



# The impact of deicer and anti-icer use on plant communities in stormwater detention basins: Characterizing salt stress and phytoremediation potential

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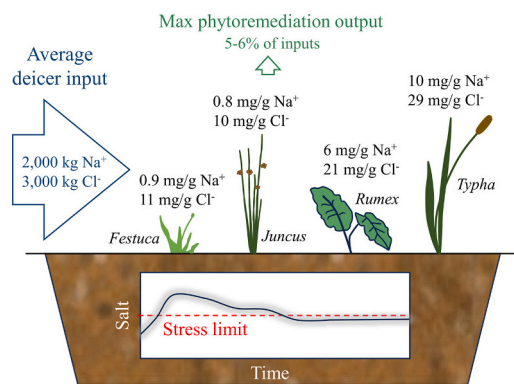
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## HIGHLIGHTS

- Plant salt stress in stormwater detention basins varied by drainage area type.
- Salt thresholds were exceeded primarily in winter, but also during spring/summer.
- 33 % of observed plant species could tolerate conductivities >2 dS/m.
- Within-tissue salt levels were highest in *Typha* (top phytoremediation candidate).
- Basins with *Typha* remediate 5–6 % of winter salt mass in an above-average snow year.

## GRAPHICAL ABSTRACT



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## ABSTRACT

We present the results of a 1-year study that quantified salt levels in stormwater, soils, and plant tissues from 14 stormwater detention basins across Northern VA in an above-average snow year. We characterize (1) the level of salt stress plants experience, (2) the extent to which current plant communities feature salt tolerant species, and (3) the capacity of these species to phytoremediate soils and reduce the impacts of deicer and anti-icer use. Our results suggest that detention basin vegetation experience a range of salt stress levels that depend on drainage area type (roads: moderate to high > parking lots: low to moderate > pervious areas: none). Established thresholds for salt sensitive vegetation ( $\text{Na}^+$ ,  $\text{Cl}^-$ , electrical conductivity, sodium adsorption ratio, exchangeable sodium percentage) were exceeded at least twice in stormwater or soils from all systems draining roads and half of systems draining parking lots. Winter exceedances were most common, but saline conditions did persist into the growing season, particularly at sites draining roads. Two hundred fifty-five plant species were identified across all detention basins, including 48 natives capable of tolerating elevated salt levels (electrical conductivity  $\geq 2$  dS/m). Within-tissue concentrations of sodium and chloride ions were highest in *Typha* (*latifolia* and *angustifolia*) (11.1 mg  $\text{Na}^+$ /g; 30 mg  $\text{Cl}^-$ /g), making it our top phytoremediation candidate. Scaling these concentrations up, we estimate that a standard-size highway detention basin (2000–3000 m<sup>2</sup>) with 100 % cattail

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cover can phytoremediate up to 100 kg of Na<sup>+</sup> and 200 kg of Cl<sup>-</sup> per year. Uptake at this level is not sufficient to offset winter salt application, constituting only 5–6 % of basin inputs. This suggests that phytoremediation should not be considered a standalone solution to basin salinization, although it could be one approach of many in a broader salt management strategy.

## 1. Introduction

Many of the world's freshwaters are salinizing, a process known as the freshwater salinization syndrome (FSS) (Kaushal et al., 2021, 2022, 2023). The FSS threatens freshwater ecosystem health, agricultural productivity, and the sustainability, reliability, and safety of drinking water supplies (Bhide et al., 2021; Grant et al., 2022; Ripsey et al., 2024; Schuler et al., 2019; Schwabe et al., 2006). The FSS may also decrease the design lifetime of urban infrastructure, including traditional grey infrastructure elements such as pipe networks, pavement, and the steel components used to reinforce bridges and tunnels (Stets et al., 2018; Shi et al., 2009), and the green infrastructure elements of today's urban stormwater systems such as detention basins and bioretention (Denich et al., 2013; Fay and Shi, 2012). Green infrastructure relies on plants for many of the services it provides (e.g., nutrient removal, stormwater infiltration, habitat provisioning, aesthetics; Nocco et al., 2016; Ebrahimi et al., 2020; Filazzola et al., 2019; Krauss and Ripsey, 2024; Payne et al., 2014; Ripsey et al., 2021; Skorobogatov et al., 2020), but most of these plant species are salt sensitive (Hasanuzzaman et al., 2014; Morteau et al., 2015). This makes salinization a credible threat to long-term green infrastructure performance, particularly in regions with cold climates where green infrastructure receives seasonal inputs of rock salts and brine from deicing and anti-icing activities (Burgis et al., 2020; Hintz et al., 2022; Kratky et al., 2017).

Growing recognition that salts are important urban pollutants has prompted multiple studies of salt fate and transport in green stormwater infrastructure in recent years (see, for instance, Brown et al., 2024; Burgis et al., 2020; Galella et al., 2023; Monks et al., 2023; Parker et al., 2021; Szota et al., 2015; Zhang et al., 2022). These studies illustrate that although a substantive fraction of reported sodium and chloride ion "removal" by green infrastructure represents rerouting of these contaminants to groundwater (Burgis et al., 2020; Snodgrass et al., 2017), certain salts, particularly sodium ions, exchange with other cations and accumulate in green infrastructure soils during winter months, slowly leaching back out during spring and summer (Burgis et al., 2020; Stagge et al., 2012; Kaushal et al., 2022a). Only a handful of studies have measured salt accumulation in green infrastructure soils directly (Barbier et al., 2018; Burgis et al., 2020; Kaushal et al., 2022b; Caplan et al., 2024; Lam et al., 2024); most infer accumulation indirectly from stormwater inflow and outflow measurements. Furthermore, when soil salinity measurements are made, the approach often differs from the method used to establish salt thresholds for plants, complicating direct comparison (Burgis et al., 2020; Levy et al., 1998; US Salinity Laboratory Staff, 1954). This has limited both our understanding of typical salt concentrations in green infrastructure soils as well as the threat they pose to vegetation.

Salinization guidelines for vegetation consider both absolute salt concentrations (soil salinity), defined based on the electrical conductivity (EC) of aqueous extracts from saturated soils, and salt composition (soil sodicity) defined based on the molar proportion of cation exchange sites in soil that are occupied by sodium ions (the exchangeable sodium percentage – ESP) (Läuchli and Grattan, 2013). Saline and slightly saline soils (electrical conductivity (EC) of 4 and 2 dS/m, respectively; Shainberg and Letey, 1984) primarily harm vegetation by inducing ionic and osmotic stress (Jiang et al., 2019; Mansour and Salama, 2019), although soil organic matter content, structure, and permeability can also be adversely affected (Läuchli and Grattan, 2013; Srivastava et al., 2019). Sodic and slightly sodic soils (exchangeable sodium percentage (ESP) > 15 and ESP > 6, respectively; Levy et al., 1998; Shainberg and

Letey, 1984; FAO and IIASA, 2023) harm plants by reducing soil permeability to water, nutrients, and oxygen, which adversely affects their growth (Qadir et al., 2007).

Although most vegetation begins to experience salt stress in the ranges reported here (e.g., EC > 2–4 dS/m and ESP > 6–15 %), it is important to recognize that salt tolerance is really a spectrum (Ayers and Westcot, 1985; Flowers and Colmer, 2015). At the lower end of the spectrum, we have the most sensitive plant species where growth and survivorship are impaired below the ranges indicated here (Ayers and Westcot, 1985). At the upper end of the spectrum, we have the most tolerant plant species (halophytes), which survive and reproduce well at salt concentrations of 200 mM or more, roughly equivalent to an EC of 25 dS/m (Flowers and Colmer, 2015). The existence of this spectrum presents a clear design opportunity – it may be possible, through careful plant selection, to establish green infrastructure plant communities that are highly salt tolerant and continue to provide services as freshwaters salinize.

Indeed, certain plant species may even be able to mitigate salinization's effects, for instance salt accumulating halophytes that assimilate and store salts in specialized plant tissues (Hasanuzzaman et al., 2014; Karakas et al., 2020). Salt accumulators have been used in many regions of the world to remediate saline soils (Flowers and Colmer, 2015; Rozema and Flowers, 2008) and are presently being explored for treating road runoff containing deicing salts (Morteau et al., 2015; Renshaw, 2021; Suaire et al., 2016; Zhang et al., 2022). Their capacity to treat salts in green stormwater infrastructure is not well understood, but likely to depend on their salt assimilation capacity, which varies by species (Flowers and Colmer, 2015; Renshaw, 2021), and their ability to survive common green infrastructure stressors (e.g., resource limitation (nutrients and water), erosive flows, transient inundation, and sedimentation; Krauss and Ripsey, 2022; Parker et al., 2021; Yuan and Dunnett, 2018). Nativeness is also a consideration given the tendency of green infrastructure design guidelines to promote native plant species that provide added value to local pollinators and other fauna (Cameron and Blanuša, 2016; Krauss and Ripsey, 2022).

