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Development of a Model for the Dispersal of Salts from Recretohalophytes

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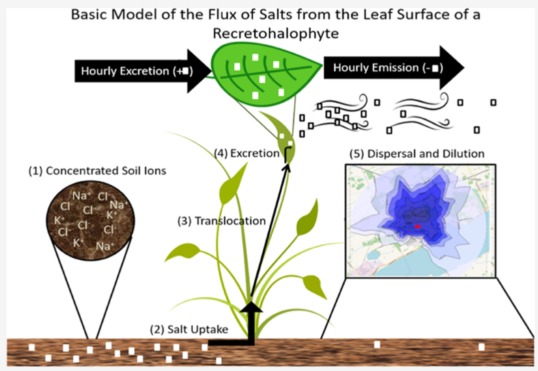
ABSTRACT: A novel method for the remediation of salinized soils utilizes recretohalophytes, plants that secrete salts onto their leaf surfaces. Wind blows the excreted salts from the leaves, dispersing and diluting them over great distances. In this study, the first model was established to estimate the amount of salt that could be transferred from a given field site via haloconduction. Further, the model allows for the determination of the location and concentrations of deposited salts. Greenhouse and wind tunnel experiments were used to determine the excretion and salt emission rates of *Spartina pectinata*. Based on this data, a theoretical emission profile for *S. pectinata* at a salt-impacted field site in Bath, ON, was generated. AERMOD View modeling software was used to visualize the dispersal of the emitted salts. Finally, a field monitoring program was implemented to determine the actual chloride deposition rates and airborne concentrations using passive wet candles and a high-volume air sampler. Based on this model, approximately 180 kg/year of potassium chloride (KCl) salt could be displaced from the Bath site and deposited over an ~70 km^2 region while maintaining deposition concentrations well below background levels.



KEYWORDS: *recretohalophytes, haloconduction, aerial dispersal model, AERMOD, remediation*

■ INTRODUCTION

Soil salinization affects many ecosystems worldwide and is becoming a growing issue in agricultural regions due to improper management of fertilizers and irrigation.[1−3] While salts are benign at low concentrations, high soil salinity reduces soil quality and can cause ion toxicity as well as osmotic stress to plants and soil organisms.[4−6] There is a growing interest in developing sustainable methods for the long-term management of soil salinity and salinized soil remediation.[3] One sustainable method is the use of plants and their phytoextraction capacities.[7]

Recretohalophytes are salt-tolerant plants that excrete salts on their leaf surfaces. Yun et al.[8] were the first to demonstrate that these salts could be dispersed by wind action as proposed by Yensen and Biel[9] via haloconduction. In this process, salt crystals formed on the leaf surface can be mobilized by the wind as it blows on the plants' leaves and causes them to flutter. Once in the air column, Gaussian plume models suggest that the space between particles in the air column will increase with increasing distance from the source due to molecular diffusion.[10] Particles leave the air column by dry deposition or wet deposition (rain) given the appropriate meteorological conditions.[7]

To determine the remediation potential of this phytotechnology at any given site, site-specific factors need to be considered. Based on the methods developed for modeling other natural aerosolized products such as plant pollen, three components are essential for site-specific analyses: (i) available aerosol pool, (ii) emission factors, and (iii) aerial dispersal based on meteorological and topographic data.[11]

There are more than 130 recretohalophytic plant species throughout the world, but only 12 are native to Canada.[12,13] Within this shortlist, the ever fewer are likely good candidates for remediation via haloconduction. The best-suited plants (i) have a high translocation capacity to move salts from the soil onto their leaf surfaces, (ii) consistently produce salt excretions, and (iii) are tall enough that wind action could actually transfer salts into the air.[7] One species that meets these criteria is *Spartina pectinata*, which grows to a height of ~1 m and was studied by both Yun et al.[8] and in preliminary studies by Litalien et al.[14]

While little is known regarding the emission factors for salt from the leaves of *S. pectinata* or recretohalophytes in general, studies on the emission of fungal spores from the leaf surfaces of plants using wind tunnels provide a valuable framework to

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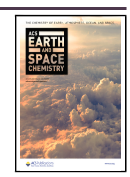

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study the phenomena.[15,16] Several models exist for the visualization of the atmospheric dispersal of particulates.[17] AERMOD is a standard Gaussian plume atmospheric modeling system used by major regulatory bodies, including the US EPA for the monitoring of industrial air pollutant emissions.[17] The objective of this study was to generate the first model of haloconduction by estimating the excretion and emission rates of salts from *S. pectinata* and visualizing the dispersal of airborne salts using AERMOD.

■ METHODS

Study Site and Field Validation. A salinized wetland site in Bath, ON, impacted by cement kiln dust leachate with concentrated amounts of potassium chloride (KCl), was selected to model and validate haloconduction. The site is hereto referred to as the "Bath site" (Figure 1A). Five plots of 1 m^2 of *S. pectinata* were planted on-site in 2015 and maintained until the end of the 2019 growing season. A weather station (Davis Instruments, WeatherLink 6.0.3) was installed on-site in April 2018 to provide surface-level meteorological data. It was supported by data from a regulatory weather monitoring station installed at the Bath cement plant, as well as the Natural Resources and Climate Change Canada (NRCCC) historical weather data from the Kingston airport station (NAVCAN Climate ID: 6104149) located ~20 km from the site.

