tolerate seasonal drought. Seeds are produced from July through August and help in the seed heads for many months if undisturbed. Germination can be difficult, with seeds requiring cold stratification and scarification to germinate. Germination rates can be rather unpredictable (Stevens *et al.*, 2012). A study by Ievinsh *et al*. (2021) that a related species, *Schoenoplectus tabernamontani,* preferentially accumulated Na^+ ions in its aboveground biomass.

Solidago mexicana, or seaside goldenrod, is a native perennial forb growing up to 6'. It produces sprouts early in the season, from February to March, and blooms from August to October and produces a large, clustered spike of yellow flowers. In nature it is often found with some of the species mentioned in this review, such as *Panicum virgatum* and *Spartina patens*. It is a facultative wetland species. Seaside goldenrod can tolerate infertile soils, drought, and pH ranges between 5.5-7.5. It is quite halotolerant and is succulent, so it may have a high rate of salt accumulation. Seaside goldenrod is an important resource for pollinators and other wildlife, serving as food and shelter. It supports the migration of the monarch butterfly as a primary food source in the fall. Seaside goldenrod has stocky, short rhizomes and a root-length of at least 14" making it excellent for erosion control. In sandy areas it contributes to dune formation. It propagates through seed and clonally. Once a stand is established it requires minimal irrigation and little to no maintenance. This species can withstand hot and dry conditions such as what is found on roadside soils. It produces better when broadcast seeded with American beachgrass (*Ammophila breviligulata*). One issue with this plant is that it is suspected to produce root exudates which negatively impact the growth of surrounding vegetation, especially native grasses such as *Triplasis purpurea* and *Cenchrus tribuloides* (Sheahan, 2014).

Spartina alterniflora, or smooth cordgrass, is a perennial, warm-season grass native to North America along eastern coasts and marshes. It grows to 1.5- 8' tall depending on conditions. Its natural habitat retains surface water year-round and includes plants such as *Distichlis spicata* and *Juncus roemerianis*. Smooth cordgrass has been successfully direct seeded on damaged marsh soils in Virginia to mitigate erosion and remediate the marsh soil by filtering heavy metals from the water column. Smooth cordgrass is quite halotolerant and is used as an indicator of salinity. It is a source of shelter for wildlife species. It germinates from April to June. Smooth cordgrass can germinate in salinities up to 6-8 percent. It establishes well through rhizomatous growth and forms a sod-like layer within the upper 5.9 inches of soil from April to October, with the upper 2 inches having the densest rhizome formations. It dominates where salinities range between 3-5% and prefers wet soil or wetland conditions. It is known for invading wet roadside ditches. While often dominant in saline environments, it is outcompeted by other *Spartina* spp., *Juncus* spp., and *Distichlis* spp. (Walkup, 1991). *Spartina alterniflora* excretes salts onto its leaf surfaces (Smart, 1982). In a study by Chai *et al.* (2013), *Spartina alterniflora* seedlings accumulated about 1050 µg $NaCl^-$/g DW. This study showed that smooth cordgrass can grow well in 600 mM NaCl substrate and likely higher salinities (Chai *et al.*, 2013). Another study by Vasquez *et al.* (2006) showed that *S. alterniflora* has a shoot Na^+

content of 2.0 mmol under 0.4 M NaCl treatment and that the plant seemed to preferentially accumulate Na^+ over K^+ for osmotic regulation. This efficient salt tolerance mechanism made *S. alterniflora* competitive over some invasive species such as *Phragmites australis* (Vasquez *et al.*, 2006). Sleimi & Abdelly (2003) showed that *S. alterniflora* accumulated 1.5 mM NaCl/g DW and 1.5 mM Cl^-/g DW at 800 mM NaCl substrate. Sleimi & Abdelly (2003) also acknowledged that *S. alterniflora*'s capacity for phytodesalination is likely underestimated because an approximate 90% of salt taken up through the plant was excreted through leaves and not sequestered in plant tissues.