Given the limited information presently available about plant salt stress in green stormwater infrastructure and the role salt accumulators might play in remediating salt pollution, our study is designed to (1) characterize salt concentrations in green infrastructure soils/stormwater to determine the level of stress plants experience over the course of a year, and (2) quantify salt accumulation in the tissues of green infrastructure plant species (native and exotic) to estimate their phytoremediation potential. Our study focuses on stormwater detention basins, a relatively common approach for managing stormwater flows along the eastern seaboard that can treat runoff at a variety of scales (i.e., large highways to small parking lots). We anticipate that plant salt stress will be relatively high in these systems, particularly those that receive runoff from surfaces that are salted or brined during winter and, that phytoremediation will represent a significant (if modest) salt sink, consistent with work by Monks et al. (2023) in the midwestern United States.

## 2. Methods

### 2.1. Site selection

Fourteen detention basins from Fairfax County, VA were selected for inclusion in this study using randomized stratified sampling (details in Appendix A). Briefly, hierarchical cluster analysis (R Core Team, v4.1.3; package FactoMinerR, Lê et al., 2008) was used to group all detention

basins in the County into homogenous strata based on the type of land surface area they drained (i.e., acres of pervious area, parking lot, or roadway) estimated using Fairfax County's Drainage Basin Delineation Tool (Fairfax County LDS, 2022) and ArcGIS pro 2.5.1. Strata were based on drainage area characteristics because stormwater runoff from different land uses can have different salinization fingerprints (ion composition, concentration, etc.) that influence downstream infrastructure (Kaushal et al., 2020). Six strata were ultimately identified, three of which can be considered drainage area endmembers (i.e., capturing sites that primarily drain one land surface type; pervious, parking lot or road; Appendix A). Five sites were selected at random from each of these endmembers with the goal of establishing a balanced study design. On-the-ground conditions prompted certain practical adjustments, however, leaving us with a final set of fourteen study sites, four draining pervious open space, six draining parking lots and four draining large highways (Fig. 1a). Individual site characteristics are provided in Table 1.

## 2.2. Measuring plant salt stress

Salt stress to plants was evaluated based on stormwater (i.e., the irrigation water plants receive) and soils. Three types of stress were evaluated: 1) ion specific toxicity (i.e., plant tolerance of sodium and chloride ions); 2) bulk salinity (EC, which can be indicative of osmotic impacts on vegetation), and 3) sodicity (ESP and SAR, which can be used to diagnose poor soil dispersion and therefore the availability of water and essential nutrients like potassium, calcium, and magnesium to basin vegetation) (see Appendix B). Below we describe our methods for collecting soil and stormwater samples and evaluating these various salt stress measures.

### 2.2.1. Sample collection and analytical methods for soils and stormwater

All sites were sampled from fall 2021, prior to winter conditions that would have necessitated deicer application to roads and parking lots, until fall 2022 (Fig. 1b). Five snow events occurred during that winter, three in January, and one each in February and March. The total snowfall depth was 401 mm, 30 % higher than the average depth reported over the past five years (308 mm). Soil cores were collected (a) prior to snow events in November and December, (b) following snow events 1, 2, and 4, and (c) four additional times through the growing season and into fall 2022. During each sampling event, six to eight 15 cm

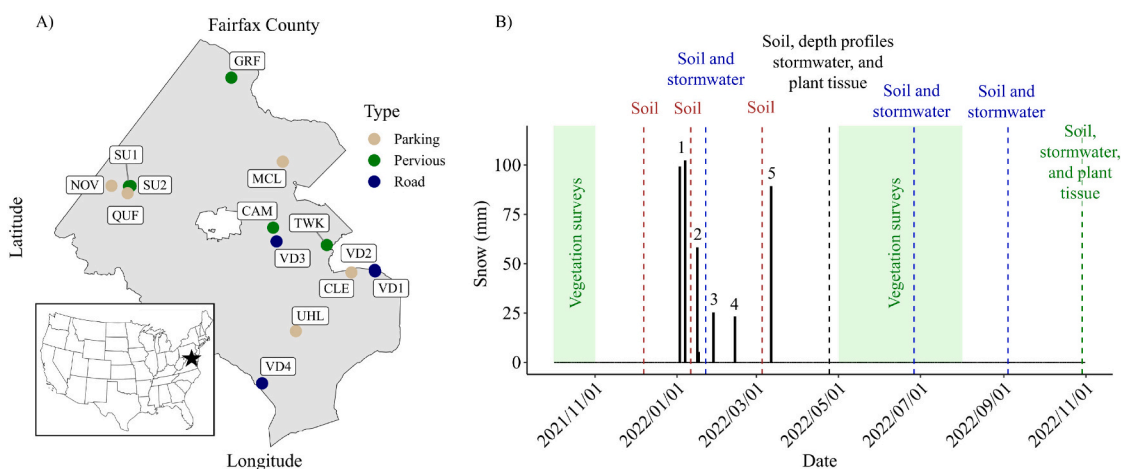
deep cores (core number scaled with detention basin size) were collected from the bottom of each basin (inlet, middle, and outlet regions) using a 2.54-cm diameter T-handle probe. Cores were transported on ice to the Occoquan Watershed Monitoring Lab, composited, placed in clean aluminum tins and air dried for 1–2 weeks (Robertson et al., 1999). Dried composite samples were ground using a Gilson soil grinder (SA-45, Gilson Company Inc.) and shipped to Logan Labs for saturated paste analysis. Saturated paste extracts were evaluated for EC, cations (sodium, potassium, magnesium, calcium), bicarbonate, and soluble chloride (details in Appendix C; Robbins and Meyer, 1990). Sodium, calcium, magnesium, and bicarbonate ion measurements were used to estimate adjusted SAR, which corrects for calcium carbonate solubility (a recommended correction in porewaters; Lesch and Suarez, 2009; Hanson et al., 2006, Appendix C). Adjusted ESP was calculated from adjusted SAR by regression as described in Appendix C (Hanson et al., 2006).

Stormwater samples were collected less frequently than soil samples (approximately four times per site), focusing primarily on the growing season (spring and summer months) when plants are most vulnerable to saline conditions. All samples were collected in pre-rinsed 50 mL falcon tubes and analyzed for the same ion suite evaluated in soils (see above). Analyses were performed using a Thermo Fisher Scientific, ICS 5000+ ion chromatograph, following standard methods (ASTM 4110 for anions and ASTM D6919-09 for cations; details in Appendix C) (Rice et al., 2011; ASTM, 2004; Rippey et al., 2022). SAR was calculated for all stormwater samples using measured concentrations of sodium, calcium, and magnesium ions (but not bicarbonate), the standard approach for surface water with pH < 8.5 (Hanson et al., 2006; equations provided in Appendix C).

Field EC was monitored whenever stormwater was collected, as well as in January, following the second snow event. Monitoring was performed using a YSI 556 Multiparameter probe (range: 0–200 mS/cm; YSI Inc., Yellow Springs, OH). A 2-point calibration of the EC sensor (0 to 200 mS/cm) was performed prior to use. Measurements were made opportunistically (i.e., when ponded water was present) and were taken at inlets, outlets, and mid-basin, to capture average site conditions.

### 2.2.2. Statistical analyses (soils and stormwater)

Principal component analysis (PCA) was used to determine if detention basins that drained different land uses had significantly different salt fingerprints. PCA was performed in R (R Core Team, 2023;



**Fig. 1.** (A) Map illustrating the location of Fairfax County, VA within the continental US (black star; see insert) and the distribution of sampled detention basins across Fairfax County. Sites are colored based on the type of land use they drain (parking lot: tan, pervious: green, road: navy). Site names are the same as reported in Table 1. (B) Timeseries illustrating sample collection relative to measured snow events (black numbered bars) in winter 2021/2022. Snow event data was sourced from Dulles Airport station USW00093738. Vegetation surveys were conducted during the timeframe shaded in green. Brown, blue, green, and black dashed lines indicate different types of sampling events (bulk soils only, soils and stormwater, soils stormwater and plant tissues, and soils, soil depth profiles, stormwater and plant tissue, respectively).