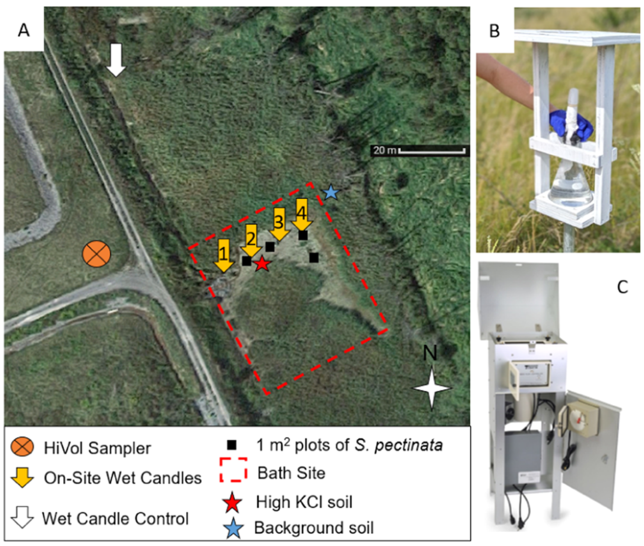

Figure 1. Site in Bath, ON, showing (A) a close-up of the site with the contaminated region delineated in red and the location of the air samplers, soil sources, and *S. pectinata* plots indicated; (B) wet candles; and (C) high-volume air sampler (HiVol).

Throughout the 2018 and 2019 field seasons, randomly selected 100 cm^2 sections of *S. pectinata* growing at the field site were washed with ultrapure water by tilting the pots and placing the shoots in a 4 L ziplock bag before spraying with water and gently massaging within the bag as per Yun et al.'s[8] method. Sufficient water was used to fully submerge the shoots. The amount of chloride in these solutions represents the amount of chloride found on the plants on the sampling date, given the meteorological conditions.

To monitor salts entering the air column, "wet candles" (2018 and 2019) and a high-volume air sampler (HiVol) (Tisch Environmental, Model 5012) borrowed from the Natural Resources Canada were used on-site. A "wet candle" is an apparatus consisting of a glass vial wrapped in a fabric that is kept continually moist by wicking ultrapure water from a flask below (Figure 1B). As wind blows past the cloth tube, the moisture in the cloth encourages the deposition of salt particles from the air.[18] High-volume air samplers suction air from the surrounding environment and collect particulates on a filter paper (Figure 1C). The volume of air is calculated from the calibrated airflow rate in cubic feet per minute (CFM) and the duration of the run. With this information, the concentration of chloride in the air can be calculated. The wet candles were sampled on a biweekly basis, while the HiVol sampler was run for ~10 h (~50 CFM) once per week. Three background samples were also collected throughout the 2019 season, with the HiVol ~5 km northeast of the site (44.200704, 76.795453) to establish the background aerial concentration of chloride within the region. Chloride deposition values and concentrations determined for the 2018 and 2019 field seasons were used to validate the AERMOD output files.

Part 1: Estimation of Excretion Rates by *S. pectinata*. Based on previous experimental data on recretohalophytes, plant size and soil chloride concentrations were assumed to be the greatest factors contributing to varied uptake and excretion rates within a species.[14] The relationship between soil chloride concentration, plant size, and excretion rates was determined experimentally via a greenhouse pot study. *S. pectinata* seedlings (sourced from Norview Gardens, Norwich, ON) were grown under greenhouse conditions (25 ± 2 °C, 40 ± 20% relative humidity (RH)) for 2 months until ~20 cm tall before being transplanted into 4 inch pots containing one of five treatment soils.

High KCl soil collected from the Bath site, near wet candle 2 (Figure 1A), and background soil collected just beyond the northern corner of the border of the site were homogenized using the two-dimensional Japanese slab cake method and mixed in proportions of 1:0, 2:1, 1:1, 1:2, and 0:1 of background soil: contaminated soil to produce five soils with approximate chloride concentrations of 150, 1000, 2000, 3000, and 4000 μg/g, respectively.[19] The plants were then grown undisturbed in the RMC greenhouse from June to August 2018 (25 ± 2 °C, 50 ± 20% RH). Throughout this period, the plants were watered every other day with tap water (25 mg Cl^-/L). Triplicates of each condition were included. After the plants were potted, the shoot portion of the plants was washed with ultrapure water on a biweekly basis as per the method used in the field and analyzed for chloride content by ion chromatography.

Sample Analyses. The cloth from the wet candles and the filter paper from the HiVol were shaken vigorously for 2 min with 300 mL of double deionized (DDI) water and then placed in a sonicator bath for 30 min to extract the salts. The chloride concentration of the resulting solutions was then determined by ion chromatography as per Yun et al.'s[8] method, as were the plant wash solutions. All analyses were conducted at the Analytical Services Unit (ASU) at Queen's University.

Quality Assurance and Quality Control. For all samples, one method blank and one Environment Canada-certified reference material (CRM), Cranberry-05, were included for each batch of samples (30) that were analyzed by ion chromatography (IC). A method blank and calibration check were also included, as well as a duplicate, every 10 samples. The environment Canada CRM Cranberry-05 was within 10% of the target value for all analyses. All of the blanks were less

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than detection limits, the calibration check standard was within 10% of the target for the chloride anions, and the mean relative standard deviation for the duplicate samples was <2%.

