Enhancing Tollway bioswale capacity with biochar and cattail harvesting

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Executive Summary

In northeast Illinois, highway transportation routes in the urban built environment are significant contributors to soil-accumulated chloride ions (Cl^-) and heavy metal runoff (Pb, Cu, Zn, Cd, Cr) particularly after spring stormflows and snowmelt. Soils adjacent to roadways act as pollutant sinks that accumulate salts and heavy metals over time. Highway runoff often exceeds Illinois Environmental Protection Agency surface water quality standards for Cl^- in the Chicago-area Waterways System leading to elevated risks to ecological integrity and human health. Control, retention, and removal of salts and heavy metals is imperative to protect downstream water quality, biodiversity, and ecosystem services. Bioswale projects are designed to slow and treat roadway runoff and thereby meter the release of salts and heavy metals, but bioswale function is compromised over time as sediments become saturated with pollutants.

This two-year project sought to test innovative practices to improve the function of Tollway bioswales, potentially extending their functional lifespan. Specifically, we investigated the effect of experimental biochar addition and invasive plant harvesting on the function of Illinois Tollway (Tollway) bioswales to retain salts and heavy metals. Harvesting wetland plant biomass from Tollway bioswales and retention basins in combination with the application of biochar is a promising technique to improve the sequestration and management of Cl^- and heavy metals. Biochar is a carbon-rich and porous material that is derived by heating organic waste biomass in a low-oxygen environment to restrict combustion to ash. As a soil amendment, biochar's high porosity, surface area to volume ratio, and negatively-charged surfaces increases soil water storage, retains plant-available nutrients, and absorbs organic compounds, heavy metal cations, and salts. Mitigating downstream water quality issues by harvesting invasive plants in roadside detention basins and bioswales is a second novel approach with potential co-benefits. Monotypic stands of invasive wetland plants (specifically cattails [*Typha* spp.]) in Tollway retention basins readily accumulate high quantities of Cl^- in their tissue. Harvesting and removing these plants from bioswales provides a straightforward strategy to remove Cl^-.

In this project a research team from Loyola University Chicago (Loyola) and the University of Illinois, –Prairie Research Institute - Illinois State Geological Survey implemented a multi-faceted study to evaluate the efficacy of biochar addition and biomass harvesting to enhance Cl^- and heavy metal removal potential from Illinois Tollway bioswales to improve water quality. The first research task involved conducting a comprehensive scientific literature review, evaluating the potential for biochar soil amendment and invasive plant harvest to enhance Tollway bioswale function (Chapter 2).

The second task involved experimentally harvesting biomass, applying biochar to Tollway bioswales, and quantifying the effects on salt and heavy metal retention (Chapter 3). This was accomplished by: selecting five Tollway bioswale systems; establishing a fully-factorial experiment with a biochar treatment (Twenty (20) metric tons [T] / hectare [ha] biochar: application / no application) and biomass harvest treatment (Vegetative biomass harvest and removal: Harvest / No Harvest); conducting field vegetation and soil sampling in each year following treatment; continuously monitoring water levels and specific conductivity (as a proxy for Cl^-) with AquaTROLL data loggers at each bioswale; chemically evaluating the plant tissue and soils for anions (including Cl^-), cations, and heavy metals; and synthesizing water, plant, and

soil results. We found that a single 20 T/ha (17,843 lb/acre) biochar application resulted in a significant increase in soil chloride retention and negligible effects on heavy metal retention. Biomass harvesting had variable effects on plant communities but did lead to an increase in harvestable chloride within plant tissues. No biochar effect was detected in the specific conductivity of bioswale water.

The third task involved quantifying the biochar saturation rate for adsorbing salts and heavy metals within Tollway bioswales. This was accomplished by: deploying bags of biochar to each bioswale and periodically (five times); collecting subsamples of the biochar over the course of a year; chemically analyzing the biochar samples for cations, anions, and heavy metals and; statistically evaluating the resulting data. We found that the bagged biochar retained chloride, cadmium, and chromium.

This two-year project has demonstrated that a single 20 T/ha (17,843 lb/acre) biochar application in concert with harvesting aboveground *Typha* biomass is a feasible management strategy to retain and remove chloride pollution in Tollway bioswales. The results of our research in Tollway systems further confirm a practical, scalable management pathway to retain and remove aquatic pollutants adjacent to highway systems in Illinois.

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1. Background

1.1 Introduction and literature review

In northeast Illinois, highway transportation routes in the urban built environment are significant contributors to soil-accumulated chloride ions (Cl^-) and heavy metal runoff (Pb, Cu, Zn, Cd, Cr) particularly after spring stormflows and snowmelt (Oberhelman and Peterson 2021). Soils adjacent to roadways act as pollutant sinks that accumulate salts and heavy metals over time (Rodríguez-Seijo et al. 2017). Highway runoff often exceeds Illinois Environmental Protection Agency (IEPA) surface water quality standards for Cl^- in the Chicago-area Waterways System (CAWS) leading to elevated risks to ecological integrity and human health. Winter road salt application to impervious surfaces and road-side soils results in pulses of water-soluble Cl^- ions that are transported to adjacent freshwater watersheds in runoff. In the Chicago region, road salt application for winter highway safety is the largest source of anthropogenic Cl^- (~450,000 metric tons introduced annually) (Kelly et al. 2012) which threaten freshwater-adapted native flora and fauna (Thunqvist 2004; Chapra et al. 2009; Dugan et al. 2017).

Heavy metal deposition and accumulation in roadway-adjacent soils depends on vehicle traffic densities, land use type, and regional climate patterns (Zafra et al. 2017). Vehicle exhaust is a main contributor of Cr, Ni, Pb, while vehicle brakes and tire wear contribute to Cu and Zn deposition (Hong et al. 2018). Storm runoff and spring melt events transport heavy metals to nearby waters and soils. A 2021 study in the Gensburg-Markham Prairie Nature Preserve (City of Markham, Cook County, IL) adjacent to the I-294 corridor found that nature preserve surface soils were enriched with Pb, Cu, Zn, and P due to atmospheric deposition and runoff accumulation in low lying areas (Hernandez Gonzalez et al. 2019). Long-term, chronic heavy metal exposure represents a significant biodiversity threat to plants and animals by reducing fitness and reproductive success (Tovar-Sánchez et al. 2018), and may increase competitiveness of invasive species (Wang et al. 2020). Furthermore, the presence of high Cl^- concentrations in soils can mobilize heavy metal ions, exacerbating heavy metal leaching and groundwater pollution (Lazur et al. 2020).

Control, retention, and removal of salts and heavy metals is imperative to protect downstream water quality, biodiversity, and ecosystem services. Bioswale projects (a type of best management practice) are designed to slow and treat roadway runoff and thereby meter the release of salts and heavy metals. For instance, within the TB7B Illinois Tollway (Tollway) bioswales, roadside heavy metals outputs (Cr, Cu, Ni, Pb, and Zn) were reduced by ~83% (Miner et al. 2016). Other studies have shown that bioswale infrastructure significantly reduced Na^+ and Cl^- loads in effluent surface water via soil storage and groundwater infiltration (Burgis et al. 2020).

Harvesting wetland plant biomass from Tollway bioswales and retention basins in combination with the application of biochar is a promising technique to improve the sequestration and management of Cl^- and heavy metals. Biochar is a carbon-rich and porous material that is derived by heating organic waste biomass (i.e., wood waste, manure, municipal biosolids) in a low-oxygen environment to restrict combustion to ash (Zafra et al. 2017). As a soil amendment, biochar’s high porosity, surface area to volume ratio, and negatively-charged surface increases soil water storage, retains plant-available nutrients, and absorbs organic compounds (Hong et al. 2018), heavy metal cations, and salts (Hernandez Gonzalez et al. 2019). Biochar is effective in reducing bioavailability of heavy metals in plants resulting in improved plant growth (Houben et al. 2013; O’Connor et al. 2018) and reduced metal mobility (Lima et al.

2010; Puga et al. 2016). In terrestrial agroecosystems, biochar application has been shown to alleviate salt stress in plant rooting zones (Saifullah et al. 2018). To date, the mechanism for plant salt stress alleviation is unclear with unknown effect in saturated soils.

Mitigating downstream water quality issues by harvesting invasive plants in roadside detention basins and bioswales is a second novel approach with potential co-benefits. Cattails (*Typha* spp., hereafter *Typha*) and common reed (*Phragmites australis,* hereafter *Phragmites*) are large, ubiquitous invasive aquatic plants in roadside ditches, detention basins, and bioswales. Both species are adapted to degraded habitats with high salinity, and excess N and P (Farnsworth and Meyerson 2003; Tuchman et al. 2009). Invasion by these species results in reduced diversity of wetland plants, amphibians, invertebrates, and birds (Lawrence et al. 2016; Monfils et al. 2014; Rowe and Garcia 2014; Tuchman et al. 2009). Also, roadside ditches can act as invasion corridors through which invasive plants spread to previously uninvaded wetlands (Ahrens et al. 2014; Brisson et al. 2010). These plants are much taller and more productive than the species that they displace; their accumulating biomass (litter) acts as a slow-release reservoir for nutrients that contributes to eutrophication in aquatic habitats downstream. Within detention basins and bioswales, *Typha* and *Phragmites* dominance degrades both visual aesthetics, by blocking views, as well as the proper functioning of these engineered systems by clogging inlets/outlets and reducing infiltration rates and water storage capacity.

Typha and *Phragmites* actively take up and store N, P, and Cl^- (and other salts) in their aboveground tissues (Carson et al. 2018; Monteau et al. 2014), therefore, harvesting their biomass directly removes these pollutants from aquatic environments. Also, harvesting biomass can increase a wetland's ability to sequester and process P (Shukla et. al 2017; Tanaka et al. 2016). There is potential for harvested biomass to be utilized for bioenergy or agricultural use (Carson et al. 2018). A series of studies, conducted at a range of scales (1 - >100 acres), have tested the efficacy of harvesting invasive plants from the Great Lakes region wetlands and utilizing the biomass for various purposes. Several methods have been evaluated to utilize harvested biomass including for energy production (anaerobic digestion and biofuel pellets) and as an agricultural input (soil amendment, compost, and cattle bedding). This research has demonstrated the effectiveness of harvesting to increase native plant diversity and remove excess nutrients (Berke 2017; Keyport et al. 2018; Lishawa et al. 2015; Lishawa et al. 2017).

Researchers at Loyola and University of Connecticut have demonstrated that monotypic stands of wetland plants (specifically cattails [*Typha* spp.]) in Tollway retention basins readily accumulate high quantities of Cl^- in their tissue (Lawrence et al. 2022). Harvesting and removing these plants from bioswales provides a straightforward strategy to remove Cl^- (Monks et al. 2023; Schurkamp et al. 2024). This remediation strategy could be enhanced with the addition of biochar by promoting plant growth and subsequent uptake of Cl^-, reducing plant heavy metal stress, and reducing Na^+ toxicity. Studies of biochar application in wetlands show that nutrients (N and P) and heavy metals are retained at higher levels (Gupta et al. 2016; Rubin et al. 2020), and methane (CH_4) emissions are typically reduced with biochar application to flooded soils (Jeffery et al. 2016). It is currently unclear how biochar applications would affect Cl^- runoff in bioswales. Research on biochar in saline systems shows enhanced plant growth (Kasak et al. 2018), which increases the capacity for wetland vegetation to take up Cl^- ions, thus Cl- could be removed via biomass harvesting. Furthermore, harvested invasive biomass can be utilized as a composting and/or biochar feedstock as demonstrated in a previous research project between Loyola and the Tollway (Lawrence et al. 2022). Together, biochar application and harvesting are promising, but unexamined, management actions to increase bioswale functionality to reduce environmentally harmful Cl^- and heavy metals in roadway runoff, thus improving downstream water quality.

Preliminary results from a controlled three-month greenhouse experiment at Loyola demonstrate the potential for biochar addition in reducing Cl^- export from Tollway bioswales. In unplanted mesocosms containing roadside Tollway soils, preliminary results suggest that the high wood-waste biochar addition (5% soil weight [100 metric tons / hectare]) reduced Cl^- export when compared to biochar-absent treatments, indicating that biochar addition alone could reduce Cl^- from the system. Moreover, the 5% biochar treatment paired with cattails (*Typha* spp.) resulted in a significant reduction in Cl^- export over time compared to control soils and common reed (*Phragmites australis*) plantings (Fig. 2; Schurkamp et al. 2024). The significant species effect observed in the controlled study is attributed to cattail's capacity to better accumulate Cl^- in plant tissues; cattails have been shown to accumulate substantially greater quantities of Cl^- in their aboveground tissue than common reed (Fig. 1, Fig. 2) (Rozema et al. 2014). Tollway supported research by Loyola quantified plant tissue concentrations of salt and heavy metal ions in common reed and cattails and the potential for harvesting to remediate polluted soils (Monks et al. 2023). Due to this high Cl^- accumulation capacity and their presence as a dominant species within a significant portion of Tollway bioswales and retention basins, cattails are a strong candidate species for phytoremediation of the Tollway's bioswale and basin polluted soils (Delattre et al. 2022). The research conducted herein will help identify strategies to improve the longevity and remediation function of these runoff collection basins.

To scale-up biochar application to management-level practice in the Tollway system, research is necessary to understand the interacting plant-water-soil effects, assess the potential to increase the functional lifespan of bioswales, and quantify improvements to surface water runoff, groundwater, and soil properties in Tollway adjacent landscapes. This project attempted to address these questions while expanding upon previously conducted laboratory-scale research.

1.2 Research objectives

Our objectives were to evaluate the efficacy of biochar addition and biomass harvesting to enhance Cl^- and heavy metal removal potential from Illinois Tollway bioswales to improve water quality and address the Illinois Tollway *Research Tasks and Required Deliverables* A-E (RRFP #22-01) through a two-year integrated research project. We hypothesized two mechanisms by which biochar addition to bioswales would reduce Cl^- and heavy metal runoff to surface waters: a) Direct: biochar's high porosity and highly charged surface would directly adsorb Na^+ ions, heavy metals, and Cl^- containing compounds; b) Indirect: biochar would reduce plant Na^+ stress, increasing growth and uptake of Cl^- into plant tissues, which could be subsequently removed through biomass harvesting.

1.3 Research tasks

A. ISGS and Loyola reviewed previous research on Illinois Tollway bioswales, past water quality data, and the Chloride Reduction plan. Loyola researchers conducted and synthesized an additional literature review on biochar and its ability to enhance the capacity of bioswales to remove and reduce pollutants (i.e. chlorides and heavy metals) from stormwater runoff.

We accomplished this task by summarizing water-quality data collected within Tollway bioswales by our team members from the Illinois State Geological Survey (ISGS) / University of Illinois (Carr, Bryant, and Pociask), who have conducted water quality sampling for the Tollway since 2007 and bioswale water-quality monitoring since the first Tollway bioswales were installed in 2010. Additionally, we expanded on our existing biochar literature review to develop a comprehensive summary of biochar's potential to remediate and enhance water quality, considering the Tollway's *Chloride Reduction Plan.*

B. Loyola researchers evaluated how biochar application impacts soil and plant sequestration of salts and heavy metals.

To accomplish task B, we conducted a large-scale, fully-factorial, replicated experiment within Tollway bioswales. Using data and knowledge from our ISGS team members, we identified and selected 5 bioswales across the Tollway bioswale system to include in the study between Tri-State Tollway (I-294) Milepost 49.9 to 51.2. Three bioswale sites are located adjacent to southbound Tri-State Tollway (I-294) between Milepost 50.2 to 51.2; two bioswales sites are located adjacent to northbound Tri-State Tollway (I-294) between Milepost 49.9 to 51.3. To reduce variability and increase our ability to detect treatment effects, we chose 5 sharing similar hydrological and plant community characteristics. In Fall 2022, we applied treatments of 1) biochar to the selected bioswale locations at a rate of 0 metric tons [T] / hectare [ha] (i.e. control plots), and 20 T / ha and 2) selected areas for harvested aboveground biomass and unharvested controls. Additionally, we installed water level and specific conductivity probes (In Situ AquaTroll 200 data loggers) in each bioswale, to allow for continuous monitoring throughout the two-year experiment. In year-1 (Summer 2023) and year-2 (Summer 2024) following biochar application, we collected plant tissue and soil samples from bioswale plots. We chemically evaluated samples to determine their heavy metal and Cl^- concentrations. Additionally, we collected plant community composition and biomass data from the bioswales in order to extrapolate results to the full Tollway system (see tasks D, E and accomplishment table).

C. Loyola researchers determined the biochar saturation rate for adsorbing salts and heavy metals.

We accomplished this task by expanding on an existing pilot study undertaken by Loyola at the bioswale near southbound Tri-State Tollway (I-294) between Milepost 43.4 (i.e. TB7B) meant to determine the saturation rate of biochar in the field. In Spring 2021, we deployed 12 porous litter bags filled with biochar into the check-dams within bioswale TB7B. The bags were placed within the check-dam in order to allow for consistent saturation for all bags and to maximize saturation time. Each month following deployment, we collected a single litter bag. After 12-months (spring 2022), we analyzed the elemental chemical composition of all collected biochar samples to assess the adsorption capacity of salt ions and nutrients. The results of this preliminary study informed the design of a second field-scale biochar chemical saturation study to include greater replication, multiple sites (5-sites), and a longer time series (24-months). This second iteration biochar saturation rate study involved deploying five (5) large volume (~50lb) biochar bags near the outlets of five bioswales in the Tollway system. Subsamples were removed from the deployed biochar bags and chemically analyzed.

D. Loyola with support from ISGS evaluated how biochar application impacts soil and plant sequestration of salts and heavy metals and its effect on the life cycle of the bioswale or basin.

By comparing results from the experiments outlined in Task B and Task C, we evaluated both soil and plant chemistry of bioswales with and without biochar addition in harvested / unharvested locations. These results will inform Tollway managers about:

1. The salt and heavy metal removal capacities of bag-contained biochar near bioswale outlets as a tool to improve freshwater quality downstream. This research determined the efficacy of a movable / potentially replaceable biochar filtration system to control and contain salt and heavy metal pollutants.
2. The salt and heavy metal sequestration capacity of biochar applied as an amendment to improve retention of contaminants and water quality. Loyola evaluated retention of contaminants. ISGS aided the Loyola research team with monitoring and analysis of water depth and conductivity data at the inlet and outlet of select bioswales.
3. Any synergistic pollutant uptake improvement in aboveground cattail biomass in the presence of biochar application. This fully factorial research question informs Tollway managers of practical mitigation strategies to facilitate salt and heavy metal removal from the system via cattail harvesting.

E. Loyola researchers extrapolated the results to determine the potential to reduce Cl^- and heavy metals in the runoff, extend the life of the bioswales and to inform the Tollway of the potential for implementation Tollway system-wide and meet the Illinois State Water Quality Standard of 500 mg/L and the goals of environmental permit conditions.

Loyola analyzed the Tollway's Cartegraph system to catalog the total acreage of wet bioswales containing harvestable cattails as the dominant vegetation and apply results from our studies to estimate total removal and sequestration of Cl^- and heavy metals by harvest and biochar application per square meter.

2. The potential for biochar soil amendment and invasive plant harvest to enhance Illinois Tollway bioswale function: A literature review

2.1 Introduction

The Illinois State Toll Highway Authority (hereafter Tollway) system has made a commitment to research and develop innovative management approaches to common highway pollutants (e.g., chloride, heavy metals) associated with stormwater and snowmelt runoff. The Tollway system presently reduces downstream water quality impacts by utilizing roadside detention basins and bioswales. These engineered wetlands support a suite of ecosystem services while buffering water quality impacts associated with highway travel and winter road safety.

The goal of this research summary is to synthesize the capacity and absorption potential of engineered wetlands to mitigate highway chloride and heavy metal runoff. This review will also summarize the potential for biochar as a soil amendment and aboveground plant harvesting to increase the functioning of these engineered wetland systems to improve downstream water quality.

This review contains:

- A *Chloride and Heavy Metal Background Research Summary* to assess sources, sinks, and ecological impacts associated with highway systems at northern latitudes
- An assessment of the *Goals of the Illinois Tollway's Chloride Reduction Plan*
- A summary of *Research and Role of Illinois Tollway Bioswales* conducted to assess 'best management practices to reduce chloride and heavy metal runoff in the Illinois Tollway system
- A *Biochar and Invasive Plant Harvest Research Review* to understand potential tools to retain and enhance removal chloride and heavy metal from roadside wetland systems

2.2 Chloride and Heavy Metal Background Research Summary

In northeast Illinois, stormwater and snowmelt associated with highway routes results in downstream water flow containing elevated concentrations of chloride ions (Cl^-) and heavy metals (Pb, Cu, Zn, Cd, Cr) (Oberhelman and Peterson 2021). Soils adjacent to roadways act as pollutant sinks that accumulate salts and heavy metals over time (Rodríguez-Seijo et al. 2017). Regional climatic patterns, vehicle traffic densities, and land use are a major determining factor for road salt application rates and heavy metal concentrations in roadway-adjacent soils (Hintz et al. 2022). Therefore, directly adjacent wetland basins and bioswales can serve as a first line of defense to protect downstream water quality by containing, accumulating, and potentially removing detrimental aquatic pollutants associated with high-density urban traffic.