**Table 1**  
Site characteristics.

Site	Lat, Long	Site area (SA; m <sup>2</sup> )	Drainage area (DA; m <sup>2</sup> )	DA/SA ratio	DA type	Details	Soil type <sup>1</sup>
VD1	38.799729, -77.077639	2804	Road: 13,881; Pervious: 6677	7.3	Road	Runoff from I-95 N & I-495E	Sandy loam
VD2	38.801260, -77.078163	1228	Road: 18,777; Pervious: 7041	21.0	Road	Runoff from I-95S & I-495 W	Sandy loam
VD3	38.833056, -77.218885	1271	Road: 3503	2.8	Road	Runoff from I-495S	Sandy clay loam
VD4	38.675007, -77.239568	2751	Road: 13,901; Pervious: 11,580	9.3	Road	Runoff from the I-95 & I-1	Sandy clay loam
NOV	38.894973, -77.455460	357	Parking lot: 1646; Pervious: 5281	19.4	Parking	Runoff from a parking lot & residential landscaping	Sandy loam
QUF	38.886763, -77.432365	359	Parking lot: 6102; Pervious: 2666	24.4	Parking	Runoff from a parking lot & commercial landscaping	Clay loam
SU1	38.894470, -77.430537	1623	Parking lot: 26,859; Pervious: 8587; Road: 90	21.9	Parking	Runoff from a mall parking lot & landscaping	Sandy loam
SU2	38.894731, -77.428009	1513	Parking lot: 17,307; Pervious: 6713	15.9	Parking	Runoff from a mall parking lot & landscaping	Sandy loam
MCL	38.921899, -77.209943	529	Parking lot: 9854; Pervious: 4373	27.9	Parking	Runoff from an office building parking lot & landscaping	Sandy loam
UHL	38.733157, -77.191191	305	Parking lot: 5359; Pervious: 2635; Road: 204	27.9	Parking	Runoff from a rental truck parking lot & landscaping	Sandy loam
CLE	38.798472, -77.111583	1399	Pervious: 22,338; Parking lot: 669; Road: 604	2.5	Pervious	Runoff from residential yards and open space	Sandy loam
TWK	38.829034, -77.146865	349	Pervious: 3850; Parking lot: 160; Road: 53	11.6	Pervious	Runoff from residential yards and open space	Sandy loam
GRF	39.015365, -77.283690	762	Pervious: 55,588; Parking lot: 332	73.4	Pervious	Green space runoff (yards, golf course)	Sandy clay loam
CAM	38.848354, -77.223750	408	Pervious: 9931	24.3	Pervious	Runoff from a sports field	Sandy loam

1: USDA soil type was evaluated in-house from air-dried soil samples using a Gilson SS-3 vibratory sieve shaker (Gilson company Inc., OH) with six nested sieves (#8, #16, #30, #50, #100, #200), run for 10 min per sample (see Krauss and Rippy, 2024 and Jillavenkatesa et al., 2001).

package FactoMineR, Lê et al., 2008) on log-transformed and standardized data (EC, Na<sup>+</sup>, K<sup>+</sup>, Mg<sup>2+</sup>, Ca<sup>2+</sup>, and Cl<sup>-</sup>) from detention basin soils. Stormwater was not included in this analysis because it was sampled less often (Fig. 1b) and was transiently present across sites, creating significant data gaps. A resampling-based stopping rule (Peres-Neto et al., 2005, Rippy et al., 2017) was used to identify principal components that captured significantly more variance in soil salts than expected due to chance ( $\alpha < 0.05$  level). Ninety-five percent data ellipses were estimated within the space defined by these principal components for each drainage area type to determine if soil salt composition differed significantly among basins draining parking lots, pervious areas, and roads (bivariate t-distribution; R Core Team, 2023, packages FactoMineR and factoextra; Lê et al., 2008).

Average EC, SAR, ESP, and ion concentrations (Na<sup>+</sup>, Cl<sup>-</sup>) in soils and stormwater from detention basins draining different land uses were compared to established salt stress thresholds for vegetation (tabulated in Appendix B) using a nonparametric bootstrap comparison of means (also called a bootstrapped-t-test). The goal was to determine if salt stress thresholds were significantly exceeded and if so, under what conditions (i.e., in which drainage area types and seasons). Significance was determined at an  $\alpha < 0.05$  level and was corrected for multiple comparisons using the false discovery rate approach (Benjamini and Hochberg, 1995).

### 2.3. Evaluating basin vegetation and their capacity to phytoremediate salts

Vegetation surveys were conducted at each detention basin in spring or summer months (Fig. 1b). For a subset of frequently observed species, above-ground specimens were collected at the beginning and end of the growing season so that within-tissue concentrations of sodium and chloride ions could be measured. These measurements were used to estimate the potential of different plant species to remediate salts, both at observed and 100 % plant cover.

#### 2.3.1. Plant community surveys and tissue analysis (sodium and chloride)

Plant surveys were conducted using the point intercept transect method (Mueller-Dombois and Ellenberg, 1974, Caratti, 2006, Kuo et al., 2022) with plants identified to the species level when possible. We did not attempt to distinguish cultivars from natural species, but did distinguish common inter-specific hybrids like *Typha glauca* from parent species, when possible. Transects (and points along them) were spaced >2 m apart (i.e., they were never wider than the widest plant; Caratti, 2006, Krauss and Rippy, 2024). At least 100 points were sampled per site, allowing plant cover to be assessed at a minimum of 1 % resolution. The R package iNEXT (Chao and Jost, 2012) was used to estimate the completeness of vegetation surveys at each site as well as plant richness and Shannon's diversity at 95 % sample coverage.

Each identified plant species was assigned a native/exotic/invasive status for the state of Virginia using the Flora of Virginia (Weakley et al., 2013), the USDA PLANTS database (USDA and NRCS, 2023), and the Virginia Department of Conservation & Recreation's Invasive Plant Species List (Heffernan et al., 2014). Salt tolerance was classified using the eHALOPH database (Santos et al., 2015), the USDA PLANTS database, which rates plants using salt tolerance scores: very low (0–2 dS/m) low (2.1–4 dS/m), medium (4.1–8 dS/m), and high (> 8 dS/m) (USDA and NRCS, 2023), and the Federal Highway Administration Ecoregional Revegetation Application (ERA), which provides comparable thresholds to USDA PLANTS (Armstrong et al., 2017). Tolerance scores provide a rough indication of the EC plants can tolerate before yield is reduced by >10 %. Plants that could not be identified to the species level were not assigned a salt tolerance or native/exotic/invasive status.

Vegetation surveys were used to identify four relatively common plants that were sampled and analyzed for within-tissue concentrations of sodium and chloride in April and October. This includes 1) *Typha latifolia* and *angustifolia*, which are native and salt tolerant, 2) *Juncus effusus*, a native species often used for phytoremediation, 3) *Rumex crispus*, a salt tolerant exotic, and 4) *Festuca rubra*, a native grass present at all sites. Three composite samples, each comprising the entire aboveground biomass of at least three plant specimens, were collected

for each plant species in all detention basins where they occurred. Samples were dried in a drying rack at 60 °C for two days, and then shipped to the North Carolina Department of Agricultural and Consumer Services Division, North Carolina State University. Upon receipt, samples were ground on a cutting mill (IKA Works, Inc., Wilmington, NC) and then analyzed for sodium and chloride ions. To evaluate sodium, samples were digested with aqueous nitric acid, filtered through a Whatman #2 filter, and then analyzed using Inductively Coupled Plasma-Optical Emission Spectrometry (Spectro Arcos EOP and Arcos II EOP, Spectro Analytical, Ametek; Mahwah, NJ) (Donohue and Aho, 1992; US EPA, 2001; Rippy et al., 2022). To evaluate chloride, samples were extracted in 2 % acetic acid, filtered through a Whatman #2 filter, and then analyzed on a segmented flow analyzer (San++ Segmented Flow Auto-Analyzer, Skalar Instruments, The Netherlands) using the thiocyanate displacement method (Miller, 1998; Skalar Analytical, 2018).

### 2.3.2. Salt accumulation and phytoremediation potential

To compare sodium and chloride accumulation in the tissues of each major plant species by drainage area type (pervious, parking lot, road) and season (spring, summer), a three-way Bayesian Analysis of Variance (ANOVA) was performed (R Core Team, 2023; package BayesFactor, Morey and Rouder, 2018). This approach is appropriate for unbalanced sampling designs, an important consideration here, given that not all plant species evaluated were present at all sites during both seasons (Kruschke, 2015). Post-hoc comparisons of sodium and chloride ion concentrations were performed using posterior distributions from the Bayesian ANOVA to identify groups of plants (i.e., combinations of species, site types, and season) that meaningfully differ. We consider posteriors with non-overlapping 95 % highest density intervals (also termed credible intervals) to be meaningfully different, as proposed by Kruschke and Liddell (2018).