Spartina patens, or saltmeadow cordgrass, is a perennial, warm-season grass native to the Atlantic coast, growing 1-5' tall in rhizomatous clumps. It flowers from June to September around Virginia and the Carolinas. It is valuable as a food source for wildlife and serves as natural pasture. It is flood tolerant and has roots that readily develop aerenchyma tissue. It regularly grows in brackish marshes, low dunes, sand flats, beaches, overwash areas, and high salt marshes (Deeter, 2002; Walkup, 1991). Salt content of soils where it occurs in nature ranges between 0.12-3.91 percent. *Juncus gerardii* is competitive against saltmeadow cordgrass and can exclude it from certain habitats (Walkup, 1991). Tobias *et al.* (2004) showed that *S. patens* accumulated up to 2.7% of its leaf tissue in Na^+.

Sporobolus airoides, or alkali sacaton, is a facultative halophyte that is a perennial, warm-season, chloridoid bunchgrass native to the western U.S.. It grows from tillers and seeds to a height of 0.5-3' tall. It is tolerant of salt, drought, and flooding conditions but not shade (Alden 2021; Deeter, 2002; Johnson, 2000; Weragodavindana, 2016). Alkali sacaton has salt glands which excrete salt on leaf surfaces (Weragodavindana, 2016). It readily forms associations with VAM fungi and produces more biomass when inoculated. It can grow in saline and non-saline soils and tolerates salinities between 0.003-3% well with optimal performance between 0.3-0.5%. It is known to invade saline flats and tolerates fluctuating saline inputs well. It flowers between July to October depending on where it's grown and produces seeds in the fall. It grows in a wide range of soils and does not require high fertility or organic matter content. It has secondary value as forage and shelter for wildlife and has grazing value for livestock. It establishes well when seeded on saline sites in mixtures with *Panicum virgatum*. It performs well in riparian zones and has been used in reclamation efforts in saline areas, oil well reserve pits, saline waste areas, sewage sludge sites with bauxite residue, and selenium contaminated sites. Best management practices for establishing alkali sacaton from seed on highly disturbed sites includes having soil moisture above 14%, soil temperature near 30 ^{o}C, using seeds at least 1 year old, prewetting site before seed application, and early irrigation to promote germination (Johnson, 2000). Weekly salt gland excretion rates of Cl^- for *Sporobolus* sp. were found to be between 16.22-75.31 mmol NaCl/g dry weight of plant and excretion rates of Na^+ ranged between 62.12-200.87 mmol Na^+/g dry weight of plant (Weragodavindana, 2016).

Suaeda maritima, or herbaceous sea-blite, is native, annual, succulent, herbaceous, obligate halophyte growing to 2' in height (Raju & Kumar, 2016). It grows in salt marshes and coastal beaches and is often found near other species such as *Salicornia virginica, Spartina alterniflora*, and *Salsola kali*. It is not a common species in the U.S. and is generally confined to Northeastern coasts (Massachusetts Division of Fisheries & Wildlife, 2015). Herbaceous sea-blite has been shown to accumulate 504 mg NaCl in a four-month season, and some *Suaeda* spp. can contain up to 10% salt by weight (Litalien & Zeeb, 2020). Flowers *et al*. (1986) showed that *S. maritima* accumulates 700 mmol concentration of cations in aboveground plant parts after 7 weeks. Clipson & Flowers (1986) showed that Na^+ concentrations in *S. maritima* xylem approximated 147 mmol grown in 200 mmol substrate. Shabala & Mackay (2011) showed that S. maritima accumulated 380-660 mmol Na^+ in leaf sap and 46-60 mM Na^+ in xylem within 200-500 mM NaCl range treatments.

Typha latifolia, or common cattail, is a rhizomatous aquatic or semiaquatic perennial growing 3-10' tall native to the US. It pioneers in disturbed soils and establishes quickly, often forming dominant stands. Clonal propagation is their primary means of propagation though it is capable of seeding if flowers present. Salt tolerance varies with growing stage, seeds being most vulnerable to salt. Vegetative cattails are regularly spotted in saline soils and waters and have been known to invade brackish marshes. It is fairly drought tolerant (Gucker, 2008). In one study, common cattail accumulated a mean concentration of 65 mg Cl^-/g DW and a mean mass of 70 mg Cl^-/plant (Morteau *et al.,* 2009)

This list of candidate halophytes is by no means exhaustive but is merely a speculative list of plants which show promise for phytoremediation of Virginia roadside soils with runoff salt pollution.