Plant Wash Data Analysis. A multiple nonlinear regression was generated from the plant wash data. Excretion is the sum of the impact of plant height (and by proxy age) and soil concentration on excretion. The MATLAB curve-fitting tool (MathWorks R2017b) was used to generate an estimated hourly excretion rate of *Spartina* plants relative to their soil concentration and height.

Part 2: Estimating Emission Factors. After conducting a multiple component analysis of weather data and field plant wash values, collected in 2018 using R Studio version 3.3.3 "Another Canoe", it was determined that high concentrations of salts found on the plants themselves correlated positively with high temperature and high humidity and correlated negatively with high wind speeds (Supporting Figure 1). Similar findings were observed when Geagea et al.[16] studied the emission of fungal spores from plant leaves and determined that temperature mainly played an indirect role by influencing humidity but did not itself impact emission.[20] Thus, the model includes the assumption that the greatest factors contributing to emission were humidity and wind speed. Based on experiments studying the emission of fungal spores from plant leaves and the preliminary work conducted by Morris et al.[21] to study the emission of salt particles from plant leaves, wind tunnel trials were conducted to determine the relationship between wind speed and the proportion of salt emitted into the air from the leaf surfaces of *S. pectinata*.

Wind Tunnel Trials. Dormant *S. pectinata* plugs were acquired from BambooPlants (Online Nursery) in January 2019, transplanted into soil collected from the Bath site, and allowed to grow for 4 months (25 ± 2 °C, 50 ± 20% RH) before beginning wind tunnel testing. The wind tunnel was designed to provide a testing zone of 45 cm tall by 45 cm wide and a maximum wind speed of 4 m/s, based on the principles outlined in Barlow et al.'s[22] Low-Speed Wind Tunnel Testing (Supporting Figures 2 and 3). Plants were placed in a covered plant stand for 1 week, before undergoing each test. Each plant ($n = 3$) was tested at 0, 0.5, 2, and 4 m/s. The 0 m/s trial was included to control for losses of salt due to the movement of the plant from the covered plant stand into the wind tunnel and related disturbances. Wind tunnel trials were conducted at room temperature (20 ± 2 °C, <40% RH). After being exposed to the given wind speed for 1 h, the plant was washed by wiping each leaf with gauze soaked in deionized (DI) water to minimize the overall disturbance. Following each trial, the testing zone of the wind tunnel was washed thoroughly using DI water to eliminate any residual salts.

Part 3: Hourly Salt Emission. *Estimated Available Salt Pool.* At any given point in time, the amount of salt available for dispersal is the sum of the salt excreted by the plant during that hour and the salt that was not dispersed in the previous hour (eq 1). However, rain can wash salts from the surface of the leaves. While in natural systems, it may require a heavy rainfall to remove all salts; to simplify, it was assumed that if rain occurs during the given hour, all salts would be removed and the available salt pool drops to 0

$$\text{salt pool} = \begin{pmatrix} \text{excretion } (\text{g/m}^2) \\ +\text{salt pool from previous hour } (\text{g/m}^2) \\ -\text{salt emitted during previous hour } (\text{g/m}^2) \end{pmatrix} \times \text{wash factor} \tag{1}$$

Wash factor: (if rain) = 0, (if no rain) = 1

Hourly Emission Profile. Meteorological data was used to calculate the emission factor based on the average wind speed for that hour (eq 2). An hourly emission profile was generated by the product of the available salt pool and the predicted emission factor. A humidity factor was also included given that above 70% humidity Morris et al.[21] determined that salt crystals of *S. pectinata* form liquid droplets as a result of their hygroscopic nature. The available chloride pool was used to determine the chloride emission profile. The chloride emission profile was converted into a potassium chloride emission profile using molar ratios as particle dispersion occurs for the whole salt, and particle size distribution data exists only for the salt crystals themselves

$$\text{emission} = (\text{salt pool})\ (\text{emission factor})\ (\text{humidity factor}) \tag{2}$$

Humidity factor: (if humidity > 70%) = 0, (if humidity < 70%) = 1.

Part 4: Modeling Dispersal of Airborne Chloride. AERMOD View (Lakes Environmental, AERMOD View 6.9.1, Version 16216r (regulatory version)) was used to determine the theoretical deposition rate and concentration of potassium chloride in the air over the course of the 2018 and 2019 field seasons. AERMET (meteorological processor) was used to convert on-site weather data into AERMOD-ready surface meteorological files for 2018 and 2019. All five plots of *S. pectinata* were modeled as area sources and assumed to have approximately the same emission rates. The validated model was then used in conjunction with weather data provided by the regulatory group at the Bath cement plant for 2011−2015 to determine long-term estimates for site remediation by haloconduction. AERMOD is most accurate at a regional scale of 5 km, so a uniform polar receptor grid was used with a radius of 5 km.

■ RESULTS AND DISCUSSION

Emission Source. When applying AERMOD View modeling software, gases or particles can be modeled, so in the case of haloconduction, salts were modeled as particles. The particle size distribution for *S. pectinata* was used from Morris et al.,[21] and it was assumed, for simplification, that the particle size distribution found on the leaf surfaces would be the same as that emitted from the leaf. To generate an hourly emission profile, chloride excretion rates were based on greenhouse and wind tunnel studies conducted to estimate the rate that the excreted chloride is transferred into the air column.