2.21 Chloride Assessment and Impacts

An emerging threat to the function of inland and coastal wetland ecosystems is the accumulation of soluble salts above natural levels, also known as salinization. Although salinity levels fluctuate naturally, anthropogenic sources represent the greatest contribution to freshwater salinization in the present day (Herbert et al. 2015). Specifically, North American inland freshwater ecosystems in colder climates are experiencing an accumulation of salt ions (Na^+, Cl^-) mainly derived from road salt application. Hintz et al. (2022) estimates that northern states apply between 175,000–1,000,000 metric tons of salt solids and 5-45 million metric liters of salt brines each year. As road safety in colder regions requires winter road salt application to prevent icy and dangerous conditions, the negative impacts of altered water quality by road salt must also be considered for flora, fauna, and ecosystem services.

In Illinois, highway water runoff often exceeds Illinois Environmental Protection Agency (IEPA) surface water quality standards for chloride (500 mg / L) in the Chicago-area Waterways System (CAWS) leading to elevated risks to ecological integrity and human health. In the Chicago region, road salt application for winter highway safety is the largest source of anthropogenic chloride (~450,000 metric tons introduced annually) (Kelly et al. 2012). In this publication, Kelly et al. (2012) also suggests that the vast majority of monitored rivers and streams in the Chicago region had significant increases in chloride and sodium concentrations since the 1970's, often exceeding 10 mg $liter^{-1}$ $year^{-1}$.

As expected, winter climatic patterns drive salt ion concentrations in waterways with increased salinity during winter and spring melt pulses. These pulses can leave a legacy of salt residues in soils and freshwater ecosystems, leading to elevated salts year-round (Kaushal et al. 2018). For example, Corsi et al. (2010) found that chloride concentration exceeded chronic water quality criteria at between 55-100% of monitored wetlands and inland lakes throughout the year in the lower Wisconsin region. After decades of road salt spreading and increased urban sprawl, northern freshwater ecosystems have higher conductivity leading to lower water quality, salty aquifers, stressful soil conditions for native plants, and an increased presence of salt tolerant invasive species (Thunqvist 2004; Chapra et al. 2009; Dugan et al. 2017; Kaushal et al. 2018). The annual salt pollution pressure in northern freshwater ecosystems, dubbed Freshwater Salinization Syndrome (Kaushal et al. 2021), is an urgent emerging concern in northern latitudes with few practical mitigation solutions.

Salt mitigation strategies must be implemented as high salinity levels reduce survival and abundance of aquatic organisms in the Great Lakes region leading to lower diversity and reduced ecosystem resilience (Piscart et al. 2006). As previously introduced, a high salinity legacy throughout the year leads to a deleterious response in aquatic organisms, plant growth, and macroinvertebrate development months even after winter application (Findlay and Kelly 2011). Organisms adapted to freshwater habitat do not have evolutionary mechanisms to adapt to large differentials in osmotic salt gradients common in anthropogenic systems. Furthermore, increased salinization can influence wetland biogeochemistry by decreasing inorganic nitrogen removal, limiting carbon storage, and increasing the generation of toxic sulfides (Herbert et al. 2015).

Reductions in freshwater biodiversity are often exacerbated by the spread of salt-tolerant invasive plant species such as the common reed (*Phragmites australis*) and cattails (*Typha spp.*). High density monocultures of these invasive species dramatically alter aquatic ecosystem structure and function compared to natural freshwater systems (Zedler and Kercher 2004; Vasquez et al. 2005). Invasive stands are known to displace native plant communities, homogenize habitats, and alter the nutrient composition of soil (Tuchman et al. 2009; DeRoy and MacIsaac 2020). Particularly, the dense layer of leaf litter that accumulates in mature stands of both species drives changes to soil temperature, light penetration, and nutrient dynamics, further driving unfavorable conditions for native plant growth (Holdredge and Bertness 2011; Larkin et al. 2012). The aggressive nature of these plants complicates restoration efforts, as multiple years of management are typically required to reduce competitive advantages (Bonello and Judd 2020). As such, high salinity concentrations in freshwater ecosystems must be addressed to improve ecosystems services and promote biodiversity.

2.22 Heavy Metal Assessment and Impacts

Heavy metal deposition and accumulation in roadway-adjacent soils depends on vehicle traffic densities, land use type, and regional climate patterns (Zafra et al. 2017). Vehicle exhaust is a main contributor of Cr, Ni, Pb, while vehicle brakes and tire wear contribute to Cu and Zn deposition (Hong et al. 2018). Storm runoff and spring melt events transport heavy metals to nearby waters and soils. A 2021 study in the Gensburg-Markham Prairie Nature Preserve (City of Markham, Cook County, IL) adjacent to the I-294 corridor found that nature preserve surface soils were enriched with Pb, Cu, Zn, and P due to atmospheric deposition and runoff accumulation in low lying areas (Hernandez Gonzalez et al. 2019). A review by Werkenthin et al. (2014) found that heavy metals are deposited by wind and water, leading to highest metal concentrations within 10 meters of a paved surface and in the upper 15 centimeters of soil. Thus, bioswale construction adjacent to highways can play a significant role in buffering ecosystems and communities further from the roadway.

Chronic heavy metal exposure to organisms represents a significant threat to plants and animals by reducing fitness and reproductive success (Tovar-Sánchez et al. 2018) and may increase the competitiveness of invasive species (Wang et al. 2020). Research suggests that both *Phragmites australis* (Bonanno and Lo Giudice 2010) and *Typha* spp. (Taylor and Crowder 1983) accumulates heavy metals in tissues with highest concentrations in belowground roots and rhizomes. Heavy metals that bioaccumulate can be found in greatest concentrations within the tissue of top predators such as fish in an aquatic food web from soils to plants to herbivores to predators (Garai et al. 2021). High concentrations of sodium and chloride ions in Tollway soils exacerbate metal toxicity by mobilizing heavy metals via ion exchange alterations in soils (Corsi et al. 2010; Schuler and Relyea 2018; Lazur et al. 2020).

2.23 Section Summary

Salt and heavy metal pollution transported into inland freshwater aquatic ecosystems via terrestrial run-off must be addressed near the pollution source (Jenny et al. 2020). For example, the Chicago Metropolitan Agency for Planning (CMAP) estimates that most sampled streams and rivers in the seven counties of northeastern Illinois are rated as poor to moderate in terms of biological quality. Great Lakes and Mississippi River water quality are inseparable from Chicagoland's low-quality rivers streams and inland waterways. Reversing the degradation of our regional water quality is critical for protecting the function of regional ecosystem services, wildlife habitats, and healthy human communities.

2.3 Goals of the Illinois Tollway's Chloride Reduction Plan

The IEPA assesses the state's water quality including chloride concentrations in surface waters. Water bodies that routinely exceed the 500 mg/L standard for chloride may be designated as impaired. Illinois Tollway roads intersect with several watersheds and water bodies in northeastern Illinois that have been designated as chloride impaired by IEPA, including Higgins Creek, Salt Creek, Addison Creek, the West Branch DuPage River, and the Des Plaines River watershed. Total Maximum Daily Loads (TMDLs) have been established in several of these watersheds to provide a target for restoring water quality and require that the Tollway reduce chloride loads to its receiving waters. Additionally, several Tollway construction projects in the *Move Illinois* program drain into IEPA impaired water bodies. To advance these projects and mitigate water quality impacts, the Tollway obtained Section 401, Clean Water Act Water Quality Certification Program permits requiring no net increase in salt usage. This permitting process resulted in the Tollway developing a two-part chloride reduction approach: a) reducing winter salt use within the project corridors and 2) the development of an offset program, wherein communities in the region receive grants from the Tollway to decrease salt application rates on arterial roadways. These efforts alone were not sufficient to meet current Tollway chloride reduction targets. Therefore, a range of additional approaches are necessary to achieve chloride reduction goals.

To achieve chloride reduction requirements, the Tollway has developed a strategy to reduce chloride across the roadway system (*Refined salting strategy for the Illinois Tollway to reduce chloride use*) (CDM Smith 2022). The primary goal of the Tollway chloride reduction plan is no net increase in salt applications from pre-project estimates plus an additional 25% reduction for added project lane-miles. The Tollway refined salting strategy report provides a summary of *Best Practices* which, if employed, could help Tollway achieve its chloride reduction goals. Promising application techniques include increasing liquid (e.g., brine, calcium chloride enhance brine, and slurry) and decreasing granular application of road salt. If applied across the system and paired with additional *Best Practices*, the Tollway has the potential to reach its chloride reduction targets (CDM Smith 2022). If the post-project salt targets are reached, these actions would result in a reduction of total salt applied to the Tollway by approximately 2,000 tons/year from the pre-project salt application rates, and approximately 9,666 tons/ year from a ‘business as usual’ approach with increased lane-miles added to the system (CDM Smith 2022).

2.4 Research and Role of Illinois Tollway Bioswales

During reconstruction of the Tri-State Tollway (I-294), the Tollway installed a series of bioswale stormwater management systems intended to reduce runoff volumes and pollutant loads to downstream natural areas (Bryant et al. 2020). *Tollway* bioswales are of two types: *Wet bioswales*, which are designed to retain runoff and *Dry bioswales,* which are designed to infiltrate runoff. The Illinois State Geologic Survey (ISGS) was contracted to monitor the efficacy of these new systems.

The ISGS has continually monitored the effectiveness of bioswales to improve Tollway runoff water quality on I-294 in northern Cook County, IL. For the main assessment study, bioswales were monitored for one year pre-installation (2009-2010) to twelve years after installation (2010-2023). Four bioswales were selected from the *wet* and *dry* bioswale types for intensive monitoring of water and soil metrics including: discharge volume, chloride and other select ion concentrations, total dissolved solids, pH, specific conductivity, turbidity, and soil heavy metal concentrations. To evaluate bioswale efficacy, ISGS scientists compared runoff water quality values from pre- and post-construction and from bioswale inputs and outputs (i.e., within a bioswale). Results demonstrate that both wet and dry roadside bioswales attenuate for chlorides and decrease total suspended solids, total dissolved solids, and roadway metals of interest (chromium, copper, lead, nickel, and zinc) from bioswales on I-294 (Miner et al. 2016). From 2011 through 2015, TB7B reduced runoff volume by an average of 31%, although other monitored bioswales with higher groundwater contributions showed increases in output volume. All monitored bioswales reduced total dissolved solids by an average of 42%, TSS of exported water by an average of 63%, and reduced roadway metals of interest transport by an average of 71%. Miner et al. (2016) also found that bioswales installed along the I-294 highway reduced chloride in runoff by up to 44% likely driven by infiltration and discharge volume reduction. Chloride concentrations may also have been reduced by dilution from rainwater, surface water overflow, or ground water. In the most recent monitoring year (2022), wet bioswale TB7B reduced total chloride load by 93%, and dry bioswale TB15B reduced chloride concentration by 70% (Carr et al., 2023).

Despite the efficacy of bioswales to improve runoff water quality, mean chloride concentrations of bioswale runoff exceeded the Illinois General Use Standard of 500 mg/L in all but one bioswale between 2012-2016. These results indicate chronic exceedance of the standard and a need for increased chloride reduction (Miner et al. 2016). Miner et al. (2016) provided a list of nine recommendations for improving functioning of future bioswales:

> *1) reduction or elimination of point-source inputs, 2) converting bioswales to a treatment train by alternating wet and dry segments prior to release of runoff to local streams, 3) siting of bioswales where they will not receive high solute groundwater inputs, 4) increasing of storage attenuation via sizing of bioswales and input/output structures, 5) installing check dams in dry bioswales to increase storage and reduce erosive overflows and flow velocities, 6) increasing dilution by increasing inputs from non-roadway surfaces, 7) increasing infiltration by siting bioswales in coarse-grained native sediments, 8) increasing temporary storage (attenuation) in dry bioswales by reducing the grain size of coarse backfill and underdrain diameter or open area, and 9) preventing erosion of dry bioswale surfaces through increased efforts to establish plants, such as additional plant bedding material or manipulation of the projected water table between storm events via backfill and underdrain choices.*

2.5 Biochar and Invasive Plant Harvest Research Review

2.51 Invasive Plant Wetland Impacts and Harvesting Research Review

Restoration ecologists and researchers are responding rapidly to develop nature-based and technological-based solutions to address aquatic pollution and invasive species proliferation. International trade, agricultural and urban eutrophication, and the anthropogenic climate crisis drives Great Lakes regional susceptibility to biological invasion (Ricciardi et al. 2000; Ricciardi 2001). Wetlands in the Great Lakes region are now encroached upon by invasive perennial rhizomatous plants such as the common reed (*Phragmites australis*) and hybrid cattail (*Typha* × *glauca*) (Carson et al. 2018). Hybrid cattail and common reed vigorously respond to elevated aquatic nutrient and salinity conditions and shift plant communities from diverse native plant dominance to monocultures (Woo and Zedler 2002; Larkin et al. 2012). These monocultures reduce plant and animal community diversity and disrupt historical wetland biogeochemical and ecosystem service function (Bansal et al. 2019).

To date, the most widely utilized method to reduce the spread of invasive *Phragmites australis* and *Typha* spp. is herbicide (Hazelton et al. 2014). While generally effective at killing the target species, this technique reduces native plant diversity and increases porewater nutrient concentrations, creating conditions in which reinvasion is likely (Lawrence et al. 2016). Herbicide application neither prevents nor removes the leaf litter accumulation which suppresses plant growth below the litter layer. Furthermore, aquatic herbicide application has been shown to reduce macroinvertebrate species diversity (Robichaud et al. 2022) and amphibian survival (Relyea 2005). Restoration ecologists should use best land management practices (i.e., plant harvesting, controlled burns) to avoid herbicide toxicity and reduce these aggressive clonal aquatic invaders for the betterment of wildlife habitat (Hazelton et al. 2014).

Harvest and removal of invasive macrophytes offer unique advantages without the drawbacks associated with herbicide application. Harvesting aquatic invasive plants is a highly effective land management approach to reduce monoculture biomass and create an open habitat for native wetland plants and animals to thrive. Well-timed harvesting reduces the overwinter storage of plant nutrients translocated from aboveground tissues to plant rhizomes during fall senescence, thus reducing plant vigor in the following growing season. Large-scale experiments have shown that repeated harvesting of *Typha* spp. in Great Lakes coastal wetlands increases biodiversity and habitat complexity in previously suppressed systems (Lishawa et al. 2015a, 2017). Harvesting also influences chemical dynamics on a landscape scale. For example, Carson et al. (2018) found that large-scale harvest of invasive *Phragmites*, *Typha* spp. and *Phalaris arundinacea* has the potential to significantly influence nutrient dynamics of Great Lakes coastal wetlands. These large plants uptake a significant amount of phosphorus and nitrogen, which are then removed from the system via harvest rather than retained in the litter after the growing season.

A harvest-removal mechanism in impaired wetland systems has the potential to decrease additional pollutants on-site. For example, *Typha* spp. and *Phragmites* have been studied for heavy metal removal in regions where these plants are native (Sasmaz et al. 2008; Kumari and Tripathi 2015; Hejna et al. 2020a). In the context of salt mitigation, phytoremediation literature generally minimizes the potential of salt uptake as a mitigation strategy, implying the primary mechanism of salt removal is the plant-soil interactions that promote sodium leaching (Qadir et al. 2001, 2005). However, differences in experimental design and a focus on crop species throughout the literature suggest the overall effect of uptake may be greater than accepted (Rabhi et al. 2009; Jesus et al. 2015).

In a recent Tollway research project, Loyola and University of Connecticut (UConn) researchers have demonstrated that monotypic stands of wetland plants (specifically cattails [*Typha* spp.]) in Tollway retention basins readily accumulate high quantities of chloride in their tissue (Monks et al. 2023). Harvesting and removing these plants from bioswales provides a straightforward strategy to remove chloride. Although harvesting is very promising, soil amendment application (i.e., biochar) may further increase aboveground biomass and pollutant uptake (i.e., chloride, heavy metals) into plant tissues. Harvesting wetland plant biomass from Tollway bioswales and retention basins in combination with the application of biochar is a promising avenue to further improve the sequestration and management of chloride and heavy metals, but further research is necessary.

2.52 Biochar Application in Wetland Restoration

Biochar (i.e., manufactured black carbon) is produced by super-heating organic waste material (e.g., wood, biosolids, invasive species biomass) to temperatures between 350º C - 700º C in a low oxygen kiln that restricts combustion to CO_2. An emerging soil amendment in terrestrial systems, biochar has the potential to chemically immobilize reactive nitrogen / phosphorus (Nelson et al. 2011; Dai et al. 2020), bind aqueous heavy metal pollutants (Qiu et al. 2021), alleviate road salt stress in plants (Ali et al. 2017), and increase long-term soil carbon storage (Lehmann et al. 2003). Furthermore, because biochar is recalcitrant, it can resist microbial degradation for 100-1000+ years when added to soils thus storing carbon over a long-term (Glaser et al. 2002).

As biochar production and application is a relatively new technology, many basic research questions still must be addressed as industry ramps up production globally. Research investigating multi-year soil and plant responses to biochar has garnered attention in agricultural spheres due to increases in crop productivity and nutrient retention properties (Amoah-Antwi et al., 2020). Although research is sparse, the use of biochar application specifically in ecosystem restoration as a tool to improve plant community biodiversity has been reviewed (Beesley et al. 2011; Biederman and Harpole 2013; Thomas and Gale 2015; Amoah-Antwi et al. 2020) but rarely explored in large, multi-year field studies (Sovu et al. 2012; van de Voorde et al. 2014; Ohsowski et al. 2018). To date, the application of biochar in aquatic systems for salt and nutrient pollution removal is not well-studied outside of small-scale laboratory analyses and managed wastewater treatment systems. Evaluating biochar's potential for chemical retention and pollution mitigation in the Great Lakes region's aquatic ecosystems requires long-term controlled laboratory experiments and concurrent large scale field studies.

Biochar as a remediation strategy has the potential to enhance plant growth and subsequent uptake of chloride, reduce plant heavy metal stress, and reduce sodium toxicity (Kasak et al. 2018). Studies of biochar application in wetlands show that nutrients (P and N) and heavy metals are retained at higher levels (Gupta et al. 2016; Rubin et al. 2020) and methane (CH_4) emissions are typically reduced with biochar application (Jeffery et al. 2016). In terrestrial agroecosystems, biochar application has been shown to alleviate salt stress in plant rooting zones, but literature primarily focuses on the growth responses of crop plants to biochar addition rather than the mechanisms by which plants are freed from salt stress (Saifullah et al. 2018; Chen et al. 2018). Due to a high cation exchange capacity, biochar has been shown to increase salt tolerance of terrestrial plants by improving soil properties to increase plant growth via salt protection and increased nutrient availability (Ali et al. 2017; Moradi et al. 2019). In one study in China's Yellow River delta, authors Xiao and Meng (2020) suggested biochar application alleviates salt stress by leaching sodium ions through replacement on cation exchange sites, but few other studies exist to corroborate such findings. At present, it is unclear whether biochar meaningfully lowers baseline soil salinization, or whether this effect is due to: 1) an increase in plant uptake, or 2) changes to soil properties which facilitate the leaching of detrimental salt ions. Understanding how biochar releases plants from salt stress and its role in ion mobility would provide necessary information on its potential as a tool in salt mitigation.

Enhanced plant growth increases the capacity for vegetation to assimilate chloride and heavy metal ions, and biomass could then be harvested from wetland complex to remove target ions. Preliminary results from a controlled three-month greenhouse experiment at Loyola demonstrate the potential for biochar addition to reduce chloride export from Tollway bioswales. In unplanted mesocosms containing roadside Tollway soils, results suggest that the high wood-waste biochar addition (5% soil weight [100 metric tons / hectare]) reduced chloride export when compared to biochar-absent treatments(Schurkamp et al. 2024). These results indicate that biochar addition alone could reduce chloride export from the system. Moreover, the 5% biochar treatment paired with cattails (*Typha* spp.) resulted in a significant reduction in chloride export over time compared to control soils and common reed (*Phragmites australis*) plantings (Schurkamp et al. 2024). Cattails have been shown to accumulate substantially greater quantities of chloride in their aboveground tissue than common reed (Monks et al. 2023; Schurkamp et al. 2024). Furthermore, Tollway supported research by Loyola and UConn quantified plant tissue concentrations of salt and heavy metal ions in common reed and cattails growing in Tollway detention basins to elucidate the potential for harvesting to remediate polluted soils (Monks et al. 2023). Due to this high chloride accumulation capacity and their presence as a dominant species within a significant portion of Tollway bioswales and retention basins, cattails are a strong candidate species for phytoremediation of the Tollways's bioswale and basin polluted soils by harvesting in the summer and then add the biochar bags at the outlets.

2.6 Synthesis of Biochar, Plant Harvesting, and Bioswales

Bioswales, constructed channels designed to filter stormwater runoff through vegetated areas, have been shown to significantly reduce downstream salt levels and retain heavy metals (Mazer et al. 2001; Anderson et al. 2016). Together, biochar application and harvesting are promising management actions to increase bioswale functionality to reduce chloride and heavy metals concentrations from highway water runoff. To scale-up biochar application to management-level practice in the Tollway system, research is necessary to understand the interacting plant-water-soil effects, assess the potential to increase the functional lifespan of bioswales, and quantify improvements to surface water runoff, groundwater, and soil properties in Tollway adjacent landscapes. This project expands upon previously conducted laboratory-scale research to develop an innovative biochar application strategy coupled with the plant phytoremediation potential at a scale applicable to Tollway managers. The incorporation of biochar and aboveground plant harvests into existing Tollway bioswales has the potential to increase bioswale water quality remediation, thereby helping to improve downstream water quality to the benefit of natural ecosystems and humanity.