Halophilic Microbes – Halophiles, or salt-loving microbes, are "halotolerant" which means they have adapted to high saline conditions. By definition, halophiles require at least 0.2 molar (M) salt for growth (Arora *et al.,* 2014). Halophilic microbes exist within a spectrum, much like halophytes, ranging from slightly halophilic which are salt tolerant (around 0.2-0.5M or ~1.3% salt) up to extremely halophilic (2.5-5.2M or 15-32% salt) (Arora *et al.,* 2014). Halophilic bacteria are often moderately halophilic (Arora *et al.,* 2014).

The rhizosphere is a very microbially active place, even when highly saline. Plants contribute primarily to the root exudates and nutritive compounds available in the rhizosphere, such as carbohydrates, amino acids, and sugars (Arora *et al.*, 2014). The microbes most commonly found in the rhizosphere include bacteria, archaea, fungi (VAM being notably prominent), viruses, and actinomycetes (Arora *et al.,* 2014). Because of this relatively high level of activity and diversity even in saline conditions, halophilic microbes should be considered an important aspect of phytoremediation.

Halophiles are conducive to phytoremediation because they can survive in high salinity, accumulate salt ions from soil, and support vegetation against salt stress (Arora *et al.,* 2014; Litalien & Zeeb, 2020). They are also used industrially for their ability to decontaminate saline or sodic wastewater and degrade toxic compounds in soil and water. They are low maintenance and have simple nutritional requirements. Their hypothesized main value in salt-affected soils comes from supporting plant growth in this harsh environment (Arora *et al.,* 2014; Singh *et al.*, 2021). The rhizosphere distribution of microbes in salt-affected soils is determined by more than the salinity levels (Quesada *et al.,* 1983). Plant-host specificity and soil characteristics such as aeration, texture, moisture, and more play important roles (Arora *et al.*, 2014).

Soil salinity is shown to decrease proportionally to the density of halophiles. Some species can consume salt from substrate (Shukla *et al.*, 2011), such as *Oceanobacillus kapialis*, which is reported to increase phytoextraction capacity and assist salt uptake and accumulation in halophytes under saline conditions (Litalien & Zeeb, 2020). Other species assist plant growth, which subsequently reduces salinity through uptake and improved soil conditions. Rhizobacteria, such as *Azospirillum* spp., are one of the best adapted microbes for living in salt-affected soils and are well-known for their role in supporting plant growth (Tripathi *et al.,* 1998). Halophilic microbes also support optimal plant growth amidst salt stress and are easy to include as inoculum during vegetation efforts (Litalien & Zeeb, 2020). Bacteria are most commonly used for this type of remediation technique, but archaea, actinomycetes, and fungi can be used as well (Arora *et al.*, 2014).

Halophiles are coated in a special protein which allows selective salinity levels into the cell (Shukla, *et al.*, 2011). Salt accumulation is another mechanism utilized by true halophiles and is seen primarily in halophilic archaea and extremely halophilic bacteria. Many microbes respond to high salinity by accumulating osmotica in their cytosol to protect against dehydration. One halophilic bacterium, *Halobacillus,* is Cl^-dependent for activities such as activation of solute accumulation because it can switch osmolyte strategies with environmental salinity by producing compatible solutes (Arora *et al.*, 2014). *Azotobacter chroococum*, are dependent upon Na^+ (Page *et al.*, 1988).

Fungi can also be halophiles. Gunde-Cinerman (2009) defined halophilic fungi as those that are regularly isolated with high frequency on selective saline media from environments with 10% or higher salinity and can grow in environments above 3 M NaCl. Fungi also exist within a halophile spectrum. True or obligate halophilic fungi are those regularly isolated from 1.7 M NaCl salinity in nature, and/or can grow *in vitro* with 17% or higher salinity (Gunde-Cinerman, 2009).