To scale up within-tissue measurements of sodium and chloride ions to basin-wide estimates of phytoremediation potential, we calculated the cumulative sodium and chloride mass uptake different plants could achieve ( $m_{plant}$ ) and divided it by estimates of the cumulative salt mass load to each roadside detention basin from winter maintenance activities ( $m_{in}$ ), returning the fraction of winter salt mass that could potentially be phytoremediated in each basin.  $m_{in}$  was estimated as:

$$m_{in} = \sum_{i=1}^n r_i \times L,$$

where  $i$  is time in days,  $n$  is the number of days,  $r_i$  is the salt application rate per lane kilometer (kg/km/d), and  $L$  is the total lane kilometers in each basin's drainage area (ESRI USA Major Highways layer, ESRI, 2023). Daily timeseries of  $r_i$  were estimated using measured temperature and precipitation data from Dulles Airport (station USW00093738) in accordance with recommended salt application guidelines from the Salt Management Strategy for Northern Virginia toolkit (SaMS, 2020), which specifies temperature and precipitation thresholds that trigger different types of salt mobilization events and their corresponding application rates (Appendix D). On a mass basis, approximately 39 % of  $m_{in}$  is sodium ( $\frac{22.99 \text{ g Na}^+}{58.44 \text{ g NaCl}}$ ) and the remainder is chloride.

The cumulative sodium and chloride mass uptake that might be achieved by plants ( $m_{plant}$ ) was estimated using the following equation:

$$m_{plant} = C_{plant} \times DM \times A_{db} \times c$$

where  $C_{plant}$  is the concentration of sodium or chloride ions measured in above-ground plant tissues for a given species (mg ion/kg tissue),  $DM$  is plant dry mass per square meter (species-specific),  $A_{db}$  is detention basin area (m<sup>2</sup>), and  $c$  is species-specific cover on a 0–1 scale (measured in the field or set equal to 1 to generate maximum estimates of salt mass uptake for a given species). This calculation assumes that plants were never salt

limited (i.e., that enough winter salts were retained in detention basin soils into the growing season to support the observed  $C_{plant}$ ). It also treats  $m_{plant}$  like a true salt sink (i.e., it does not include a term for the return of assimilated salts to detention basin soils when plants senesce). This best-case scenario requires all above-ground biomass to be harvested and removed from the basin prior to plant senescence (Herzog et al., 2021; Monks et al., 2023). The calculation also assumes that plants exhibit 1 full growth cycle (i.e., juvenile through adult) per year. More complex life histories can be accommodated by summing accumulated mass across multiple growth cycles. This was necessary at VD1, where vegetation was harvested mid-summer and regrew, with many species completing two growth cycles.

## 3. Results

### 3.1. Differences in basin salinity by drainage area type

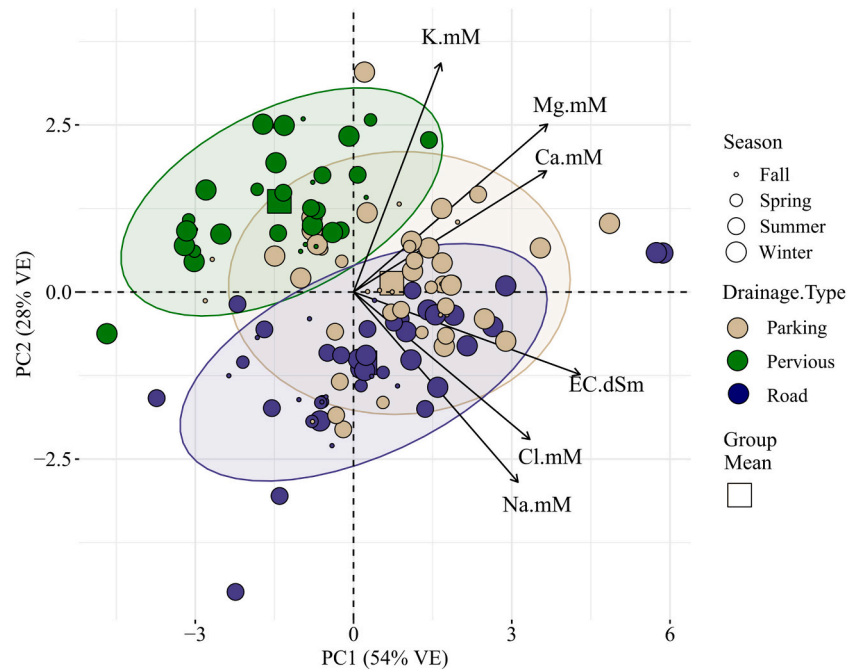
PCA revealed two significant PC axes ( $p < 10^{-15}$ ) that explained 82 % of the variance in soil ion concentrations and EC across detention basins (Fig. 2). EC and soil ions loaded positively on PC 1, suggesting that this principal component distinguishes samples with higher EC and soil ion concentrations (positive PC 1) from those with lower EC and soil ion concentrations (negative PC 1). With respect to PC 2, potassium, magnesium, and calcium ions loaded positively on PC 2 and EC, sodium, and chloride ions loaded negatively on PC 2. This suggests (1) that EC is strongly associated with NaCl, the most common winter maintenance chemical in Virginia, and (2) that soils can be “salty” in different ways, with samples in negative PC 2 space containing more winter salts and higher EC, but lower magnesium, potassium, and calcium ion concentrations, and samples in positive PC2 space having the opposite salinization fingerprint. Soils collected at basins draining different land uses separated most cleanly along PC2, with sites draining roads (navy symbols, Fig. 2) biasing towards negative PC 2, sites draining pervious areas (green symbols) biasing towards positive PC2, and parking lots (tan symbols) falling somewhere in between. The 95 % data ellipses for basins draining parking lots exhibited substantial overlap with other drainage area types. Data ellipses for basins draining roads and pervious areas, however, exhibited minimal overlap (< 0.1 %), suggesting they have relatively unique salinization fingerprints.

### 3.2. Salt stress to vegetation

#### 3.2.1. Ion-specific toxicity thresholds

Stormwater only exceeded ion-specific toxicity thresholds at basins draining roads (navy symbols, Fig. 3a,b). Below the slight-to-moderate toxicity threshold few plants experience sodium or chloride stress. Above the severe toxicity threshold most plants (particularly woody species) experience stress, reduced yield and visible foliar damage (e.g., leaf chlorosis). Concentrations of sodium and chloride ions were above severe toxicity thresholds during the spring growing season (200 mg/L Na<sup>+</sup>, 350 mg/L Cl<sup>-</sup>; solid black line, Fig. 3a,b) as well as slight-to-moderate toxicity thresholds during summer and occasionally during fall (70 mg/L Na<sup>+</sup>, 140 mg/L Cl<sup>-</sup>; dashed black line, Fig. 3a,b).

Comparable sodium and chloride toxicity thresholds for vegetation have not been established for soils. It is evident, however, that detention basins draining roads and parking lots had significantly higher sodium ion concentrations in soil than detention basins draining pervious areas ( $p = 3.5 \times 10^{-9}$ ; Fig. 3a). Chloride ion concentrations were also elevated in the soils of basins draining parking lots and roads, but only during winter and spring. In summer and fall, chloride ion concentrations increased in the soils of basins draining pervious areas, reaching levels comparable to other basin types. This late summer/fall increase was also evident for sodium ions, but occurred across all basins, not just basins draining pervious areas.



**Fig. 2.** Biplot illustrating dominant patterns in molar ion concentrations and electrical conductivity in detention basin soils. The first principal pattern (PC1) is on the x-axis: positive PC1 indicates higher overall ion concentrations and electrical conductivity. The second principal pattern (PC2) is on the y-axis: positive PC2 indicates higher molar concentrations of potassium magnesium and calcium and lower electrical conductivity and molar concentrations of sodium and chloride ions. Observations (points) are colored by drainage area type (same as Fig. 1). The mean of these groups is shown using a square of corresponding color. Ninety-five percent data ellipses about these means (also colored by drainage type) illustrate the degree of separation across soils collected in basins that drain different land uses. Season-specific data ellipses were also evaluated and can be viewed in Appendix E.