3. Evaluating the effects of biochar addition and biomass harvesting on bioswale function: A field experiment

3.1 Study objectives

A) Evaluate the effects of biochar addition and biomass harvest on salt and heavy metal retention

To accomplish this objective, we conducted a large-scale, multi-year fully-factorial experiment within Tollway bioswales. Using data and knowledge from our ISGS team members, we identified and selected 10 bioswales across the Tollway bioswale system to potentially include in the study. To reduce variability and increase our ability to detect treatment effects, we chose 5 pairs of bioswales sharing similar hydrological and plant community characteristics. In Fall 2022, we applied biochar to five of the selected bioswales at a rate of 20 T / ha; the second bioswale of each pair were treated as an experimental control. Nested within each biochar and control bioswale section, half of each unit was designated to be harvested in Fall 2022 and Fall 2023 to serve as the aboveground harvest treatment. Interacting treatment effects of biochar and aboveground harvest were assessed to determine Cl^- and heavy metal concentrations over the study period. Additionally, we installed water level and specific conductivity probes (In Situ AquaTroll 200 data loggers) in each bioswale to allow for continuous monitoring throughout the two-year experiment. In year-1 (Summer 2023) and year-2 (Summer 2024) following biochar application, we collected plant tissue, and soil samples, from all 10 bioswales. We chemically accessed ionic concentrations (ppm) of plant tissue and soil samples to determine heavy metal and Cl^- concentrations. Additionally, we collected plant community composition and biomass data from the selected 5 bioswales in order to extrapolate results to the full Tollway system (see tasks D, E and accomplishment table).

B) Determine the biochar saturation rate for adsorbing salts and heavy metals

We sought to determine the saturation rate for biochar to sorb Cl^- and heavy metal concentrations through a field experiment conducted within the Tollway bioswales selected in the study. To accomplish this, we deployed bags of wood-waste biochar at the end of the experimental stretch of each bioswale, collected biochar subsamples through time, and evaluated ionic concentrations extracted from the biochar samples.

3.2 Methods

3.21 Bioswale Selection

After consulting with Tollway staff and partners, we selected 5 bioswales to include in the study using the Illinois Tollway Cartegraph system and the following selection criteria:

1. **Bioswale Type:** IS Type 2 – Wet
2. **Route:** IS I-294
3. **Length.amount:** Is Greater Than (>) 150
4. **Length.amount:** Is Less Than (<) 1000

The selected criteria generated a list of 28 potential bioswales that would account for the implementation of the experimental design, study objectives, an ecologically meaningful scale, and provide applicable management interpretations. To select candidate bioswales, Geoffrey Pociask and Keith Carr of ISGS shared expertise of Tollway bioswales with Loyola researchers Brian Ohsowski, Sam Schurkamp, and Shane Lishawa to finalize site selection for research project establishment.

Between September 27 and October 6, 2022, we scouted candidate bioswales and selected five (5) bioswales between Tri-State Tollway (I-294) Milepost 49.9 to 51.2. Three bioswale sites are located adjacent to southbound Tri-State Tollway (I-294); two bioswales sites are located adjacent to northbound Tri-State Tollway (I-294) (Fig. 1; Table 1). Bioswales were selected based on vegetation similarity along the length of the bioswale, presence of our target plant species (*Typha* sp.; common name: cattail), minimal apparent external hydrological inputs into bioswales, and hydrological similarity across the bioswales.

As outlined in the April – June 2023 quarterly report, one replicate bioswale was completely removed from the study. This bioswale was heavily disturbed by a mowing accident on 5-31-2023. Within this experimental unit, the vegetative community, hydrology, and soils were compromised for this replicate block thus reducing our replication from 5 blocks to 4 blocks. The mowing accident also impacted AquaTROLL specific conductivity (µS/cm) loggers data collection and the biochar bag deployment phase of the experiment.

Figure 1 Locations of the five bioswales included in the study within the Illinois Tollway system. Five (5) blocked bioswales were chosen along Tri-State Tollway (I-294) Milepost 49.9 to 51.2. Two (2) bioswales located northbound; Three (3) bioswales located southbound.

Bioswale #4 removed due to gouged bioswale after mowing equipment accident in the plot.

Table 1 Bioswales selected in the Tollway Cartegraph system that meet criteria for experimental selection. The column entitled “Chosen for Experiment” represents the selected bioswale location in the funded study.

Bioswale ID	Bioswale Type	Location description	Direction	Chosen for Experiment	Notes
294N050.23BSW050.26	Type 2 - Wet	42.3	northbound	NO	
294N050.38BSW050.49	Type 2 - Wet	49.9	northbound	YES	
294S043.74BSW043.88	Type 2 - Wet	49.9	southbound	NO	
294S043.59BSW043.73	Type 2 - Wet	50.2	southbound	YES	
294S051.21BSW051.35	Type 2 - Wet	51.3	southbound	YES	
294S050.79BSW051.15	Type 2 - Wet	51.1	southbound	YES	
294N050.01BSW050.23	Type 2 - Wet	50	northbound	NO	
294N050.26BSW050.38	Type 2 - Wet	50.2	northbound	YES	REMOVED due to major disturbance

3.22 Experimental Design

An experimental paired block design was finalized in October 2022 at the five (5) selected bioswales that met the criteria stated in the previous section. The fully-factorial experimental treatments were as follows:

- Twenty (20) metric tons [T] / hectare [ha] biochar: *Application / No Application*
- Vegetative biomass harvest and removal: *Harvest / No Harvest*

Within each block, experimental treatment units (hereafter “cells”) were approximately 4 m wide × 10 m long (Fig. 2). Each cell contains three (3) equidistant and permanent 1-meter squared subplots for data collection (Fig. 2).

Pre-treatment Data Collection

After plot establishment, pre-treatment vegetation data and soil samples were collected and analyzed to determine block similarities. Note that no significant differences were detected across all collected variables in Fall 2022 [living cattail cover, total plant litter, soil ion concentration (chloride, heavy metals)(ANOVA: $p > 0.05$)]. Pre-treatment data was collected prior to the first aboveground biomass harvest and the single biochar application.

Initial Fall 2022 Aboveground Biomass Harvesting

The first aboveground biomass harvest was conducted with aquatic weedwhackers capable of cutting biomass underwater in corresponding cells in early November 2022 (Fig 3a). All living and standing-dead biomass was clipped near the soil surface, raked, and hand-removed from the treatment. Vegetation was removed to simulate an aboveground mowing treatment and mechanical biomass removal.

Single 20 T/ha Biochar Application

Biochar was hand applied at a rate of 20 T/ha (17,843 lb/acre) to corresponding cells between November 20, 2022 – November 21, 2022 (Fig. 3b). In the appropriate treatment areas, biochar was spread on the surface of each bioswale and evenly raked to ensure homogenous coverage of the soil amendment. Note that biochar was only applied once during the experimental study period.

Water Depth and Conductivity Probe Installation

We installed water depth / conductivity probes (AquaTROLL 200 Data Logger, In-Situ Inc. Fort Collins CO, USA), in each bioswale to monitor water level variation and electroconductivity signals (Fig. 2). Probes were deployed in December 2022 and removed in October 2024 thus covering data collection across the span of the study period. In each block, three (3) AquaTROLL specific conductivity (µS/cm) loggers data loggers were installed between December 5, 2022 – December 9, 2022 to continuously monitor water depth and conductivity (as a surrogate for chloride) for the duration of the experiment. AquaTROLLs were installed within Telespar posts at the input of each block, between no-biochar applied and biochar applied cells, and the terminus of each block (Fig. 1). To concentrate water flow to the AquaTROLL Data loggers, Telespar posts were sunk at the terminus of a concrete ditch checks when present. If no concrete ditch checks were present, a single line of 70-lb sandbag tubes were laid to span the bioswale in a chevron pattern. The sandbags served to direct water flow to the AquaTROLL data loggers (Fig. 3c). AquaTROLL probes were collected and calibrated periodically to ensure proper function and range standardization.

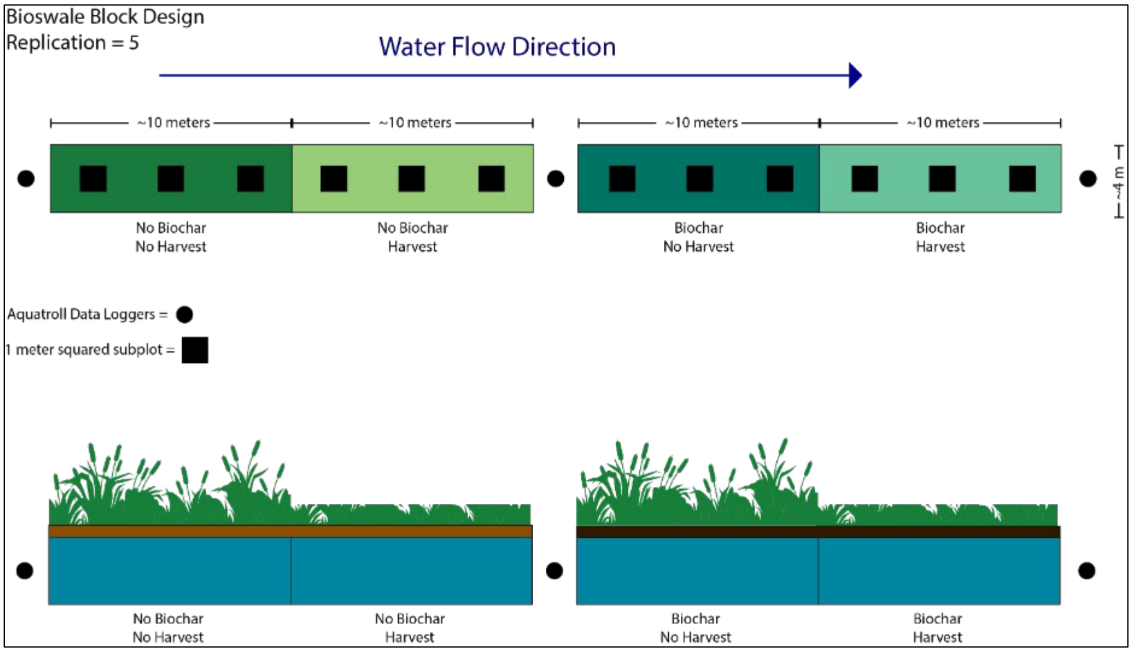


Figure 2 Bioswale block design illustrating the employed treatments (no biochar, no harvest; no biochar, aboveground harvest; 20 T/ha (17,843 lb/acre) biochar, no harvest; 20 T/ha (17,843 lb/acre) biochar, aboveground harvest), locations of water-level and electroconductivity probes, subplot locations, and water flow from an aerial view (above) and cross-section (below).

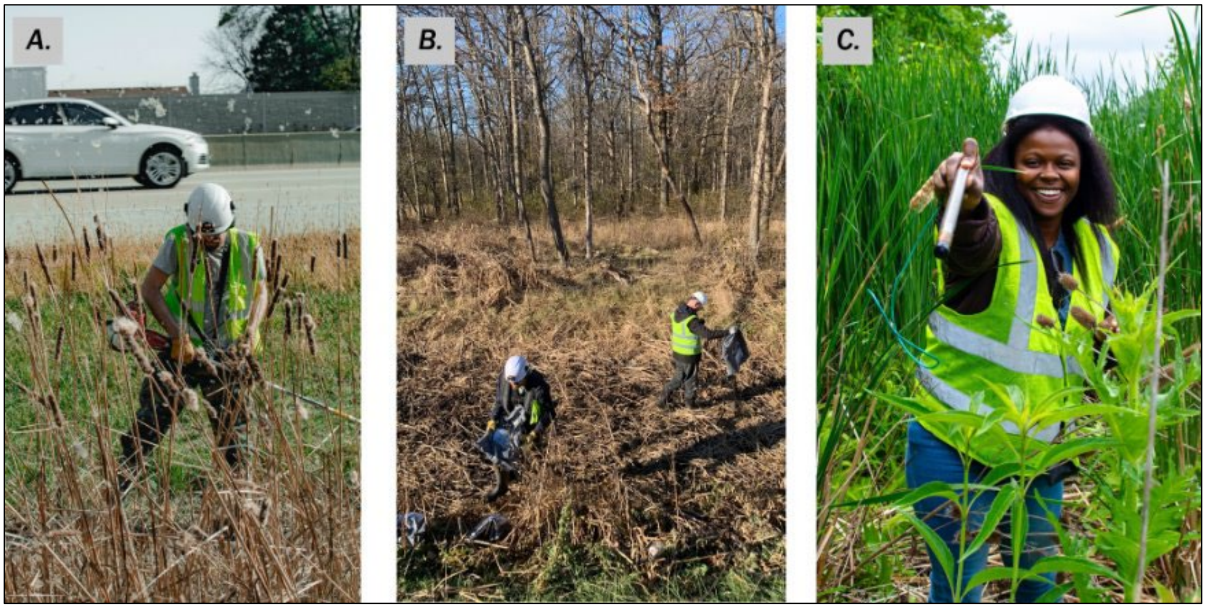


Figure 3 A. Harvest plot establishment (Oct 2022), B. Biochar application [20 T/ha (17,843 lb/acre)] (Oct 2022), C. Probe Installation and Monitoring (Dec 2022 – November 2024).

3.23 Field Methods

Vegetation Sampling

In Fall 2023 and Fall 2024, we collected vegetation data from all bioswales to capture peak plant community growth prior to fall vegetative die-back. Within each 1 × 1 m subplot (Fig. 2), we estimated the total vegetation cover, cover of each plant species present, and litter cover to the nearest percentage value. Additionally, we collected plant and litter tissue samples from each bioswale for chemical analyses. To accomplish this, we randomly selected and collected a *Typha* stem within each subplot and collected a random grab sample of approximately 100 g of standing dead litter. All living and dead tissue samples were dried and ground in the lab prior to chemical analyses.

Typha heights and inflorescence presence were measured in each subplot for all aboveground stems per m^2 in Fall 2023 and Fall 2024. This sampling period captured peak biomass before plant senescence prior to the onset of winter. Individual aboveground *Typha* stem biomass was predicted via the developed standard curve and summed per subplot for each season resulting in an estimate of grams *Typha* biomass / m^2.

To assess predicted *Typha* biomass non-destructively in the field, a standard curve and biomass prediction procedure was developed and published in Ohsowski et al. (2024). Briefly, single *Typha* stems were measured in the field with a suite of variables to potentially predict aboveground *Typha* biomass. *Typha* stems were collected, dried at 60^{o} C, and weighed. In Ohsowski et al. (2024), the study selected *Typha* height, inflorescence presence, and stem circumference at 30 cm as the highest resolution predictors of biomass in the field. In the Tollway field study, the second highest resolution predictive model (aboveground *Typha* heights and inflorescence presence) was employed in the field due to the time intensity of measuring stem area at 30 cm. For further details on the model selection technique, see Ohsowski et al. (2024).

Soil Sampling

During each Fall sampling period, we collected one soil sample in each subplot using a 3.6-cm radius × 10-cm depth bulb planter. Soils were labeled, bagged, and frozen until sample analyses were conducted at Loyola. Prior to chemical extraction for ionic analyses, soils were thawed, dried, and ground to ensure a homogenized sample.

AquaTROLL and BaroTROLL Continuous Monitoring

AquaTROLL data loggers collected pressure and specific conductivity (SC) data points every 15 minutes during the study period. Chloride concentrations (mg/L) were estimated from 15-minute interval specific conductivity values using an ISGS model developed from 94 bioswale samples that equate with AquaTROLL derived field specific conductivity data with laboratory measured chloride conductivity data ($R^2 = 0.98$; Appendix A).

Biochar Bag Saturation Curve Study

Three jute sacks were filled with roughly 30 pounds of biochar and deployed at the end of each experimental block on April 6, 2023 (Fig. 2; Fig. 4). Due to unforeseen conditions, jute bags disintegrated rendering experimental data collection impossible by September 2023. To adjust the experiment design, biochar bags were redeployed in plastic flow-through bags in the field on October 20, 2023. Baseline biochar samples were archived to establish a time zero data set. To establish the saturation curve for ionic sorption, biochar subsamples were collected over one year at five time points (12-19-2023, 4-22-2024, 5-29-2024, 9-13-2024, and 10-30-2024).

Figure 4 Original jute biochar sacks deployed at the end of each bioswale block to investigate biochar chemical surface adsorption and biochar saturation rates. These biochar bags were replaced with plastic flow-through bags which were sampled at five-time intervals to establish the biochar saturation curve in the field.

3.24 Lab Analyses

Plant Tissue Chemical Analysis

Plant aboveground biomass and litter samples were oven dried at 60° C for 48 hours and then ground in a Thomas Wiley® mill prior to chemical analyses. Tissue samples were prepared for ionic analyses with HCl extraction following a protocol modified from Cataldi et al. (2003). Cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (Cl^-, PO_4^{3-}, NO_3^-) were quantified with ion chromatography (IC) in Loyola's analytical chemistry lab.

Soil Chemical Analysis

Soils were dried samples for 48 hours at 60° C, sieved using a 2-mm sieve to separate out roots, and pulverized in a Humboldt Soil Grinder w/ 10 plate. Soil samples were prepared for ionic analyses with HCl extraction following a protocol modified from Cataldi et al. (2003). Cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (Cl^-, PO_4^{3-}, NO_3^-) were quantified with ion chromatography (IC) in Loyola's analytical chemistry lab. Soil samples were sent to the University of Delaware Soil testing Lab (UDSTL) for heavy metal analyses (As, Cd, Co, Cr, Cu, Ni, Pb, Zn) following EPA3051 protocols (USEPA 2007).

Biochar Bag Saturation Curve Chemical Analysis

Biochar samples were dried at 60°C for 48 hours, pulverized in a Humboldt Soil Grinder w/ #10 plate, and stored at Loyola prior to chemical analyses. Biochar samples were prepared for ionic analyses with HCl extraction following a protocol modified from Cataldi et al. (2003). Cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (Cl^-, PO_4^{3-}, NO_3^-) were quantified with ion chromatography (IC) in Loyola's analytical chemistry lab. Samples were analyzed for heavy metals (As, Cd, Co, Cr, Cu, Ni, Pb, Zn) by the University of Delaware Soil Testing Lab following EPA3051 protocols (USEPA 2007).

3.25 Data Analyses

3.25.1 Field Sample and Biochar Bag Saturation Curve Statistical Analyses

The field study employed a nested repeated measures design to track changes in soil and plant response, thus requiring linear mixed effects (LME) modeling using the lme4 package in R (Bates et al. 2015). Fixed effects terms (i.e. harvest / no harvest, 20 T/ha biochar / 0 T/ha biochar) were assessed with a Bayesian Information Criteria (BIC) model selection analysis to statistically choose the best fitting model from a matrix of log10 and square root transformed models with and without interaction possibilities. BIC model values with delta ≤ 2 are considered statistically equivalent. Each model included a random effect structure (1|time/block) to account for repeated multiple time point measurements at each block and subplot location. After selecting the best fitting model, estimated marginal means (EMMs) were calculated to determine treatment level contrasts using the emmeans package in R. Reported p-values ($p \leq 0.05$) and trends ($0.10 \geq p > 0.05$) for each statistical contrast are displayed graphically with each LME analysis. All LME model assumptions were assessed to confirm residual normality and homogeneity of variance. All statistical analyses were conducted in R version 4.4.2 and R Studio version 2024.12.0 (R Core Team 2024, RStudio Team 2024). As Bioswale #4 was compromised during the experiment, all Bioswale #4 data were removed from the statistical analyses for continuity.

Statistical procedures for the biochar bag saturation curve objective employed a similar repeated measure approach by subsampling deployed biochar bags multiple times during the experiment. Model selection, statistical analyses, and interpretation procedures followed a similar LME protocol described above. Each model selection iteration included a fixed effect (i.e. sample event) and a random effect structure (1|time/bag_ID) to account for repeated measures for each sample collection time point.

3.3 Results and Discussion

3.31 Bioswale Plant Communities

Overall, the bioswale plant communities were significantly influenced by the single 20 T/ha (17,843 lb/acre) biochar application in the two-year field study. Conversely, plant community metrics were significantly influenced by aboveground plant harvest treatments over the two-year field study. Prior to treatment implementation in Fall 2022, total plant cover

(%/m^2) and cattail cover (%/m^2) was assessed to establish detectable differences in base-line plant community metrics existed. Total plant cover ($p > 0.05$) and *Typha* cover ($p > 0.05$) were ***not significantly*** different in Fall 2022 indicating that base-line plant community metrics were similar across the 4 blocks and associated nested subplots in the experimental design (graphs not shown). This result is important for interpretation in the field study as significant changes detected in plant community metrics can be associated with implemented field treatments.

Our focal plant genus, *Typha*, responded ***significantly*** to the single Fall 2022 biochar application. Surprisingly, *Typha* plant metrics results were ***not significant*** when responding to aboveground plant harvests employed in Fall 2023 and Fall 2024. The selected model for predicted *Typha* biomass was: log10(ppm) ~ biochar treatments + harvest treatment + random effect(1|time/block). Predicted *Typha* biomass ***significantly increased*** in the presence of the single 20 T/ha (17,843 lb/acre) biochar application compared to control (EM Means Contrast: $p \geq 0.05$) with ***no significant response*** to aboveground harvest (EM Means Contrast: $p < 0.05$) (Figure 5AB). Furthermore, predicted *Typha* stem density count / m^2 ***significantly increased*** in the presence of the 20 T/ha (17,843 lb/acre) biochar application compared to control (EM Means Contrast: $p \geq 0.05$) with ***no significant response*** to aboveground harvest (EM Means Contrast: $p < 0.05$) (Figure 6AB).