Halophilic fungi were often neglected in hypersaline ecosystem studies until recently (Gunde-Cinerman, 2009). Some of these fungi were identified in Gunde-Cinerman's (2009) study. *Saccharomyces cerevisiae* grows up for 1.2 M NaCl making it halotolerant. *Debaryomyces hansenii* is commonly found in air, soil, and salt-preserved foods and tolerates salt fluctuations and accumulation well without symptoms of toxicity. Black yeast (*Hortaea werneckii*) can grow up to 5M NaCl and persists in even higher salinities. *Aureobasidium pullulans* grows up to 3M NaCl. *Wallemia ichthyophaga* tolerates salinities up to and perhaps above 5.2 M NaCl and requires 1.5M NaCl to grow making it a true halophile. Halophilic fungi commonly found in hypersaline environments include *Cladosporium* spp., *Wallemia* spp., *Scopulariopsis* spp., *Alternaria*, spp. *Aspergillus* spp., and *Penicillium* spp. (Gunde-Cinerman, 2009).

Mycorrhizal fungi, especially VAM, can support plant growth in saline soils by increasing access and uptake of water and nutrient, accumulation of compatible solutes, preventing salt ion toxicity, enhancing photosynthesis, and activating antioxidant enzymes (Dashtebani *et al.*, 2014). One study (Porrias-Soriano *et al.*, 2009) showed that mycorrhiza helped olive plants perform in saline conditions. The most efficient fungus for olive plant growth assistance in saline conditions was *Glomus mosseae* (Porrias-Soriano *et al.*, 2009). The Dashtebani *et al.* (2014) showed that *P. distan*s inoculated with *Claroideoglomus etunicatum* produced higher biomass and showed less salt stress than uninoculated plants. The interaction between hyphae associations and host plants changes with salinity levels. Often, the number and type of fungal spores or fungal infectivity change with different saline concentrations (Arora *et al.*, 2014). In a study by Dashtebani *et al.* (2014), AMF colonization was shown to be lower in salt-treat *P. distans* plants but still efficient for colonization.

Halophilic fungi orders of interest identified in Gunde-Cinerman's (2009) paper include Capnodiales, Dothideales, and Eurotiales within the phylum Ascomycota and Wallemiales, in the phylum Basidiomycota.

Within Ascomycota, Capnodiales and Dothideales often have halophilic expression. The dominant halophilic Ascomycete fungi species are generally regarded to be *Hortanea werneckii*, *Phaetotheca triangularis*, *Trimmatostroma salinum*, and *Aureobasidium pullulans*. Eurotiales is another Ascomycete group which has many halotolerant species, such as *Aspergillus niger*, *Aspergillus sydowii, Eurotium amstelodami,* and *Penicillium chrysogenum* which have been isolated from brines in nature. Other species commonly detected in brines include *Aspergillus versicolor, Aspergillus flavus, Eurotium herbariorum, Penicillium citrinum,* and *Penicillium steckii*. Those with confirmed cosmopolitan distribution include *Cladosporium* spp., *Penicillium chrysogenum* and *Penicillium brevicompactum*. Those with suspected cosmopolitan distribution include *Aspergillus niger* and *Eurotium amstelodami*. Halotolerant yeasts isolated from saline environments include *Candida, Debaryomyces, Metschnikowia*, and *Pichia* spp. The order Saccharomycetales are often associated with plant saps and exudates and have notable osmotolerance, such as *Debaryomyces hansenii. D. hansenii* accumulates more Na^+ than *Saccharomyces cerevisiae* and uses Na^+ to protect itself from other stress factors (Gunde-Cinerman, 2009).

Basidiomycota have three notably halotolerant orders: Trichnonosporales containing *Trichosporon mucoides* which has been isolated in hypersaline waters, Sporiadiales containing *Rhodotorula* spp., and Wallemiales which contains the entirely halophilic/xerophilic genus *Wallemia* (Gunde-Cinerman, 2009).

Some fungi, such as *Wallemia ichthyophaga* and *Debaryomyces hansenii*, accumulate more Na^+ ions than *Hortaea werneckii*, which employs salt exclusion as its primary mechanism for salt tolerance (Gunde-Cinerman, 2009).

Halophilic bacteria generally tolerate a wider range of salinities and osmotic stress than fungi, which are more sensitive and prefer more stable concentrations of saline. However, fungi likely do more for soil structure and plant support than bacteria (Arora *et al.,* 2014).