Estimation of Excretion Rates by S. pectinata. A positive correlation (root-mean-square error (RMSE) = 0.008) was observed between chloride excretion and both plant height and soil chloride. This is intuitive as plants take up more chloride when it is available, but then need to dispose of the chloride.[23] Larger plants also have a greater surface area over which to excrete salts.[24] The relationship between plant height and chloride excretion can be described as exponential. The relationship between soil chloride and chloride excretion can be described as sigmoidal as the rate of increase in chloride excretion tapers off after approximately 2000 μg/g soil chloride (Figure 2). When combined, excretion rates of *S. pectinata* can

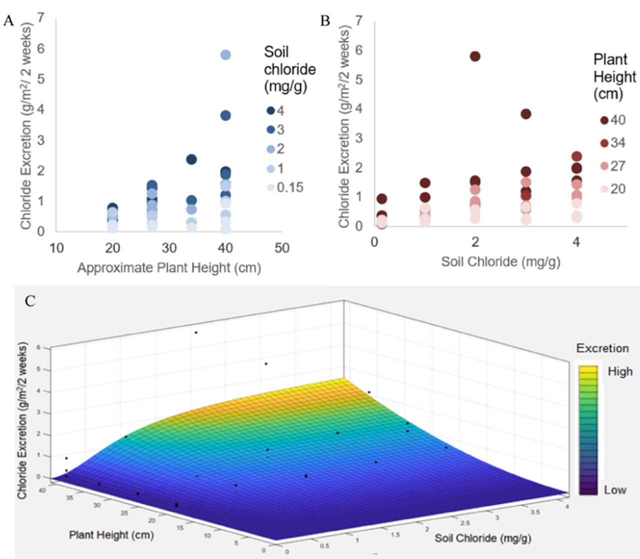

Figure 2. Excretion rate of *S. pectinata* in relation to (a) plant height and (b) soil chloride concentration. (c) Three-way relationship between plant height, excretion, and soil chloride. The color ramp provides visual contrast and is another representation of the excretion.

be described by eq 3. Yun et al.[8] observed that recretohalophytes excreted more salts under a field setting, so a site-specific conversion factor of 10 was used. Based on field observations, *S. pectinata* generally begins to grow in early May and reaches a maximum height of approximately 100 cm by the beginning of August in southeastern ON, CAN. The plants maintain their height until mid-September when the seasons begin to change (Supporting Table 1 and Figure 4)

$$\text{extimated excretion} = \frac{(1.5 \times 10^{-3})\,(\text{soil chloride concentration } (\mu g/g)^2)}{1.5 + \text{soil chloride concentration } (\mu g/g)^2 + \text{plant height } (cm)^2} \quad (3)$$

Particle Emission. Wind at the site blows predominantly from the southwest to the northeast (Figure 3). The most common wind speed category observed in 2018 and 2019 was 0.5−2 m/s (23.4% of the time), but gusts reached up to 10 m/s. Up to 50% of the time was considered "calm" or less than 0.5 m/s (Figure 3).

When exposed to wind speeds below 0.5 m/s, negligible chloride emission was observed, so during calm periods, particle emission is unlikely. This is similar to Aylor et al.'s[15] finding that the minimum wind speed to release powdery mildew (*Erysiphe graminis*) from barley leaves was between 0.5 and 1 m/s. The mean release rate of the total chloride found on the *S. pectinata* plants was 20 and 30% at 2 and 4 m/s, respectively (Figure 4). Thus, the majority of the time that

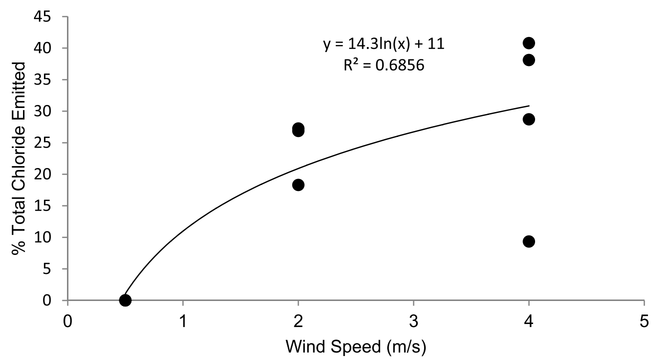

Figure 4. Proportion of the total chloride emitted from the leaves of *S. pectinata* with respect to wind speed as determined by wind tunnel trials $n = 9$.

winds are blowing, 20% of the chloride found on the leaf surfaces of *S. pectinata* is likely to be transferred into the air column. Due to the constraints of the wind tunnel, wind speeds above 4 m/s were not performed; however, based on the observed wind speeds and emission rates, the relationship between wind speed and chloride emission was deemed approximately logarithmic for the purpose of estimating emission rates. It is possible that higher wind speeds could produce greater than predicted emission rates, and thus the estimated emission may be an under-representation. For this reason, separate runs in AERMOD were also conducted as if emission were 100% to evaluate if there would be a significant