### 3.2.2. Salinity (EC) and sodicity (SAR, ESP) thresholds for vegetation

In basins draining roads, and occasionally parking lots, stormwater exceeded the recommended limits for surface irrigation of vegetation beyond which the growth and survivorship of sensitive plant species is expected to decline ( $EC > 0.75$  dS/m,  $SAR > 10$ ; Ayers and Westcot, 1985) (Fig. 3c,d). EC limits for surface irrigation were always exceeded during winter (parking lots, roads) and spring (roads) and transiently exceeded during other seasons (note position of small brown and blue squares, Fig. 3c). SAR limits for surface irrigation were only exceeded at basins draining roads, consistently during spring and occasionally during summer (note position of small blue squares, Fig. 3d). The stormwater permeability hazard level was typically within the slight-to-moderate hazard range, suggesting that plants may experience impaired growth and drought-like stress if repeatedly irrigated with stormwater (Fig. 4a).

Soil EC was generally lower than stormwater EC, as well as established thresholds for slightly saline (2 dS/m) and saline (4 dS/m) soils (dashed and solid black lines, respectively; Fig. 3c). While soils were never fully sodic ( $ESP > 15$ ), the slight sodicity threshold ( $ESP > 6$ ) was occasionally exceeded ( $ESP > 6$ ; dashed line, Fig. 3d), which can cause drought-like stress and limit the growth of certain plant species. Most detention basin soils were neither sodic nor saline, posing minimal-to-no risk to vegetation (left corner, Fig. 4b). Soils at basins draining parking lots were slightly sodic 5 % of the time (middle bottom, Fig. 4b). Basins draining roads had slightly sodic soils more often (19 % of the time), particularly during winter, with some remaining slightly sodic into the growing season. Soils in one roadside basin (VD1) became both slightly saline and slightly sodic (center, Fig. 4b), but only during winter.

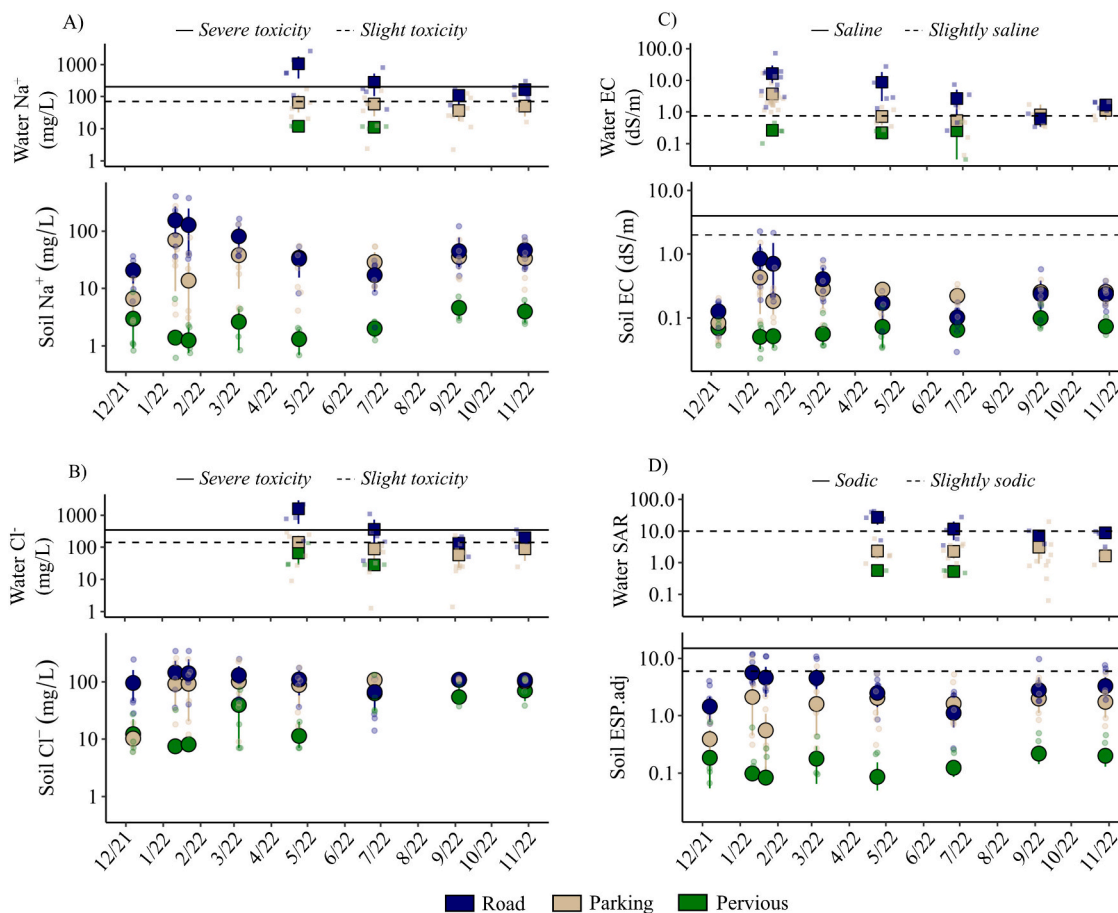
### 3.3. Detention basin plant communities - salt tolerance and native status

Two hundred fifty-five plant species were identified across all detention basins. Sample coverage at each basin was at least 95 %, suggesting that additional sampling effort was unlikely to significantly

increase the number of species observed (see rarefaction curves in Appendix F). The most biodiverse basin was Sully 2 (parking lot site; 69 species observed, Shannon's diversity of 29), and the least biodiverse was CAM (pervious site; 19 species observed, Shannon's diversity of 7) (site-specific biodiversity details are provided in Appendix F). The three most common plants, present at 71 % of sites, include two turf grass species (*Festuca rubra*, *Cynodon dactylon*) and common dandelion (*Taraxacum officinale*).

Few plant species were found in only one detention basin and basins that drained different land uses were as likely to have plant species in common as basins that drained the same land use type (i.e., the chords in Fig. 5 are as likely to bridge pervious, parking lot, and road sites as they are to occur within them). Basins that drained roads had a significantly greater fraction of plant species with high salt tolerance ( $EC > 8$  dS/m) than other site types (non-parametric bootstrap comparison of means;  $p = 0.02$ ; note black segments in first outer ring, Fig. 5). VD3 and VD4 (road) had the most salt tolerant plant species (29 %) and TWK (pervious) had the fewest salt tolerant plant species (8 %). The fraction of native plant species ranged between 16 % (QLF – parking lot) and 72 % (GRF – pervious) and did not significantly differ in basins that drained different land uses ( $p = 0.31$ ; note green segments in second outer ring, Fig. 5). At some basins (VD1, VD2, GRF), invasive plant species were relatively prevalent (22–23 % of observed plant species). The most common high threat invasive was *Ampelopsis brevipedunculata*, present at 50 % of sites.

Across all detention basins, we identified 13 plant species that are both native to Virginia and exhibit a high degree of salt tolerance (e.g., are tolerant of  $EC \geq 8$  dS/m). These species include: five graminoids (*Eleocharis palustris*, *Festuca rubra*, *Panicum virgatum*, *Leptochloa fusca*, *Schoenoplectus tabernaemontani*), four forbs (*Solidago semipervirens*, *Typha angustifolia*, *Typha latifolia*, *Xanthium strumarium*), one vine (*Calystegia sepium*), one shrub (*Baccharis halimifolia*), and two trees (*Robina pseudoacacia*, *Taxodium distichum*). We also identified 35 native plants with low-moderate salt tolerance ( $EC > 2$ , but  $< 8$  dS/m), bringing



**Fig. 3.** Timeseries of average (A) sodium ion concentration, (B) chloride ion concentration, (C) electrical conductivity (EC), and (D) two measures of sodicity (the sodium adsorption ratio; SAR and adjusted exchangeable sodium percentage; ESP.adj) in stormwater and soils. Large squares and circles are averages in water and soil, respectively. Small squares and circles are individual measurements. Error bars are 95 % bootstrapped confidence intervals about the mean at each timepoint. Observations are colored by drainage area type (same as Fig. 1). Stormwater samples were not collected in late summer/fall at sites draining pervious areas because ponded water was not present. Horizontal lines reflect different risk thresholds (details in Table S1). The dashed and solid black lines in panels (A) and (B) are toxicity thresholds for surface irrigation of plants. Below the slight toxicity threshold (dashed) few plants experience  $\text{Na}^+$  or  $\text{Cl}^-$  stress. Above the severe toxicity threshold (solid) many plants experience  $\text{Na}^+$  or  $\text{Cl}^-$  stress, reduced yield and visible damage (e.g., leaf chlorosis). Dashed and solid black lines in panels (C) and (D) are established salinity and sodicity thresholds for plants. Below the slightly sodic and slightly saline thresholds (dashed) few plants experience salinity or sodicity-related stress. Above the saline and sodic thresholds (solid), many plants experience osmotic or drought-like stress, reducing plant growth rates and yield.

our total count of salt tolerant, native species to 48 (see Appendix G for a complete species list).