Few hypersaline environments have been carefully surveyed using molecular methods for microbial diversity. More work is needed to discover which microbes can be most beneficial for supportive use in phytoremediation of salt-affected soils (Arora *et al.,* 2014), particularly for microbes which are capable of salt-accumulation. More research is needed to investigate salt accumulation rates, halotolerance mechanisms, bioregional suitability, and plant-microbe interactions for halophilic microbes to determine suitability for use in remediation projects. Halophilic yeasts and fungi grow best under aerobic conditions with moderate temperatures and acidic to neutral pH (Arora *et al.*, 2014), which is what many Virginia roadside conditions provide.

Microbe assisted remediation may be quite successful on Virginia roadside salt-affected soils. However, more research is needed to identify species which can be most helpful as inoculant amendments. There is also a need for future research regarding genetic manipulation techniques which can imbue plants and other microbes with enzymes from halophiles to help them tolerate and grow in saline environments (Arora *et al.*, 2014).

Soil Amendments **–** A major challenge of phytoextraction of salt in roadside soils is that many plants are dormant when salt runoff is likely to be the highest in the winter and spring months (Alden, 2021; Welbaum, 2021). In order to best remove salt from the soil, salt must be suspended in the rhizosphere so that plants can reactivate and effectively desalinate the soil before leachates become pollution. The properties of soil determine whether salt is held in the rhizosphere or leached out. Soil aggregates, OM density, and composition all affect the adsorption properties of the soil by increasing cation and anion exchange capacity (CEC and

AEC) sites of soil and the subsequent adsorption of Na^+ and Cl^- ions (Ashraf *et al*., 2010; Camberato, 2001).

The VDOT is most likely to apply deicing salts from the months of November to March (Fitch *et al.*, 2005). These 5 months generally have high precipitation, with melting rates increasing into the spring. Most halophytes used in this type of remediation are not active during these colder, wetter months. One possible strategy to overcome this is adding soil amendments with high cation exchange capacity which can temporarily bind Na^+ cations and prevent them leaching until plant dormancy ends. Plants can then glean them from CEC sites before salts leach into the water systems (Alden, 2021). Green, efficient, and low-cost adsorbent amendments are shown to be effective for separating pollutants from water and soil. While more studies need to be conducted on how absorbent materials perform in salt-affected soils, there is much promise for their efficacy in remediation efforts where the aim is holding cations in topsoil for more efficient phytoextraction (Amer & Hashem, 2018; Bée *et al.*, 2017).

Potential soil amendments to hold salt within the rhizosphere covered in this review include biochar, natural fibers and plant materials like cellulose, hemp, and sawdust or other compostable plant material products, chitosan, clay beads and clay composites, and organic cation exchange resins like those used in water decalcification systems.

Biochar is produced via pyrolysis of organic materials, such as plants and manure. Hyperaccumulator biomass can be processed as biochar and recycled back into the roadside environment to further improve soil quality (Litalien & Zeeb, 2020). As a soil amendment, biochar is a green adsorbent with a porous structure, corrosion resistance, and abundant functional groups (Han *et al.*, 2019). It can improve texture, drainage and water holding capacity, soil nutrient retention and binds toxic ions (Camberato, 2001; Han *et al.*, 2019; Lawrinenko *et* *al*., 2015; Litalien & Zeeb, 2020). The biochar system is carbon negative, because it sequesters carbon from biomass carbon into stable carbon structures in the soil ("Guidelines for a Sustainable Biochar Industry," 2012). It is easily compostable and sustainable. Loose biochar added to soil will contribute to the organic matter density of soil, which increases the CEC of soil further contributing to its salt remediation capability (Camberato, 2001; Lawrinenko *et al.*, 2015; Litalien & Zeeb, 2020). While the overall effectiveness of biochar depends upon the feedstock of materials used to produce it, biochar that is produced at low temperatures (below 250°C) was generally found to have the highest number of CEC sites. Low temperature produced biochars retain sufficient functional groups to produce a high negative charge while retaining its structure and an optimal amount of surface area (Weber & Quicker, 2018). Biochars produced from plant biomass and other materials with high cellulose, hemicellulose, and lignin content are more likely to retain their structure during the production process and result in optimal stability, porosity, CEC sites, and water holding capacity in the final product (Weber & Quicker, 2018). There are challenges with using biochar, as it is dusty and can pose a risk to human health (Alden, 2021; Welbaum, 2021). For these reasons, it might be best to use biochar in a contained manner, such as using it in porous bags to function as a roadside salt catching barrier or integrating it into soil to best utilize its remediation potential while avoiding negative side effects.