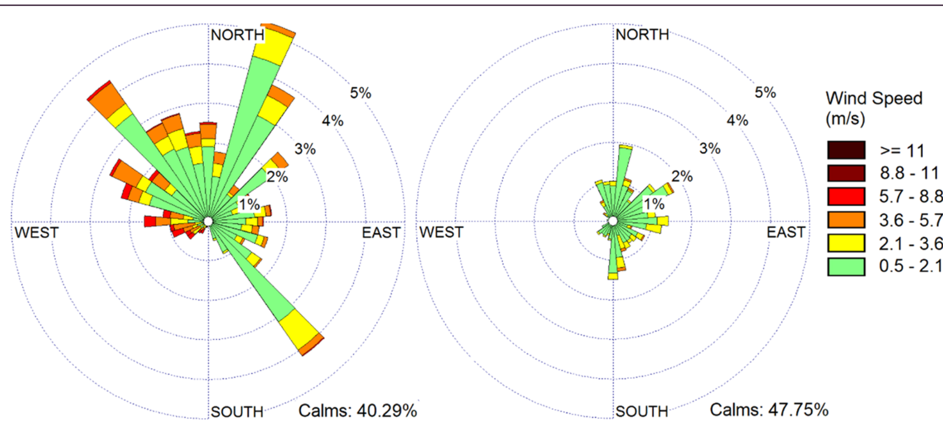

Figure 3. Wind flow vectors for the Bath site in (A) 2018 and (B) 2019 for May through August. The frequency of the wind vector is indicated by the band length, while the wind speed is indicated by the color of the band. The rings are numbered with the frequency that the wind speed occurs. "Calms" indicates the % of time that wind speeds were below 0.5 m/s.

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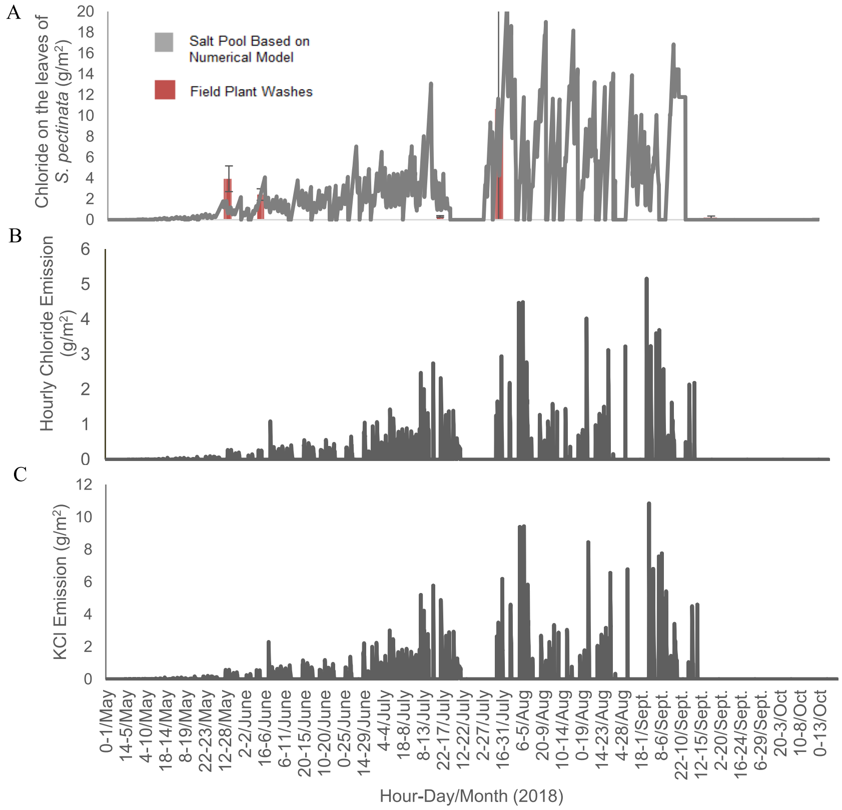

Figure 5. (A) Theoretical salt pool as calculated (line in gray) and the actual salt pool as represented by the amount of chloride found on *S. pectinata* plants growing at the Bath site (orange bars) at different times throughout the 2018 season. This is representative of the true "available chloride pool" for that given time point. Note that 100 cm^2 sampling regions were used and converted to m^2 estimates. (B) Chloride emission profile calculated from the 2018 available salt pool. (C) Potassium chloride emission profile calculated from the chloride emission profile and molar ratios. Dates read as hour−day/month; for example, 20−19/May refers to the 20th h (24 h clock: 00−23) of the 19th day in May 2018.

difference (Supporting Figure 5). Furthermore, wind gusts are also not accounted for as the duration and timing are not represented in the meteorological data and thus difficult to predict. Again, this means that the emission rate calculated here is likely underestimated.

Available Salt Pool and Emission Profiles. Only about 30% of hours within the 2018 and 2019 field seasons fell within the requirements of no rain and <70% humidity. When the theoretical chloride pool is compared to the actual amount of chloride found on *S. pectinata* plants growing at the field site, the chloride concentration per square meter of plants is on the same order of magnitude. Fluctuations in the amount of chloride found on the plants also aligned with peaks and troughs in the theoretical salt pool (Figure 5A). Thus, it is likely that the estimated excretion and emission rates are sufficiently accurate for further modeling using the AERMOD (Figure 5B,C).