Contrary to our prediction, increased predicted *Typha* biomass and stem density to biochar was not anticipated in the field study. Previous wetland mesocosm research indicates either significant reductions in *Typha* sp. biomass with high-nutrient saturated soils (Ohsowski et al., in-prep) or neutral biomass responses in saturated, high chloride Illinois Tollway soils (Schurkamp et al, 2024). Visual observations during site visit sampling and calibration campaigns also indicate variable water levels, as the bioswales were often dry. Variability in saturated conditions can result in shifts in plant growth conditions for *Typha*. Biochar's surface chemistry, large surface area, and high porosity are known to improve soil conditions by retaining nitrogen and phosphorus availability, increasing cation exchange capacity (CEC), and acting as a liming agent to increase pH (Smith 2016, Palansooriya et al. 2019). Previous research has also shown that biochar can decrease plant salt stress in terrestrial soil (Chen et al. 2018).

Further research is needed as the biological and chemical mechanisms to free plants from salt stress remain unconfirmed. Emerging research indicates that biochar feedstock and pyrolysis temperature strongly influence both cation and anion ionic surface retention (Banik et al. 2018). Undoubtedly, variable hydrologic soil saturation would also alter soil and biochar redox chemistry, thus further influencing biochar surface retention of available cations and anions (Yuan et al. 2017). In the Tollway field study, the increase of *Typha* biomass to a moderate, single 20 T/ha (17,843 lb/acre) wood-waste biomass warrants future study due to conflicting research results in the field and the greenhouse.

Typha's neutral response to aboveground plant harvesting was another unexpected result. Previous research indicates harvesting aboveground *Typha* biomass consistently results in reduced *Typha* regrowth in greenhouse and field studies (Lishawa et al. 2015b). Research indicates that *Typha* biomass is reduced significantly and consistently after two years of harvesting prior to plant senescence. In this study, aboveground biomass was harvested in late Fall 2022 after plant senescence began due to logistical constraints. As the plant community was harvested during mid-fall senescence, the translocation of nutrients to roots and rhizomes may have built sufficient reserves for regrowth in 2023. Continued annual aboveground harvesting for multiple years would be needed to determine the influence of this treatment, if any.

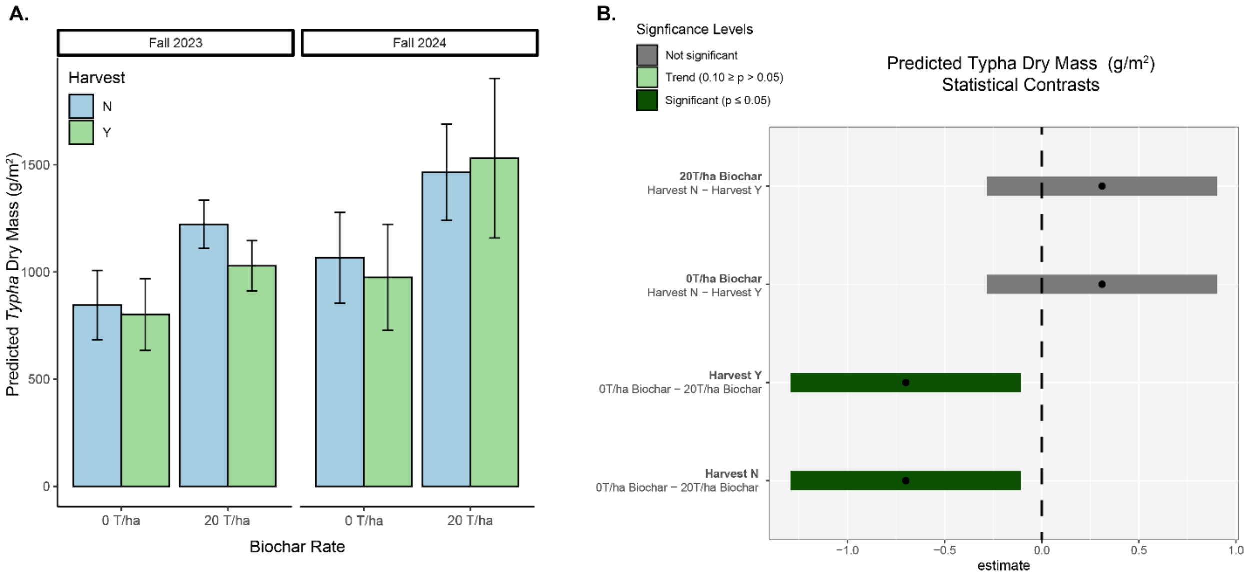


Figure 5 (A.) Predicted Fall 2023 and Fall 2024 total *Typha* biomass (grams/m^2) in biochar treatments and harvest treatments for 4 Tollway blocks. Bar graphs given as raw data means ± standard error. X-axis shown as experimental biochar rate with harvest treatment indicated within the legend. (B.) The statistical significance graph indicates detected significance ($p \leq 0.05$) and trend ($0.10 \geq p > 0.05$) linear mixed effect model contrasts resulting from the best fitting selected model. *Selected Model:* log(ppm) ~ biochar treatments + harvest treatment + random effect(1|time/block).

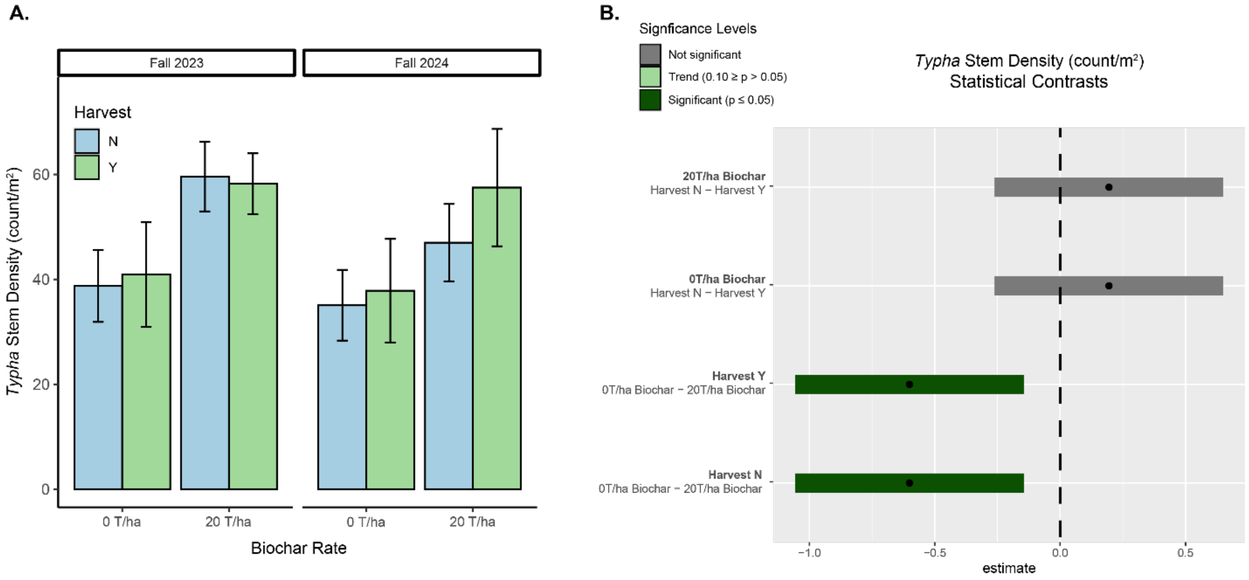


Figure 6 (A.) Fall 2023 and Fall 2024 total *Typha* stem density (count/m^2) in biochar treatments and harvest treatments for 4 Tollway blocks. Bar graphs given as raw data means ± standard

error. X-axis shown as experimental biochar rate with harvest treatment indicated within the legend. (B.) The statistical significance graph indicates detected significance ($p \leq 0.05$) and trend ($0.10 \geq p > 0.05$) linear mixed effect model contrasts resulting from the best fitting selected model. *Selected Model:* log(ppm) ~ biochar treatments + harvest treatment + random effect(1|time/block).

Total plant richness (species count / m^2) *was not significantly affected* by the biochar application or aboveground harvesting treatment ($p > 0.05$). A *trend was detected* ($p=0.059$) that supports a potential reduction in total plant richness associated with the 20 T/ha (17,843 lb/acre) biochar application (Figure 7AB). This result would be consistent with increased predicted *Typha* biomass and *Typha* stem density detected in the study. Plant competition pressures are expected to increase as *Typha* has a high demand and uptake of essential macro- and micronutrients. Furthermore, increased *Typha* biomass and stem density reduce available light resources in the plant community. Contrary to our prediction, plant biomass and litter removal did not significantly increase plant community richness. Research shows that *Typha* eventually excludes other aquatic plants, thus reducing species richness and diversity (Farrer and Goldberg 2009; Tuchman et al. 2009; Vaccaro et al. 2009). In the Tollway bioswales, no appreciable seedbank persisted after installation as the applied seedbank was uncompetitive due to high salinity and heavy growth pressure by *Typha* sp. and *Phragmites australis*. During the plant harvest, living aboveground plant tissues and plant litter were cut with aquatic weedwhackers and removed from the bioswale surface. *Typha* is known to accumulate a dense detritus layer which alters temperature and light availability for its plant competition (Freyman 2008; Farrer and Goldberg 2009). Interestingly, aboveground plant harvesting did not significantly influence plant species richness ($p = 0.91$) in our study. In natural wetlands, plants tend to emerge from a sediment seed bank following harvest. In contrast, it is likely that the seed bank in Tollway bioswales is depauperate of native species, and seeding following harvest is therefore necessary to stimulate a robust biodiversity response in the presence of frequent annual harvesting.

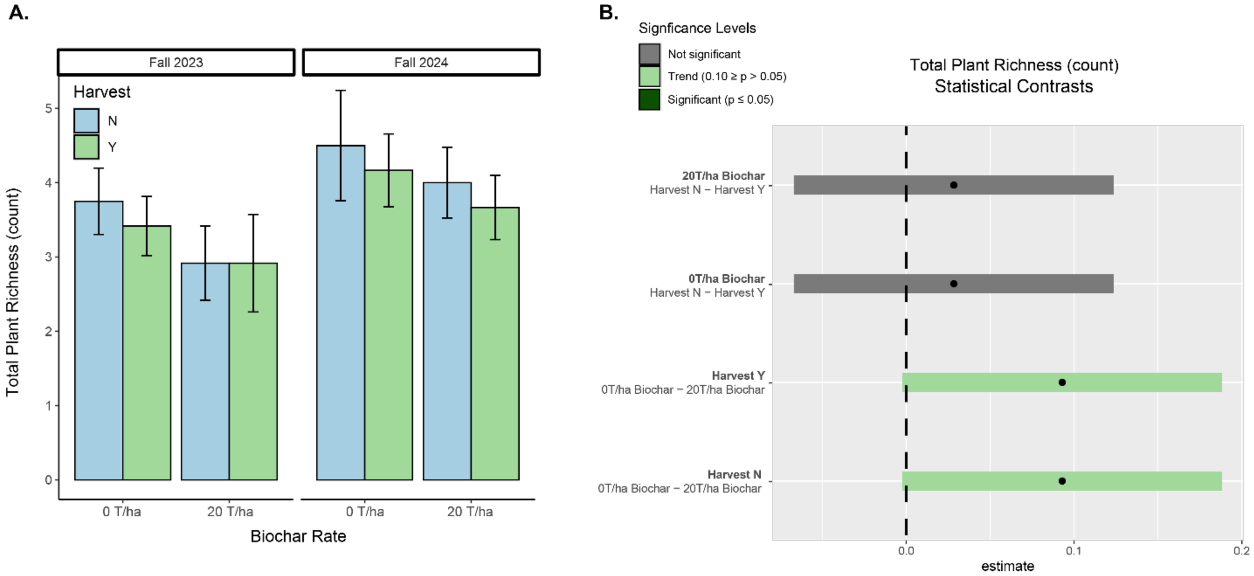


Figure 7 Fall 2023 and Fall 2024 total plant richness (count) in biochar treatments and harvest treatments for 4 Tollway blocks. Bar graphs given as raw data means ± standard error. X-axis

shown as experimental biochar rate with harvest treatment indicated within the legend. (B.) The statistical significance graph indicates detected significance ($p \leq 0.05$) and trend ($0.10 \geq p > 0.05$) linear mixed effect model contrasts resulting from the best fitting selected model. *Selected Model:* log(ppm) ~ biochar treatments + harvest treatment + random effect(1|time/block).

3.32 AquaTROLL Specific Conductivity

In the Tollway field study, high variability in specific conductivity (µS/cm) for bioswales stretches applying 0 T/ha and 20 T/ha biochar led to *inconclusive and non-significant findings*. As described in the methodology, specific conductivity (SC) data were filtered to assess flowing water at each AquaTROLL installation. No significant pattern in salt release and salt retention across each bioswale unit may be expected as contact time with surface applied biochar during flow events is minimal. Furthermore, the length of the experimental unit in this study is relatively short lengthwise and water flow's is flashy with precipitation events reducing biochar sorption opportunities (Appendix A).

3.33 Field Study Chloride Ion Patterns in Soil and Plant Tissues

Overall, the chloride ion concentration in sampled soils were significantly increased by the single 20 T/ha (17,843 lb/acre) biochar application in the two-year field study. Soil chloride concentration was not significantly influenced by aboveground plant harvesting. The best model to represent chloride soil concentration was: log(ppm) ~ biochar treatments + harvest treatment + random effect(1|time/block). Biochar application at 20 T/ha (17,843 lb/acre) *significantly increased* soil chloride ions compared to control locations ($p \leq 0.001$) (Figure 8AB). Aboveground biomass harvesting had *no significant influence* on soil chloride ion concentration ($p = 0.808$) (Figure 8AB). As discussed in the vegetative community analyses, emerging research indicates that biochar feedstock and pyrolysis temperature strongly influence both cation and anion ionic surface retention (Banik et al., 2018). Biochar research on improved cation exchange capacity within terrestrial soils is well developed. The results of our soil samples further highlight the need for investigating biochar's anion exchange capacity for chloride and other soil available ions. Although mechanistically unclear, we show that **the single 20 T/ha (17,843 lb/acre) biochar application can increase chloride ion retention leading to a promising strategy for slowing chloride ion release from Tollway bioswales despite the variable hydrologic soil saturation conditions.** Furthermore, AquaTROLL results show that biochar did not alter surface flow specific conductivity during the study. These results show that more detailed future research is necessary to provide clear predictions of chloride retention capacity, retention time, and scale to improve downstream chloride ion release.

As discussed in the plant community metrics section, 20 T/ha (17,843 lb/acre) biochar application *significantly increased* both predicted *Typha* biomass/m^2 and stem density/m^2 compared to control. In a recent meta-analysis, biochar application to salt-affected terrestrial soils improved crop productivity with an application rate ranging from 40–50 T/ha (Wu et al. 2024). This meta-analysis did not include periodically saturated soil systems but results of 173 studies further indicate plant growth benefits in salt-affected soils. Our findings indicate that surface salt retention with a single 20 T/ha (17,843 lb/acre) biochar rate significantly increases chloride retention over the two-year study period.

The chloride ion concentration in living *Typha* tissues were not significantly influenced by biochar application or aboveground plant harvesting. The following model predicted chloride in living *Typha* tissue concentration (ppm): log(ppm) ~ biochar treatments + harvest treatment + random effect (1|time/block). Biochar application at 20 T/ha (17,843 lb/acre) and aboveground plant harvest had *no significant influence* on chloride ion tissue concentrations compared to controls ($p > 0.05$) (Figure 9AB). The practice of harvesting salt-tolerant invasive plants for salt phytoremediation needs to be explored in greater depth to quantify species-specific salt removal potential in wetlands. Emergent wetland macrophytes have varying capacities to uptake and retain tissue chloride concentration in salt-affected, saturated soils. Halophytic tolerant emergent macrophytes have developed several evolutionary adaptations to maximize plant growth potential in extreme environments. Confirming the Tollway soil results described in Schurkamp et al. (2024) and Monks et al. (2023), our results support the result that *Typha* is a salt accumulating macrophyte. *Typha*'s evolutionary mechanism to establish high salt tissue concentrations has been shown to offset *Typha*'s osmotic adjustment or evapotranspiration potential (Yensen and Biel 2008).

The harvestable grams of chloride per m^2 in living *Typha* tissues is significantly increased by adding 20 T/ha (17,843 lb/acre) of biochar. Aboveground plant harvesting did not significantly influence harvestable grams of chloride per m^2. Scaled aboveground living green tissue chloride (g/m^2) resulted in the following selected model: log(ppm) ~ biochar treatments + harvest treatment + random effect(1|time/block). Biochar application at 20 T/ha (17,843 lb/acre) *significantly increased* harvestable grams of chloride ions compared to no biochar application ($p \leq 0.05$) (Figure 10AB). Aboveground biomass harvesting had *no significant influence* on harvestable chloride ($p > 0.05$) (Figure 10AB). When tissue chloride ion concentrations are scaled to predict *Typha* biomass results, our study indicates that the 20 T/ha (17,843 lb/acre) biochar application significantly increased grams of chloride removal potential in Tollway bioswales. The current field study confirms previous research that harvesting aboveground *Typha* biomass has the potential to remove significant quantities of deicing salts from Tollway retention basins as recommended in (Monks et al. 2023). Although *Typha* removal via harvest would not necessarily result in an increased lifespan of bioswales, the mechanical removal of salts via harvesting would improve bioswale function as an engineered pollution control system.

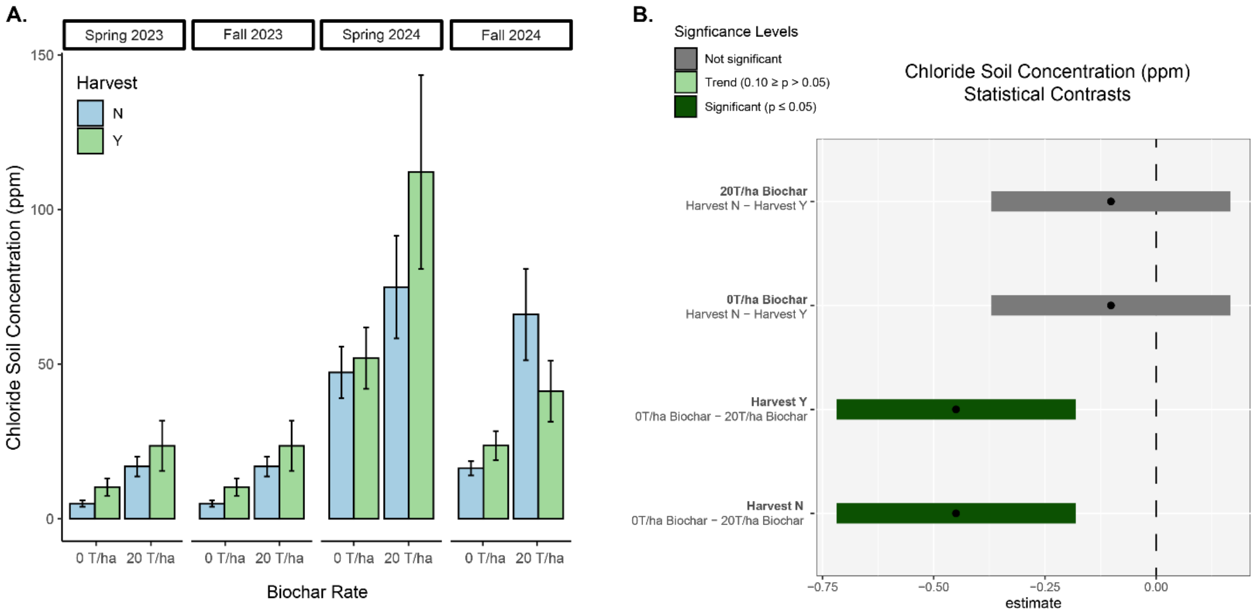


Figure 8 (A.) Soil chloride concentration (ppm) in biochar treatments and harvest treatments for 4 IL Tollway bioswales at each sampling period. Bar graphs given as raw data means ± standard error. X-axis shown as experimental biochar rate with harvest treatment indicated within the legend. (B.) The statistical significance graph indicates detected significance ($p \leq 0.05$) and trend ($0.10 \geq p > 0.05$) linear mixed effect model contrasts resulting from the best fitting selected model. *Selected Model:* log(ppm) ~ biochar treatments + harvest treatment + random effect(1|time/block).

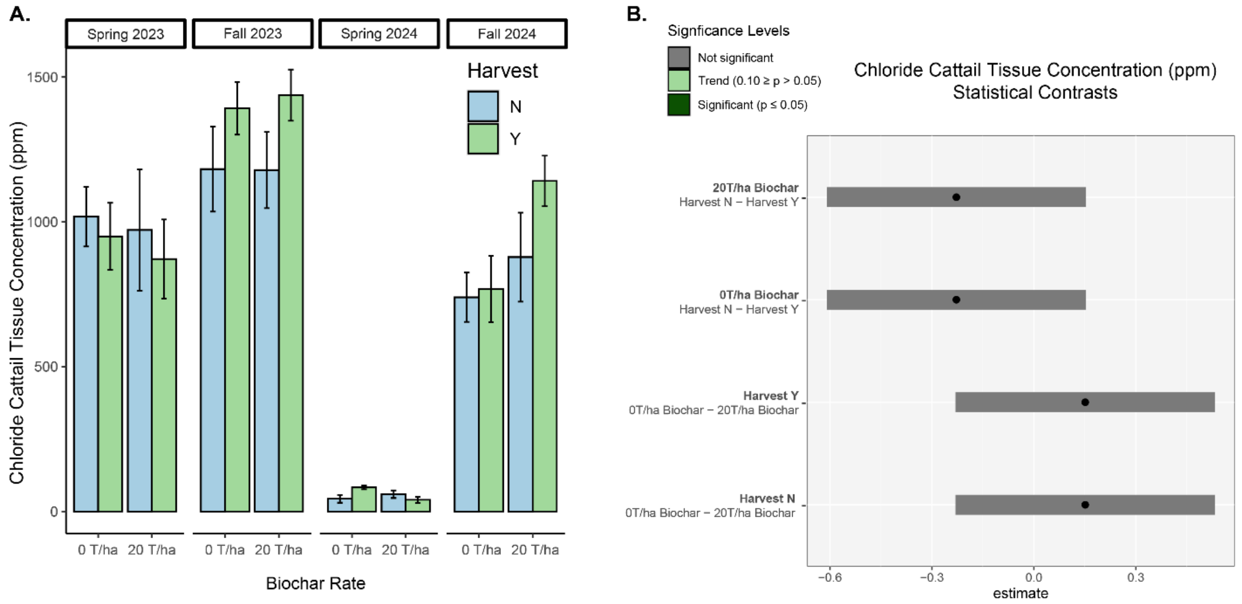


Figure 9 (A.) Aboveground *Typha* tissue Cl− concentration (ppm) in biochar treatments and harvest treatments for 4 IL Tollway bioswales. Bar graphs given as raw data means ± standard

error. X-axis shown as experimental biochar rate with harvest treatment indicated within the legend. (B.) The statistical significance graph indicates detected significance ($p \leq 0.05$) and trend ($0.10 \geq p > 0.05$) linear mixed effect model contrasts resulting from the best fitting selected model. *Selected Model:* log(ppm) ~ biochar treatments + harvest treatment + random effect(1|time/block).