Compostable plant materials such as sawdust, woodchips, bark, straw, and hemp fibers contain cellulose, hemicellulose, pectin, lignin, and extractives. Hemp fibers have many micropores, microcracks, and "sticky" functional groups which work to bind ions (Na^+ and other metal cations, particularly). These properties also help the fibers to stick to themselves, forming a physical net which aids in filtration and adsorption (Vukcevic *et al.*, 2014). Compost of plant materials supports phytoextraction, improves soil structure, water holding capacity, increased organic matter, pH buffer capacity, and aggregate retention in addition to immobilizing other metals with fulvic and humic acid groups and adsorption of contaminants onto mineral surfaces (Grobelak, 2016).

Chitosan, the deacetylated form of the abundant biopolymer chitin, is a long-chain polysaccharide polymer obtained from insects, fungal cell walls, and marine shellfish (Bée *et al.*, 2017; Chawla *et al.*, 2015). It is inexpensive, non-toxic, and biodegradable (Bée *et al*., 2017; Hamed *et al*., 2016). It has many uses including food processing, medicine, and phytoremediation (Hamed, *et al*., 2016; Pirbalouti *et al*., 2017). For phytoremediation strategies, chitosan is valuable because it has been shown to enhance plant defense against bacteria, fungi, and micropredators, promote plant growth and production, and alleviate certain nutrient deficiencies (Vasconcelos, 2014). Chitosan is of interest for this type of phytoremediation for its capacity to chelate metal ions (Vasconcelos, 2014).

Clay is known for its negative charge, high CEC, and high buffer capacity, giving it great potential for adsorption of loose Na+ ions from runoff (Camberato, 2001). The addition of clay is expected to be a great aid in binding salt to the rhizosphere. However, excessive natural clay can be detrimental to soil structure. This is especially true for high clay soils often found in Virginia, where adding more clay will contribute to drainage issues. For this reason, clay beads are a possible alternative because clay beads will retain their integrity through natural processes while offering many of the benefits of loose clay (Bée *et al.*, 2017; Han *et al.*, 2019).

Clay composites are also of interest for phytoremediation strategies because often they possess characteristics superior to their individual components (Bée *et al*., 2017; Han *et al.*, 2019). There are many types of clay composites, some potentially more suitable than others for soil remediation though more studies need to be performed to evaluate their efficacy in soil (Han *et al.*, 2019). Combining chitosan and clay in the form of magnetic clay-chitosan composite beads show promise for remediation of salt affected soils. Magnetic clay-chitosan composite beads were shown to significantly adsorb positively charged pollutants in studies involving wastewater. These composites are capable of adsorbing cationic and anionic pollutants either separately or together (Bée *et al.*, 2017) and are likely to work similarly in soil environments. Another clay composite of interest for this work is clay-biochar composites. Clay biochar composites are valuable for their high carbon content, multipore structure, compatibility, suitability as a reusable medium, resistance to corrosion, abundant functional groups, non-toxic nature, and inexpensive cost (Han *et al.*, 2019).

Water softener resin is used commercially to remove excessive mineral cations (namely Ca^+ and Mg^+) from water which interfere with tasks such as cleaning (Scherer, 2017). For commercial purposes, the resin is usually charged with NaCl brine, and the Na^+ exchanges with Ca^+ and Mg^+ (Scherer, 2017). Once the resin is coated in water hardening cations, a NaCl brine is once again used to charge the resin (Scherer, 2017). Na^+ and Ca^+ are capable of ion exchange within the soil, with high Ca^+ leachates in soil solutions appearing after applications of deicing salts (Baeckstroem *et al.,* 2004). For remediation of salt-affected soils, resin charged with calcium chloride (CaCl) could potentially be held in porous bags to avoid being released to the environment and placed as a barrier along roadsides to adsorb Na^+ ions from saline road runoff before it infiltrates the soil, reducing the salt load to roadside soils and vegetation bands.