Validation Based on Aerial Concentration and Deposition Rates for 2018 and 2019. Over the course of a season, deposition does not occur near the site but instead downwind. As the season progresses, airborne salt concentrations steadily increase and deposition increases as well. Stark differences were observed between the 2018 and 2019 projections, highlighting the importance of meteorological factors and their influence on emission and dispersal (Figure 6). While in the 2018 season, deposition became quantifiable by June 6, 2019, the deposition was not significant until July 18. This highlights the need for a longer time frame to provide meaningful long-term predictions to allow averaging between years.

Compared to the deposition rates predicted by the model for 2018, the wet candles collected significantly more chloride than was expected (Figure 6A). This could be due to an underestimation of emission in the model. It could also be due to the close proximity of the wet candles for the recretohalophytes. AERMOD is a regional model, and therefore, it determines the average concentration within a section of the receptor grid used by the model, and hence, the high concentrations found immediately on-site are averaged with the nearby lower concentrations within the same area of the grid.[17,25] However, the most likely reason is that background chloride concentrations in this region may be elevated due to dust from adjacent industrial activities. The magnitude of the difference between the expected and observed concentrations of chloride, recorded for both the wet candles and the HiVol air sampler, is greater than that observed even if emission was 100% of the quantity of salts excreted by the recretohalophytes. This suggests that salt emission from recretohalophytes is likely negligible compared to that produced by other activities.

Dispersal: Long-Term Site Predictions. If the entirety of the 1000 m^2 plot was planted with *S. pectinata* in 2011, by the end of 2015, approximately 915 kg of KCl could be dispersed over an area of approximately 68 km^2 with an average deposition concentration of 0.0123 g/m^2. Assuming a bulk density of approximately 1.33 g/cm^3 and a depth of 1 cm, only about 0. 9 $\mu g/g$ of potassium chloride would be added over the

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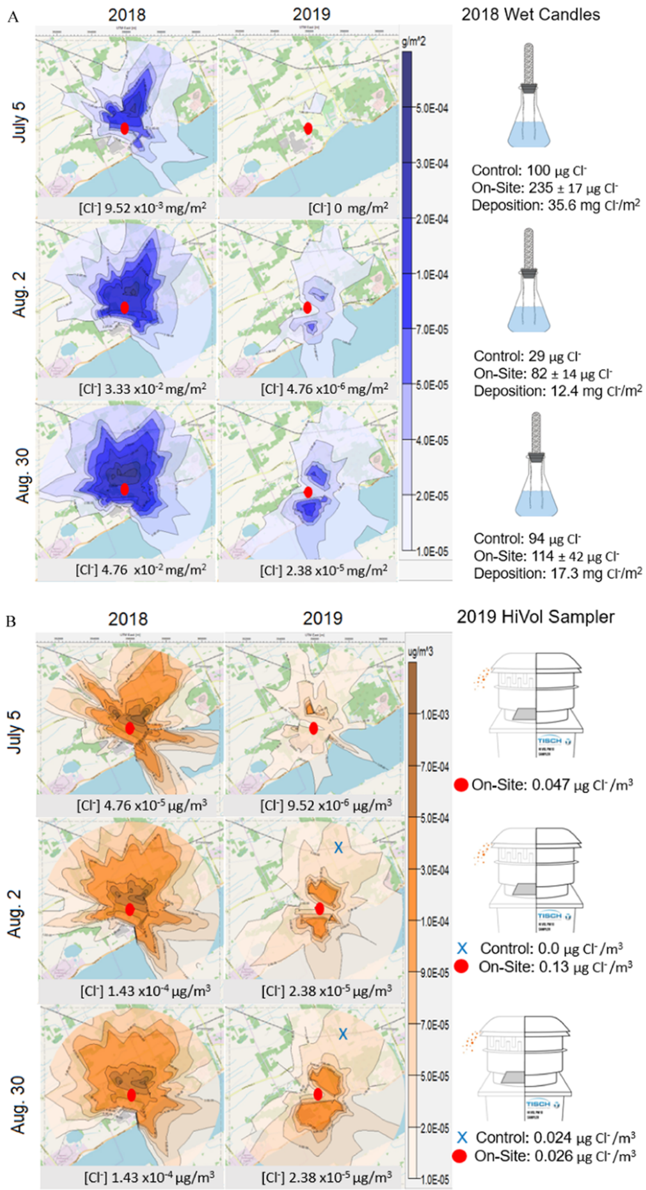

Figure 6. AERMOD View generated maps of the theoretical (A) deposition (g/m^2) and (B) concentration ($\mu g/m^3$) of KCl for the 2018 and 2019 field seasons, given the estimates based on the actual *S. pectinata* plots at the Bath site. The red dots represent the location of the Bath site. On-site chloride concentrations calculated for each date, based on molar ratios and the AERMOD output, are shown at the bottom of each map. The amount of chloride collected by the wet candle devices (n = 4 on-site, n = 1 control) for each date in 2018 is illustrated in (A) along with the deposition rate calculated from these values. Similarly, the concentrations of chloride measured using the high-volume air sampler (n = 1) in 2019 are shown in (B). The blue X indicates the location where the control air samples were collected.

course of 5 years, with only about 0.44 μg/g of chloride, a concentration well below background levels (∼20−100 μg/g soil chloride) for the region.[26] Not only is deposition below background levels, but it is also added progressively through time, and thus, there is the opportunity for plants and other organisms to take up and use these small amounts of KCl. At these low concentrations, salt is not only harmless but would actually act as a macro/micronutrient.[27] An average of 183 kg of KCl could be removed per year without harm to the surrounding ecosystems (Figure 7). As this may be an underestimate, runs with 10×, 100×, and 1000× emissions were also conducted to include a safety factor (Supporting Figure 6). With emission rates up to 100× those produced from the model, the average deposition concentration would remain within background concentrations. Even at 1000×, the yearly input rates would remain within 200 μg/g over 5 years. Thus, the use of recretohalophytes is unlikely to cause harm to the surrounding environment while providing a significant benefit in the dispersal and dilution of salts.