### 3.4. Salt concentrations in plant tissues and phytoremediation potential

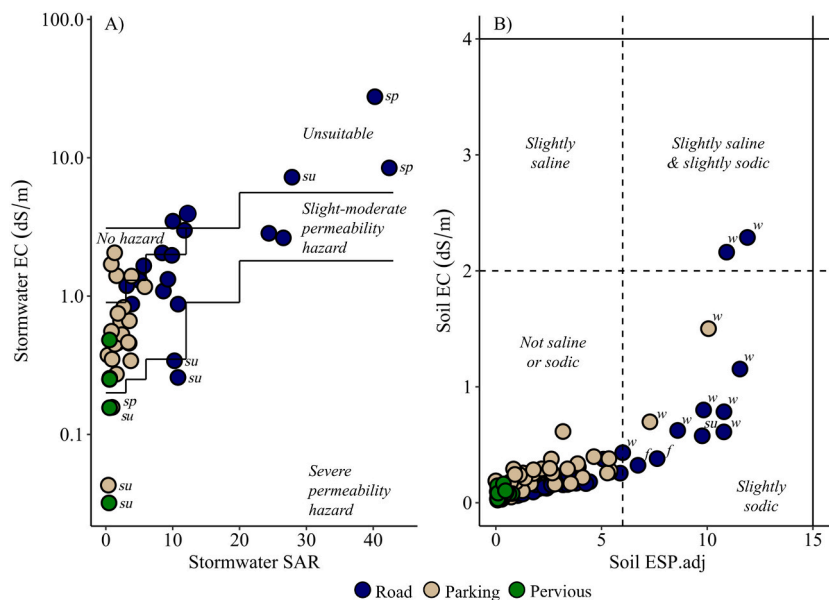
Plants collected from detention basins draining parking lots or roads had significantly higher within-tissue concentrations of sodium ions than plants collected from detention basins draining pervious areas, suggesting that all plant species assimilate more sodium when exposed to higher sodium concentrations (black brackets illustrate pairwise significance, Fig. 6a). Sodium concentrations in plant tissues were relatively stable by season (only significantly different for *Rumex crispus* at parking lot sites). Chloride assimilation was more species-specific (Fig. 6b). In some species (e.g., *Festuca rubra*, yellow symbols, Fig. 6b), concentrations of chloride ions varied by drainage type in a manner similar to sodium. In others, concentrations of chloride ions differed more by season than by drainage type (e.g., *Typha*, elevated in spring; red symbols, Fig. 6b) or were relatively stable, with few significant differences by drainage type or season (e.g., *Rumex crispus* and *Juncus effusus*, blue and purple symbols, Fig. 6b).

On average, *Typha* and *Rumex* had significantly higher concentrations of both sodium and chloride ions in their tissues than *Festuca* or *Juncus* (colored letters, Fig. 6), with *Typha* exhibiting the highest within-

tissue concentrations of both ions across all sites and seasons (average of 9.5 mg/g  $\text{Na}^+$  and 28.5 mg/g  $\text{Cl}^-$ ). Given that *Typha* was both our strongest salt accumulator and is native to Virginia, we elected to focus our analysis of phytoremediation potential solely on *Typha* (see Table 2). At observed levels of *Typha* cover in roadside detention basins, the total mass of sodium and chloride that could have potentially been assimilated over the growing season was between 0.03 and 29 kg of sodium and 0.08 and 56 kg of chloride. The amount of these ions introduced by winter maintenance chemicals was several orders of magnitude higher (i.e., 2136 to 2900 kg of sodium and 3273 to 4500 kg of chloride), such that only 0.001 to 0.6 % of winter sodium mass and 0.002 to 1.7 % of winter chloride mass could have been phytoremediated. These estimates increase at 100 % *Typha* cover, with as much as 5 % of winter sodium mass and 6.1 % of winter chloride mass potentially assimilated. These maximum values are for VD1, the only basin where *Typha* was harvested and removed in early summer, and then subsequently regrew, assimilating additional salt.

## 4. Discussion

The overarching goal of this study was to determine if salinization of stormwater and soils in green stormwater infrastructure poses a threat to vegetation and whether salt tolerant plants could help mitigate that



**Fig. 4.** Phase diagrams illustrating combinations of electrical conductivity (y-axis) and either the sodium adsorption ratio (A – surface irrigation with stormwater) or the adjusted exchangeable sodium percentage (B – soil saturated paste) that pose different levels of risk to plants (x-axis). Colored symbols indicate different drainage area land uses (same colors as Fig. 1). Observations in regions where risk to plants is elevated (details provided in Appendix B) have been labeled by season (sp: spring, su: summer, f: fall, w: winter).

threat by assimilating salts during the growing season. Our results suggest that present salt levels in detention basin stormwater and soils do pose a threat to salt sensitive vegetation but only in basins draining certain land uses (e.g., roads and perhaps parking lots, but not pervious areas; Figs. 2–4). We also find that detention basins support a wide range of native species that are candidates for remediating salts (48 species total; Fig. 5), and that some of these species (e.g., *Typha*) can accumulate appreciable amounts of sodium and chloride ions, albeit not enough to offset the mass of deicing and anti-icing chemicals that enter roadside detention basins in an above-average snow year (Fig. 6, Table 2). This is not to say that plants don't play a role in increasing basin resilience to future deicing events. Removing up to 100 kg of sodium ions and 200 kg of chloride ions each year, the equivalent mass of 1–2 adult people, is undoubtedly beneficial. The challenge here is one of scale – if phytoremediation can only remove 5–6 % of winter salt mass, then it is at most a partial solution for managing basin salinization. Subsequent sections of this discussion contextualize these findings and explore their implications for green stormwater infrastructure performance and resilience.

#### 4.1. Contextualizing observed salt levels

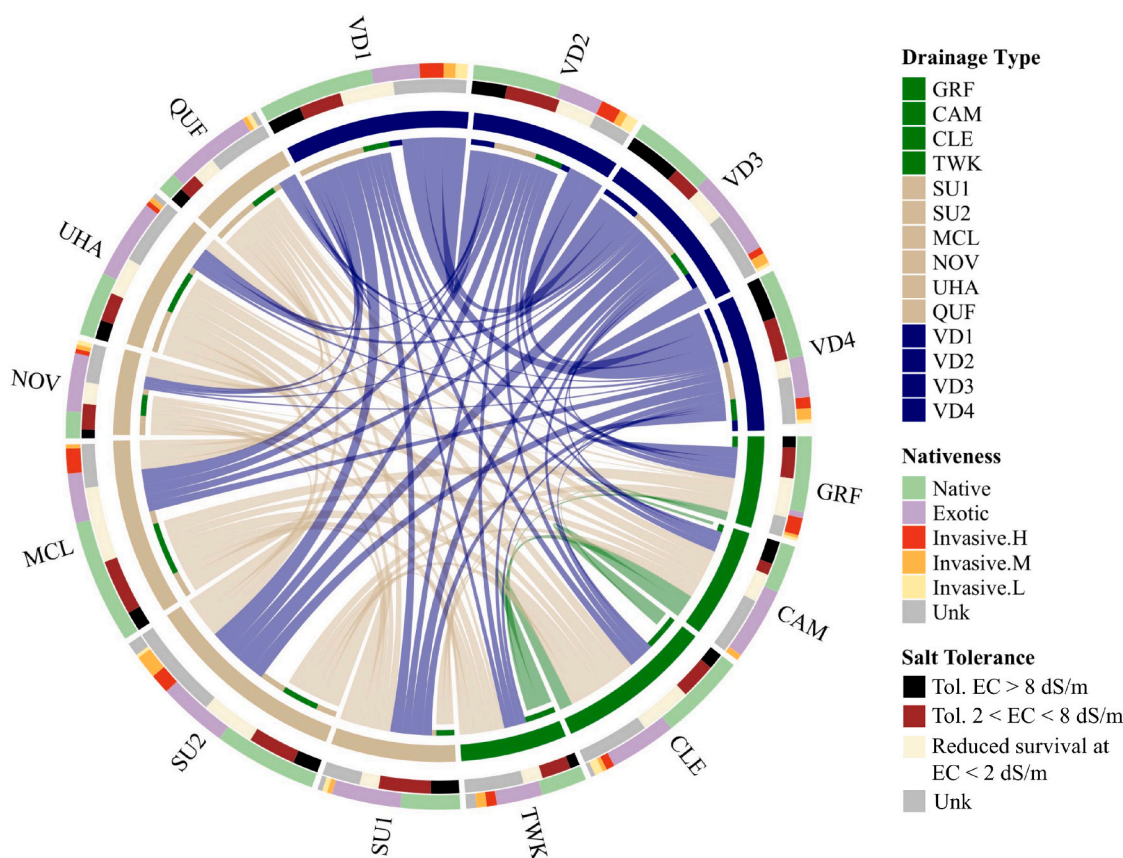
Soil EC in detention basins draining parking lots and roads fell within, but on the lower end of reported ranges for detention basins in cold climate regions of the United States (this study - average of 0.25–0.35 dS/m; other studies - average of 0.16–2.9 dS/m; Mills et al., 2020; Shannon et al., 2020; and Monks et al., 2023). Measured EC, SAR, and sodium and chloride ion concentrations in stormwater also fell within reported ranges for green infrastructure in Virginia, Maryland, and Pennsylvania, suggesting that the salt levels we observed are generally representative of the levels plants experience in urban stormwater infrastructure across the Mid-Atlantic US (this study - EC: 0.04–72 dS/m; SAR: 0.06–42;  $\text{Na}^+$ : 0.07–2642 mg/L and  $\text{Cl}^-$ : 0.19–3858 mg/L; other studies - EC: 0.01–100 dS/m; SAR: 0.4–172;  $\text{Na}^+$ : 15–4976 mg/L;  $\text{Cl}^-$ : 4–8050 mg/L, Caplan et al., 2024; Burgis et al., 2020; Galella et al., 2023).