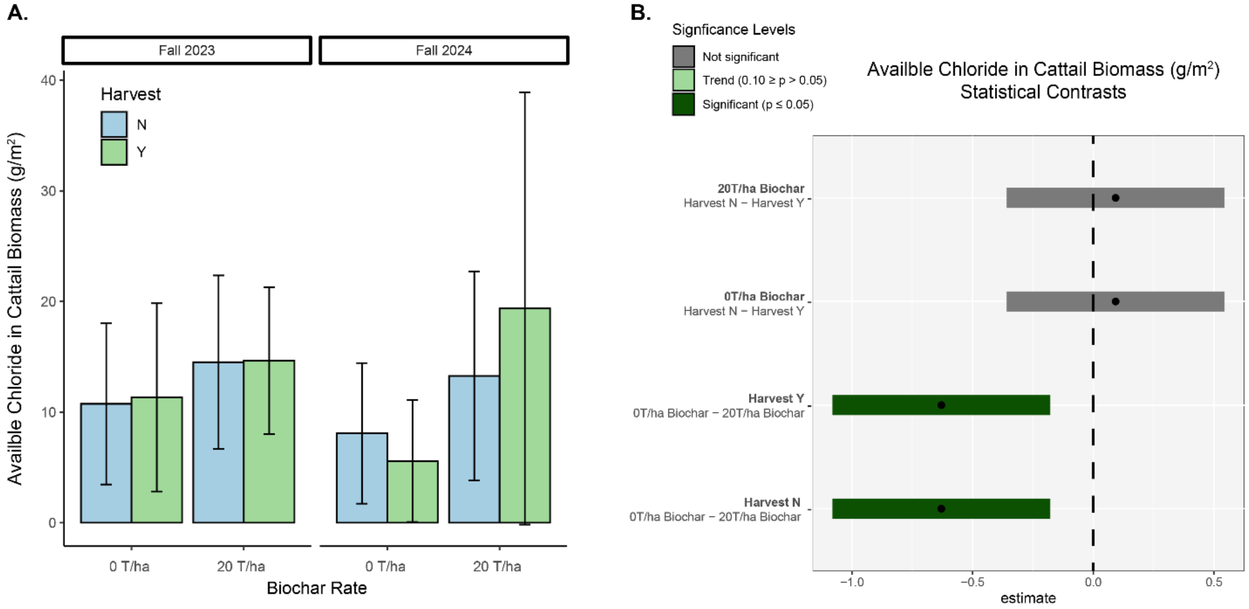


Figure 10 (A.) Fall 2023 and Fall 2024 *Typha* tissue Cl^- grams / m^2 in biochar treatments and harvest treatments for 4 IL Tollway bioswales. Bar graphs given as raw data means ± standard deviation. X-axis shown as experimental biochar rate with harvest treatment indicated within the legend. (B.) The statistical significance graph indicates detected significance ($p \leq 0.05$) and trend ($0.10 \geq p > 0.05$) linear mixed effect model contrasts resulting from the best fitting selected model. *Selected Model:* log(ppm) ~ biochar treatments + harvest treatment + random effect(1|time/block).

3.34 Heavy Metal Retention in Sampled Soils

Overall, all heavy metal ion concentrations in sampled soils were not significantly influenced by either the single 20 T/ha (17,843 lb/acre) biochar application or aboveground plant harvesting in the two-year field study. For the focal heavy metal ions (arsenic, cadmium, chromium, lead) in this study, the selected model for each analysis was: log10(ppm) ~ biochar treatments + harvest treatment + random effect(1|time/block). Biochar application at 20 T/ha (17,843 lb/acre) and aboveground plant harvest *did not significantly influence* any heavy metal ions concentrations compared to controls during the two-year study period ($p > 0.05$) (Figure 11AB-14AB).

Our research team predicted that the single 20 T/ha (17,843 lb/acre) biochar application would increase heavy metal retention within bioswale cells. A large body of research indicates that biochar's high cation exchange capacity would be expected to sorb and retain free heavy metal ions in aqueous systems (Qiu et al. 2021; Liu et al. 2022). Suggested chemical mechanisms to reduce bioavailability of heavy metals include surface complexation with biochar functional groups, sorption, precipitation resulting from altered pH, and electrostatic chemical interactions (Inyang et al. 2016). In this Tollway field study, the lack of cation heavy metal retention by biochar is surprising, especially in light of the significant increase of chloride retention, a negatively charged anion. Biochar has a limited surface for sorption of available ions in the soil solution. Research suggests the possibility that chemically interactable biochar surface area may become saturated. Additional biochar feedstock and production methods may have influenced our study's outcomes. (Zhou et al. 2022) suggest that in practical biochar application (i.e. outside of highly controlled laboratory conditions) heavy metal sorption potential will be reliant upon feedstock, pyrolysis conditions, pH, biochar rate, competition for available biochar surface area, and heavy metal concentrations. Further targeted study of the influence of biochar on heavy metal sorption in the Tollway system is warranted.

As aquatic macrophytes, *Typha* are known to be heavy metal accumulators that have been shown to uptake heavy metals from the environment (Hejna et al. 2020b). Precautions should be taken when considering *Typha*'s role in heavy metal uptake and stabilization and as a phytoremediation tool, however. Compartmentalization of heavy metals is expected as research indicates higher concentrations of heavy metals in roots and rhizomes compared to aboveground tissues (Taylor & Crowder, 1983, Klink et al, 2013).

Our field study did not indicate heavy metal concentration differences in bioswale soils over the two-year study period. Furthermore, heavy metal concentrations in *Typha* tissues were not assessed in the field study. Note that soils were collected and ground after removing root tissues from the sample. Further research is warranted to assess if aboveground harvesting and biochar application influenced root and rhizome heavy metal accumulation in the Tollway system. This may be a potential mechanism to improve the function of Tollway bioswales to reduce downstream heavy metal pollution through root tissue immobilization.

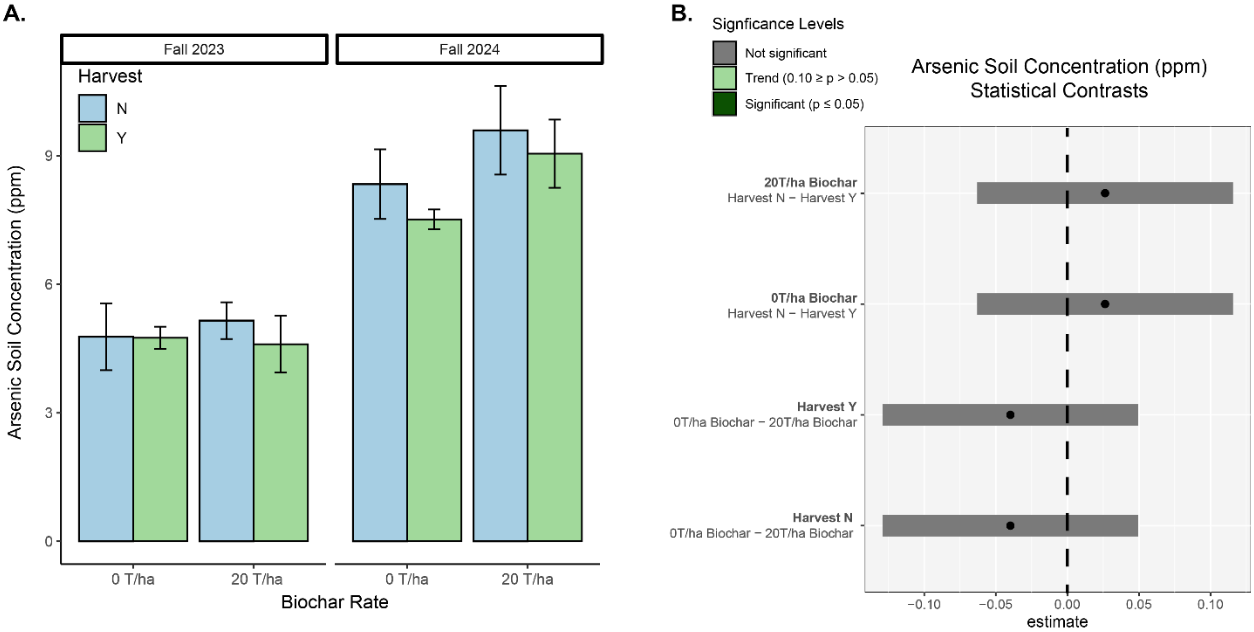


Figure 11 (A). Arsenic soil concentration (ppm) in biochar treatments and harvest treatments for 4 IL Tollway bioswales at each sampling period. Bar graphs given as raw data means ± standard error. X-axis shown as experimental biochar rate with harvest treatment indicated within the legend. (B.) The statistical significance graph indicates detected significance ($p \leq 0.05$) and trend ($0.10 \geq p > 0.05$) linear mixed effect model contrasts resulting from the best fitting selected model. *Selected Model:* log(ppm) ~ biochar treatments + harvest treatment + random effect(1|time/block).

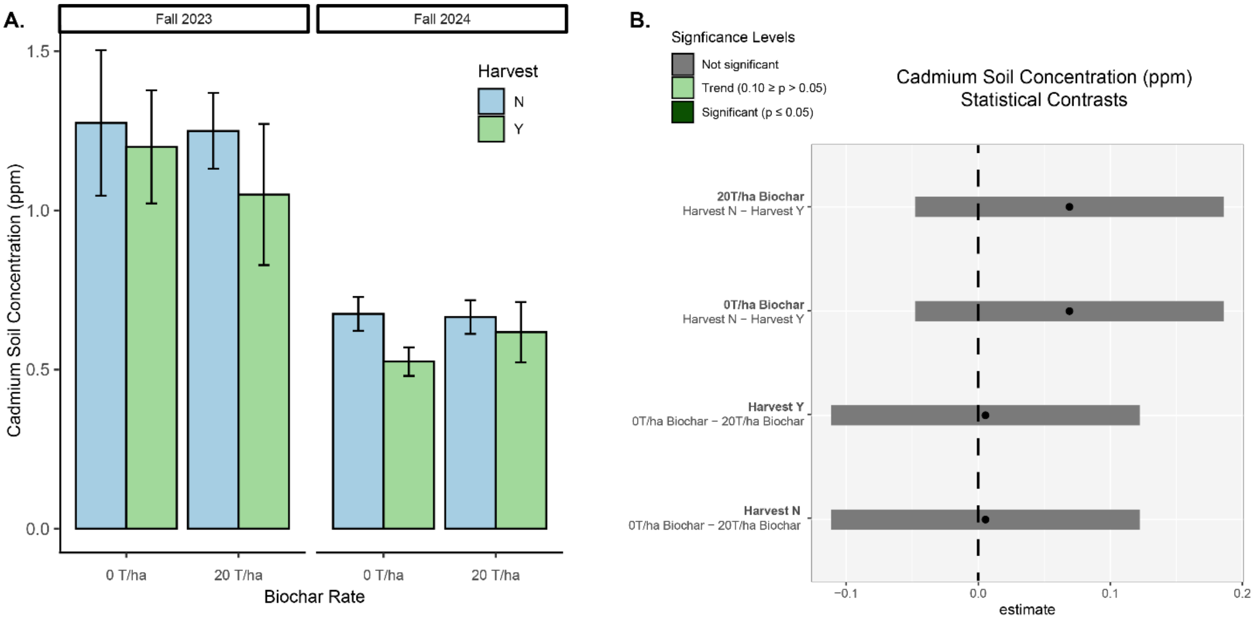


Figure 12 (A.) Cadmium soil concentration (ppm) in biochar treatments and harvest treatments for 4 IL Tollway bioswales at each sampling period. Bar graphs given as raw data means ± standard error. X-axis shown as experimental biochar rate with harvest treatment indicated within the legend. (B.) The statistical significance graph indicates detected significance ($p \leq 0.05$) and trend ($0.10 \geq p > 0.05$) linear mixed effect model contrasts resulting from the best fitting selected model. *Selected Model:* log(ppm) ~ biochar treatments + harvest treatment + random effect(1|time/block).

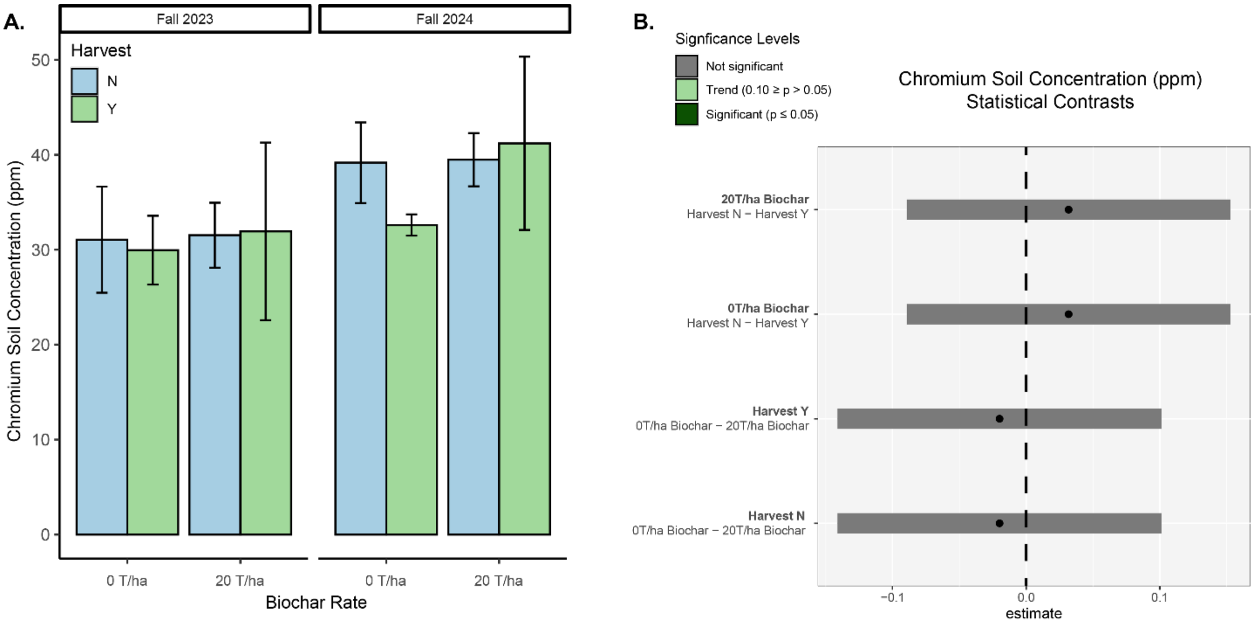


Figure 13 (A.) Chromium soil concentration (ppm) in biochar treatments and harvest treatments for 4 IL Tollway bioswales at each sampling period. Bar graphs given as raw data means ± standard error. X-axis shown as experimental biochar rate with harvest treatment indicated within the legend. (B.) The statistical significance graph indicates detected significance

($p \leq 0.05$) and trend ($0.10 \geq p > 0.05$) linear mixed effect model contrasts resulting from the best fitting selected model. *Selected Model:* log(ppm) ~ biochar treatments + harvest treatment + random effect(1|time/block).

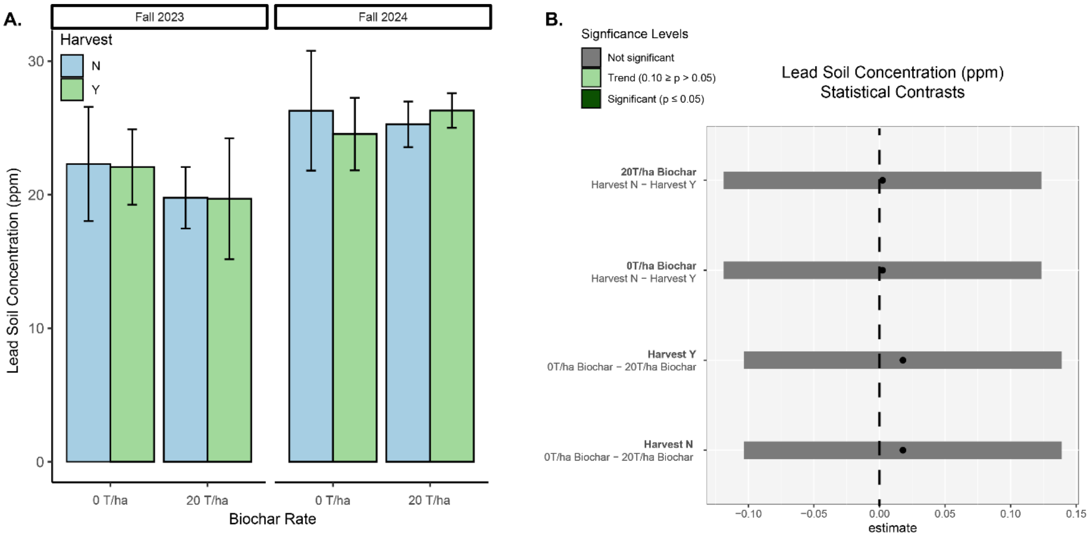


Figure 14 (A.) Lead soil concentration (ppm) in biochar treatments and harvest treatments for 4 IL Tollway bioswales at each sampling period. Bar graphs given as raw data means ± standard error. X-axis shown as experimental biochar rate with harvest treatment indicated within the legend. (B.) The statistical significance graph indicates detected significance ($p \leq 0.05$) and trend ($0.10 \geq p > 0.05$) linear mixed effect model contrasts resulting from the best fitting selected model. *Selected Model:* log(ppm) ~ biochar treatments + harvest treatment + random effect(1|time/block).

3.35 Summary of Experimental Biochar Saturation Rates

This section will describe three time series studies to assess the potential for chloride and heavy metal sorption by biochar:

- Southbound Tri-State Tollway (I-294) between Milepost 43.4 (i.e. TB7B) Bioswale Biochar Saturation Curve (preliminary study)
- Loyola Stream Simulation Lab (Loyola funded study)
- Bioswale Biochar Saturation Curve (Tollway Funded Current Study)

3.35.1 TB7B Bioswale Biochar Saturation Curve (preliminary study)

The bioswale near southbound Tri-State Tollway (I-294) between Milepost 43.4 (i.e. TB7B) bioswale study was established to determine preliminary chemical sorption properties of wood-waste biochar. Briefly, four (4) replicate locations containing seven jute bags [wood-waste biochar = 40g each] were deployed in the TB7B bioswale near southbound Tri-State Tollway (I-294) between Milepost 43.4. The timespan of the preliminary study was 6/3/2021 (Day 0) to 3/29/2022 (Day 934). At five collection dates (Julien Dates: 32, 61, 103, 138, 934), biochar bag samples were collected, dried, ground, and analyzed for ionic analyses with HCl extraction following a protocol modified from Cataldi et al. (2003). Cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (Cl^-, PO_4^{3-}, NO_3^-) were quantified with ion chromatography (IC) in Loyola's analytical chemistry lab. Heavy metal concentrations were not assessed in the preliminary study.

Overall, results indicate no significant accumulation of sodium or chloride in the biochar sorption study in TB7B (p > 0.05). Interestingly, both sodium and chloride were initially released from the biochar surface after placement in the check dam channels in TB7B (Figure 15, 16). After 2.5 years, biochar surface sorption recovered to the time zero control concentrations, but did not significantly exceed sorption. Overall, this preliminary study had vastly different environmental conditions compared to the next two described sorption studies. Over this experimental period, TB7B had minimal flowing / standing water at the experimental check dam locations. As such, rainwater would have been a major hydrological input source, potentially washing the biochar surfaces and minimizing contact time with flowing water on-site. Research on biochar's chemical surface chemistry related to periodic wetting and long drying exposure and aging is sparse and inconclusive.