Conclusion – This review is intended to be an overview of technologies for future research in the hopes of building a standardized treatment for salt-affected roadside soils in

Virginia. Research is still needed to evaluate field performance using an integrated halophyte, halophile, and soil amendment approach to phytoremediation of salt runoff in roadside soils.

For halophytes, determining ideal candidates by their regional suitability and salt accumulating capabilities is essential. Studying how vegetation treatment stands of hyperaccumulators, recretohalophytes and mixed stands of both halophyte types for their biomass production, most effective cover densities, and phytoextraction capabilities could be valuable in determining vegetation choices for roadsides. The impact of salt on soil EC decreases as distance from the pollution sources (roadways, in this case) increases. There is a zone of immediate impact within 10m of the road (Baeckstroem *et al.*, 2004) so having a band of effective vegetation close to the road and within treatment ponds is essential (Gonsalves *et al.*, 2014). Planting a mixture of halophytes may be a beneficial approach because halophytes support other plants, halophytes and glycophytes (plants which are not halotolerant) alike, against saline stress. Also, a stratified vegetation system which utilizes terrestrial and aquatic plants to provide treatment along roadsides as well as ditch seeps and detention ponds could maximize desalination efforts.

Similar research is needed for halophilic microbes to determine their regional suitability and ability to accumulate salt or support growth and performance of hyperaccumulating halophytes. While many halophiles can support growth halophytes and glycophytes in salt-affected soils, the nature of this support is often salt exclusion for the plant which could negatively impact the desired effect of ultimate salt removal using halophytes. However, vegetative support against salt stress may aid plants in establishing and producing sufficient biomass to perform phytoextraction as intended. This may overall neutralize the effect of salt exclusion.

Soil amendments have potential for increasing CEC in soil, but field studies are needed to observe their performance for holding salt within the rhizosphere. Ideal materials have yet to be identified, though biochar, natural fibers, compostable plant material products, clay beads, clay composites, chitosan and organic cation exchange resin seem to be promising amendments for increasing CEC in soil. Estimates for salt retention on ion exchange sites need to be calculated in the field. Additionally, more studies are needed to quantify and qualify halophyte ability to glean salts from soil amendment exchange sites *in situ*.

Salt pollution is a growing global issue and the need for sustainable, reasonable, and safe alternatives grows with it. Road salts affect human health and damage roadside vegetation, contaminate water, damage hydraulic properties of roadside soils, as well as corrode vehicles, bridges, concrete, and road surfaces (Baeckstroem *et al.*, 2004; Gonsalves *et al.*, 2014). Researching effective and safe alternatives to road salt is essential for sustainability, and the only way to truly reduce salt pollution (Snodgrass *et al.*, 2017). Potentially suitable alternatives include, but are not limited to, mixtures from refined corn, MgCl, sand, CaCl, calcium magnesium acetate (CMA), and environmentally sound additives such as carbohydrate byproducts (Robinson & Thomson, 2015). CaCl is a much safer alternative to NaCl salt, doesn't contain as many chemical additives as NaCl salt, and is effective at lower temperatures than NaCl. However, it is more expensive and still produces Cl^- pollution and subsequent damage to water resources. CaCl is often used on bridges and areas which freeze faster than grounded roadways. CMA is a mixture of limestone and acetic acid which works within the temperature range as NaCl and is more sustainable, less corrosive, and less damaging to aquatic systems than NaCl (Gonsalves *et al.*, 2014). Carbohydrate-based products such as beet, corn, molasses, and alcohol byproducts can be used as a prewetting agent and are biodegradable, non-corrosive, and while they don't actively de-ice they do prevent the formation of ice crystals and would make a suitable addition to deicing mixes (Gonsalves *et al.*, 2014; Robinson & Thomson, 2015).

Salt pollution is a complex issue with many factors to consider and requires an interdisciplinary focus for remediation. A combination of effective phytoremediation and salt alternatives could significantly reduce salt pollution and improve quality of water and soils in urban and agricultural areas for the future.

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