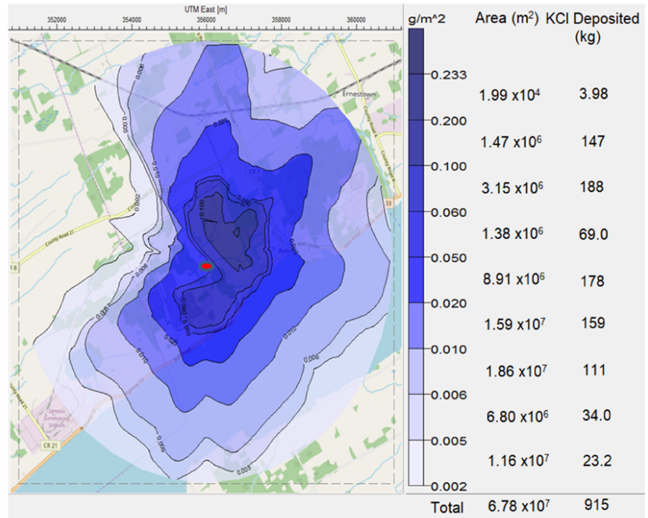

Figure 7. Total deposition of potassium chloride at the end of 2015, if the entire 1000 m^2 Bath site (represented by the red dot) was planted with *S. pectinata* in 2011. The deposition map was generated using AERMOD View based on meteorological data from Lafarge Canada.

CONSIDERATIONS

While AERMOD is intended to model various sources, including surface sources, the release height of the salt from the leaf surfaces and the complexity of the grassy region may not be addressed fully by the model, which could under or overestimate dispersion.[28] Further, recretohalophytes were modeled as an area source, and AERMOD does not address a plume meander for area sources that can lead to overestimations of concentration predictions in low wind conditions (<1.0 m/s).[29]

This being said, the model described herein is the first to predict the amount of salt that can be phytoextracted by a recretohalophyte and determine where, and at what concentrations, the salts will deposit. Remediation time frames can thus be more accurately projected while ensuring that deposition remains below background levels. Based on this model and estimates of the total amount of salts found of-site by McSorley et al.,[30] the Bath site could be fully remediated with *S. pectinata* in an ∼3−4 year time frame while posing a minimal threat to the surrounding environment. Furthermore, this model only studies the 5 km region surrounding the site, so extraction rates could be even higher as the low-concentration plumes likely extend further than presented here. Future studies could involve long-distance-transport models or site-specific numerical models that can account for surface-level turbulence in greater detail. This study is a novel starting point that illustrates that haloconduction could be a suitable treatment option in agricultural regions where the land is relatively flat. Future studies could look at recretohalophytic

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species that prefer a dry ecotype such as *Bouteloua curtipendula* and *Bouteloua gracilis* for use in an agricultural setting as these could potentially be used as cover crops.[13] Hence, we propose that with very minimal maintenance costs, recretohalophytes may provide an efficient means of saline soil remediation.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsearthspacechem.0c00080.

Principal component analysis of meteorological factors and the amount of chloride found in *S. pectinata* plants; wind tunnel design, validation; relationship between the time of year and the height of *S. pectinata;* relationship between the plant age and plant height; estimated vs actual deposition and concentration data for the 2018 and 2019 field seasons; and KCl deposition (PDF)

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Nelson, M.; Mareida, M. In *Environmental Impacts of the CGIAR: An Assessment*, Doc. No. SDR/TAC:IAR/01/11 presented to the Mid-Term Meeting, Durban, South Africa, May 21–25, 2001; Vol. 84, pp 123–133.

(2) Endo, T.; Yamamoto, S.; Larrinaga, J. A.; Fujiyama, H.; Honna, T. Status and Causes of Soil Salinization of Irrigated Agricultural Lands in Southern Baja California, Mexico. *Appl. Environ. Soil Sci.* **2011**, 1–12.

(3) Cuevas, J.; Daliakopoulos, I. N.; del Moral, F.; Hueso, J. J.; Tsanis, I. K. A Review of Soil-Improving Cropping Systems for Soil Salinization. *Agronomy* **2019**, *9*, No. 295.

(4) Setia, R.; Gottschalk, P.; Smith, P.; Marschner, P.; Baldock, J.; Setia, D.; Smith, J. Soil salinity decreases global soil organic carbon stocks. *Sci. Total Environ.* **2013**, *465*, 267–272.

(5) Deinlein, U.; Stephan, A. B.; Horie, T.; Luo, W.; Xu, G.; Schroeder, J. I. Plant salt-tolerance mechanisms. *Trends Plant Sci.* **2014**, *19*, 371–379.