Of course, salt concentrations in green infrastructure soils are not expected to be consistent year to year due to variable snowfall and corresponding deicer application rates. Indeed, the values we report here are for an above-average snow year in a time of declining winter

snowfall. In Fairfax County, where this study was conducted, there was an average of 86 freeze-thaw days and 69 days below freezing per year, between 1991 and 2020 (CPR, 2022). Under moderate future warming (RCP4.5; WCRP, 2011), the average number of freeze thaw days and days below freezing is projected to drop 30–37 % by 2085 (CPR, 2022). Combined with projected increases in precipitation intensity (i.e., more rainfall, distributed over fewer days; CPR, 2022), it appears likely that roadside detention basins will receive reduced deicer loads and more flushing rains in the future, which may reduce salt persistence into the growing season. This outcome would likely reduce salt stress on basin plant communities, but it is difficult to anticipate how much. Further study is required to explore this and other climate-related outcomes.

#### 4.2. Impacts on vegetation and the services they provide

Current salt levels in the soils and stormwater of roadside detention basins during the growing season are high enough to have both lethal and sublethal effects on vegetation. Sublethal effects may include reduced leaf size, chlorosis, impaired root development, reduced growth rate and reduced stomatal conductance/evapotranspiration, to name a few (Bernstein, 1975; Glenn et al., 1995; Shainberg and Letey, 1984; Levy et al., 1998; Caplan et al., 2024; Brown et al., 2024). These effects could alter the role plants play in green stormwater infrastructure with respect to hydrologic and water quality services. On the hydrologic side, the sensitivity of stomatal conductance and root/leaf development to sodicity is a concern. Evapotranspiration and interception by plant canopies can be responsible for 2–7 % of stormwater volume reduction, with root-mediated infiltration (e.g., channeling by woody vegetation) responsible for another 39–50 % (Wissler et al., 2020). This makes the contribution of healthy vegetation to water volume management, considerable. On the quality side, plants play an important role in the management of nutrients (particularly nitrogen) and metals (Read et al., 2008; Payne et al., 2018; Szota et al., 2015; Monks et al., 2023). Plants exposed to saline stormwater can exhibit reduced metal uptake (Szota et al., 2015), although this effect is not always seen (Beral et al., 2023). Nitrogen uptake can also decline when salt stress becomes acute and plant tissues decay or the plant senesces, resulting in total loss of the nutrient sink (Szota et al., 2015; Pessarakli et al., 2012; Brown et al., 2024). Thus far, effects like these have primarily been documented in



**Fig. 5.** Chord plot representing the number of shared plant species across detention basin sites. The size of inner ring segments indicates the number of times plants from one site appear in all other sites. The width of individual chords indicates the number of plants shared between any pair of sites. Inner ring colors indicate drainage area type (same colors as Fig. 1). Chord colors also reflect drainage type; note that when plants are shared by sites that have different drainage types, chord color will arbitrarily reflect one of the two. The first outer ring of the chord plot illustrates plant salt tolerance, specifically the fraction of plant species in each detention basin that can tolerate high salt levels ( $EC > 8$  dS/m; black), the fraction that can tolerate low to moderate salt levels ( $2 < EC < 8$  dS/m; brown), the fraction that exhibit reduced survival even at low salt levels ( $EC < 2$  dS/m; cream), and the fraction that have unknown salt tolerance (grey). The outermost ring of the chord plot illustrates the fraction of plant species in each detention basin that are native (light green), exotic (purple), invasive (high threat: red, medium threat: orange, low threat: yellow), or of unknown native status (grey). Site abbreviations are the same as Fig. 1 and Table 1.

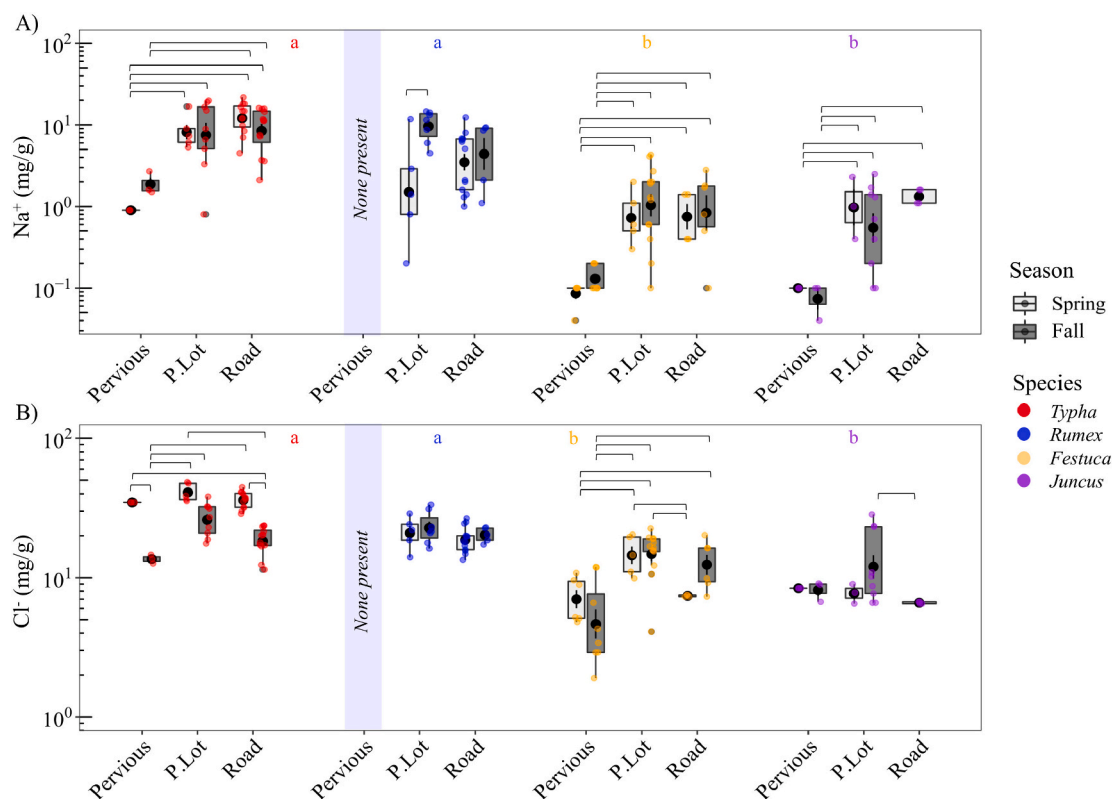
experimental mesocosm studies (Szota et al., 2015; Beral et al., 2023; Brown et al., 2024). Field-scale efforts are needed to characterize whether and how performance changes under real world conditions. Such efforts would benefit from considering both within-system performance and the potential downstream impacts of saline discharges on aquatic and riparian ecosystems, ensuring the breath of services that salinization might impact are fully accounted for (further discussion in Appendix H).