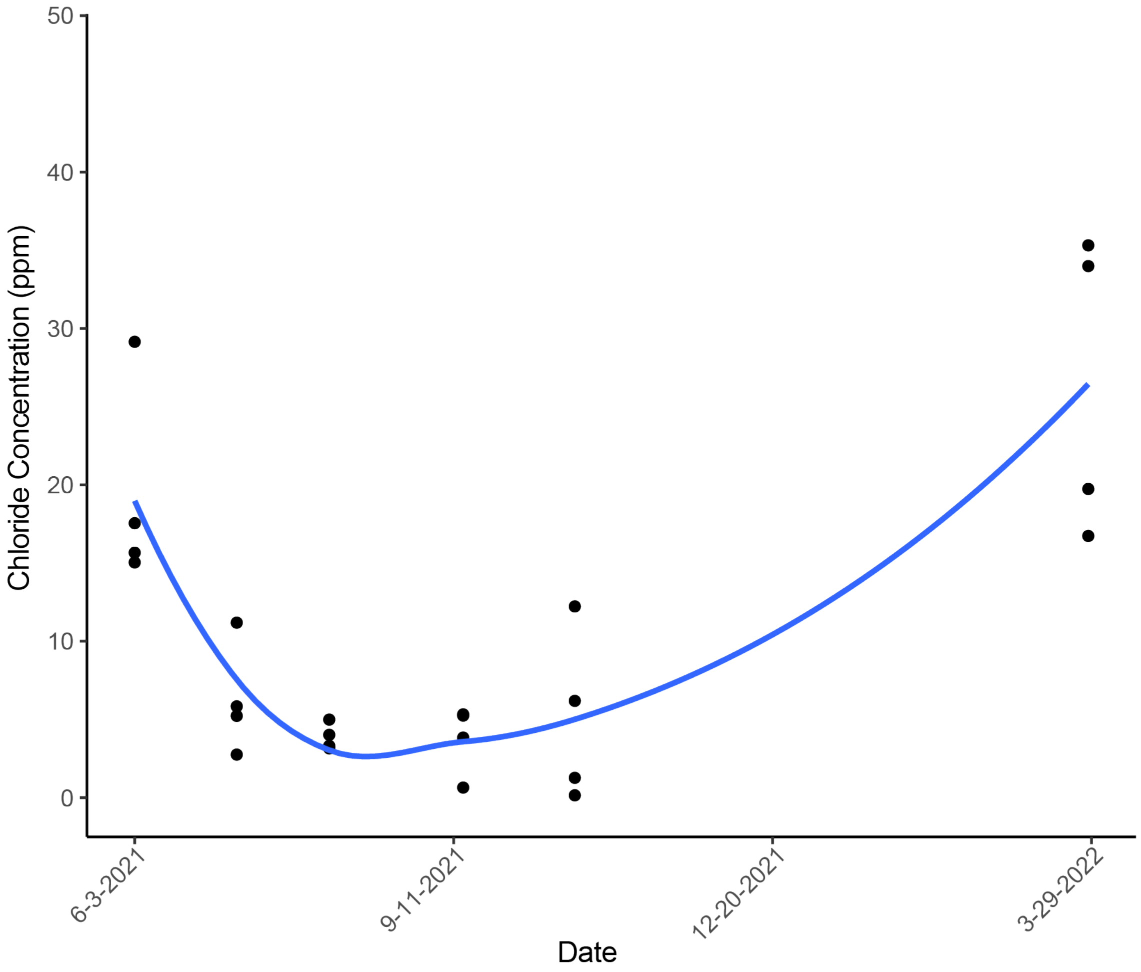


Figure 15 Extractable chloride ions (ppm) for biochar bag saturation curve (replication = 4) deployed in bioswale near southbound Tri-State Tollway (I-294) between Milepost 43.4 (i.e. TB7B) as a preliminary experiment between 6/3/2021 (Day 0) to 3/29/2023 (Day 299).

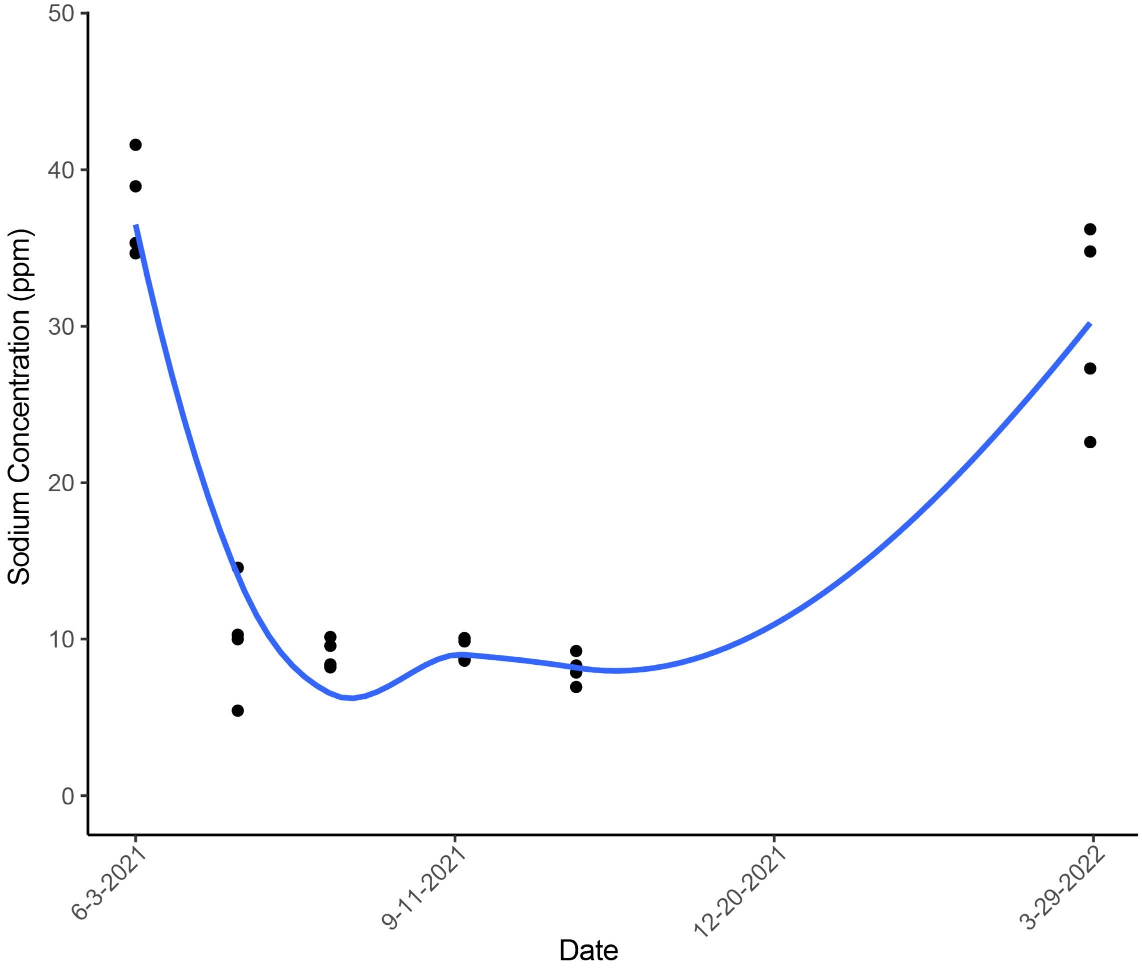


Figure 16 Extractable sodium ions (ppm) for biochar bag saturation curve (replication = 4) deployed in bioswale near southbound Tri-State Tollway (I-294) between Milepost 43.4 as a preliminary experiment between 6/3/2021 (Day 0) to 3/29/2023 (Day 299).

3.35.2 Loyola Stream Simulation Lab (Loyola Funded Study)

A fully factorial Loyola Stream Simulation Study was established to determine chemical sorption properties of wood-waste biochar for chloride and macro-nutrients. Note: This study was NOT funded by Tollway funds, but fundamental results are directly applicable to the current Tollway hypotheses. Publication of these Loyola Stream Simulation Lab results are currently in preparation (Ohsowski et al., in-preparation).

Our research team utilized flowing water stream simulators in Loyola's Stream Simulation Lab. Twenty-four (24) simulator streams were built with rotors to consistently push water throughout the system track (Figure 17). Stream simulators were filled with roughly 75 gallons of reverse osmosis water and deployed in four replicate blocks. Fully factorial experimental treatments were: Salt [0 mg L-1; 500 mg/L], and Fertilizer [None: phosphorus (0.0mg/L) & nitrogen

(0.0mg/L); Low: phosphorus (0.1mg/L) & nitrogen (2.0mg/L); and High: phosphorus (3.5 mg/L) & nitrogen (20.0 mg/L). One hundred and forty-four (144) jute bags were each filled with 40 grams of dried wood-waste biochar derived from paper mill waste. Six (6) jute bags were placed in each simulated stream and one bag was removed each week for chemical analysis. At each sample period, biochar bag samples were collected, dried, ground, and analyzed for ionic analyses with HCl extraction following a protocol modified from Cataldi et al. (2003). Cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (Cl^-, PO_4^{3-}, NO_3^-) were quantified with ion chromatography (IC) in Loyola's analytical chemistry lab.

Overall, chloride results indicate significant accumulation of chloride in the biochar sorption study. As discussed in the chloride dynamics section above, biochar surface properties are well-known for the high cation exchange capacity. The accumulating evidence generated by Team *Typha* is illuminating wood-waste biochar's ability to sorb and hold free chloride ions in flowing aqueous solutions over the six-week study period. Compared to control salt conditions, biochar surfaces significantly sorbed free chloride, as determined by linear mixed modeling [*Selected Model:* log(ppm) ~ salt treatment + random effect(1|week/block).] ($p \leq 0.01$) (Figure 18AB). The predicted asymptote of sorbed chloride after 1 week of high salt treatment was 74.6 ppm chloride compared to control chloride concentrations of 5.2 ppm chloride (Figure 18A).

As shown in the current Tollway bioswale research project, bioswale soils with a single 20 T/ha (17,843 lb/acre) wood-waste biochar application had higher chloride concentrations compared to controls. Coupled with our presented Tollway results, the Stream Simulation provides further evidence of biochar's chemical properties to sorb chloride ions. This finding is highly promising and warrants further research to develop a mechanistic model of chloride sorption by biochar. This biochar surface sorption research suggests at least one pathway of chloride retention is through direct chemical electrostatic mechanisms. Further research is required to determine the ubiquity of this biochar-chloride relationship in terms of biological availability, retention longevity, and biochar production variables [i.e. feedstock source, pyrolysis time, pyrolysis temperature].

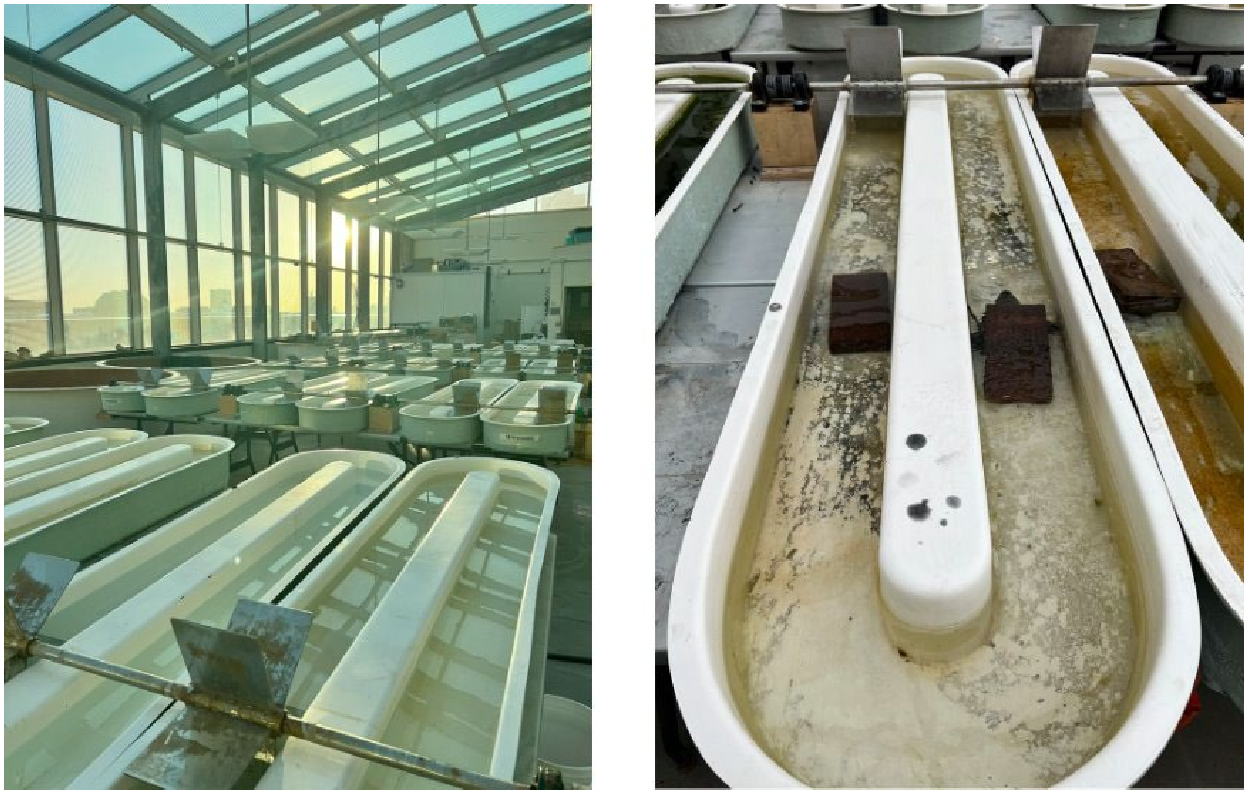


Figure 17 Sodium chloride and fertilizer were added at respective treatment rates: Salt (0.0 mg/L, 500 mg/L), phosphorus (0 mg/L, 0.1 mg/L1, 3.5 mg/L), and nitrogen (0 mg/L, 2.0 mg/L, 20 mg/L). For five weeks, individual wood–waste biochar bags were removed weekly for chemical analysis.

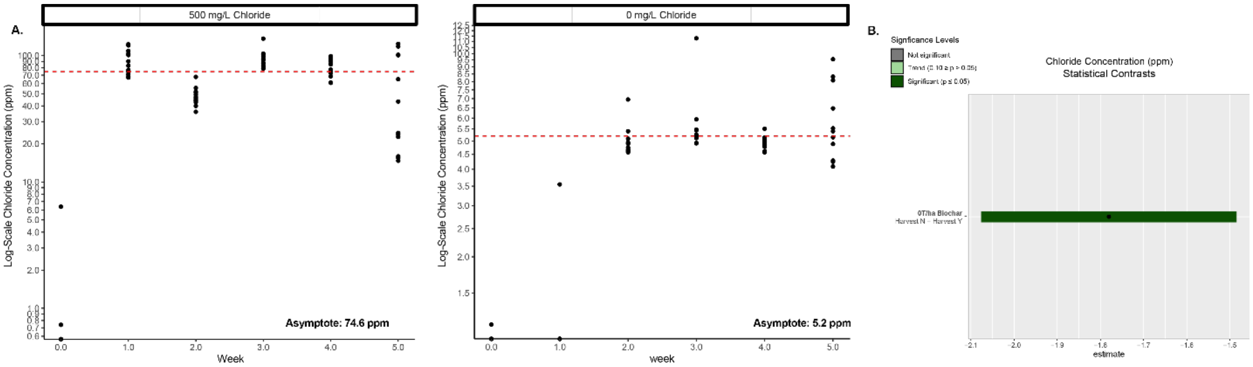


Figure 18 Extractable chloride concentration (ppm) saturation curve in the stream lab experiment in the Loyola Stream Simulation Facility. Salt concentration treatment levels: 0 mg chloride / liter; 500 mg chloride / liter. Biochar bags removed once per week for five experimental weeks. Note log-scale on y-axis. (A) *Selected Model:* log(ppm) ~ salt treatment + random effect(1|week/block). The statistical significance graph indicates statistical significance and trend contrasts based on the best fitting model (B).

3.35.3 Bioswale Biochar Saturation Curve (Tollway Funded Current Study)

A bioswale biochar saturation curve was established to determine chemical sorption properties of wood-waste biochar for chloride and heavy metal ions in the field. **Overall, chloride concentration results indicate significant accumulation of chloride in the biochar sorption study.** The *Selected LME Model:* log(ppm) ~ Julian Date + random effect(1|week/block) resulted in significant chloride surface sorption compared to time zero controls ($p \leq 0.05$). The LME determined an asymptotic surface saturation value estimated by linear mixed effects model average to be 85.6 ppm over the 376-day experimental period (Figure 19). The asymptotic surface sorption capacity of biochar for free chloride ions from this study is in high agreement with the Loyola Stream simulation experiment (see above 3.35.2). These data provide additional evidence that wood-waste biochar is sorbing chloride ions and its application has high potential as a management technique to capture and remove free chloride ions in Tollway systems.

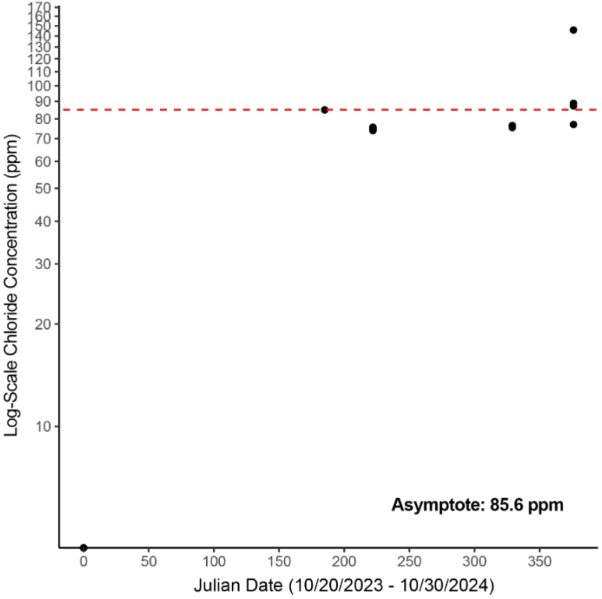


Figure 19 Extractable chloride ions (ppm) for biochar bag saturation curve (replication = 4) deployed in the four bioswales during the experiment. Note the log-scale on the y-axis. Asymptote value estimated by linear mixed effects model average between 10/20/2023 (Day 0) to 10/30/2024 (Day 376).

Overall, heavy metal ion sorption to biochar's surface resulted in variable accumulation patterns during the study period. All heavy metal analyses employed the following *Selected LME Model:* log(ppm) ~ Julian Date + random effect(1|week/block). Lead and arsenic heavy metal concentrations were below detectable limits on the biochar subsamples extracted from the saturation study (Figures: 20, 21). Chromium and cadmium resulted in significantly increased surface sorption compared to time zero controls ($p \leq 0.05$) (Figures: 22, 23). Biochar's high cation exchange capacity suggests that it has a high capacity for sorption and retention of heavy metal ions in aqueous systems (Qiu et al. 2021; Liu et al. 2022). The increased retention of chromium and cadmium heavy metals [charged cation] in this study agrees with the peer-reviewed literature, which suggests heavy metal surface retention. Our current study is innovative as we have isolated biochar in bags and deployed them in the field. To the best of our knowledge, no other study has determined biochar saturation curves in the field for heavy metals.

Our results suggest that biochar has capacity to sorb and retain cadmium and chromium, thus reducing bioavailability of heavy metals and downstream release.

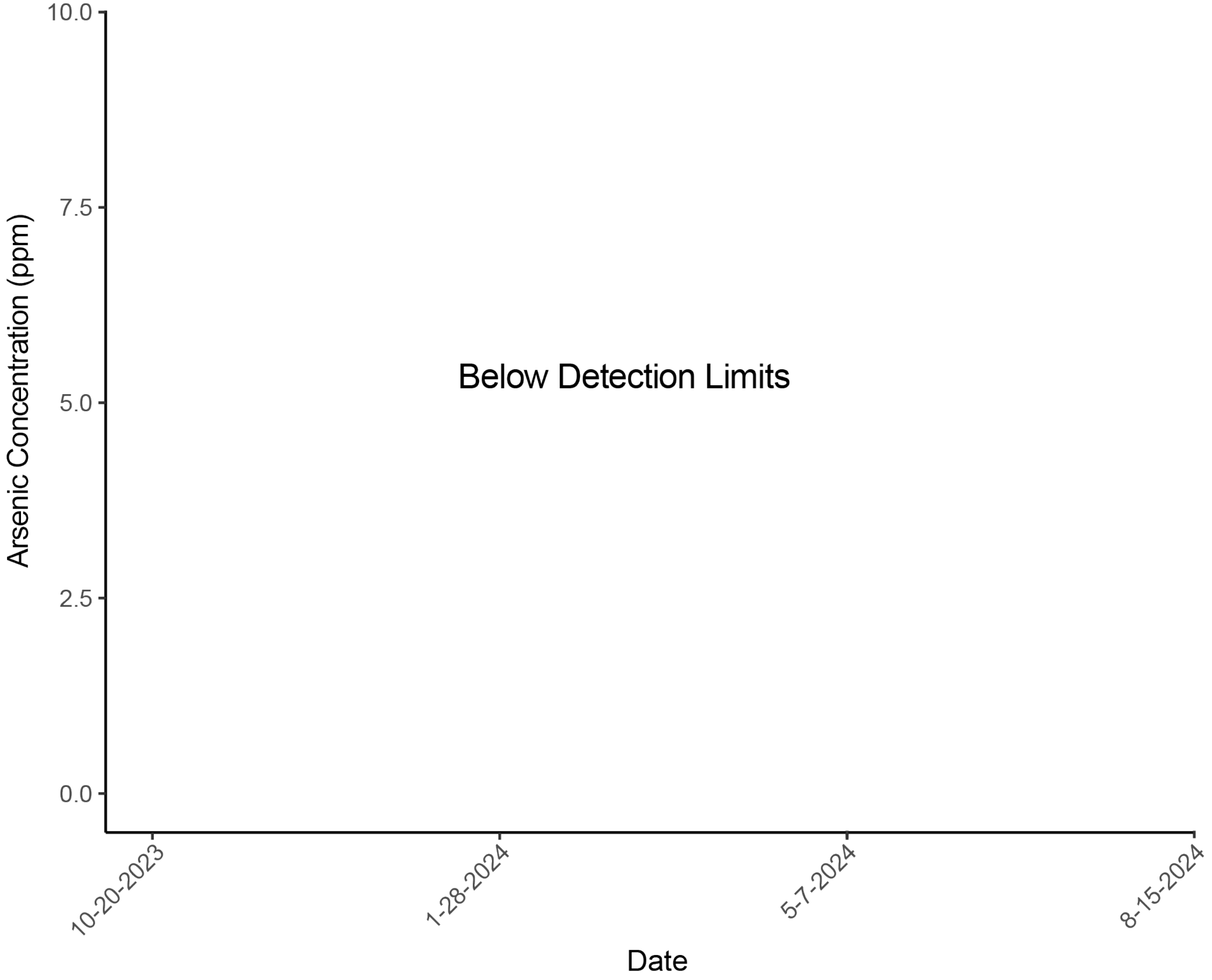


Figure 20 Extractable arsenic metal ions (ppm) for biochar bag saturation curve (replication = 4) deployed in the four bioswales during the experiment between 10/20/2023 (Day 0) to 10/30/2024 (Day 376).