(6) East, J. L.; Wilcut, C.; Pease, A. A. Aquatic food-web structure along a salinized dryland river. *Freshwater Biol.* **2017**, *62*, 681–694.

(7) Litalien, A.; Zeeb, B. Curing the earth: A review of anthropogenic soil salinization and plant-based strategies for sustainable mitigation. *Sci. Total Environ.* **2020**, *698*, No. 134235.

(8) Yun, K.; Koster, S.; Rutter, A.; Zeeb, B. A. Halonconduction as a remediation strategy: Capture and quantification of salts excreted by recretohalophytes. *Sci. Total Environ.* **2019**, *685*, 827–835.

(9) Yensen, N.; Biel, K. Soil remediation via salt-conduction and the hypothesis of halosynthesis and photoprotection. *Ecophysiol. High Salinity Tolerant Plants* **2008**, 313–344.

(10) Leelőssy, Á.; Molnár, F.; Izsák, F.; Havasi, Á.; Lagzi, I.; Mészáros, R. Dispersion modeling of air pollutants in the atmosphere: a review. *Cent. Eur. J. Geosci.* **2014**, *6*, 257–278.

(11) Zhang, R.; Duhl, T.; Salam, M. T.; House, J. M.; Flagan, R. C.; Avol, E. L.; Vanreken, T. M.; et al. Development of a regional-scale pollen emission and transport modeling framework for investigating the impact of climate change on allergic airway disease. *Biogeosciences* **2014**, *11*, 1461–1478.

(12) University of Sussex. eHALOPH: Halophytes Database, 2019. https://www.sussex.ac.uk/affiliates/halophytes/index.php?content=plantList (retrieved April 3, 2018).

(13) USDA Plant Database. Natural Resources Conservation Service, United StatesDepartment of Agriculture, 2019. https://plants.sc.egov.usda.gov/java/.

(14) Litalien, A. A. S.; Rutter, A.; Zeeb, B. A. The impact of soil chloride concentration and salt type on the excretions of four recretohalophytes with different excretion mechanisms. *Int. J. Phytorem.* **2020**, 1–7.

(15) Aylor, D. E. Force Required to Detach Conidia of Helminthosporium maydis. *Plant Physiol.* **1975**, *55*, 99–101.

(16) Geagea, L.; Huber, L.; Sache, I. Removal of urediniospores of brown (Puccinia recondita f.sp. tritici) and yellow (P. striiformis) rusts of wheat from infected leaves submitted to a mechanical stress. *Eur. J. Plant Pathol.* **1997**, *103*, 785–793.

(17) US EPA. Air Quality Dispersion Modeling-Preferred and Recommended Models, 2018. https://www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models.

(18) Baboian, R. *Corrosion Tests and Standard: Application and Interpretation-Robert Baboian-Google Books*, 2nd ed.; ASTM International, 2005.

(19) Gy, P. M. *Sampling of Heterogeneous and Dynamic Material Systems: Theories of Heterogeneity, Sampling and Homogenizing*; Elsevier, 1992; pp 419–421.

(20) Jones, A. M.; Harrison, R. M. The effects of meteorological factors on atmospheric bioaerosol concentrations—a review. *Sci. Total Environ.* **2004**, *326*, 151–180.

(21) Morris, L.; Yun, K.; Rutter, A.; Zeeb, B. A. Characterization of Excreted Salt from the Recretohalophytes *Distichlis spicata* and *Spartina pectinate*. *J. Environ. Qual.* **2019**, *48*, 1775–1780.

(22) Barlow, J. B.; Rae, W. H.; Pope, A.; Pope, A. *Low-speed Wind Tunnel Testing.*; Wiley, 1999.

(23) Rozema, J.; Gude, H.; Pollak, G. An Ecophysiological Study of the Salt Secretion of Four Halophytes. *New Phytol.* **1981**, *89*, 201–217.

(24) Leng, B.; Yuan, F.; Dong, X.; Wang, B. Salt secretion in different leaf ages and leaf positions of Limonium bicolor. *IOP Conf. Ser.: Earth Environ. Sci.* **2017**, *100*, No. 012165.

(25) Lakes Environmental. AERMOD View [Software], 2019. https://www.weblakes.com/products/aermod/index.html.

(26) Mann, E.; Rutter, A.; Zeeb, B. *Phytoremediation of Road Salt using Native Halophytes [PDF]*; Queen's University, Department of Environmental Studies, 2019.

(27) Marschner, P. *Mineral Nutrition of Higher Plants*, 3rd ed.; Elsevier, 2012. 978-0-12-384905-2.

(28) US EPA. Latest Features and Evaluation of Results, 2003. https://www3.epa.gov/scram001/7thconf/aermod/aermod_mep.pdf.

(29) US EPA. AERMOD Implementation Guide, 2019. https://www3.epa.gov/ttn/scram/models/aermod/aermod_implementation_guide.pdf.

(30) McSorley, K. A.; Rutter, A.; Cumming, R.; Zeeb, B. A. Chloride accumulation vs chloride excretion: Phytoextraction potential of three halophytic grass species growing in a salinized landfill. *Sci. Total Environ.* **2016**, *572*, 1132−1137.

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