#### 4.3. Contextualizing salt levels in plant tissues and phytoremediation estimates

Average concentrations of sodium and chloride ions measured in *Festuca* and *Juncus* at basins draining parking lots and roads were consistent with studies of non-bioretenion roadside vegetation in the US and EU (mixed grasses: 1.3 mg  $Na^+$ /g – this study, 1.4 mg  $Na^+$ /g – other studies; *Juncus effusus*: 10.9 mg  $Cl^-$ /g – this study, 8.3 mg  $Cl^-$ /g – other studies; Barker et al., 2003; Dolegowska et al., 2022). Our measurements for *Typha* were also consistent with other studies from salt impacted systems (11.1 mg  $Na^+$ /g and 30 mg  $Cl^-$ /g – this study; ~8 mg  $Na^+$ /g and 20–63 mg  $Cl^-$ /g – other studies; Morteau et al., 2009, 2015 and Rozema et al., 2014). No comparison was possible for *Rumex crispus*, where sodium ion concentrations have only been reported for a single maritime variant, not observed in this study (Ivenish et al., 2021).

Although species-specific information about plant salt uptake can

often be sourced from lab studies or field work conducted in coastal or roadside soils (i.e., the values presented above), only a handful of studies have explicitly focused on field-scale green infrastructure, providing a point of comparison for this study (Monks et al., 2023; Caplan et al., 2024). The closest comparator is work by Monks et al. (2023) in Illinois, which showed that a single detention basin planted with *Typha* could remediate up to 0.4 % of the chloride mass applied annually per km of road, consistent with our finding that detention basin vegetation only removes a fraction of the total salt mass applied during winter maintenance activities each year. Because salt removal totals are a function of environmental salt concentration, nutrient availability, and the timing of plant emergence, among other factors (Morteau et al., 2009, 2015; Beral et al., 2023), variability is expected, both across plant species and by basin. We see hints of this variability in the spread of within-tissue sodium and chloride ion concentrations for different plant species reported in the literature, which can span orders of magnitude (Samson and Ivenish, 2018; Renshaw, 2021; Delattre et al., 2022). It is also evident in our results for sodium uptake in plant tissues, which differed both by plant species and drainage area type, often increasing an order of magnitude or more moving from low-salt, pervious to more saline, impervious sites (Fig. 6a). This degree of variability could make it difficult to predict how well plants will actually remediate salt in any given system or year.



**Fig. 6.** Box and whisker plots illustrating variability in within-tissue sodium ion concentrations (A) and chloride ion concentrations (B) by drainage type and season. Boxplots are grouped by plant (red: *Typha*, blue: *Rumex*, yellow: *Festuca*, and purple: *Juncus*), drainage area type (pervious, parking lot (P.Lot) and road), and season (white boxplots for spring, black boxplots for fall). Significant differences in average within-tissue ion concentrations across plant groups are shown using colored letters (different letters, different ion concentrations). Significant pairwise comparisons (i.e., across plant types, drainage type, and season) are indicated using black brackets. Significance is assessed at a 95 % credibility level.

**Table 2**

Salt assimilation potential of *Typha* (cattail) at roadside detention basins where it was present.

Site	Plant type	Cover	Na <sup>+</sup>			Cl <sup>-</sup>		
			$m_{in}$ (kg) <sup>1</sup>	$m_{plant}$ (kg) <sup>2</sup>	% $m_{in}$ uptake	$m_{in}$ (kg) <sup>1</sup>	$m_{plant}$ (kg) <sup>2</sup>	% $m_{in}$ uptake
VD1	<i>Typha</i> *	c = 0.28	2136	29*	0.6	3273	56*	1.7
		c = 1		105	5.0		199	6.1
VD2	<i>Typha</i>	c = 0.002	2889	0.03	0.001	4454	0.08	0.002
		c = 1		14	0.5		40	0.9
VD4	<i>Typha</i>	c = 0.26	2139	12	0.6	3298	22	0.7
		c = 1		47	2.2		87	2.6

<sup>1</sup>  $m_{in}$ : cumulative salt mass load from winter maintenance activities.

<sup>2</sup>  $m_{plant}$ : cumulative salt mass load assimilated by *Typha* at observed cover levels and at 100 % cover; assumes an adult *Typha* dry mass of 1.22 kg/m<sup>2</sup>; average of values from Maddison et al., 2009, Gagnon et al., 2012, and Grosshans, 2014.

\* : *Typha* exhibited two growth cycles at VD1, and one growth cycle at all other sites.

#### 4.4. Study limitations and implications for best management practices

Our estimates of phytoremediation potential suggest that the halophyte *Typha* can remove up to 100 kg of sodium ions and 200 kg of chloride ions from stormwater detention basins each year, but how reliable are these estimates? One important factor to consider is the time delay between road salt application and the start of the growing season (Snodgrass et al., 2017; Renshaw, 2021). Our calculations presume that winter salts remain in detention basin soils through the growing season for plants to take up, such that phytoremediation potential is limited by plant assimilation capacity, not salt availability. This assumption is difficult to validate, however. We can say that concentrations of sodium and chloride ions did remain elevated into the growing season at basins draining parking lots and roads, which suggests that salt was available to vegetation (Fig. 3a,b). However, *Typha* has been shown to exhibit higher

salt uptake in other studies (Morteau et al., 2009; Delattre et al., 2022), so we cannot dismiss the possibility that more uptake might have occurred if additional winter salts had been retained. Further work is needed to determine which factors (plant physiology or salt retention) generally limit phytoremediation, with the goal of developing practical design solutions. If salt retention is the problem, media amendments that increase cation exchange capacity (e.g., biochar, hemp, clay beads, or vermiculite; Renshaw, 2021; Rippy et al., 2022) represent a potential path forward, assuming plants can access the salt they bind. If assimilation capacity is the problem, however, it may be plant selection practices that need to change, focusing on species that can assimilate as much (or ideally more) salt than *Typha* (further discussion in Appendix G).

When interpreting our phytoremediation estimates, it is also important to consider the ultimate fate of assimilated salt. Our estimates

presume that plants represent a salt sink because their biomass can be harvested and disposed of at the end of the growing season (Monks et al., 2023; Herzog et al., 2021). Although many agencies do recommend mowing or pruning vegetation to maintain sight lines and accessibility (Philadelphia Water, 2016; Phoenix Metro GI, 2019), with VDOT specifically noting that plant clippings should be removed (e.g., harvested) to minimize clogging (VDOT, 2016), full biomass harvest is not particularly common. In our study, this practice was only evident at VD1. To achieve the phytoremediation potentials estimated here, it would need to have occurred across all detention basins.

## 5. Conclusions

This study shows that current levels of salt stress in stormwater detention basins in Northern Virginia vary by drainage type and season, but and occasionally exceed established plant thresholds (primarily in basins draining roads during winter, spring, and summer), and are conducive to the survival of at least 255 unique plant species, including 48 natives that can tolerate elevated soil EC ( $\geq 2$  dS/m). The capacity of these species to assimilate salt differs, but removal is generally low,  $\leq$  to 5–6 % of winter salt application. Whether this 5–6 % is worth pursuing is ultimately a decision for managers. In basins that are already mowed or bushhogged, biomass disposal may be a logical next step. In basins that are not, the costs and benefits of phytoremediation must be weighed to determine whether it makes sense as part of a broader salt management strategy. Because winter salt application may ultimately decline under climate change and bring the magnitude of winter salt sources more in line with vegetative salt sinks, climate is an important factor to consider when making such determinations.

Although our findings are broadly consistent with other cold climate studies, we expect our work to be most extensible to other transitional climate zones where freeze thaw cycles and a combination of winter rain and snow events are the norm or expected to become so under climate change. In regions where snow cover is more persistent, the timing of deicer wash-off and plant emergence differs (Beral et al., 2023). This could significantly alter salt stress profiles as well as the capacity of plants to remediate soils and improve the resilience of stormwater infrastructure to future deicing events.

## CRedit authorship contribution statement

**S. Long:** Writing – original draft, Investigation, Formal analysis. **M. A. Rippy:** Writing – original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization. **L. Krauss:** Writing – review & editing, Investigation. **M. Stacey:** Writing – review & editing, Investigation. **K. Fausey:** Writing – review & editing, Investigation.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2024.178310>.

## Data availability

Data will be made available on request.

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