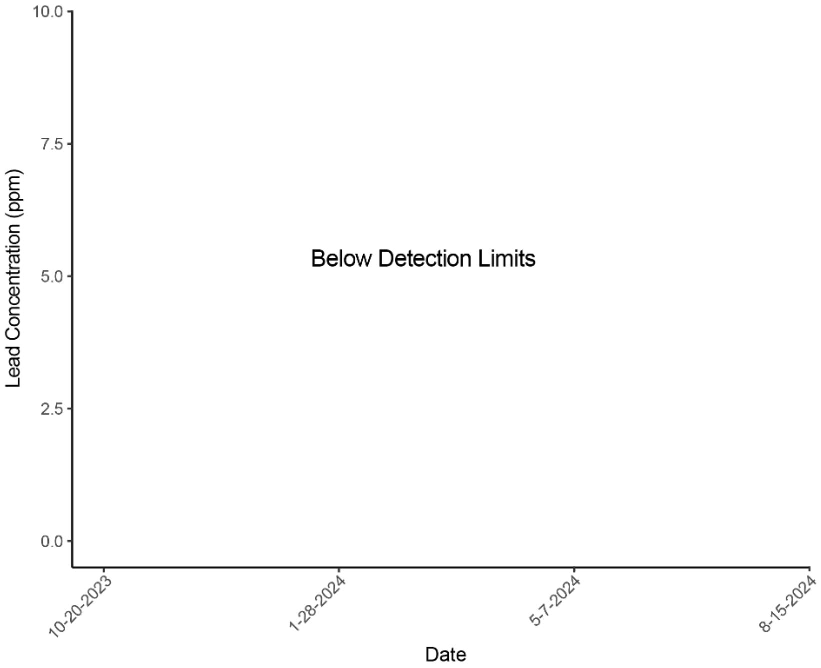


Figure 21 Extractable lead metal ions (ppm) for biochar bag saturation curve (replication = 4) deployed in the four bioswales during the experiment between 10/20/2023 (Day 0) to 10/30/2024 (Day 376).

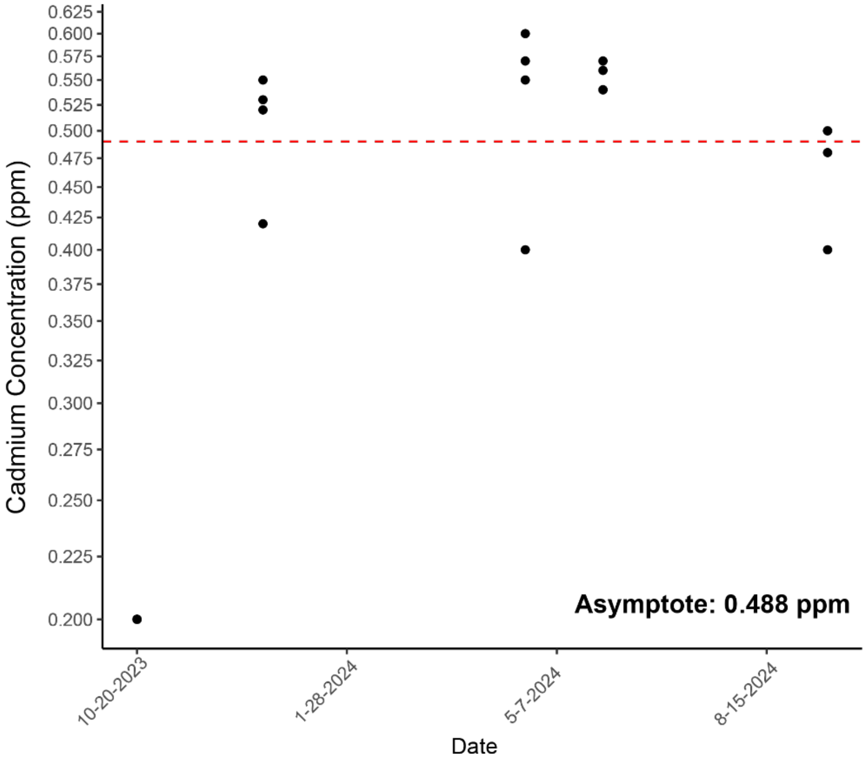


Figure 22 Extractable cadmium metal ions (ppm) for biochar bag saturation curve (replication = 4) deployed in the four bioswales during the experiment. Note the log-scale on the y-axis. Asymptote value estimated by linear mixed effects model average between 10/20/2023 (Day 0)

to 10/30/2024 (Day 376).

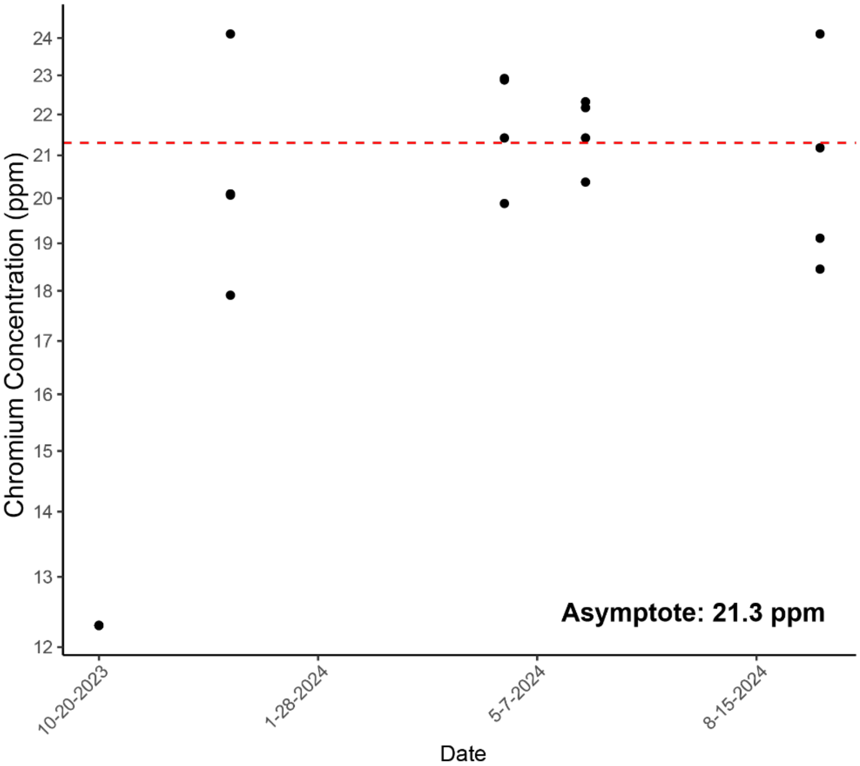


Figure 23 Extractable chromium metal ions (ppm) for biochar bag saturation curve (replication = 4) deployed in the four bioswales during the experiment. Note the log-scale on the y-axis. Asymptote value estimated by linear mixed effects model average between 10/20/2023 (Day 0) to 10/30/2024 (Day 376).

3.4 Application and Implications

This Illinois Tollway research project fostered innovative partnerships between university and state entities to improve knowledge of bioswale structure, function, and maintenance. The research demonstrates straightforward technology strategies to potentially mitigate freshwater pollution with aboveground *Typha* and wood-waste biochar application to bioswales. Our research explored practical management solutions meant to improve downstream water quality, reduce highway run-off, and retain biological stressors (i.e. chloride, heavy metals).

3.4.1 Implications for Bioswale Lifespan and Function

Several CAWS waterways currently exceed the IEPA standard for chloride of 500 mg/L. Likely increases in the frequency and intensity of winter storms may necessitate increased deicing salt application and further chloride impairment of Illinois waterways. Furthermore, as bioswales age across the Tollway system, monitoring and maintenance are required to ensure their continued effectiveness to retain pollutants. Decreased efficacy of bioswales with age could potentially increase both chloride and heavy metal export into Illinois waterways. Our results indicate that routine biochar application and aboveground invasive plant harvesting, especially *Typha*, has the potential to increase chloride soil retention and increase physical removal of chloride via harvesting.

In contrast with chloride, our 2-year study results showed negligible heavy metal remediation effects when harvesting plant tissues and applying biochar in Tollway bioswales. The heavy metal finding is surprising, given the known properties of biochar, warranting further research. In sum, these conclusions should be validated with further studies that focus on increased biochar application rates, increased biochar application frequency, and increased data collection intensity.

3.4.1.1 Chloride Management

Chloride concentration responses to a single 20 T/ha (17,843 lb/acre) biochar application and two aboveground biomass harvests led to conflicting, but promising results, for the management of chloride ions in the Tollway bioswale system. Conflicting responses are connected to the scale and scope of the analytical techniques employed in the study. AquaTROLL measured specific conductivity data, provided a proxy for chloride concentration, suggesting exposure of the experimental blocks ranging from 249 to 1688 mg/L chloride (Appendix A). However, the effect of a single 20 T/ha (17,843 lb/acre) biochar application resulted in no conclusive response in specific conductivity values. Thus, there is no clear evidence supporting the hypothesis that biochar application reduced chloride ions within the bioswales treatment blocks. The lack of a quantifiable treatment effect may be a result of the relatively short treatment blocks and hydrological residence time within the experimental blocks.

In contrast, finer-scale analysis of soil chemical and plant tissue sampled within bioswales indicate a significant improvement in chloride concentrations for bioswale soils amended with biochar and scalable removal via harvesting aboveground *Typha* biomass. Specifically, bioswale soils with a single 20 T/ha (17,843 lb/acre) biochar application resulted in consistently strong chloride retention signals compared to control soils. Contrary to our prediction, biochar application significantly increased *Typha* biomass and stem density over the study period. Although an unexpected growth response, increased *Typha* biomass resulted in a significant increase in removable chloride ions via aboveground harvesting due to *Typha's* chloride accumulation properties. Taken together, our research indicates that the Tollway can leverage a single 20 T/ha (17,843 lb/acre) biochar application and harvest aboveground *Typha* tissues to retain and remove chloride ions from the system.

Furthermore, our biochar saturation curve studies in Tollway bioswales and the Loyola Stream Simulation lab show a high level of promise for biochar to serve a chloride sorption medium. Mean surface retention of extractable chloride in the Tollway biochar saturation time series (85.6 ppm) and Loyola Stream Simulation lab biochar saturation time series (74.6 ppm) have a high level of agreement, providing additional validation of this retention effect. We conclude that biochar is highly promising as a management tool for retaining chloride, and additional trials with biochar filters (i.e., a pure biochar medium that water is passed through), could result in significant chloride retention.

Variability in precipitation, salt application frequency, winter temperatures, and point source / non-point source water quality will ultimately determine the capacity of the experimental treatments to retain chloride and improve downstream water quality. A further complication within our study system was that the flashy hydrology in bioswales during the study period complicated data interpretation. Despite this, our fine-scale results in the bioswale field experiment and biochar surface saturation experiments indicate a highly promising chloride retention management solution to reduce downstream salinization.

3.4.1.2 Heavy Metal Management

The Tollway bioswale field study and Bioswale Biochar Saturation Standard Curves field study had negligible influences on heavy metals ion retention or release. In the bioswale field study, no significant differences were detected in soils with the biochar application or harvesting treatments in the 2-year study. The Bioswales Biochar Standard Curve study did show significant surface sorption for cadmium and chromium during the 376-day study period. In contrast, the surface application of biochar did not influence heavy metal retention in bioswale field soils. Comparatively, these results contrast with the wider body of published literature confirming biochar's role in heavy metal sorption compared to controls. Further research, including increased biochar application rates, would be required to verify the role of biochar in heavy metal sorption for the Tollway system.

3.42 Potential Implications Across the Illinois Tollway System

This two-year project has demonstrated that a single 20 T/ha (17,843 lb/acre) biochar application in concert with harvesting aboveground *Typha* biomass is a feasible management strategy to reduce chloride pollution in Tollway bioswales. This current research report builds upon our previous work supported by Tollway grant funds in highway detention basins (Monks et al., 2022, Schurkamp et al., 2024). In our detention basin work and greenhouse study, our research team demonstrated that aboveground harvesting is a viable strategy for reducing salts, nutrients, and heavy metal pollution downstream while generating a potentially useful compost product. The results of our combined research in Tollway systems further confirm a practical, scalable management pathway to retain and remove aquatic pollutants adjacent to highway systems in Illinois.

3.43 Applicability of Results and Recommendation for Illinois Tollway Practice

The Tollway could potentially harvest several basins per year with access to proper equipment such as a Softrak Cut and Collect system. In this current study, harvesting aboveground biomass did not have a significant influence on *Typha* biomass and stem density. In contrast, our previous Tollway research led to a reduction in biomass and plant height in Tollway basins, especially after consecutive years (Monks et al., 2022). Biomass reduction should benefit overall basin filtration and function. Furthermore, reduced vegetation heights after consecutive years of harvesting would improve visibility across the basin.

To maximize the benefits of bioswale chloride retention and potential removal, our research team would recommend harvesting basins on a 2-3 year mowing rotation. Treatment efficacy can be maximized by harvesting bioswales / basins during peak biomass of *Typha* and *Phragmites,* (i.e.

maximal green plant height and prior to fall dieback). In northern IL, the Tollway window of peak biomass ranges from Mid-July to early October, ~14 weeks. Following each harvest, site access will be greatly improved, thus allowing for a seamless biochar application on-site.

The largest logistical challenge is collecting, transporting, and disposal of harvested plant biomass. In our previous basin research project, Tollway staff played a crucial role in facilitating biomass logistics by using current equipment (empty salt trucks and front-end loaders) and staff to load and transport harvested materials. One potential disposal method is partnering with Waste Management and applying a tipping fee. While composting Tollway-harvested biomass is feasible, further chemical analysis of the compost prior to widespread implementation and spreading is warranted, as salts and metals accumulated in harvest plant tissues likely persist in the compost. Biochar production or green energy through anaerobic digestion are also viable options for the Tollway to consider. These products may also prove more value than compost although potentially more logistically challenging.

3.5 Future Research Directions

The 2-Year Bioswale Field Experiment, the Bioswale Biochar Saturation Curve Experiment, and the Loyola Stream Simulation Biochar Saturation Curve Experiment highlight the link between biochar usage and chloride ion sorption in Tollway bioswale and detention basin systems. Biochar applications have the potential to retain chloride ions mobilized in aquatic environments characteristic of engineered bioswales and water detention basins.

Possible Future Studies Valuable to Tollway Goals Could Include:

- Evaluating biochar application rate and frequency for pollution abatement. Increasing the rates and frequency of biochar application, within a practical range, is warranted to test if downstream water quality could be measurably improved. The current study used a moderate biochar application at 20 T/ha (17,843 lb/acre). Research shows that practically feasible rates of biochar can be applied up to 100 T/ha. Furthermore, multiple applications over time may also improve the retention and storage of chloride.
- Evaluating the effect of deploying large-scale biochar filters (i.e., pure biochar media that runoff water is passed through) into the Tollway system to improve water quality. Results from our Bioswale Biochar Saturation Curve Experiment and Stream Simulation Biochar Saturation Curve Experiment indicate that a biochar media can retain chloride and some heavy metals. Introducing biochar into engineered settling vaults would likely improve their function to retain pollutants, though this requires additional study.
- Evaluating large-scale biochar application and invasive plant harvest at a water detention basin scale. For example, the Tollway detention basin at Elmhurst Road and I-90 would provide an opportunity to scale up both test blocks and harvesting and verify findings in a more controlled experimental setting than typical roadside bioswales.
- Implementing a closed loop biochar and invasive plant management system. It is feasible to make biochar from harvested Tollway cattail and re-apply the biochar to Tollway retention basins and/or bioswales. Such an approach has the potential to

simultaneously achieve multiple Tollway management goals, namely invasive plant control, increasing bioswale or retention basin functionality, and reduce downstream pollution.

Appendices

Appendix A: Bioswale water depths and estimated chloride concentrations

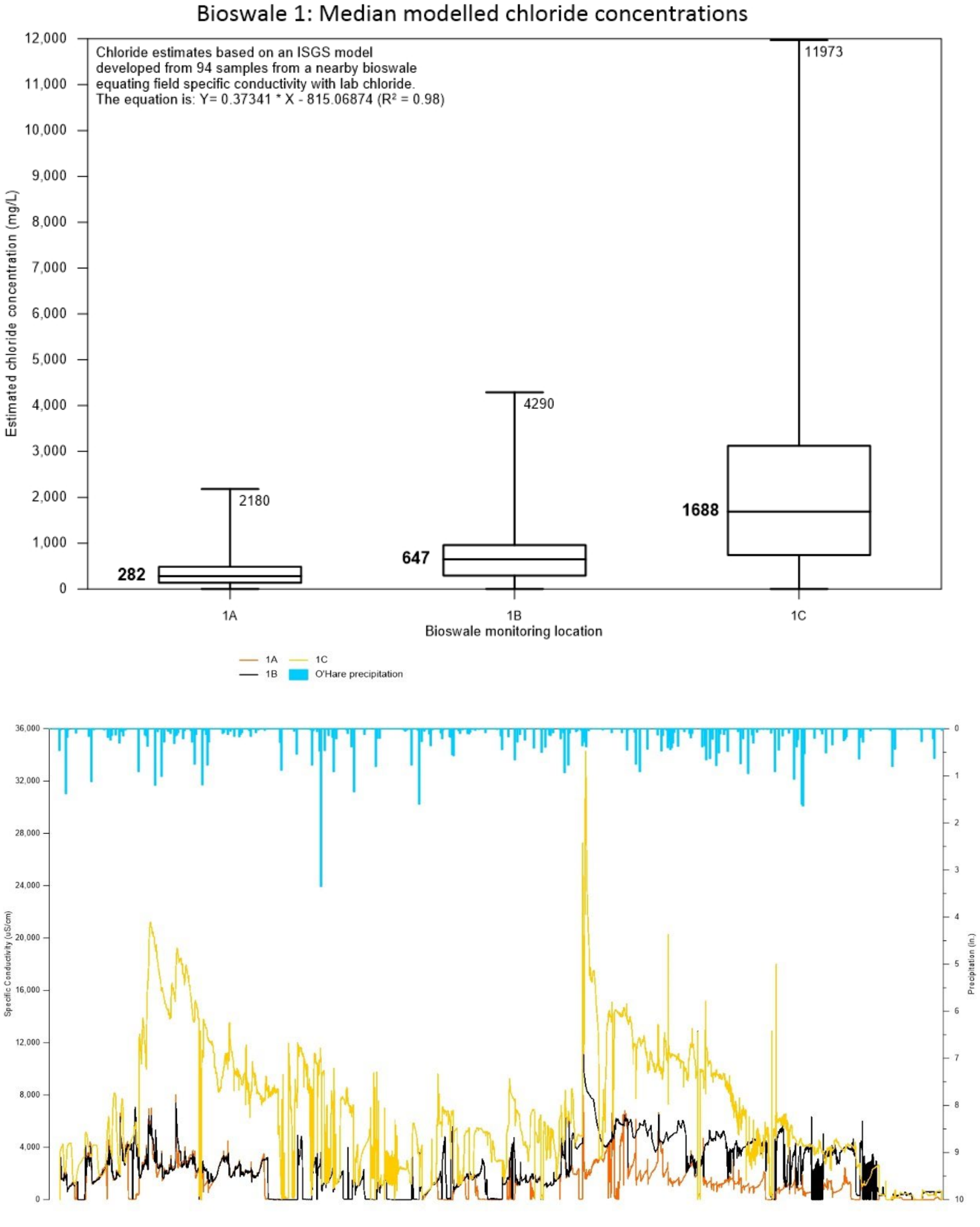


Figure 24 Boxplots of estimated chloride in mg/L for Bioswale 1 (Top; center line denotes medians and whiskers represent the minimum and maximum data values) and water depth data from three units (Bottom) for the Period of Record (12/9/2022 to 11/21/2024).

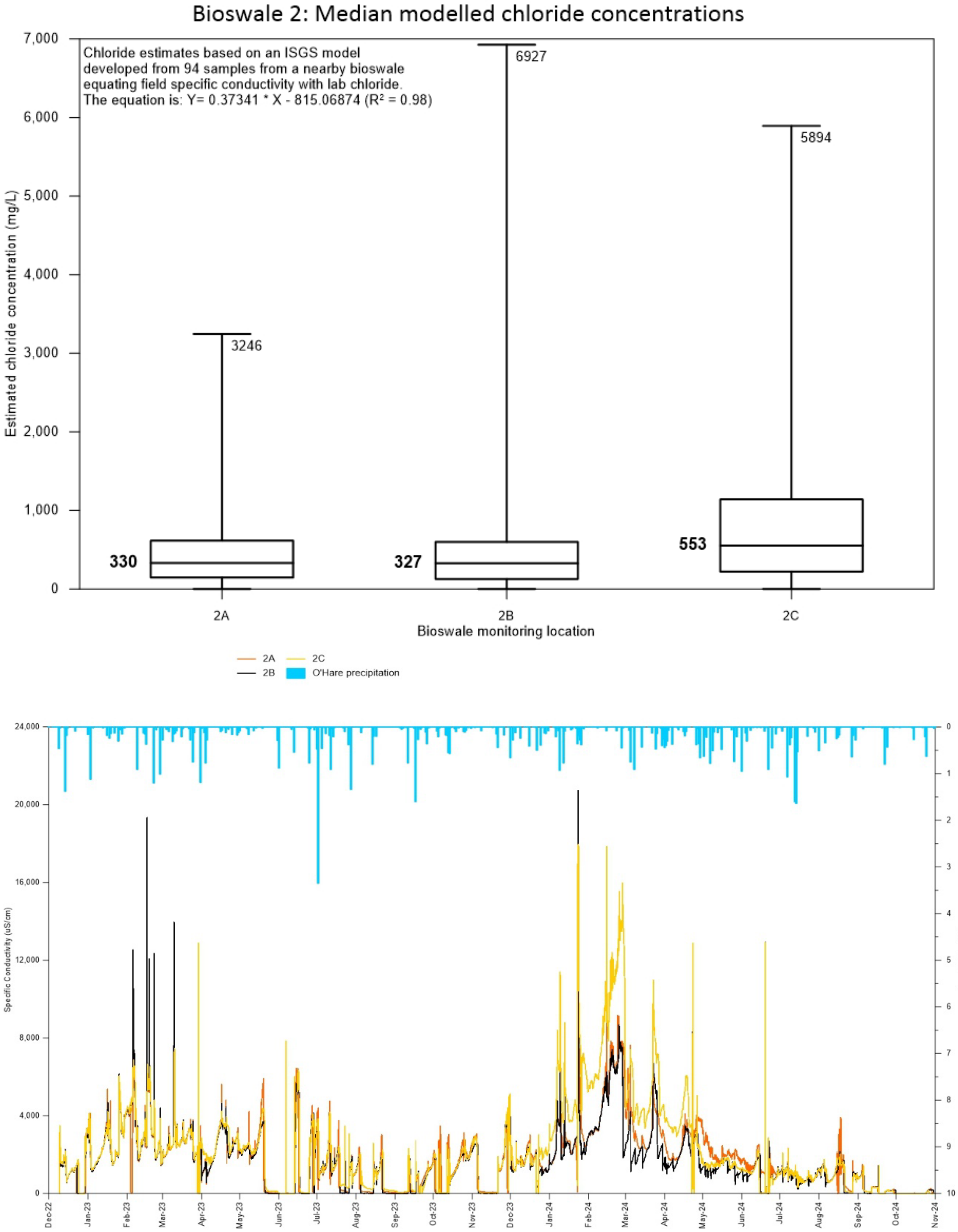
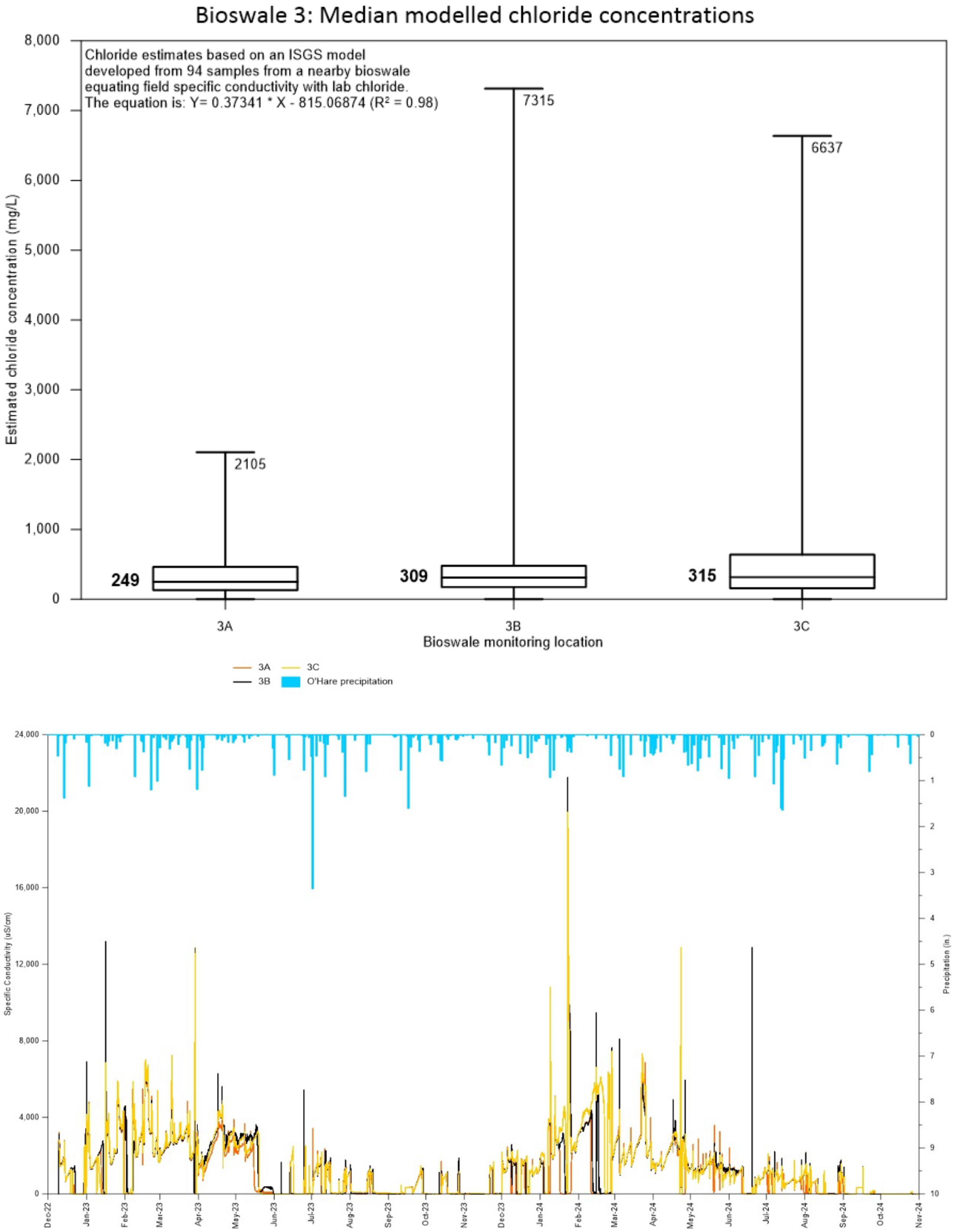


Figure 25 Boxplots of estimated chloride in mg/L for Bioswale 2 (Top; center line denotes medians and whiskers represent the minimum and maximum data values) and water depth data from three units (Bottom) for the Period of Record (12/9/2022 to 11/21/2024).



Chloride estimates based on an ISGS model developed from 94 samples from a nearby bioswale equating field specific conductivity with lab chloride.
The equation is: $Y = 0.37341 * X - 815.06874$ ($R^2 = 0.98$)

Figure 26 Boxplots of estimated chloride in mg/L for Bioswale 3 (Top; center line denotes medians and whiskers represent the minimum and maximum data values) and water depth data from three units (Bottom) for the Period of Record (12/9/2022 to 11/21/2024).

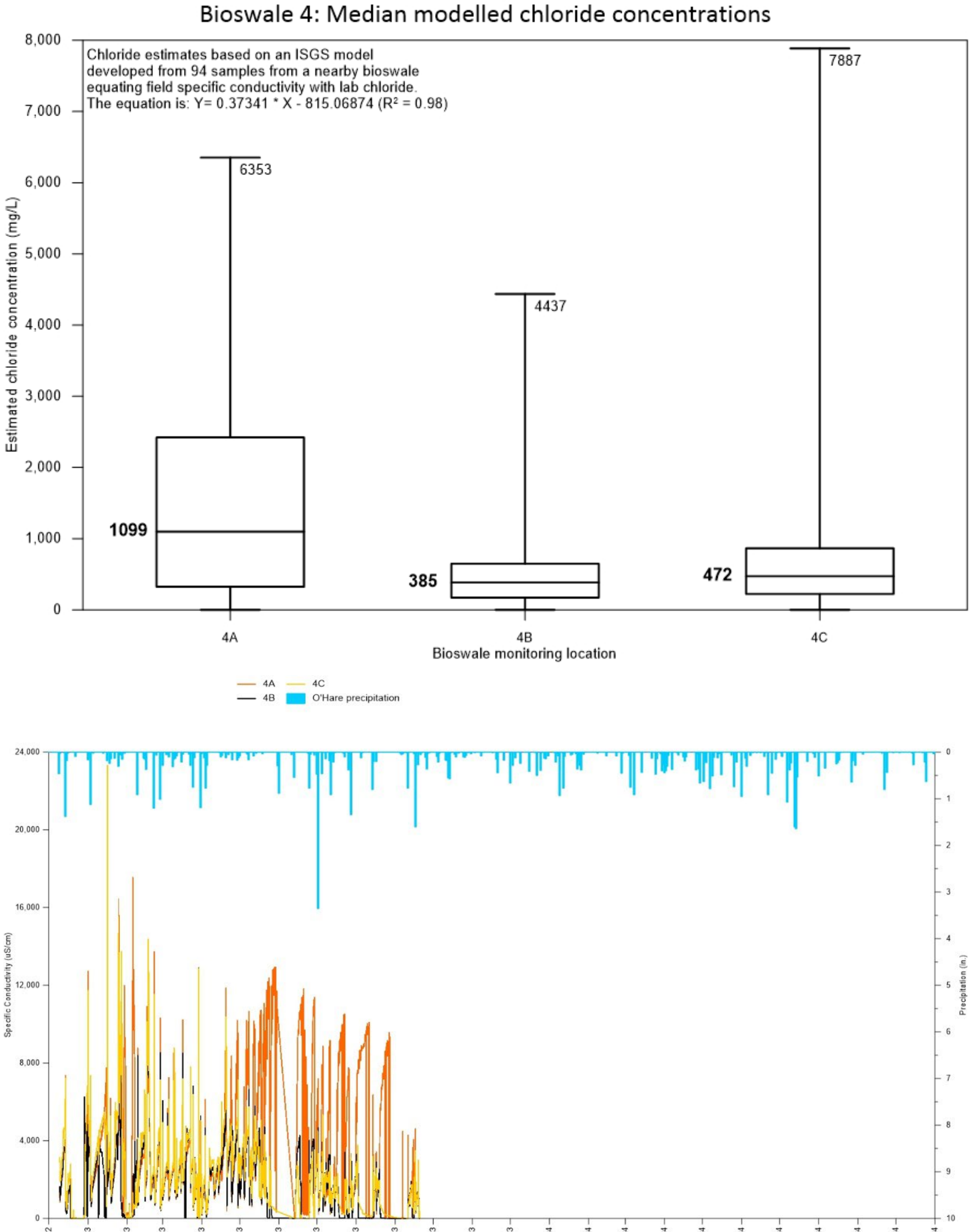


Figure 27 Boxplots of estimated chloride in mg/L for Bioswale 4 (Top; center line denotes medians and whiskers represent the minimum and maximum data values) and water depth data from three units (Bottom) for the Period of Record (12/9/2022 to 11/21/2024).

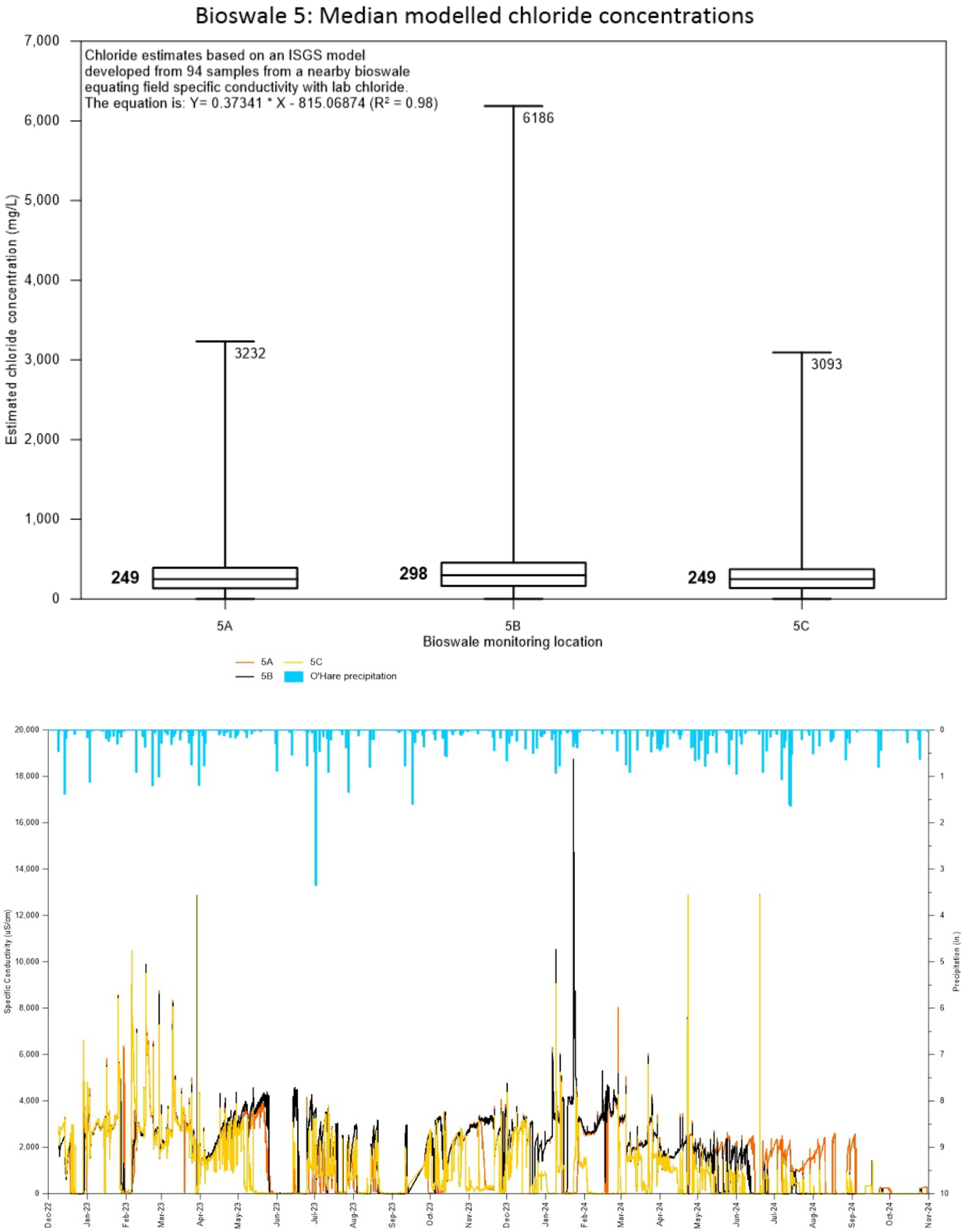
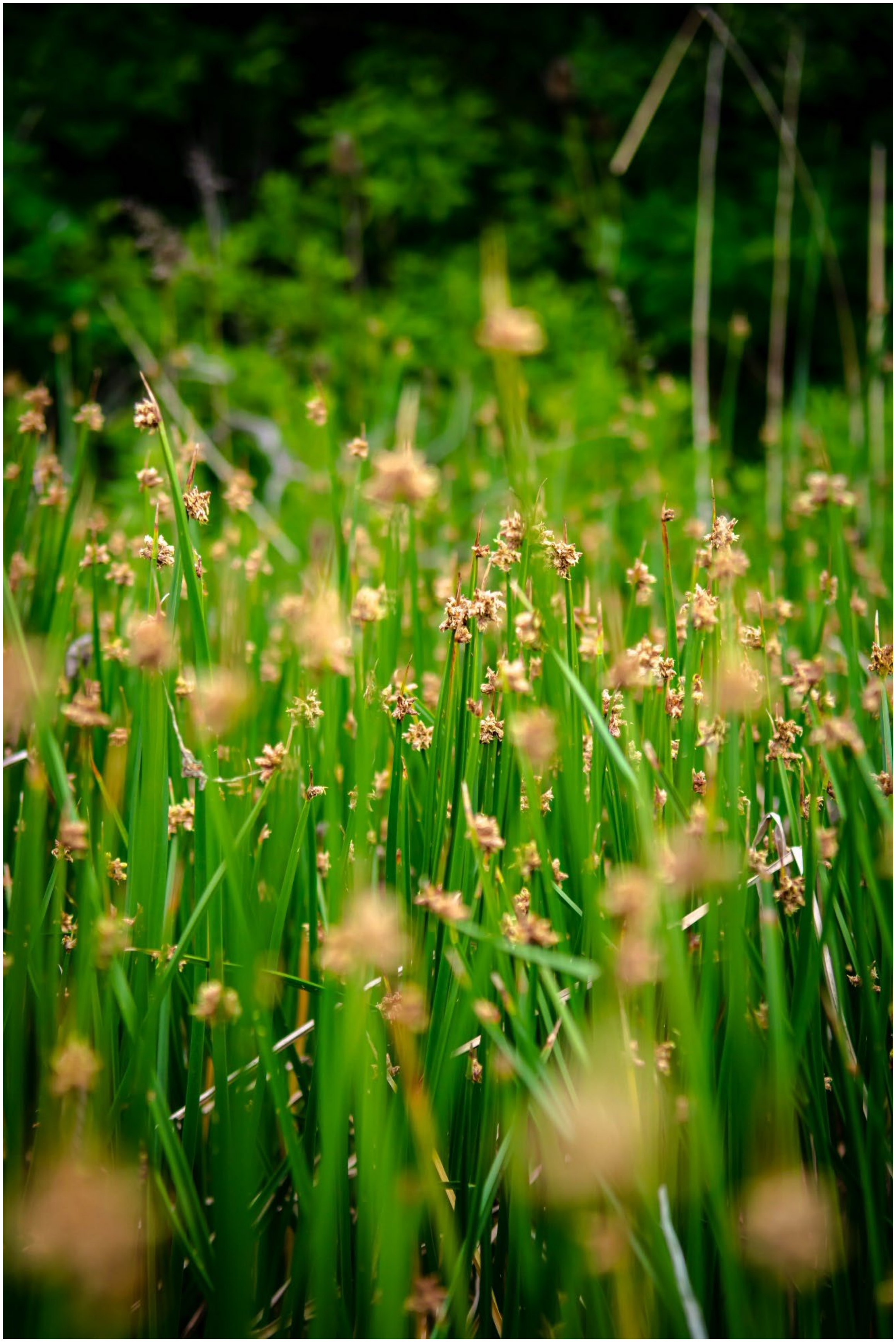


Figure 28 Boxplots of estimated chloride in mg/L for Bioswale 5 (Top; center line denotes medians and whiskers represent the minimum and maximum data values) and water depth data from three units (Bottom) for the Period of Record (12/9/2022 to 11/21/2024).



Appendix C. Qualifications and Accomplishments of the Research Team

Geoffrey Pociask (PI) is an Associate Scientist-Wetlands Geologist at the ISGS, a division of the Prairie Research Institute at the University of Illinois. He has supervised the Wetlands Geology Section at ISGS, a workgroup of 16, since 2018. His 22 years of experience includes research on wetland hydrologic function and wetland mitigation, watershed and stream assessment, and assessing the effects of road construction and other development activities on hydrology and water quality in aquatic habitats. He leads the Illinois Department of Transportation Statewide Hydrologic Monitoring Program at ISGS and is currently conducting research on wetland hydrologic function under the Illinois Department of Natural Resources Coastal Management Program.

Keith Carr (Co-PI) is an Associate Scientist-Wetlands Geologist at the Illinois State Geological Survey since 1994. Keith has been involved in research into bioswales and water quality improvement on various contracts with the Illinois Tollway since 2007 as a researcher, co-PI and currently as the principal PI. As a co-PI, he will interact with Loyola researchers in site selection, field instrument deployment, and the sharing and collection of water quality data. Keith has authored or co-authored 18 contract reports to the Tollway on bioswales and water quality and given four presentations at national and regional meetings summarizing these studies.

Brian Ohsowski (Co-PI) is an Assistant Professor focused on Conservation Biology and Restoration Ecology at Loyola's School of Environmental Sustainability. Dr. Ohsowski has been researching ecological restoration in the Great Lakes region for 17 years. His current research interests center on large-scale applied ecological restoration in biologically degraded sites within the Great Lakes watershed using applied land management tools (e.g. harvesting invasive species, biochar, compost) and developing advanced statistical methodology to inform ecological management. He is an author of 14 peer-reviewed publications and is committed to scientific education and high-quality student research.

Shane Lishawa (Co-PI) has 15-years of experience as a Faculty Research Associate at Loyola. His research focuses on invasive plant impacts on wetland ecosystems and wetland restoration. Since 2008, Lishawa has obtained (as PI or Co-PI) and managed over $3 million in federal and state grants and has published 24-peer reviewed articles. As co-PI, he will assist in overseeing the project, co-manage the Loyola budget, conduct data analysis, co-author publications, and assist in all reporting efforts.

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